

Concurrent Aerobic and Strength Training



Scientific Basics
and Practical Applications

Moritz Schumann
Bent R. Rønnestad
Editors



Concurrent Aerobic and Strength Training

Moritz Schumann • Bent R. Rønnestad
Editors

Concurrent Aerobic and Strength Training

Scientific Basics and Practical
Applications



Springer

Editors

Moritz Schumann
Department of Molecular and Cellular
Sports Medicine
German Sport University
Cologne
Germany

Bent R. Rønnestad
Department of Sports Sciences
Lillehammer, Inland Norway University of
Applied Sciences
Lillehammer
Norway

ISBN 978-3-319-75546-5

ISBN 978-3-319-75547-2 (eBook)

<https://doi.org/10.1007/978-3-319-75547-2>

Library of Congress Control Number: 2018957403

© Springer International Publishing AG, part of Springer Nature 2019

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publisher, the authors, and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, express or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: G  werbestrasse 11, 6330 Cham, Switzerland

Preface

Endurance and strength create the foundation of sports performance and are considered as basic elements of physical fitness and health. In addition, global exercise recommendations strongly recommend both aerobic and strength training for improvements of physical fitness and health as well as the prevention of chronic diseases across the life span. However, aerobic and strength training induce dissimilar biological adaptations, which may in combination result in compromised training adaptations. Thus, designing concurrent aerobic and strength training programs for various populations requires special consideration.

Typically, exercise and health professionals as well as sport practitioners are similarly concerned about the optimal concurrent training mode in an attempt to maximize both aerobic and muscular adaptations. Most frequently, questions such as whether concurrent aerobic and strength training should be performed on the same day or separated onto different days or whether endurance training performed first in a training session may negatively affect the quality of a subsequent strength training session and, thus, compromises long-term adaptations are controversially discussed. Furthermore, the importance of strength training for athletic performance of both team and individual sports has not yet received thorough acceptance among coaches and athletes.

While concurrent training has been practically applied in exercise training and sports coaching for multiple decades, it has been of scientific interest for a much shorter time. In fact, it was not until 1980 when Robert C Hickson found that strength but not endurance development may be compromised when intensive running and strength training were performed concurrently [1]. Ever since his pioneering study this phenomenon is known as the “interference effect” and has been of extensive scientific interest.

Interestingly, in contrast to these early observations, more recent studies have actually shown that concurrent training may not necessarily compromise neuromuscular adaptations to the extent that was initially suggested. Much rather, it was shown that the magnitude of blunted neural and muscular adaptations appears to be depending on a complex interplay of training program variables and biological predispositions. This was also underlined by scientific studies in which strength training was shown to be beneficial for endurance athletes by enhancing aerobic performance.

Nearly four decades after the appearance of the initial studies on concurrent aerobic and strength training, a large body of scientific studies on this topic is available. Nevertheless, numerous myths and false assumptions exist in fitness and health communities but also among top-level sports coaches and athletes, much of which is fueled by non-evidence-based knowledge. *Concurrent Aerobic and Strength Training: Scientific Basics and Practical Applications* aims to elucidate the concept of concurrent training for physical fitness and sports performance by providing a comprehensive overview on the latest stand of research.

Divided into 5 parts and 27 chapters, this book provides an extensive guide for exercise and health professionals, students, scientists, sport coaches, athletes of various sports, and those with a general interest in concurrent aerobic and strength training. Following a brief historical overview of the past decades of research on concurrent training, in Part I the physiological and neuromuscular differences of endurance and strength training are discussed. Thereafter, Part II aims at providing an up-to-date analysis of existing explanations for the interference phenomenon, while in Part III the training-methodological difficulties of combined aerobic and strength training are elucidated. In Parts IV and V the theoretical considerations reviewed in the previous parts are then practically applied to specific populations, ranging from children and elderly to athletes of various sports.

With *Concurrent Aerobic and Strength Training: Scientific Basics and Practical Applications*, we were privileged to work together with leading scientists and coaches from across the world to provide a novel book on one of the “hot topics” of exercise training. Our highest priority was to make this book an easily understandable and at the same time scientifically supported guide for the daily practice. We sincerely hope you will share our joy when reading this book.

Cologne, Germany
Lillehammer, Norway

Moritz Schumann
Bent R. Rønnestad

References

1. Hickson RC. Interference of strength development by simultaneously training for strength and endurance. Eur J Appl Physiol Occup Physiol. 1980;45(2–3):255–63.

Contents

1	A Brief Historical Overview on the Science of Concurrent Aerobic and Strength Training	1
	Moritz Schumann and Bent R. Rønnestad	
Part I Aerobic Versus Strength Training		
2	The Functional Genome in Physical Exercise	9
	Wilhelm Bloch	
3	Molecular and Physiological Adaptations to Endurance Training	19
	Anthony C. Hackney	
4	Neural Adaptations to Endurance Training.....	35
	Guillaume Y. Millet and John Temesi	
5	Physiological and Molecular Adaptations to Strength Training	51
	Juha P. Ahtiainen	
6	Neural Adaptations to Strength Training.....	75
	Simon Walker	
Part II The Interference Effect		
7	Proposed Mechanisms Underlying the Interference Effect	89
	Stian Ellefsen and Keith Baar	
8	Molecular Adaptations to Concurrent Strength and Endurance Training	99
	Eduardo O. De Souza	
9	Effects of Endurance-, Strength-, and Concurrent Training on Cytokines and Inflammation	125
	Jorming Goh, Chin Leong Lim, and Katsuhiko Suzuki	

- 10 Immediate Effects of Endurance Exercise on Subsequent Strength Performance.....** 139
Thomas W. Jones and Glyn Howatson
- 11 Acute Effects of Strength Exercise on Subsequent Endurance Performance.....** 155
Kenji Doma
- 12 Long-Term Effects of Supplementary Aerobic Training on Muscle Hypertrophy** 167
Tommy Lundberg

Part III Training-Methodological Considerations for Concurrent Aerobic and Strength Training

- 13 Methodological Considerations for Concurrent Training.....** 183
David J. Bishop, Jon Bartlett, Jackson Fyfe, and Matthew Lee
- 14 Effects of the Concurrent Training Mode on Physiological Adaptations and Performance** 197
Moritz Schumann
- 15 Recovery Strategies to Optimise Adaptations to Concurrent Aerobic and Strength Training** 213
Nicholas G. Allen, Samuel M. Higham, and Rob Duffield
- 16 Nutritional Considerations for Concurrent Training** 229
Timothy Etheridge and Philip J. Atherton

Part IV Concurrent Aerobic and Strength Training Throughout the Lifespan

- 17 Concurrent Training in Children and Adolescents** 255
Martijn Gäbler and Urs Granacher
- 18 Concurrent Training in Elderly** 277
Eduardo Lusa Cadore and Mikel Izquierdo
- 19 Concurrent Aerobic and Strength Training for Body Composition and Health.....** 293
Eurico Nestor Wilhelm and Ronei Silveira Pinto
- 20 Sex Differences in Concurrent Aerobic and Strength Training** 309
Olav Vikmoen

Part V Concurrent Aerobic and Strength Training for Athletic Performance

21 Long-Term Effects of Strength Training on Aerobic Capacity and Endurance Performance	325
Øyvind Sandbakk	
22 Strength Training for Endurance Cyclists	333
Bent R. Rønnestad	
23 Strength Training for Endurance Runners	341
Kris Beattie	
24 Strength Training for Cross-Country Skiers	357
Thomas Losnegard	
25 Strength Training for Swimmers	369
Iñigo Mujika and Emmet Crowley	
26 General Aspects of Concurrent Aerobic and Strength Training for Performance in Team Sports	387
Julien Robineau	
27 Concurrent Aerobic and Strength Training for Performance in Soccer	397
Joao Renato Silva	



A Brief Historical Overview on the Science of Concurrent Aerobic and Strength Training

1

Moritz Schumann and Bent R. Rønnestad

Introduction

The history of our humankind is characterized by pioneers such as Marco Polo, Christopher Columbus, and Sir Edmund Hillary, all of whom have attempted to explore the limits of human existence. Also exercise scientists are driven by the desire to expand the boundaries of biological factors limiting physical performance. However, even though exercise has been part of humanity since the antiquity, it was not until the early twentieth century, that the first attempts were made to scientifically explore the biological processes underlying the adaptations induced by regular physical exercise. As a pioneer in exercise science, between 1910 and 1920 August Krogh developed the first devices to study in depth the physiology of physical activity. Among those were for example an electromagnetic bicycle ergometer and an apparatus for gas analysis, both of which allowed him to study the relative contribution of carbohydrates and fat as sources for energy of muscular contractions [1]. Krogh was also the first to show that capillaries are the drive for oxygenation during physical exercise [2], for which he was awarded the Nobel Prize in medicine and physiology a few years later. These first discoveries did also set off a number of other ground-breaking explorations, such as the Nobel Prize of A.V. Hill of England for his findings related to the production of heat in muscles in 1922 and the later work of Roger Bannister in the 1950s and Bengt Saltin in 1960 [3, 4], all of which are nowadays considered as the foundation of exercise science research.

M. Schumann (✉)

Department of Molecular and Cellular Sports Medicine, German Sport University,
Cologne, Germany

e-mail: m.schumann@dshs-koeln.de

B. R. Rønnestad

Department of Sports Sciences, Lillehammer, Inland Norway University of
Applied Sciences, Lillehammer, Norway

e-mail: bent.ronnestad@inn.no

Also the science of progressive resistance training is a development of the twentieth century. Actually during World War II, most physicians still believed that strength training may be adverse to health and well-being, by sharing views of a well-known newspaper columnist stating that “extreme effort is not desirable in any kind of physical training nor is it good for the heart” [5]. However, only a few years later the first scientific papers of progressive overload resistance training were published by Thomas L. Delorme, who utilized progressive resistance training (defined as lifting multiple sets of the individual 10 repetition maximum) for the rehabilitation of injured servicemen [5]. Delorme’s book “Progressive Resistance Exercise: Technic and Medical Application” and his academic publications are nowadays understood as the foundation for the science of strength training and his research continued way beyond the official end of World War II. Apparently, the first publication utilizing strength training for fitness purposes appeared in 1946 in “The Physiotherapy Review” and showed that young women training 5 days a week would more than double their maximal strength within only 4 weeks—a finding which was truly ground-breaking at that time [6]. Thus, also during the subsequent years, research on strength training gained further popularity throughout the 1970s and 1980s, for example through pioneering research by Paavo Komi [7], as well as Michael H Stone, William J Kraemer, and Keijo Häkkinen in the 1980s [8, 9].

Concurrent Training and the “Interference Effect”

Interestingly, it was not until 1980 when the first studies of combining aerobic and strength training were published. Robert C Hickson discovered that the strength but not endurance development may be compromised when a high frequency of intensive running and strength training sessions (11 weekly sessions in previously untrained persons!) were performed concurrently for more than 6–8 weeks [10]. In fact, the conclusion of this study reads that it might be deleterious for strength athletes to perform strenuous endurance activities simultaneously. Even more remarkable, Hickson also concluded that the compromised strength adaptations were not attributed to residual fatigue, despite the high volume of aerobic and strength training but the possible mechanisms behind these findings remained to be elucidated. Ever since his pioneering study, this phenomenon is known as the “interference effect.”

Already 5 years later, in 1985 Dudley and Djamil revisited the initial observations by Hickson by performing a study with a much lower training frequency (i.e., 3 weekly sessions of aerobic and resistance training, respectively) but also a much shorter training duration of only 7 weeks [11]. The main findings of this study were that the “interference effect” was only observed at high but not low angular velocities. While it was concluded that rapid force development might be more susceptible for concurrent aerobic training, it needs to be acknowledged that the duration of 7 weeks may have also been too short to show impaired maximal strength development because in the study of Hickson strength improvements started to plateau after 6–8 weeks in the concurrent training group [10].

The early conclusions on the incompatibility of aerobic and strength training were challenged about 10 years later, when the first papers on the effects of different concurrent training modes were published. It was hypothesized that residual fatigue induced by aerobic exercise may compromise the ability to develop tension during the subsequent strength loading [12, 13], when both exercises are performed in close proximity. In fact, it was speculated that the resulting compromised “quality” of the strength training (indicated by a lower absolute lifted load) may lead to impaired chronic neuromuscular adaptations, as observed in the initial study by Hickson [12]. Interestingly, in this study only minor lower body strength gains in previously untrained students were observed when running was consistently performed prior to strength training but no impairments were found in upper body strength, indicating the “interference effect” to be a local rather than a central phenomenon.

Around the same time, Sale and colleagues comprehensively investigated the effects of concurrent training performed on the same day compared to concurrent training carried out on alternating days by including muscle tissue sampling [14]. In their study, young men performed concurrent training twice a week for a duration of 20 weeks. While the magnitude of improvements in maximal strength was much larger in the group training on alternating days, no differences between the groups were observed for muscle hypertrophy and improvements in aerobic capacity. However, training on alternating days increased citrate synthase activity which might be beneficial for the total aerobic capacity and fractional utilization of maximal oxygen uptake ($\text{VO}_{2\text{max}}$).

In 1993, Collins and Snow [15] expanded on the findings of these earlier studies by comparing the physiological adaptations to two different exercise orders (i.e., aerobic followed by strength training and vice versa), which is nowadays understood as the “order effect” [16, 17]. In this study, both men and women performed either of the two exercise orders three times weekly, over a period of 7 weeks. It was found that both neuromuscular and cardiorespiratory adaptations appeared to have occurred independent of the exercise order following short-term training. Moreover, Collins and Snow actually did not observe differences in the training intensities (i.e., “quality”) of aerobic and strength exercises, irrespective of the training sequence [15].

A further development in the history of concurrent training was set only a few years later by a study of Häkkinen et al. [18], who confirmed the assumption that the training volume might be a crucial mediator in the magnitude of interference over a training period of 21 weeks [18]. While in this study no impaired maximal strength development was observed, the adaptations in rapid force development commenced to plateau already after 7 weeks of training, indeed confirming the observation from Dudley and Djamil in 1985 that explosive strength might possibly be more prone to the aerobic exercise-induced interference than maximal strength development [11]. In fact, this phenomenon remains a scientific interest until today [18, 19].

Yet another milestone was set concomitantly with the advances in the molecular science and the possibilities to look closer at the mechanisms underlying the potential interference in the signaling pathways during concurrent training. Among the

first proposed mechanisms behind the interference effect was the “AMPK-PKB switch” hypothesis presented by Atherton and colleagues [20]. This hypothesis was based on a model where rodents were electrically stimulated to mimic endurance and strength training. They proposed that AMPK activation by the endurance stimulus could ultimately inhibit mTOR activation and thereby reduce translation initiation and elongation [20]. This hypothesis was further developed in subsequent review papers, e.g., by Coffey and Hawley [21] and Hawley [22] and still remains one of the hypothesis being investigated, although evidence is emerging for this explanation representing an oversimplification [23].

Strength Training and Aerobic Performance

In his initial study, Hickson also concluded that there is little or no benefit for endurance athletes to strength train at the same time [10]. However, already in a paper published in the same year, the same group showed that untrained men nearly doubled time to exhaustion on the cycle ergometer after 10 weeks of pure strength training, without presenting significant changes in $\text{VO}_{2\text{max}}$ [24]. Because the effects were much smaller during treadmill running, it was concluded that improvements in cycling performance were predominantly attributed to increased maximal strength rather than changes in oxidative capacity. Moreover, the participants in this study were previously untrained and, thus, any type of training would have probably induced performance benefits.

In 1988, again Hickson expanded on his previous studies by incorporating strength exercise into the training routine of endurance athletes and concluded that at least endurance performance requiring fast-twitch fiber recruitment (i.e., short-term, anaerobic endurance performance) may actually be improved by strength training supplementation [25]. Moreover, no indications for impaired endurance performance were apparent and body mass and thigh girth were maintained (although this study lacked a control group performing endurance training only in the intervention period). Despite a lack of evidence for excessive increases in muscle mass, especially muscle hypertrophy is nowadays still of concern for endurance athletes and coaches, as increased bodyweight might hinder performance in weight-bearing disciplines, such as endurance running.

Throughout the subsequent years, the effects of strength training for aerobic performance were of minor research interest. However, in 1999 studies by Paavolainen et al. [26] and Hoff et al. [27] provided evidence for improved exercise economy and consequently overall endurance performance in cross-country skiers. Similarly to the early study by Hickson, also these studies showed that performance improvements occurred independent of improvements in $\text{VO}_{2\text{max}}$ and were much rather related to changes in neuromuscular characteristics. This is because in the study by Paavolainen et al. the improvements in 5 km running time were actually associated with a shorter ground contact times and, thus, a more economic running pattern.

Interestingly, even though only a few studies had investigated the effects of strength training for endurance athletes by the end of the last century, the majority

of these studies pointed towards favorable changes of endurance performance. However, in a textbook focusing on training and nutritional strategies for sport [28], this was reflected quite controversially. In the chapter “Training techniques for successful endurance performance,” the effects of strength training for sports such as swimming, rowing, cross-country-skiing, and endurance cycling were discussed. The conclusion for all of these endurance sports was that regular resistance training does not beneficially affect performance of endurance athletes but much rather may restrict the volume of “beneficial,” sport-specific training. Moreover, “The evidence against well-trained endurance athletes incorporating resistance training into their normal workouts to improve their endurance performance appears to be strong” ([28], pp. 136). While the early studies of Hickson and others were acknowledged, it was further suggested that “[...] for highly-trained athletes who are already capable of generating high power outputs in their chosen discipline, further improvements in strength are a less important factor in enhanced endurance performance. At the highest level of competition, increases in strength and power per se are not as critical to successful performance as the development of correct technique. The bottom line is that modern training studies do not support the use of resistance training programs for improving the performance of highly-trained athletes” ([28], pp. 137–138).

While this view is still shared by numerous coaches and athletes, about 20 years later a large number of studies have accumulated to provide evidence for strength training being an integral part of successful sports performance, also in endurance sports. Thus, it is about time to summarize the potential of regular strength training to improve athletic performance, thereby discussing the “does” and “don’t’s” of concurrent training prescription in order to convince sport practitioners, coaches, and athletes of the importance of combining aerobic and resistance training for optimal sports performance and health.

References

1. Rehberg PB. August Krogh, November 15, 1874–September 13, 1949. *Yale J Biol Med.* 1951;24(2):83–102.
2. Krogh A. The number and distribution of capillaries in muscles with calculations of the oxygen pressure head necessary for supplying the tissue. *J Physiol.* 1919;52(6):409–15.
3. Bannister RG. The effects on the respiration and performance of adding oxygen to the inspired air during exercise. *J Physiol.* 1953;120(4):66P–7P.
4. Christensen EH, Hedman R, Saltin B. Intermittent and continuous running. (A further contribution to the physiology of intermittent work.). *Acta Physiol Scand.* 1960;50:269–86. <https://doi.org/10.1111/j.1748-1716.1960.tb00181.x>.
5. Todd JS, Shurley JP, Todd TC. Thomas L. DeLorme and the science of progressive resistance exercise. *J Strength Cond Res.* 2012;26(11):2913–23. <https://doi.org/10.1519/JSC.0b013e31825adcb4>.
6. Houtz SJ, Parrish AM, Hellerbrandt FA. The influence of heavy resistance exercise on strength. *Physiotherap Rev.* 1946;26(6):299–304.
7. Komi PV, Buskirk ER. Reproducibility of electromyographic measurements with inserted wire electrodes and surface electrodes. *Electromyography.* 1970;10(4):357–67.
8. Häkkinen K, Komi PV. Electromyographic changes during strength training and detraining. *Med Sci Sports Exerc.* 1983;15(6):455–60.

9. Stone MH, Byrd R, Tew J, Wood M. Relationship between anaerobic power and olympic weightlifting performance. *J Sports Med Phys Fitness*. 1980;20(1):99–102.
10. Hickson RC. Interference of strength development by simultaneously training for strength and endurance. *Eur J Appl Physiol Occup Physiol*. 1980;45(2–3):255–63.
11. Dudley GA, Djamil R. Incompatibility of endurance- and strength-training modes of exercise. *J Appl Physiol (Bethesda, MD: 1985)*. 1985;59(5):1446–51. <https://doi.org/10.1152/jappl.1985.59.5.1446>.
12. Craig BW, Lucas J, Pohlman R, Stelling H. The effects of running, weightlifting and a combination of both on growth hormone release. *J Strength Cond Res*. 1991;5(4):198–203.
13. Lee, A.; Craig, B. W.; Lucas, J.; Pohlman, R.; Stelling, H. (1990): The effect of endurance training, weight training and a combination of endurance and weight training upon the blood lipid profile of young male subjects. In: *J Strength Cond Res* (4(3)), S. 68–75.
14. Sale DG, Jacobs I, MacDougall JD, Garner S. Comparison of two regimens of concurrent strength and endurance training. *Med Sci Sports Exerc*. 1990;22(3):348–56.
15. Collins MA, Snow TK. Are adaptations to combined endurance and strength training affected by the sequence of training? *J Sports Sci*. 1993;11(6):485–91. <https://doi.org/10.1080/02640419308730017>.
16. Schumann M, Eklund D, Taipale RS, Nyman K, Kraemer WJ, Häkkinen A, et al. Acute neuromuscular and endocrine responses and recovery to single-session combined endurance and strength loadings: “order effect” in untrained young men. *J Strength Cond Res*. 2013;27(2):421–33. <https://doi.org/10.1519/JSC.0b013e31827f4a10>.
17. Taipale RS, Häkkinen K. Acute hormonal and force responses to combined strength and endurance loadings in men and women. The “order effect”. *PLoS One*. 2013;8(2):e55051. <https://doi.org/10.1371/journal.pone.0055051>.
18. Häkkinen K, Alen M, Kraemer WJ, Gorostiaga E, Izquierdo M, Rusko H, et al. Neuromuscular adaptations during concurrent strength and endurance training versus strength training. *Eur J Appl Physiol*. 2003;89(1):42–52. <https://doi.org/10.1007/s00421-002-0751-9>.
19. Schumann M, Küüsmaa M, Newton RU, Sirparanta A-I, Syväoja H, Häkkinen A, Häkkinen K. Fitness and lean mass increases during combined training independent of loading order. *Med Sci Sports Exerc*. 2014;46(9):1758–68. <https://doi.org/10.1249/MSS.0000000000000303>.
20. Atherton PJ, Babraj J, Smith K, Singh J, Rennie MJ, Wackerhage H. Selective activation of AMPK-PGC-1alpha or PKB-TSC2-mTOR signaling can explain specific adaptive responses to endurance or resistance training-like electrical muscle stimulation. *FASEB J*. 2005;19(7):786–8. <https://doi.org/10.1096/fj.04-2179fje>.
21. Coffey VG, Hawley JA. The molecular bases of training adaptation. *Sports Med (Auckland, NZ)*. 2007;37(9):737–63.
22. Hawley JA. Molecular responses to strength and endurance training. Are they incompatible? *Appl Physiol Nutr Metab*. 2009;34(3):355–61. <https://doi.org/10.1139/H09-023>.
23. Apró W, Wang L, Pontén M, Blomstrand E, Sahlin K. Resistance exercise induced mTORC1 signaling is not impaired by subsequent endurance exercise in human skeletal muscle. *Am J Physiol Endocrinol Metab*. 2013;305(1):E22–32. <https://doi.org/10.1152/ajpendo.00091.2013>.
24. Hickson RC, Rosenkoetter MA, Brown MM. Strength training effects on aerobic power and short-term endurance. *Med Sci Sports Exerc*. 1980;12(5):336–9.
25. Hickson RC, Dvorak BA, Gorostiaga EM, Kurowski TT, Foster C. Potential for strength and endurance training to amplify endurance performance. *J Appl Physiol (Bethesda, MD: 1985)*. 1988;65(5):2285–90. <https://doi.org/10.1152/jappl.1988.65.5.2285>.
26. Paavolainen L, Häkkinen K, Hämäläinen I, Nummela A, Rusko H. Explosive-strength training improves 5-km running time by improving running economy and muscle power. *J Appl Physiol (Bethesda, MD: 1985)*. 1999;86(5):1527–33. <https://doi.org/10.1152/jappl.1999.86.5.1527>.
27. Hoff J, Helgerud J, Wisloff U. Maximal strength training improves work economy in trained female cross-country skiers. *Med Sci Sports Exerc*. 1999;31(6):870–7.
28. Hawley J, Burke L. Peak performance. Training and nutritional strategies for sport. St. Leonards: Allen & Unwin; 1998.

Part I

Aerobic Versus Strength Training



The Functional Genome in Physical Exercise

2

Wilhelm Bloch

Introduction

Different kinds of physical exercise such as aerobic, anaerobic, and resistance training as well as the combination of these trainings essentially contribute to an enhancement of physical performance in elite and recreational sports. Furthermore, physical activity leads to a risk reduction, better prognosis, and decrease of specific medical treatment side effects of several common diseases, including cancer, cardio-vascular-, metabolic-, and neurodegenerative disorders [1–3]. Recent research suggests that exercise acts as a potent regulator of the functional genome through epigenetic modifications. The functional genome may explain short and long-lasting variations in health and performance in relation to the physical activity and training. Moreover, the functional genome is a product of the genome, including polymorphisms, and epigenetic modulations of gene availability. Therefore, it is necessary to consider gene polymorphisms and epigenetic modifications as well as the combination of both in order to understand the functional genome underlying the individual performance.

Polymorphisms/Genome

The genome is derived from the blueprint of the human organism in the form of the deoxyribonucleic acid (DNA) sequence of the 23 pairs of chromosomes found in every nucleated cell and the genes encoded in the mitochondrial DNA. A chromosome is formed by two complementary strands of DNA. DNA molecules are large polypeptides in which the backbone of the molecule is composed of five-carbon sugar residues, i.e., deoxyribose. The genetic information of each chromosome is

W. Bloch

Department of Molecular and Cellular Sport Medicine, German Sport University Cologne,
Cologne, Germany
e-mail: w.bloch@dshs-koeln.de

stored in a long string of the four DNA bases: adenine (A), cytosine (C), guanine (G), and thymine (T). The order and number of the bases determine the information content of each gene, coding the blueprint for specific proteins. Every gene consists of coding sequences (exons), noncoding regions (introns), and regulatory sequences. The genes can reveal variations in the base sequence of the DNA [4]. DNA sequence variations that are common in the population are called polymorphisms, as opposed to rare gene variations that are called mutations. The less common base must have a frequency of at least 1% in the population. The most common type of genetic variations among individuals is a single nucleotide polymorphism, mostly described as SNPs (pronounced “snips”). Single bases are replaced by another base leading to a change of the genetic sequence. Such variations of the DNA sequence can affect the expression of the gene and alter the products coded by this gene. Furthermore, these gene variants may explain differences in the individual phenotype. The SNPs may reveal differences in physical capabilities and training-induced effects between subjects. Therefore, research has focused for more than 20 years on recognizing polymorphisms relevant for the prediction of physical capacity and exercise engagement [4], even though it is obvious that such polymorphisms cannot sufficiently explain the human phenotype or the exercise-related individual variants.

Epigenetics/Functional Genome

The basis for understanding the relevance of the functional genome was provided by Conrad Waddington. He defined it as “The branch of biology which studies the causal interactions between genes and their products, which bring the phenotype into being” [5]. Today, we know that the epigenetic mechanisms behind the regulation of the functional genome are “causal interactions” consisting of three major mechanisms:

1. DNA modifications by methylation of bases which do not affect the base sequence
2. Posttranslational modifications of histone proteins by different mechanisms such as acetylation, methylation, and phosphorylation
3. Expression of small RNA molecules, also known as micro (mi) RNAs.

The cytosine methylation within the DNA is the leading mechanism for longtime changes of the functional genome. Such modifications can alter the functional genome for different time periods, from short (minutes to days) to long (weeks to years). Furthermore, it becomes obvious that these changes are partially stable throughout the lifetime and also across generations. A hypermethylation in cytosine-rich regions (i.e., called CpG islands) correlates with gene suppression and modulation of the transcriptional activity of the gene, depending on the localization of the methylated gene side. Methylation of CpG islands in the promotor region makes the DNA inaccessible for transcriptional-relevant factors. Furthermore, it can lead to recruitment of enzymes, provoking further inhibitory epigenetic modifications. DNA-methyltransferases (DNMTs) are the enzymes which perform the DNA-methylation [6].

A second mechanism regulating the activity of gene availability is the histone packing of the DNA-strand. This mechanism is essential to condense the DNA-strand in a relatively small nucleus without a loss of DNA availability. Histone proteins and the adjacent DNA are called chromatin. The histone isoforms 2A, 2B, 3, and 4 build an octameric structure where the DNA is recoiled on with 2.5 turns each. The DNA part (Linker DNA) which connects two of those complexes is stabilized by histone 1 proteins. Electrostatic attraction forces of the negatively charged DNA-backbone and positively charged amino-acid side-chains in the N-terminus of histone proteins are responsible for the DNA/histone protein connection. The connection can be prevented by neutralization of the binding force through positive charges between these amino-acid side-chains. Neutralization of binding force leads to a less compact and better accessible DNA and/or produce recruiting sites for gene-activating and silencing proteins. The modifications are performed by specific enzymes such as histone acetyl transferases (HATs) and histone deacetylases (HDACs) [7, 8]. HATs and HDACs are mediating the modulation of the acetylation stage of the histones.

The third epigenetic mechanism underlying the DNA-methylation and histone modifications is the expression of miRNAs which does not regulate the DNA availability but the stability of the transcription products, i.e., the messenger mRNAs. MicroRNAs are short RNA molecules (21 bases on average) which can bind to complementary messenger (m)RNA, thereby inhibiting the translation and inducing mRNA degradation [9]. In addition to the classic role suggested for miRNAs, new research revealed that they are also capable of activating translational processes [10].

The first descriptions of epigenetic alterations were in context of imprinting and X-chromosome silencing. Epigenetic regulations were primarily understood as static and long-lasting alterations. Today, the understanding changed towards a modulation of the functional genome by epigenetic mechanisms. Depending on the type of epigenetic alterations, these were considered roughly dynamic. Especially histone modifications and expression of miRNAs are rather dynamic processes. They are highly sensitive to intrinsic and extrinsic factors leading to short up to long-lasting alterations of gene and gene product availability. It is, however, important to bear in mind that epigenetic modifications are mainly gene- and tissue-specific alterations with different time courses [11]. Therefore, it is not surprising that epigenetic modifications by different types of stimuli (i.e., different training stimuli) are mainly shown for all organs, tissues, and cells in the mammalian organism. Furthermore, changes of the functional genome by epigenetic modifications are important for physical performance and several chronic diseases which can be modulated by physical exercise [12].

Interaction of Polymorphisms and Epigenetic Modulations

Changes in the DNA sequence, e.g., by polymorphism are the major cause for gene regulations. On the other hand, chromatin structure regulates gene activity at the epigenetic level. If polymorphism results in punctual depletion of a methylable site

and this has spreading effects on adjacent sequences, one would expect to observe an association between the DNA-methylation state and proximal DNA sequence. In addition, histone-dependent epigenetic regulations are influenced by polymorphism showing the complex interaction between genome and epigenome. A further layer of complexity in the interplay between both genome and epigenome exists in the miRNA. It is indicated that polymorphisms can impact on miRNA function [13]. Therefore, it can be assumed that the functional genome can only be understood if epigenetic modulations are related to the structural genome including the polymorphisms and vice versa.

Physical Exercise Changes the Functional Genome Dependent on Polymorphisms and Epigenetic Modulations

The discussion on the relevance of genome and epigenome in physical performance may be easier and understood if the focus is set on the ACE gene. The ACE I/D polymorphism (i.e., insertion/deletion polymorphism) is related to endurance performance. However, consistent with studies in which genetic associations between the ACE gene and the corresponding I/D polymorphism were shown; it appears that epigenetic modulations also affect ACE gene activity, both with and without the ACE polymorphism. It is speculated that the epigenetic regulation of the ACE gene is as relevant to human endurance performance as the I/D polymorphism [14]. On the other hand, physical activity affects health and physical fitness/performance by epigenetic modulation of the functional genome, which may aid explaining long-lasting effects of physical activity.

About 10 years ago, Pedersen and colleagues [15] revealed that acute physical exercise leads to a short inflammatory-like cytokine pattern (particularly an increase in Interleukin (IL)-6) which is followed by mid-term anti-inflammatory response (i.e., an increase in IL-10, depression of TNF- α production, and expression of soluble receptors of pro-inflammatory cytokines). Therefore, they proposed a model which stated that regular exercise has a chronic anti-inflammatory effect, possibly explaining the preventive effects of exercise against several chronic diseases. Furthermore, numerous studies reported decreased serum levels of the inflammatory acute phase protein C-reactive protein (CRP) after different kind of exercise interventions [16]. Such mid- and long-term alterations of the inflammatory status could be related to epigenetic modifications [12]. Therefore, it is not surprising that the group of Nakajima et al. [17] showed that the ASC gene (a gene which encodes for pro-inflammatory cytokines) reveals an age-dependent loss of methylation in the promotor region. The consequence of this hypomethylation is an increased expression of pro-inflammatory cytokines in older subjects and can be partially restored by a 6-month interval endurance exercise program Nakajima et al. [17]. The higher levels of methylation in the promotor region of the ASC gene compared to sedentary controls can lead to a decreased expression of pro-inflammatory cytokines. Despite these examples, several exercise-induced alterations of the functional genome by epigenetic mechanisms are reported.

Skeletal Muscle

Epigenetic regulation, such as DNA-methylation, histone modifications, and microRNAs, are believed to be crucial to morphological changes. DNA-methylation affects the expression of many genes that are critical to skeletal muscle development, such as the homeobox genes, T-box genes, and sine oculis-related homeobox 1, which is strongly hypermethylated, whereas contractile fiber genes are hypomethylated. Furthermore, exercise induces a whole genome hypomethylation in human skeletal muscle and a dose-dependent expression of the pyruvate dehydrogenase kinase isozyme 4, of the peroxisome proliferator activator receptor delta and of the glucose transporter GLUT4, which counteracts age and diseases-dependent hypermethylation [18]. Beside several further examples for histone modifications by exercise, McGee and colleagues [19] detected HDAC-specific inhibition patterns and changes in histone acetylation after a single bout of exercise. While HDAC4 was translocated from the nucleus to the cytosol, HDAC5 showed elevated ubiquitination levels through exercise. Furthermore, high blood lactate levels induced by exercise may alter histone acetylation and affect p38 MAPK signaling, gene expression, and thereby cell differentiation and adaptation in myoblasts and skeletal muscle in vitro and likely in vivo [20]. Safdar et al. [21] showed increased levels of miRNA 1 as well as a decreased expression of its target HDAC4 in exercising mice. Since HDAC4 is known to be a transcriptional repressor for muscle-specific differentiation factors (e.g., MyoD), this study illustrates the complexity of epigenetic modifications and its own epigenetic regulation. Further studies aimed at providing a better understanding of DNA-methylation, histone modulation, and miRNA regulation in muscle development and homeostasis may help to better understand the role of physical exercise for skeletal muscle maintenance, growth, adaptation, and repair.

Vascular System

The functioning and health of the vascular system is dependent on vascular smooth muscle cell (SMC), and endothelial cell (EC) structure and function as well as on extra cellular matrix (ECM). The phenotype of the SMCs and ECs as well as the composition of ECM plays a key role in the protection against atherosclerosis and other vascular diseases. SMCs and their products contribute to almost 70% of the mass of lesions in atherosclerotic events [22, 23]. They are highly adaptive in response to environmental alterations [24]. Epigenetic modifications are involved in the adaptation of SMCs phenotypes [25]. Several examples can be given for the epigenetic regulations of the vascular system, all of which are relevant for the explanation of changes of the functional genome. For example: (1) Specific histone modifications, like the acetylation of H3K9 and deacetylation at different lysine-residues in H4 induce the binding of SRF to its DNA binding-site leading to alteration of proliferation of SMCs. (2) Myocardin (a SRF-co-activator protein) recruits different types of HATs and HDACs which may lead to the modifications mentioned above

[26, 27]. (3) Epigenetic modifications in the superoxide dismutase gene lead to SMC proliferation and a decreased apoptosis rate [28, 29]. (4) Increased oxidative stress levels are associated with an altered activity of HDACs and HATs [30]. (5) Matrix-metallo-proteinases (MMPs) which have the potential to reorganize the extra cellular matrix (ECM). Besides MMP-2 and -9 the expression of other MMPs -1, -3, -13 also underlies an epigenetic regulation [31]. In addition to exemplary described DNA- and histone modifications, miRNAs are critically involved in hypertensive-induced pathological changes of SMCs [32]. Although it is well known that exercise can influence all of the described mechanisms, less is known about the impact of exercise on epigenetic modifications of the vascular system in humans. Exercising mice revealed altered endothelial function, leading to significantly lower levels of angiotensin 2, endothelin 1, plaques, and foam cells compared to sedentary animals in a high-fat diet atherosclerosis model. These modulations were associated with changes of miRNA expression (miRNA 155 up-regulation; miRNA 146, and miRNA 126 down-regulation) in trained animals [33]. Interestingly, the expression of vasodilatory eNOS is known to be inhibited by miRNA 155 [34] providing evidence for an exercise-induced epigenetic regulation of endothelial function with regard to NO production. A down-regulation of miRNA 126 leads to endothelial dysfunction and suppresses the expression of integrins which is followed by impaired properties for leukocyte extravasation [35]. Therefore, the exercise-triggered increase in miRNA 126 might also be a positive epigenetic effect. It seems interesting for further studies to relate exercise-mediated shear stress with epigenetic regulation of eNOS as well as further epigenetic gene modulations by exercise stimuli in endothelial cells [36]. Furthermore, exercising mice revealed decreased levels of miRNA 16 and 126 which are both known to suppress the expression of VEGF [37] and thereby vascular growth, repair, and remodeling. Regarding endothelial and vascular repair, recent studies demonstrated that epigenetic mechanisms are important transcriptional regulators of angiogenic genes in endothelial cells (including modifications of DNA and histones as well as noncoding RNA) [12]. Additionally, they play an important role in the regulation of endothelial stem/progenitor cell function [38] but up to now, a direct link between epigenetic modulations of endothelial cells and endothelial stem/progenitor cells is missing.

Heart

The functional genome plays an important role in the physiological and pathophysiological development and adaption of cardiomyocytes in the context of adaptive and maladaptive cardiac-hypertrophy and function/dysfunction. Epigenetic mechanisms seem crucial for the determination of the functional genome in cardiomyocytes. Animal studies indicate that the inhibition of HDAC3 leads to the development of cardiomyopathies in a time point and nutrition-dependent manner [39]. The cardiomyopathy may develop more severe, if HDAC are early inhibited and a high-fat diet is given, ultimately leading to increased lethality. Furthermore, the inhibition of

HDAC4 promotes cardiac-stem-cell-induced regeneration and repair [40]. A miRNA-mediated induction of cardiac-hypertrophy is also reported in numerous studies [41]. On the chromatin level, human studies have not investigated the impact of exercise on cardiomyocytes, while first evidence for epigenetic regulation of chromatin is recently given in mice. It has been demonstrated that exercise can alter the HDAC4 level influencing the occurrence of heart failure and cardiac fatigue [42]. With regard to miRNAs, it has been reported that exercise decreased cardiac miRNA 208a expression in mice [43]. Further speculation for an exercise-dependent regulation of cardiomyocytes by miRNA is given for miRNA208a, which leads to a reversion of pathological changes in myosin heavy chain (MHC) expression [44]. The pathological changes are characterized by an overexpression of the fetal β MHC, leading to slow ATPase activity as well as a down-regulation of the adult α MHC (fast ATPase activity). The fact that exercise improves the balance of α MHC and β MHC was already described earlier but the results of these studies reveal that the underlying mechanism is potentially based on epigenetic alterations.

Extracellular Matrix, Adipocytes, and Immune Cells

Beside maladaptation of cardiomyocytes, pathophysiological alterations of the ECM are a hallmark of several diseases including cardiac diseases. Changes of the ECM are mostly characterized by an accumulation of collagen, induced by either an over-expression or decrease in collagen degradation through MMPs and an altered function of fibroblasts (e.g., cytokine production, such as TNF- α and TGF- β). Furthermore, changes of DNA-methylation are related to these mechanisms [45] and numerous miRNAs were also described to be involved in these fibrotic processes. Exercise is known to directly impact the ECM in different tissues and may alter the collagen pattern (e.g., in the heart of exercising rats by down-regulation of several active MMPs), while it seems to counteract an age-dependent increase in TGF- β [46]. Furthermore, exercise induces an up-regulation of miRNA 29c, which has been recognized to be involved in fibrotic alterations. Since this increased miRNA 29 c expression was accompanied by a decreased expression of collagen I and III, further evidence for a positive exercise-induced epigenetic regulation is provided [47].

Besides fibroblasts, other mesenchymal derived cell types, such as adipocytes are also epigenetically regulated. In adipocytes a 6-month exercise program can induce an increased hypermethylation of HDAC4 and a reduced expression of HDAC4. This could counteract obesity by reduction of lipogenesis in adipocytes [48]. Furthermore, other bone marrow-derived non-mesenchymal cell types are targets for exercise-induced epigenetic regulation. It has been suggested that a 4-week high intensity exercise program in young healthy adults has a sensitive impact on the methylome of leukocytes. In addition, the demethylation of numerous CpG islands by exercise leads to an epigenetic activation of lymphocytes [49]. Actually, the same group also showed that resistance exercise training improves muscular strength is associated with reprogramming of the leukocyte DNA methylome and transcriptome [50]. These results support the findings from other studies, which

described an exercise-induced epigenetic regulation of leukocytes [17, 51, 52]. These findings reveal a distinct influence of exercise for the functional genome on bone marrow-derived mesenchymal and hematopoietic cell lines.

Summary

As mentioned above, both the genome and epigenome are interacting to determine the individual human phenotype including characteristics of physical fitness, performance, and health. However, the knowledge about this interplay and the underlying mechanisms are still sparse. In particular, the knowledge about the regulation of the functional genome by the type of physical exercise is rare. Most epigenetic studies do not differentiate between types of physical exercise, although it is well known that aerobic and strength training induces different mechanisms and signaling, potentially relevant for the determination of the functional genome. Furthermore also the predictive value of the functional genome including polymorphism and epigenetics for aerobic and strength performance and trainability is not yet sufficiently deciphered. Nevertheless, distinct evidence suggests that besides epigenetic drugs, physical activity has the potential to regulate the human phenotype by altering the functional genome as well as the product of the genome and epigenome. As such it becomes evident that the functional genome builds the foundation for biological adaptations to exercise training. Sophisticated research strategies are needed to transfer study results from bench to practice. These strategies must respect the type and mode of exercise, as well as the underlying mechanisms and signaling.

Acknowledgments The author would like to thank Mrs. Christine Koliamitra for editorial support.

References

1. Lee IM, Shiroma EJ, Lobelo F, Puska P, Blair SN, Katzmarzyk PT, Lancet Physical Activity Series Working Group. Effect of physical inactivity on major non-communicable diseases worldwide: an analysis of burden of disease and life expectancy. *Lancet*. 2012;380(9838):219–29.
2. Mattson MP. Lifelong brain health is a lifelong challenge: from evolutionary principles to empirical evidence. *Ageing Res Rev*. 2015;20:37–45.
3. Schmid D, Leitzmann MF. Association between physical activity and mortality among breast cancer and colorectal cancer survivors: a systematic review and meta-analysis. *Ann Oncol*. 2014;25(7):1293–311.
4. Bouchard C, Rankinen T, Timmons JA. Genomics and genetics in the biology of adaptation to exercise. *Compr Physiol*. 2011;1(3):1603–48.
5. Waddington CH. The epigenotype. *Endeavour*. 1942;1:18–20.7.
6. Klose RJ, Bird AP. Genomic DNA methylation: the mark and its mediators. *Trends Biochem Sci*. 2006;31(2):89–97.
7. Kouzarides T. Chromatin modifications and their function. *Cell*. 2007;128:693–705.
8. Kouzarides T, Berger SL. Chromatin modifications and their mechanism of action. In: Allis CD, Jenuwein T, Reinberg D, editors. *Epigenetics*. 1st ed. New York: Cold Spring Harbor Laboratory; 2006. p. 191–209.

9. Mercer TR, Dinger ME, Mattick JS. Long non-coding RNAs: insights into functions. *Nat Rev Genet.* 2009;10(3):155–9.
10. Lee S, Vasudevan S. Post-transcriptional stimulation of gene expression by microRNAs. *Adv Exp Med Biol.* 2013;768:97–126.
11. Jenuwein T, Allis CD. Translating the histone code. *Science.* 2001;293:1074–80.
12. Zimmer P, Bloch W. Physical exercise and epigenetic adaptations of the cardiovascular system. *Herz.* 2015;40(3):353–60.
13. Zaina S, Pérez-Luque EL, Lund G. Genetics talks to epigenetics? The interplay between sequence variants and chromatin structure. *Curr Genomics.* 2010;11(5):359–67.
14. Raleigh SM. Epigenetic regulation of the ACE gene might be more relevant to endurance physiology than I/D polymorphism. *J Appl Physiol* 2012;112:1082–3.
15. Pedersen BK, Febbraio MA. Muscle as an endocrine organ: focus on muscle-derived interleukin-6. *Physiol Rev.* 2008;88(4):1379–406.
16. Hayashino Y, Jackson JL, Hirata T, Fukumori N, et al. Effects of exercise on C-reactive protein, inflammatory cytokine and adipokine in patients with type 2 diabetes: a meta-analysis of randomized controlled trials. *Metabolism.* 2014;63(3):431–40.
17. Nakajima K, Takeoka M, Mori M, Hashimoto S, et al. Exercise effects on methylation of ASC gene. *Int J Sports Med.* 2010;31:671–5.
18. Moresi V, Marroncelli N, Coletti D, Adamo S. Regulation of skeletal muscle development and homeostasis by gene imprinting, histone acetylation and microRNA. *Biochim Biophys Acta.* 2015;1849(3):309–16.
19. McGee SL, Fairlie E, Garnham AP, Hargreaves M. Exercise-induced histone modifications in human skeletal muscle. *J Physiol.* 2009;587(Pt 24):5951–8.
20. Willkomm L, Gehlert S, Jacko D, Schiffer T, Bloch W. p38 MAPK activation and H3K4 trimethylation is decreased by lactate in vitro and high intensity resistance training in human skeletal muscle. *PLoS One.* 2017;12(5):e0176609.
21. Safdar A, Abadi A, Akhtar M, Hettinga BP, et al. miRNA in the regulation of skeletal muscle adaptation to acute endurance exercise in C57Bl/6J male mice. *PLoS One.* 2009;4:e5610.
22. Owens GK. Regulation of differentiation of vascular smooth muscle cells. *Physiol Rev.* 1995;75(3):487–517.
23. Ross R. The pathogenesis of atherosclerosis: a perspective for the 1990s. *Nature.* 1993;362:801–9.
24. Hoofnagle MH, Wamhoff BR, Owens GK. Lost in transdifferentiation. *J Clin Invest.* 2004;113(9):1249–51.
25. Alexander MR, Owens GK. Epigenetic control of smooth muscle cell differentiation and phenotypic switching in vascular development and disease. *Annu Rev Physiol.* 2012;74:13–40.
26. McDonald OG, Owens GK. Programming smooth muscle plasticity with chromatin dynamics. *Circ Res.* 2007;100:1428–41.
27. McDonald OG, Wamhoff BR, Hoofnagle MH, Owens GK. Control of SRF binding to CARG box chromatin regulates smooth muscle gene expression in vivo. *J Clin Invest.* 2006;116:36–48.
28. Archer SL, Marsboom G, Kim GH, et al. Epigenetic attenuation of mitochondrial superoxide dismutase 2 in pulmonary arterial hypertension: a base for excessive cell proliferation and a new therapeutic target. *Circulation.* 2010;121:2661–71.
29. Kim GH, Ryan JJ, Archer SL. The role of redox signaling in epigenetics and cardiovascular disease. *Antioxid Redox Signal.* 2013;18(15):1920–36.
30. Ito K, Hanazawa T, Tomita K, Barnes PJ, Adcock IM. Oxidative stress reduces histone deacetylase 2 activity and enhances IL-8 gene expression: role of tyrosine nitration. *Biochem Biophys Res Commun.* 2004;315:240–5.
31. Chen KC, Wang YS, Hu CY, Chang WC, et al. OxLDL up-regulates microRNA-29b, leading to epigenetic modifications of MMP-2/MMP-9 genes: a novel mechanism for cardiovascular diseases. *FASEB J.* 2011;25(5):1718–28.
32. Bátka S, Thum T. MicroRNAs in hypertension: mechanisms and therapeutic targets. *Curr Hypertens Rep.* 2012;14:79–87.
33. Wu XD, Zeng K, Liu WL, Gao YG, et al. Effect of aerobic exercise on miRNA-TLR4 signaling in atherosclerosis. *Int J Sports Med.* 2014;35(4):344–50.

34. Zhang J, Zhao F, Yu X, Lu X, Zheng G. MicroRNA-155 modulates the proliferation of vascular smooth muscle cells by targeting endothelial nitric oxide synthase. *Int J Mol Med.* 2015;35(6):1708–14.
35. Zhuang Y, Peng H, Mastej V, Chen W. MicroRNA regulation of endothelial junction proteins and clinical consequence. *Mediat Inflamm.* 2016;2016:5078627. <https://doi.org/10.1155/2016/5078627>.
36. Gielen S, Sandri M, Erbs S, Adams V. Exercise-induced modulation of endothelial nitric oxide production. *Curr Pharm Biotechnol.* 2011;12(9):1375–84.
37. Fernandes T, Magalhães FC, Roque FR, Phillips MI, et al. Exercise training prevents the microvascular rarefaction in hypertension balancing angiogenic and apoptotic factors: role of microRNAs-16, -21, and -126. *Hypertension.* 2012;59:513–20.
38. Shiva Shankar TV, Willems L. Epigenetic modulators mitigate angiogenesis through a complex transcriptomic network. *Vascul Pharmacol.* 2014;60(2):57–66.
39. Montgomery RL, Hullinger TG, Semus HM, Dickinson BA, Seto AG, et al. Therapeutic inhibition of miR-208a improves cardiac function and survival during heart failure. *Circulation.* 2011;124:1537–47.
40. Zhang LX, DeNicola M, Qin X, Du J, et al. Specific inhibition of HDAC4 in cardiac progenitor cells enhances myocardial repairs. *Am J Physiol Cell Physiol.* 2014;307(4):C358–72.
41. Nguyen MA, Karunakaran D, Rayner KJ. Unlocking the door to new therapies in cardiovascular disease: microRNAs hold the key. *Curr Cardiol Rep.* 2014;16(11):539.
42. Lehmann LH, Jebessa ZH, Kreusser MM, Horsch A, et al. A proteolytic fragment of histone deacetylase 4 protects the heart from failure by regulating the hexosamine biosynthetic pathway. *Nat Med.* 2018;24(1):62–72.
43. Soci UP, Fernandes T, Rosa KT, Irigoyen MC, et al. The role of microRNA-208a in cardiac hypertrophy. *Clin Sci.* 2016. pii:CS20160480 Epub ahead of print.
44. Montgomery RL, Potthoff MJ, Haberland M, et al. Maintenance of cardiac energy metabolism by histone deacetylase 3 in mice. *J Clin Invest.* 2011;118(11):3588–97.
45. Tao H, Yang JJ, Shi KH, Deng ZY, Li J. DNA methylation in cardiac fibrosis: new advances and perspectives. *Toxicology.* 2014;323:125–9.
46. Kwak HB. Aging, exercise, and extracellular matrix in the heart. *J Exerc Rehabil.* 2013;9(3):338–47.
47. Soci UP, Fernandes T, Hashimoto NY, Mota GF, et al. MicroRNAs 29 are involved in the improvement of ventricular compliance promoted by aerobic exercise training in rat. *Physiol Genomics.* 2011;43:665–73.
48. Rönn T, Volkov P, Davegårdh C, Dayeh T, et al. A six months exercise intervention influences the genome-wide DNA methylation pattern in human adipose tissue. *PLoS Genet.* 2013;9(6):e1003572.
49. Denham J, O'Brien BJ, Marques FZ, Charchar FJ. Changes in the leukocyte methylome and its effect on cardiovascular related genes after exercise. *J Appl Physiol (1985).* 2015;118(4):475–88.
50. Denham J, Marques FZ, Bruns EL, O'Brien BJ, Charchar FJ. Epigenetic changes in leukocytes after 8 weeks of resistance exercise training. *Eur J Appl Physiol.* 2016;116(6):1245–53.
51. Zimmer P, Bloch W, Schenk A, Zopf EM, et al. Exercise-induced natural killer cell activation is driven by epigenetic modifications. *Int J Sports Med.* 2015;36(6):510–5.
52. Zimmer P, Baumann FT, Bloch W, Schenk A, et al. Impact of exercise on pro inflammatory cytokine levels and epigenetic modulations of tumor-competitive lymphocytes in Non-Hodgkin-Lymphoma patients-randomized controlled trial. *Eur J Haematol.* 2014;93(6):527–32.



Molecular and Physiological Adaptations to Endurance Training

3

Anthony C. Hackney

Introduction

The purpose of this chapter is to provide an overview of the research addressing the molecular and physiological adaptations to endurance exercise training. The history of research examining the adaptive responses of the human organism to endurance exercise training is lengthy. One can argue the historical reports of the physical training by Greek Olympians or Roman military units in ancient civilizations may be some of the first recorded information. More contemporary reports based upon the use of the “scientific method” and empirical evidence begin in the eighteenth century and span to the present day [1]. The progression and details of this latter work over the last four centuries is fascinating and provide a contextual framework for the understanding of the scientific investigations done in our present, contemporary times. The historical context and insights of this prior research provides the organization constructs of the topics covered in this chapter. Specifically, these topics are

- Molecular adaptations
- Cardiovascular adaptations
- Metabolic adaptations
- Skeletal muscle, tendon, and bone adaptations
- Hormonal-endocrine adaptations

A. C. Hackney

Department of Exercise and Sport Science, University of North Carolina,
Chapel Hill, NC, USA

Department of Nutrition, Gillings School of Global Public Health,
University of North Carolina, Chapel Hill, NC, USA
e-mail: ach@email.unc.edu

Each one of these topics warrants and deserves a chapter unto themselves, as a simple PubMed and Scopus search on these topics results in nearly 100,000 publications suggesting there is ample evidence to discuss; but, space limitations herein necessitate addressing these topics in a concise and succinct fashion only. The reader is directed to some of the key literature cited within this chapter if they desire more extensive discussions on elements of any of the select topics.

Adaptive Responses to Endurance Exercise Training

Molecular Adaptations

Molecular mechanisms are critical in allowing organisms to adapt to and survive diverse environmental challenges—whether imposed or selected by the organism—hence understanding these mechanism provides great insight to the physiological capacity. In recent years, genomic and proteomic approaches have been key drivers of advancement in the field of biological sciences, e.g., providing knowledge about gene and protein expression, regulation of signal transduction pathways, and functional control of enzymes/proteins by reversible protein phosphorylation. These scientific advances have been evident in exercise physiology and sports performance as well as other of the biological life sciences.

Research evidence strongly supports that the repetitive muscular contractions with endurance exercise training generates specific mechanic stimuli which result in and promote adaptation. That is, there are a series of primary mechano-sensor stimuli “switching on” this adaptive response at the molecular level. Some of the key stimuli involved with this mechanism include muscular stretch, intracellular calcium flux, fuel substrate utilization, overall stored energy status, and oxygen stress within the organism [2–4]. Furthermore, it is important to recognize the necessity for exercise training to be performed at appropriate levels (e.g., intensity, duration, frequency) in order to invoke stimuli-driven perturbations of a magnitude to induce adaptation.

The molecular adaptation response(s) invoked by these exercise stimuli center on taking a sequence of the genetic code from DNA for a specific cell protein and generating functional gene products—termed gene expression—for critical endurance-related physiological processes such as mitochondrial respiration and biogenesis, signaling and catalytic enzymes, and transporter proteins. To this end, it is well-recognized exercise-induced increase in skeletal muscle mitochondrial content—specifically termed mitochondrial biogenesis—is fundamental to endurance training adaptation and a key regulator of this process is the transcription co-activator PGC-1 α (peroxisome proliferator-activated receptor gamma co-activator 1-alpha). Figure 3.1 depicts the basic aspects of the PGC-1 α pathway through which this process is activated with exercise training and the critical outcomes from activation [4, 5].

Additionally, endurance training mediates molecular-based changes in substrate availability and utilization. For example, the capacity to transport glucose and fatty acids into and from the blood into the muscle cells are enhanced by increasing the

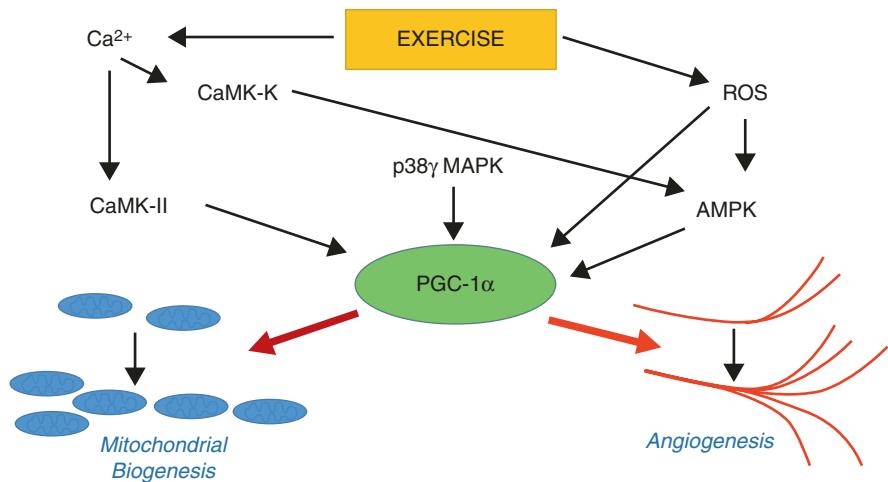


Fig. 3.1 Proposed signaling pathways involved in exercise-induced peroxisome-proliferator-activated receptor- γ co-activator-1 α (PGC-1 α) regulation in skeletal muscle. Current evidence suggests roles for calcium (Ca^{2+}), calcineurin (CnA), Ca^{2+} /calmodulin-dependent protein kinases (CaMK), AMP-activated protein kinase (AMPK), and p38 γ mitogen-activated kinase (p38 γ MAPK) in PGC-1 α regulation. ROS reactive oxygen species

level of the substrate transporters GLUT4 and FAT/CD36. Glucose transporter type 4 (GLUT4) is critical in their metabolic role as an insulin-regulated facilitator of glucose uptake in a resting state and their ability to be insulin independent during exercise. FAT/CD36 (fatty acid translocase) is equally important as a membrane transporter increasing the uptake of fatty acids into the muscle for use in lipolysis-based metabolism-respiration (i.e., β -oxidation). As mitochondrial biogenesis is augmented, there is an enhanced capacity for β -oxidation and the Citric Acid Cycle (CAC; frequently referred to as the Krebs Cycle) ATP production. This leads to a greater potential utilization of these key substrates during exercise as uptake capacity increases (see later section—Metabolic Adaptation) [4, 6].

A key extra-cellular response is angiogenesis, the physiological process through which new blood vessels are formed. This development results in an improved capillary to fiber ratio at the skeletal muscle, leading to an enhanced blood flow and oxygen delivery to the muscle (see next section). The vascular endothelial growth factor (VEGF) protein has been identified as a central regulator of angiogenesis that is released by the skeletal muscle to stimulate vascular growth. Interestingly, the expression of VEGF in muscle appears to be one of the genes whose expression is also regulated by the PGC-1 α pathway (Fig. 3.1) [4, 6, 7].

The maximal activation of the molecular adaptation response and the increase in the functional proteins in skeletal muscle by exercise training is rapid. In fact, this is achieved within hours to days of repeated endurance exercise exposure (Fig. 3.2). In time, however, with the repeated exposure the stimulus is deemed maximal and plateaus (shortly thereafter) as exercise training exposure continues (i.e., unless there is a progression to higher levels of stimulus—“progressive overload”) [4].

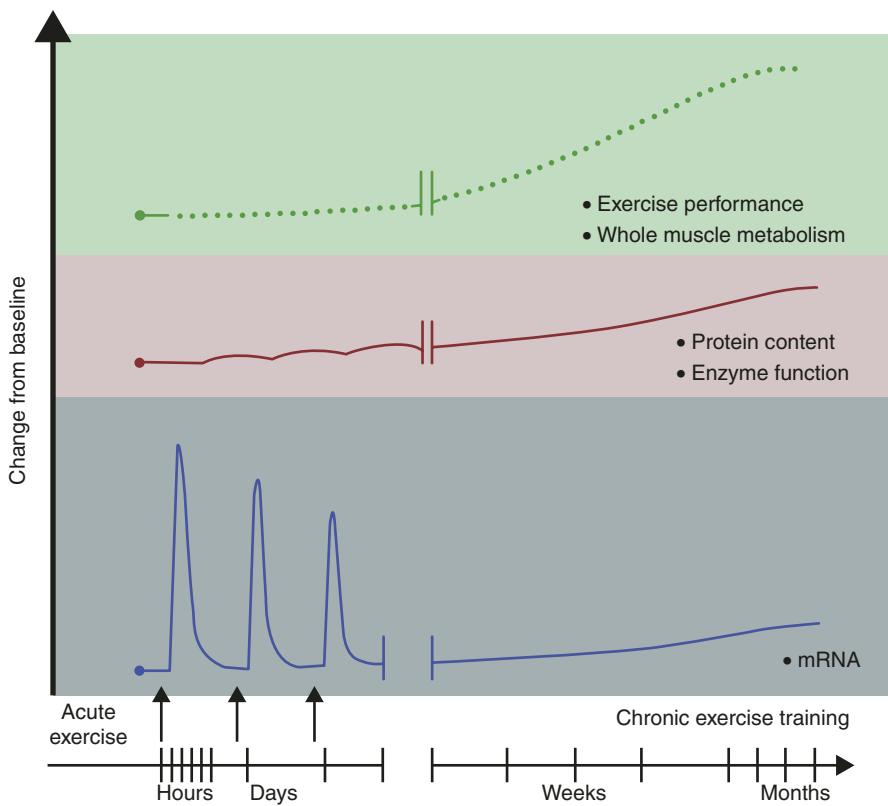


Fig. 3.2 Diagram depicting changes in gene (mRNA) expression (bottom panel) and protein content (middle panel) over time as a consequence of acute exercise and chronic (repetitive) exercise training. With gene upregulated by exercise and training, an individual exercise session elicits a rapid, but transient, increase in relative mRNA expression of a given gene during recovery. Alterations in mRNA expression are typically greatest at 3–12 h after cessation of exercise and return to basal levels within 24 h. Translational processing and an elevated rate of post-exercise protein synthesis result in the same-directional change in protein content. Chronic exercise session exposure results in the gradual accumulation of protein in response to repeated, pulsed increases in relative mRNA expression. Long-term adaptation to training is due to the cumulative effects of each acute exercise session leading to a new functional threshold. Training-induced changes in protein content/enzyme function lead to altered metabolic responses to exercise (e.g., substrate metabolism), resulting in improved exercise performance (upper panel). Used with permission; Egan B, Zierath JR. Exercise metabolism and molecular regulation of skeletal muscle adaptation. *Cell Metabolism*. 2013; 17(2): 162–184

Cardiovascular Adaptations

Cardiovascular response to exercise revolves around the classic physiological elements of heart rate, stroke volume, cardiac output, mean arterial pressure, and total peripheral resistance. These determinants of cardiovascular function influence the primary physiological factors associated with success in endurance exercise events: maximal oxygen uptake ($\text{VO}_{2\text{max}}$), the ability to work at a high fractional utilization of $\text{VO}_{2\text{max}}$, and overall work economy (N.B., the terms “economy” and “efficiency”

are sometimes used synonymously. However, economy refers to the relationship between oxygen consumption and movement speed [e.g., running velocity], while efficiency is the ratio between the mechanical energy produced during exercise and the energy cost of the exercise.).

These three factors associated with endurance exercise success are influenced by cardiovascular function through its central role in oxygen delivery—a well-documented key determinant of aerobic capacity and performance in endurance athletes [3]. An efficacious endurance exercise training program will result in an athlete developing an augmented $\text{VO}_{2\text{max}}$, the ability to work at a higher fractional utilization of $\text{VO}_{2\text{max}}$, and an improved work economy [3, 8].

Enhancement of cardiac output plays a central role in the determination of the improvement in $\text{VO}_{2\text{max}}$. While $\text{VO}_{2\text{max}}$ has a strong heredity component to potential genotypic expression, the ability to facilitate the cardiac output (CO) through training is a powerful effector of $\text{VO}_{2\text{max}}$ phenotype expression as maximal CO can be 20–50% greater in endurance-trained versus untrained, matched individuals [8–10].

The major cardiac adaptations to improve CO from endurance training is the enhanced capacity for ventricular filling (\uparrow end-diastolic volume [EDV] parameters) and the ability to use the Frank-Starling mechanism during exercise to increase the ejection fraction. Collectively, these changes result in an improved capacity to increase stroke volume. Key factors responsible for increased EDV capacity after training include enhancement in left ventricle (LV) compliance, increased cardiac dimensions (i.e., pre-load LV hypertrophy), increased rate of LV pressure decline, reduced pericardium-mediated diastolic ventricular interactions, enhanced diastolic suction, increased rate of calcium uptake within myocardial sarcoplasmic reticulum, and increased changes in vascular volume. Taken together, these changes result in a greatly improved pumping capacity (CO) for the heart [8–10]. Also, coupled to these changes are training-induced blood hypervolemia and erythropoiesis leading to greater hemoglobin content and, therefore, oxygen carrying capacity and arterial-venous oxygen differential (a-v O_2 difference) [3, 8, 9]. In short, essentially all those factors driving the $\text{VO}_{2\text{max}}$ capacity changes as determined by the Fick equations are enhanced (see following equation [3]).

$$\text{Fick Equation : } \text{VO}_2 = \text{CO} \times \text{a} - \text{v O}_2 \text{ difference}$$

Relative to the lactate threshold, endurance exercise training results in a shifting of the “break point” for accelerated anaerobic energy contributions during an exercise session to a higher exercise intensity [2]. Such representations are typically depicted and quantified by examination of the lactate threshold profile responses in athletes [3]. This occurrence is driven to a large extent by the increases in mitochondrial biogenesis (noted earlier) leading to a greater mitochondrial density. This biogenesis coupled with the improved oxygen delivery capacity of the cardiovascular system leads to reduced lactate production and accumulation due to increased pyruvate oxidation. Metabolically, this adaptation also means increased ability of muscle cells to uptake and oxidize fat and reduce carbohydrate oxidation through glycolysis (i.e., reduced pyruvate formation, see the following section). Furthermore, the increased CO ability following training translates into increased blood lactate removal during exercise [2, 3]. These events allowing for a shift of the lactate

Table 3.1 Summary of the cardiovascular adaptation resulting from an exercise training program (i.e., specifically one focusing upon aerobic endurance-based physical activities)

Measurement	Resting	Submaximal exercise	Maximal exercise
Heart rate	↓	↓	↓, NC
Stroke volume	↑	↑	↑
Cardiac output	↓, NC	↓, NC	↑
a-v O ₂ diff	↑, NC	↑	↑
VO ₂	NC	↓, NC	↑
Systolic BP	↓, NC	↓, NC	NC
Diastolic BP	↓, NC	↓, NC	↓, NC
MAP	↓, NC	↓, NC	NC
TPR	NC	↓, NC	NC
Blood volume	↑	–	–
Plasma volume	↑	–	–
Erythrocyte mass	↑	–	–
Heart volume	↑	–	–

Symbols: ↑ increase, ↓ decrease, NC no change, – not applicable

Abbreviations: a-v O₂ diff arterial-venous oxygen difference, VO₂ oxygen uptake, BP blood pressure, MAP mean arterial pressure, TPR total peripheral resistance

breakpoint to a higher intensity helps the athlete to perform at higher intense efforts with reduced likelihood of muscular fatigue [2]. Finally, the enhanced metabolic capacity-efficiency from training combined with an improved biomechanical efficiency through adaptation to chronic repetitive movement patterns yields an improved exercise economy (i.e., less energy required for any given level of movement) [3, 8].

Table 3.1 summarizes the adaptive responses in the critical cardiovascular components in response to an endurance exercise training program [2, 3, 8, 9].

Metabolic Adaptations

This section focuses on the metabolic changes within skeletal muscle that are associated with the improved capacity and performance from endurance exercise training. In general, the key metabolic adaptive component of endurance training is the increased capacity for skeletal muscle to oxidize fuel for energy production. In light of the fact that a major endurance event such as a running marathon (42.2 km) can have a total energy cost greater than 10,000 kJ in a roughly 2 h period, an increased capacity and rate for fuel oxidation is critical to improving performance (*N.B.*, long course triathlons, cycling races, or certain Nordic ski events can exceed even this value for energy cost!) [2, 3].

The increased fuel utilization capacity is a direct result of increased mitochondrial content (see earlier biogenesis discussion) and the associated enzyme activity profile from that content change; in particular, those enzymes associated with β-oxidation and the CAC energy pathways of aerobic metabolism [2]. Essentially an increased metabolic flux of both energy pathways results in a greater production of electrons for the electron transport chain and, hence, enhanced and ultimately upregulated

mitochondrial oxidative phosphorylation (aerobic metabolism) (*N.B.*, metabolic flux is the rate of turnover of molecules through a metabolic pathway). The up-regulation of oxidative phosphorylation enables a more efficient energy production and reduces the glycolytic pathway flux and therefore the accumulation of cytosolic waste products that contribute to muscle fatigue associated with that pathway [11–13].

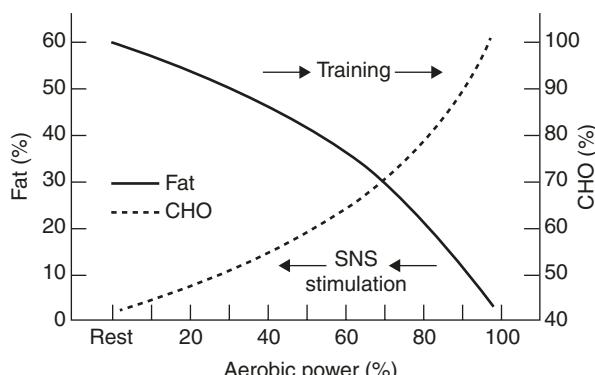
Additional consequences of the metabolic adaptation to training are an increased utilization of fats as fuel and a subsequent decrease in the utilization of carbohydrate as a fuel at any given submaximal exercise intensity. This shifting of fuel use results in a muscle glycogen sparing, thereby attenuating muscle glycogen use and depletion during prolonged submaximal exercise and abating another potential fatigue factor (i.e., muscle glycogen depletion is a critical factor in an endurance event of sufficient duration [$\sim 60\text{--}90$ min, $>60\% \text{VO}_{2\text{max}}$]). Along these lines, following training, there is an increased level of resting muscle glycogen stores and intramuscular triglycerides, resulting in a more efficient use of fuels due to proximity to the exercising muscle tissue. Additionally, the availability of extra-muscular fuel sources is also enhanced due to transporter changes noted and discussed earlier in the Molecular Adaptations section [11–14].

In brief, endurance exercise training shifts the metabolic energy production towards a greater reliance on fats as a fuel, leading to a stored carbohydrate sparing. Figure 3.3 conveys this change in fuel utilization with training, as a shifting in the “cross-over” point to higher exercise intensities. At the same time, these are an enhancement of carbohydrate stores (i.e., glycogen). Coupled with the molecular adaptation noted earlier, this leads to a greatly improved ability in the rate and yield of ATP production during exercise, thereby, increasing the capacity for physical work, overall and at higher intensities.

Skeletal Muscle, Tendon, and Bone Adaptations

The skeletal-musculotendinous unit is a remarkable organ system within the human body and has a tremendous capacity to display plasticity. The positive adaptations in this system due to its plasticity are significant contributors to the performance enhancement associated with endurance training [1, 2, 15].

Fig. 3.3 Cross-over concept and the influence of endurance exercise training. CHO carbohydrate, SNS sympathetic nervous system. (Image adapted from: Brooks GA, Mercier J. Balance of carbohydrate and lipid utilization during exercise: the “cross-over” concept. *Journal Applied Physiology*. 1994;76 (6): 2253–2261)



In skeletal muscle, the smallest functional unit to be activated (i.e., recruited) and utilized in tension development is the motor unit and the muscle fibers within that unit. Individual motor units have fibers of identical characteristics, but intact whole skeletal muscle is comprised of three distinct and differing fiber types. The nomenclature utilized to distinguish these fiber types have varied since their identification some 50+ years ago, which can lead to confusion when reading literature [2, 15, 16]. Here in the Roman numeral naming system is employed, that being Type I, Type IIa, and Type IIId/x. Type I are “slow-twitch” oxidative fibers which are slow in force generation have a highly developed oxidative capacity due to high mitochondrial content and oxidative enzyme expression and a dense capillary supply. Type IIa are “fast-twitch” oxidative fibers which are relatively fast in force generation but have similar oxidative profiles to Type I fibers. Type IIId/x are “fast-twitch” fibers with a highly developed glycolytic metabolic profile (i.e., rich in glycolytic enzymatic expression), poor mitochondrial and capillary development, and fast force generation capacity. For these fibers, the tension development capacity within twitch responses is IIId/x > IIa > I (i.e., greater to lesser). Research studies where fiber-typing has been conducted supports that athletes in endurance sports tend to have a higher proportion of Type I fibers in the musculature used in their sporting activity [17]. That said, though, the evidence does not support that fiber type alone serves as a strong predictor of performance capacity [15, 17].

Earlier it was noted that endurance training facilitates changes in mitochondrial content, oxidative enzymatic expression, and capillary density within skeletal muscle fibers. These characteristics are components of the classification criteria for muscle fiber-typing. Changes due to training in these characteristics beg the question—“Does exercise training result in fiber type transformation?” This has long been a question in exercise research, with some contradictory findings when a variety of animal species were examined [1, 15]. Currently, there is no direct experimental evidence for fiber-type transformation in humans. It is important to remember that the fiber type determined is a function of a multitude of neural, metabolic, functional, histological, and morphological characteristics [3]. Nonetheless, chronic endurance training does transform the biochemical characteristic phenotype of muscle fibers towards the Type I metabolic profile, but the extent of such expressional change varies with individual fiber types [1, 16]. Moreover, there is at least some evidence that regular endurance training (cycling) may also induce muscle hypertrophy in previously untrained subjects [18].

In a related fashion, resistance training is associated with neural and hypertrophic adaptation which leads to improved muscular strength-power capacities. For years, it was postulated resistance training and endurance training interfered with the adaptive responses of each individual form of training. Recent work, however, supports when endurance and resistance training are applied concurrently there can be some degree of an optimization of the magnitude of muscle hypertrophy, maximal strength, and endurance capacity development [18]. These effects have been observed in untrained as well as trained runners and translate into improved high-intensity running characteristics with obvious implications to performance [19].

Nonetheless, this line of research work is not entirely conclusive and is in need of much further exploration.

Tendon and bone are instrumental to the health and functionality of the endurance athlete, yet relative to some of the other adaptive components discussed in research literature they are seldom addressed as extensively [20–22]. Frequently, the available related discussions focus upon injury, damage, or maladaptation with health-related comorbidities such as the osteoarthritis or the female athlete triad [22–24].

Tendons display good ability to adapt to different states of loading through movements encountered in endurance activities; that is, provided the timeframe for adaptation is sufficiently long enough and gradual in loading (e.g., weeks, months, and years) [20] although the longitude effect of chronic exercise training on tendon health status over a lifetime seems inadequately addressed in research. Similar to a tendon, bone show comparable positive responsiveness to endurance exercise, as regular and varied loading has constructive effects on bone health [21]. Consistent exercise loading consisting of high-magnitude impacts is highly stimulatory to osteogenic activity of the bone promoting thick cortical bone development. Furthermore, endurance training is a good overall promoter for improvement of bone strength through adaptation in geometric modeling. However, not all endurance training activities are universal in this effect. For example, running is associated with increased bone density, particularly in the legs, whereas cycling is associated with a mild decrease in bone density in the spine; and, in athletes who do both, running exerts a stronger influence than cycling [25]. These effect differences being most likely do to weight bearing vs. non-weight bearing aspects of the activities.

Collectively, these tendon-bone adaptive responses to endurance training result in an improved resilience to injury from the chronic, repetitive nature of the exercise activity although chronic over-use or overtraining exposure are counterproductive and have negative effects and greatly increase the risk of injury (see Hormonal-Endocrine Adaptation section) [20–26].

Hormonal-Endocrine Adaptations

In humans, there are a variety of hormones and hormone-acting substances that exhibit endocrine, paracrine, and autocrine actions on a multitude of tissues. These substances are involved in the regulation of many physiological processes such as metabolism, growth and development, hydration, cardiovascular functions, immune responses, and stress reactivity. A large number of research findings support that endurance exercise training profoundly affects hormones, the endocrine glands/tissues responsible for their production, and thus the processes these substances regulate and control [2, 3].

Acute exercise is a powerful stimulant to the endocrine system and results in a multitude of hormonal changes. Table 3.2 summarizes the effects of a single acute, endurance exercise session (of various intensity, duration) on the major human

hormones; *in nuce*, essentially exercise serves as a stressor provoking increases in circulating levels of the hormones (exception → insulin↓)—the more demanding the exercise stress, the greater the response. Table 3.2 also depicts how endurance training (chronic) effects hormones response to subsequent exercise sessions—i.e., generalizing, the training responses is to lower the blood level of hormones at rest, and in response to performing an acute exercise session post-training [26–29]. The greater the overall training adaption incurred typically the greater the attenuation of the hormonal response to exercise. The exception to this is maximal or supramaximal exercise. In these situations, the training adaptations allow for a greater level of workload to be performed in maximal or supramaximal efforts and the greater workload achieved produces a greater physiological stimulus and thus commonly a greater hormonal response [26, 27].

In most situations, when endurance exercise training regimes are well constructed and executed, the hormonal effects (adjustments) are highly positive and lead to improved exercise capacity and through genomic and non-genomic means facilitate many of the adaptation processes already noted in this chapter [26–28]. Regrettably, however, poorly developed or implemented exercise training regimes can result in counterproductive hormone responses and negative physiological consequences (maladaptations).

The attenuated endocrine responses following endurance training come about by a greater sensitivity of target tissue to the hormonal stimulus and diminished levels of neural, humoral, and hormonal stimuli disturbances in the blood and other body fluids regulating the various endocrine glands [29]. Relative to the former point of sensitivity, in response to an exercise training program, many target tissues increase the expression of functional hormone receptors, receptor affinity for hormones becomes increased, and post-receptor amplification mechanisms in the cells of target tissues are typically increased. Essentially, all these changes result in a target tissue needing less amount of a hormonal signal to bring about a physiological outcome/change in “down-stream” events within cells [29–31].

Hormonal-Endocrine Adaptations

If training regimes are excessive in the amount of intensive training or overall volume of training and, or an athlete has too many additional life stresses compounding their situation while training, it is possible for maladaptive hormone response occurrences. Such responses are usually associated with overreaching or overtraining scenarios [32]. In brief, normally, if an individual is subjected to gradual increases of “training overload” stress followed by a period of time to rest and recovery they will adapt in a positive fashion and promote adaptations leading to an improved performance capacity. If the training overload stress is too much, or adequate rest is not allowed, then the athlete may not be able to adapt and their performance declines rather than improves. That is, they may progress from “normal” training to experiencing “overreaching” training and in due course “overtraining.” If not checked in

Table 3.2 Generalized hormonal responses to “acute” endurance-type exercise of varying intensity and duration

Hormone	Principal physiological function ^a	Exercise response				Chronic Endurance training
		Acute	Short-term submaximal	High intensity	Prolonged submaximal	
ACTH	Adrenoregulatory	↑ (e.g., <30min; ≈, >LT)	↑ (>50% VO _{2max})	↑↑ (e.g., ≈LT)	↑↑ (e.g., >60 min; <LT)	↔, ↓ ↔
AVP	Hydration, fluids	↑ (e.g., lipolysis, glycogenolysis), cardio-regulatory	↑ (e.g., lipolysis, proteolysis), stress reactivity (>60% VO _{2max})	↑↑ ↑↑	↑↑ ↑↑	↔, ↓ ↔, ↓
Aldosterone	Hydration, fluids	↑	↑	↑↑	↑↑	↔
Catecholamines	Catabolic, (e.g., lipolysis, glycogenolysis), cardio-regulatory	↑	↑	↑↑	↑↑	↔, ↓
Cortisol	Catabolic (e.g., lipolysis, proteolysis), stress reactivity	↑ (>60% VO _{2max})	↑↑	↑↑	↑↑	↔, ↓
Estradiol-β-17	Bone metabolism, catabolic (e.g., lipolysis), reproductive	↑	↑	↑ (if excessive)	↑ (if excessive)	↔, ↓
FSH-LH	Reproductive	↑	↑, ↔	↑, ↓, ↔	↑	↓
Glucagon	Glucoregulatory	↑	↑	↑↑	↑↑	↓
Growth hormone	Anabolic (e.g., myoplasticity, osteogenic)	↑	↑↑	↑↑	↑↑	↔, ↑
Insulin	Glucoregulatory	↓	↓	↓	↓	↓
Parathyroid	Calcium metabolism	↑	↑	↑	↑	↔

(continued)

Table 3.2 (continued)

Hormone	Principal physiological function ^a	Exercise response			
		Acute	Short-term submaximal (e.g., <30min; ≈, >LT)	High intensity	Prolonged submaximal
Prolactin	Immune, stress reactivity Reproductive	↑	↑↑	↑↑	↑, ↓
Progesterone		↑	↑	↑ (if excessive)	↔, ↓
Testosterone	Anabolic (e.g., myoplasticity, gluconeogenesis, erythropoiesis)	↑	↑	↑ (if excessive)	↔, ↓
T ₄ -T ₃	Calorigenesis, endo-permissive	↔	↔	↑, ↓	↔, ↓
TSH	Thermoregulatory	↑	↔, ↑	↔, ↑	↔

The influence of “chronic” endurance exercise training on hormonal response to subsequent exercise after training is also depicted [e.g., exercise ACTH still ↑s after training, but the magnitude of the ↑ is either unaffected (↔) or slightly lessened (↓)]
 Abbreviations/symbols: LT lactate threshold, ↑ increase, ↑↑ strong increase, ↓ decrease, ↔ no change, ACTH adrenocorticotrophic hormone, AVP arginine vasopressin, FSH-LH follicle-stimulating hormone-luteinizing hormone, T₄-T₃ thyroxine-triiodothyronine, TSH thyroid-stimulating hormone
^aPrincipal role relative to exercise

this progression, the athlete may ultimately develop and display the clinical characteristics of the Overtraining Syndrome, a serious medical condition [32, 33].

The research in endurance athletes who are overreaching or overtraining suggests the endocrine system response is in two phases: an initial hyperactivity phase, followed by a latter hypoactivity phase [33, 34]. In the hyperactivity phase, elevations in the circulating levels of hormones such as adrenocorticotropic hormone, cortisol, prolactin, and catecholamines have been reported at rest and/or in response to an acute exercise session [33, 34]; although, these hormonal findings are not completely universal [32]. This hyperactivity phase may be reflective of the “over-reaching” status in the training continuum. Interestingly, it should be noted that in some situations during “overreaching” if the athlete is given short-term rest and recovery (~2 weeks) they may actually compensate with greater than normal adaptations and enhancements of performance (i.e., tapering) [32]. The hypoactivity phase seems to more closely correspond to the classic “overtraining” status and, or with the occurrence of the Overtraining Syndrome medical classification—i.e., a state of chronic fatigue, lethargy, and underperformance. For this phase, certain glucoregulatory and reproductive hormones are found to be suppressed [34, 35]. The development of the hypoactivity phase appears to be the more serious outcome as it may require months of rest and recovery by the athlete in order to regain normal endocrine function and performance capacity [34]. Whether this state and the attenuated hormone responses associated with it represent an endocrine gland exhaustion or regulatory axis dysregulation remains unclear.

The exact physiological mechanism that induces the Overtraining Syndrome is unknown, but for many years it was thought to reflect some degree of the final stage (exhaustion) of Selye’s General Adaptation Syndrome model [36]. However, Dr. Lucille Lakier Smith [37] proposed in 2004 that overtraining causes too much excessive musculoskeletal loading which becomes compounded by inadequate rest, recovery, and poor nutrition resulting in tissue damage-related local and systemic inflammation development. Pro-inflammatory cytokines such as IL-6, TNF- α , and IL-1 β become elevated and act upon multiple levels of the hypothalamic-pituitary-adrenal (HPA) medullary-cortical axis, influencing the hormones of the axis which are associated with impacting effective mood state, sexual function, metabolism, and cardiovascular function [34, 37]. Furthermore, the cytokine changes noted may facilitate a suppression of the cell-mediated aspects of the adaptive immune system. This creates an increased risk for infection and the so-called sick response which is associated with many of the characteristics found in overtrained athletes [38, 39]. This proposed mechanism, while not entirely encompassing of all symptomology, does reconcile and connect many of the major pathogenic and clinical manifestations associated with the Overtraining Syndrome. Nonetheless, more experimental research and empirical data are necessary on this topic.

A relative new terminology associated with exercise and endocrine-related maladaptation is “Relative Energy Deficiency in Sports” (RED-S). This was proposed by an International Olympic Committee Medical Commission working-group as a new language to apply to the reproductive endocrine disorders that affect female and male athletes [40], typically in a high prevalence within endurance-related sports.

Principally, these disorders are the “Female Athlete Triad” and the “Exercise-Hypogonadal Male Condition” (EHMC) [41, 42]. RED-S was proposed as an omnibus gender inclusive term. There is some controversy whether this is entirely appropriate for use with both genders. That is, the etiology of the female triad being related to energy intake and availability (i.e., energy deficient) is well documented, but relative to EHMC this point is not entirely conclusive and remains to be substantiated [42]. Nonetheless, both conditions are associated with endocrine disregulation of the HPA and hypothalamic-pituitary-gonadal axes.

Summary

Endurance training has the ability to affect a multitude of bodily systems. The effects manifest in changes in resting as well as in exercise responses for nearly all physiological parameters. The net impact of these changes is to improve the ability and efficiency of the body to perform prolonged aerobic activities. These adaptive changes span the continuum of organizational structure for humans—molecular, cellular, tissue, organ, organismal systems. To this end, the key endurance exercise adaptive changes are:

- ↑ Mitochondrial biogenesis
- ↑ Angiogenesis
- ↑ Fat oxidation
- ↑ $\text{VO}_{2\text{max}}$ (via ↑ CO and a-v O_2 difference)
- ↑ Ability to work at higher fractional utilization of $\text{VO}_{2\text{max}}$
- ↑ Work economy
- ↑ Musculotendinous resiliency
- ↑ Bone mineral density (i.e., weight bearing activities)
- ↑ Hormone—target tissue sensitivity
- ↑ Endocrine “down-stream” actions

It is important to recognize that these adaptations are not only critical to the endurance athlete, but equally important to improving the health and well-being of the general public. Regrettably, the vast majority of the research conducted on exercise adaptive responses has centered on men, with the assumption that male findings are directly transferable to females. In some parameters, this assumption is valid, but not all, and far more research is necessary to understand the adaptive responses of women to endurance exercise training [43].

References

1. Hamilton MT, Booth FW. Skeletal muscle adaptation to exercise: a century of progress. *J Appl Physiol*. 2000;88(1):327–31.
2. Hackney AC. Exercise, sport, and bioanalytical chemistry: principles and practice. New York: Elsevier Publishing; 2016.

3. Stegemann J. Exercise physiology: physiologic bases of work and sport. Stuttgart: Georg Thieme Verlag; 1981.
4. Coffey VG. The molecular basis of endurance training adaption. In: Mujika I, editor. Endurance training: science and practice. Vitoria-Gasteiz: I. Mujika S.L.U. Publisher; 2012.
5. Lira VA, Benton CR, Yan Z, Bonen A. PGC-1 α regulation by exercise training and its influences on muscle function and insulin sensitivity. *Am J Physiol Endocrinol Metab*. 2010;299(2):E145–61.
6. Coffey VG, Hawley JA. The molecular basis of training adaptation. *Sports Med*. 2007;37: 737–63.
7. van der Schaft D, van Spreeuwel AC, van Assen HC, Baaijens F. Mechanoregulation of vascularization in aligned tissue engineered muscle: a role for VEGF. *Tissue Eng Part A*. 2011;17:2857–65.
8. Warburton DER, Bredin SSD. Cardiovascular adaptation to endurance training. In: Mujika I, editor. Endurance training: science and practice. Vitoria-Gasteiz: I. Mujika S.L.U. Publisher; 2012.
9. Ekblom B, Astrand PO, Saltin B, Stenberg T, Wallstrom B. Effects of training on circulatory to exercise. *J Appl Physiol*. 1968;24:518–28.
10. Ekblom B, Hermansen L. Cardiac output in athletes. *J Appl Physiol*. 1968;25:619–25.
11. Coyle EF. Substrate utilization during exercise in active people. *Am J Clin Nutr*. 1995;61:968S–79S.
12. Henriksson J. Training induces adaptation of skeletal muscle and metabolism during submaximal exercise. *J Physiol*. 1977;270:661–75.
13. Holliday A, Jeukendrup AE. The metabolic adaptation to endurance training. In: Mujika I, editor. Endurance training: science and practice. Vitoria-Gasteiz: I. Mujika S.L.U. Publisher; 2012.
14. Kiens B, Essen-Gustavsson B, Christensen NJ, Saltin B. Skeletal muscle substrate utilization during submaximal exercise in man: effects of endurance training. *J Appl Physiol*. 1993;469:459–78.
15. Hawley JA. Adaptation to prolonged, intense endurance training in human skeletal muscle. In: Mujika I, editor. Endurance training: science and practice. Vitoria-Gasteiz: I. Mujika S.L.U. Publisher; 2012.
16. Holloszy JO, Coyle EF. Adaptations of skeletal muscle to endurance exercise and their metabolic consequences. *J Appl Physiol*. 1984;56:831–8.
17. Joyner MJ, Coyle EF. Endurance exercise performance: the physiology of champions. *J Physiol*. 2008;586:35–44.
18. Mikkola J, Rusko H, Izquierdo M, Gorostiaga EM, Häkkinen K. Neuromuscular and cardiovascular adaptations during concurrent strength and endurance training in untrained men. *Int J Sports Med*. 2012;33(9):702–10.
19. Mikkola J, Vesterinen V, Taipale R, Capostagno B, Häkkinen K, Nummela A. Effect of resistance training regimens on treadmill running and neuromuscular performance in recreational endurance runners. *J Sports Sci*. 2011;29(13):1359–71.
20. Kannus P. Structure of the tendon connective tissue. *Scand J Med Sci Sports*. 2000;10:312–20.
21. Kannus P, Sievänen H. Tendon and bone adaptation to endurance training. In: Mujika I, editor. Endurance training: science and practice. Vitoria-Gasteiz: I. Mujika S.L.U. Publisher; 2012.
22. Sievänen H. Immobilization and bone structure in humans. *Arch Biochem Biophys*. 2010;38:597–600.
23. Harkey MS, Luc BA, Golightly YM, Thomas AC, Driban JB, Hackney AC, Pietrosimone B. Osteoarthritis-related biomarkers following anterior cruciate ligament injury and reconstruction: a systematic review. *Osteoarthritis Cartilage*. 2015;23(1):1–12.
24. Matzkin E, Curry EJ, Whitlock K. Female athlete triad: past, present, and future. *J Am Acad Orthop Surg*. 2015;23(7):424–32.
25. Stewart SD, Hannan J. Total and regional bone density in male runners, cyclists, and controls. *Med Sci Sports Exerc*. 2000;32(8):1373–7.
26. Galbo H. Hormonal and metabolic adaptation to exercise. Stuttgart: Georg Thieme Verlag; 1983.

27. Hackney AC. Stress and the neuroendocrine system: the role of exercise as a stressor and modifier of stress. *Expert Rev Endocrinol Metab.* 2006;1(6):783–92.
28. McMurray RG, Hackney AC. The endocrine system and exercise. In: Garrett W, Kirkendall D, editors. *Exercise & sports science*. Philadelphia: Williams & Wilkins Publisher; 2000. p. 135–62.
29. Viru A, Viru M. Biochemical monitoring of sports training. Champaign: Human Kinetics Publishing; 2001.
30. Lavoie C. Glucagon receptors: effect of exercise and fasting. *Can J Appl Physiol.* 2005;30(3): 313–27.
31. Bricout VA, Germain PS, Serrurier BD, Guezenne CY. Changes in testosterone muscle receptors: effects of an androgen treatment in physically trained rats. *Cell Mol Biol (Noisy-le-grand).* 1994;40(3):291–4.
32. Meeusen R, Duclos M, Gleeson M, Rietjens G, Steinacker J, Urhausen A. Prevention, diagnosis and treatment of the overtraining syndrome: ECSS position statement ‘Task Force’. *Eur J Sports Sci.* 2006;6(1):1–14.
33. Lehmann M, Lormes W, Opitz-Gress A, Steinacker J, Netzer N, Foster C, Gastmann U. Training and overtraining: an overview and experimental results in endurance sports. *J Sports Med Phys Fitness.* 1997;37:7–17.
34. Fry AC, Steinacker JM, Meeusen R. Endocrinology of overtraining. In: Kraemer WJ, Rogol AD, editors. *The endocrine system in sports and exercise*. Oxford: Blackwell Publishing; 2005. p. 584–93.
35. Barron JL, Noakes TD, Levy W, Smith C, Millar RP. Hypothalamic dysfunction in overtrained athletes. *J Clin Endocrinol Metab.* 1985;60:803–6.
36. Selye H. A syndrome produced by diverse noxious agents. *Nature.* 1936;138:32–6.
37. Smith LL. Tissue trauma: the underlying cause of the overtraining syndrome? *J Strength Cond Res.* 2004;18:185–93.
38. Robson PJ. Elucidating the unexplained underperformance syndrome in endurance athletes. *Sports Med.* 2003;33:771–81.
39. Robson-Ansley PJ, Blannin A, Gleeson M. Elevated plasma interleukin-6 levels in trained male triathletes following an acute period of intensive interval training. *Eur J Appl Physiol.* 2007;99:353–60.
40. Mountjoy M, Sundgot-Borgen J, Burke L, Carter S, Constantini N, Lebrun C, Meyer N, Sherman R, Steffen K, Budgett R, Ljungqvist A. The IOC consensus statement: beyond the Female Athlete Triad—Relative Energy Deficiency in Sport (RED-S). *Br J Sports Med.* 2014;48(7):491–7.
41. Hackney AC. Effects of endurance exercise on the reproductive system of men: the “exercise-hypogonadal male condition”. *J Endocrinol Invest.* 2008;31(10):932–8.
42. Lane AR, Hackney AC. Reproductive dysfunction from the stress of exercise is not gender specific: the “exercise hypogonadal male condition”. *J Endocrinol Diabet.* 2014;1(2):4–5.
43. Prakash MD, Stojanovska L, Nurgali K, Apostolopoulos V. Exercise in menopausal women. In: Hackney AC, editor. *Sex hormone, exercise, and women*. New York: Springer; 2017.



Neural Adaptations to Endurance Training

4

Guillaume Y. Millet and John Temesi

Neural adaptations induced by strength training have been widely described although recent technical developments (e.g., transcranial magnetic stimulation) have provided new insights. Neural adaptations to endurance training are not as well-known and usually considered to be much smaller than those observed following strength training. In this chapter, we will not use the real definition of endurance, that is the ability to sustain a high percentage of maximal oxygen uptake ($\text{VO}_{2\text{max}}$). Instead, we will use common usage of the word endurance, i.e., prolonged, low-intensity exercise, usually with large muscle mass such as cycling, running, and cross-country skiing. The theory behind chronic adaptations is related to acute deleterious effects and recovery. In the first part of this chapter, the tools used to assess neural adaptations will be briefly described. Then, we will focus on the acute neural responses induced by a single endurance training session. Special consideration will be given to the difference between endurance running and cycling/cross-country skiing at the end of this second section. The third part of this chapter will be dedicated to chronic adaptations to the neural command induced by endurance training.

Tools Used to Assess Neural Adaptations

The tools used to assess neural adaptations are described in Fig. 4.1. The outcome measures used to assess neuromuscular fatigue and training adaptations are force and (usually surface) electromyographic activity (EMG). EMG involves the placement of electrodes on the muscle(s) of interest (agonist and antagonist muscles) to measure electrical activity (i.e., sum of the action potentials) within the muscles. Force is

G. Y. Millet (✉) · J. Temesi

Human Performance Laboratory, Faculty of Kinesiology, University of Calgary,
Calgary, AB, Canada
e-mail: gmillet@ucalgary.ca

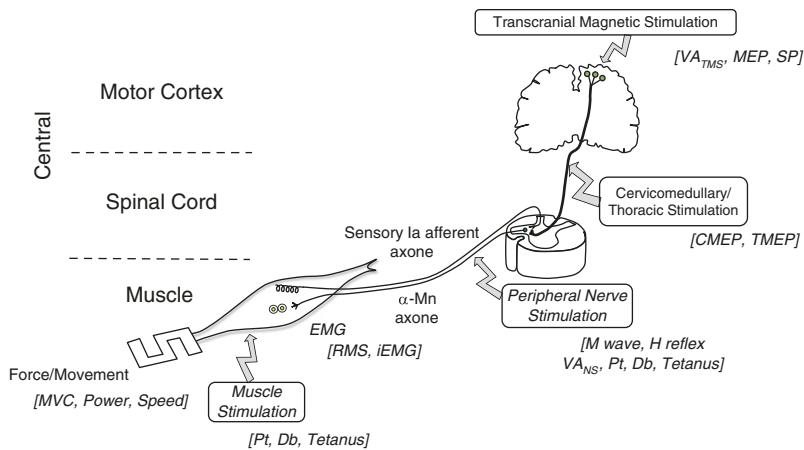


Fig. 4.1 Neuromuscular function: how to measure it? Adapted from [3]. The main outcomes are presented in italics. *CMEP* cervicomedullary motor-evoked potential, *Db* doublet, *H-reflex* Hoffmann reflex, *iEMG* integrated EMG, *MEP* motor-evoked potential, *MVC* maximal voluntary contraction, *M wave* compound muscle action potential, *NS* nerve stimulation, *Pt* peak twitch, *RMS* root mean square, *SP* silent period, *TMEP* thoracic motor-evoked potential, *TMS* transcranial magnetic stimulation, *VA* maximal voluntary activation

generally assessed isometrically via force transducer in line with the applied force. The gold standard for assessing central drive and central fatigue development is voluntary activation (VA) measured with the interpolated twitch technique. During a maximal voluntary contraction (MVC), a supramaximal stimulus is delivered to the peripheral nerve or muscle at maximal voluntary force and the resulting superimposed twitch (i.e., additional force elicited by the stimulus) is compared to a twitch (the evoked mechanical response to a supramaximal stimulus) elicited by supramaximal stimulation immediately afterwards in the relaxed muscle [4]. This provides a comparison of the force produced by recruiting all unrecruited motor units (MUs) (all MUs are theoretically recruited during MVCs) and the maximal force capacity by simultaneously recruiting all MUs in the muscle. While this method only quantifies fatigue for the central component as a whole (i.e., central nervous system including the brain and motoneurons), the assessment of VA using TMS provides information on supraspinal fatigue [5]. A methodological difference when employing TMS to determine VA is that the resting twitch must be estimated from superimposed twitches from a series of contractions between 50 and 100% of MVC because during the transition from rest to light/moderate-intensity voluntary contractions, the corticospinal pathway excitability increases rapidly. Other methods for assessing central drive to the muscles utilize EMG. The overall electrical activity of the muscle (i.e., central drive) is usually expressed as root mean square (RMS) or integrated EMG (iEMG). Supramaximal stimulation of the motor nerve during strong or maximal voluntary contractions can also be used to elicit V waves. V waves are the result of collisions between evoked antidromic and voluntary orthodromic volleys and the

resulting reflex response. Only axons actively involved in the voluntary contraction will contribute to the subsequent EMG response [6].

Motoneuronal excitability can be assessed by submaximal stimulation of the motor nerve in a relaxed or lightly contracting muscle to elicit an afferent volley before recruiting motoneurons. The resulting EMG response is referred to as the Hoffmann reflex (H-reflex). While indicative of motoneuronal excitability, use of this method is limited to certain muscles (e.g., soleus, SOL) and is influenced by presynaptic inhibition [6]. Increasingly common is the use of spinal stimulation via direct (usually electrical) stimulation of the descending tracts in the spinal cord. Providing information on the excitability of the motoneuron pool, transmastoid stimulation elicits cervicomedullary motor-evoked potentials (CMEP) in upper-limb muscles that are recorded as EMG [7]. Due to difficulties in eliciting CMEPs in the lower limbs, spinal stimulation is generally performed at the upper-thoracic level to elicit thoracic motor-evoked potentials (TMEP) [6].

The investigation of cortical excitability employs transcranial magnetic stimulation (TMS) to deliver a magnetic pulse to the motor cortex that trans-synaptically excites pyramidal axons to elicit a response that is transmitted via the motoneurons to the muscle and recorded in EMG as a motor-evoked potential (MEP) [8]. Since the MEP is indicative of the excitability of the entire corticospinal pathway, it must be normalized to a corresponding CMEP or TMEP elicited at the same time and under the same conditions to isolate cortical excitability. Another TMS-elicited parameter, the silent period (SP), is commonly regarded as indicative of intracortical inhibition, although the first 150 ms are mainly influenced by spinal mechanisms and, thereafter, by cortical mechanisms [9].

Since EMG is recorded at the muscle level, methods using EMG responses to quantify central fatigue and changes in motoneuronal and corticospinal excitability must take into account any changes that occur within the muscle. Supramaximal stimulation of the motor nerve elicits a compound muscle action potential (M wave, M_{max}) in EMG from the efferent volley, indicative of sarcolemmal propagation within the muscle. M waves elicited at the same time and in the same muscle state are used to normalize EMG responses to account for muscle changes.

However, it is important to recognize the limits of the aforementioned methods for assessing neural adaptions and acute changes. Methods such as the V-wave and H-reflex are performed in very specific conditions that may not always be applicable to certain situations or applications [6]. Observed changes in MEPs and SPs in fatigued conditions may also be influenced by TMS stimulus intensity alone [10] and, as observed in later sections, may result in conflicting responses for the same exercise bout. Methodological advances also continue to be made so that investigations can more accurately capture both the type and magnitude of fatigue. One example of a recent methodological development is a new cycling ergometer permitting dynamic exercise and subsequent isometric neuromuscular evaluations within ~1 s after the end of exercise [11]. This new ergometer eliminates recovery prior to post-exercise evaluations, an important development since fatigue-related neuromuscular changes recover quickly, sometimes within seconds [12–14].

Acute Neural Responses Induced by a Single Endurance Training Session: Central Fatigue

Definition of Fatigue and Its Central Component

Fatigue is the reduction in the capacity to voluntarily produce force (e.g., [15]). Fatigue can be further categorized as being either peripheral or central. Peripheral fatigue occurs distal to the neuromuscular junction. Central fatigue occurs within the central nervous system and results in a decrease in maximal neural drive to the muscle. This most commonly presents as a decrease in the ability to voluntarily contract a muscle maximally and the presenting fatigue can be further identified as being within the entire central component (i.e., from the brain and motoneurons) or solely at the supraspinal level (i.e., within the brain), depending on the technique used (see section “Tools Used to Assess Neural Adaptations” on methods to assess fatigue).

Central Fatigue Induced by Endurance Exercise

Numerous studies have explored the etiology of acute fatiguing endurance exercise (i.e., a single exercise bout). Central fatigue has been observed following acute exercise bouts, most specifically cycling and running. As such, this chapter focuses solely on the knee-extensor and plantar-flexor muscle groups since these muscle groups pertain directly to cycling and running. In the knee-extensor muscles, the magnitude of supraspinal fatigue (i.e., decrease in VA_{TMS}) increases as exercise duration increases, from approximately 8–11% for exercise lasting several hours [16, 17] to 16% for exercise longer than 13 h [10]. One exception is Klass et al. [18], who did not observe any change in VA_{TMS} after 60 min of cycling at 55% of maximal aerobic power (W_{max}) followed by a ~30-min time-trial; however, VA_{TMS} was measured 10 min after the cycling exercise terminated. The magnitude of knee-extensor central fatigue increases from <20% for exercise lasting up to 5 h (e.g., [16, 19–22]) to >25% for exercise longer than 13 h [10, 20, 21]. The magnitude of central fatigue observed in the plantar flexors is less than for the knee extensors and ranges from 6 to 15% for exercise longer than 13 h [20, 21, 23]. The inhibitory effect of group III and IV afferents has been highlighted as a major contributing factor to voluntary activation impairment following fatiguing cycling exercise [16, 24].

Potential changes to the corticospinal pathway, as measured by EMG responses, have also been observed. There may be increases [10, 16] or no change [10, 16–18, 25] in knee-extensor corticospinal excitability (i.e., MEP size) following a prolonged acute exercise bout. Decreased motoneuronal excitability was observed following 90 min of running as demonstrated by a decreased magnitude of both V-wave and H-reflex responses in the plantar flexors [26]. Conversely, motoneuronal excitability as indicated by CMEP area was unchanged following shorter duration (~8–9 min), high-intensity cycling bouts [27, 28]. There may also be increases [10] or no change [10, 16, 18, 24, 29] in knee-extensor SP duration following an acute

cycling bout. One limitation of all of these studies is that the delay to post-exercise evaluations permitted recovery to occur, meaning that the amount of central fatigue and changes to the corticospinal pathway were very likely underestimated. As described above, recent methodological developments have allowed this limitation to be overcome.

Does the Type of Endurance Activity Impact Central Fatigue?

The response to this question is a definite yes. Even though a direct comparison with the same subjects exercising for the same duration and at the same intensity still needs to be conducted, we systematically found that running induced more central fatigue than either cycling or cross-country skiing, two activities that induce less mechanical stress/fatigue in the muscles [30, 31]. This was the case when comparing 5-h running and cycling bouts at 55% of VO_{2max} [19, 22] and a ski-skating marathon vs a 30-km trail-running competition [15, 32]. These results suggest that neurobiological changes such as the accumulation of serotonin, play only a moderate role, if any, in central fatigue development during prolonged exercise. The potential inhibitory action from thin afferent fiber (group III–IV) signaling, which may be sensitized by pro-inflammatory mediator production during prolonged running exercise, may explain the large central fatigue after ultra-marathons [20, 21, 33]. Yet, indirect evidence showing that a large inflammatory response persisted 2 days after a 165-km mountain ultra-marathon while VA had returned to pre-race values [21] does not support this hypothesis. Another possible explanation for the difference between the magnitude of fatigue elicited by running and cycling is that the disinhibition of group Ia afferents may be more pronounced in running than cycling due to repeated eccentric muscle actions. This could induce fatigue/damage at the spindle level or simply increase muscle compliance [34].

Neural Adaptations Induced by Chronic Systematic Endurance Training

It is well-known that endurance training improves fitness. Mechanisms such as increased stroke volume, partly due to greater blood volume, and increased muscle oxidative capacity (e.g., mitochondrial content) have been proposed to explain the improvements in aerobic fitness (e.g., [35, 36]). It is also well-known that strength training, particularly explosive and plyometric training, can trigger neural adaptations (e.g., [37, 38]). For instance, using a combination of V-wave, H-reflex, and Mmax responses, Aagaard et al. [37] demonstrated that 14 weeks of heavy-weight resistance training induced an increase in maximal central drive, likely mediated by a combination of both supraspinal and spinal adaptations. Earlier MU activation, an increase in the number of doublets and triplets and an enhanced maximal discharge rate were observed after 12 weeks of dynamic training (at 30–40% of maximal force) [39]. Changes in corticospinal excitability were also evidenced after resistance

training (see below). Here, we aim to describe the lesser known neural adaptations after endurance training. Although adaptations within the nervous system are not the main reason patients, sedentary people or athletes perform endurance exercise, it is important to understand the potential benefits or, conversely, the deleterious role that endurance training can have on central drive. We will first compare central nervous system (CNS) outcomes (e.g., VA, H-reflex) in endurance athletes vs untrained subjects and athletes trained in sports that require greater levels of power or strength. Thereafter, we will review the studies that have investigated the effects of an endurance training intervention on the nervous system, at rest and then during and after exercise (i.e., in a fatigued state).

Comparison of CNS Outcomes in Endurance Athletes Versus Explosive Athletes and Sedentary People

One way to examine training adaptations is to compare populations with different training backgrounds. This method has obvious flaws (e.g., impact of genetics, uncontrolled type, and amount of training) but it also has one main advantage: it allows examination of training adaptations due to several years of training as opposed to several weeks (generally 3–12) in interventional studies, i.e., a very limited time period compared to an athlete's or patient's life. Lattier et al. [40] showed that although power-trained athletes (POW) performed much better for squat jumps than endurance-trained athletes (END), the two groups were equally strong for isometric MVC. Also, both groups were stronger than sedentary subjects (SED). The difference might be due to a significantly lower VA in SED while VA was similar between END and POW. The results of Lattier et al. [40] were confirmed by Garrandes et al. [41], who did not find any difference in knee-extensor VA, measured with the interpolated twitch technique, between END and POW. This suggests that both POW and END athletes are equally capable of maximally driving their muscles when activation is measured in isometric conditions. This is likely no longer true when a much higher discharge rate is needed during explosive movements. However, these results have been challenged by Cohen et al. [42], who observed no difference in isometric MVC between END and SED. Although VA was not reported in this study, it is very unlikely that VA was lower in SED than in END. However, both Lattier et al. and Cohen et al. [40, 42] observed a lack of difference in squat jump and rate of force development (RFD) for SED and END. It has also been shown that even when force is expressed as a percentage of maximum, the force-time curves of POW were faster than END. While the amount of neural activation can partly explain this result, these data do not rule out the qualitative characteristics of the muscle tissue itself [43]. Interestingly, RFD was not lower in END than in strength-trained athletes.

In agreement with other studies (see [44]), Maffiuletti et al. [45] showed that the SOL H-reflex normalized to Mmax was significantly smaller in POW than END, suggesting increased α -motoneuronal excitability after endurance training. However, POW exhibited a greater force-to-EMG ratio, meaning POW produced greater force

per number of MUs activated [46]. While the larger H-reflex may simply reflect a greater percentage of type I fibers, presynaptic inhibition, through activation of GABA_A and/or GABA_B receptors of Ia afferent terminals, may be greater for END than either POW or SED [47]. Likewise, it has been shown that stretch reflexes [48, 49] were different depending on training background, possibly due to a higher percentage of type I fiber muscle-spindle density in END.

Training Interventions: Effects on CNS at Rest

Endurance training has been shown to enhance cognitive and neural plasticity in several brain regions including the cerebellum, hippocampus, and cerebral cortex and angiogenesis in the motor cortex [48]. Here, we will only examine the effects of endurance training on motor cortical and corticospinal factors, mainly VA, MEP, and SP as well as V-wave and H-reflex measured at rest, i.e., without fatigue. Data are summarized in Table 4.1.

Unlike the vast majority of strength training programs, MVC did not change in most (e.g., [25, 44, 50, 52, 54]) endurance training interventions. MVC was found to increase in one study [53] but the training was of low-force concentric and isometric muscle actions, i.e., not a traditional cycling or running intervention. The most global indication of neural adaptation, i.e., VA (PNS or TMS), does not change with endurance (or strength) training but this is likely due to a ceiling effect. Indeed, in healthy subjects lower-limb VA is nearly complete prior to training, thus there is little room for improvement. In addition, VA is known to be a semi-quantitative measure that probably does not allow quantification of small increases in central drive [55]. One must also keep in mind that while dynamic training is employed, tests of voluntary activation (and often MVC) are isometric. In other words, the lack of improvement may be indicative of the highly specific nature of the adaptations [56]. One difference between endurance and strength training that could partly explain the difference in terms of MVC improvements (even short-term training where only neural adaptations occur [44]) could be the increased descending drive that occurs after strength training only. Indeed, while V waves were found to increase by 50–80% after strength training (e.g., [37, 44], and the changes in V waves also correlated to MVC gains [44]), this factor did not change after endurance training [44, 50].

At the spinal level, in line with cross-sectional studies (e.g., [45]), it was initially found that the H-reflex increased with endurance training [44, 51]. For instance, Perot et al. [51] found that H reflexes and tendon-tap reflexes increased in 75% of the participants after 8 weeks of endurance (running) training. It was suggested that endurance training increased both the excitability of the motoneurons and the response of the muscle spindles to stretching. Yet the effect of endurance training on the H-reflex pathway has been recently challenged [50]. Behrens et al. [50] used a better experimental design in the sense that they had a control group. As stated by the authors, a dependent t-test on the Hmax/Mmax ratio from pre- to post-training was significant and based on this result, they could have concluded that endurance

Table 4.1 Effects of endurance training on CNS characteristics at rest

Study	Subjects	Age as mean ± SD or [range] (year)	Control group	Training duration (weeks)	Number of sessions or duration/week	Training characteristics	Muscle(s) (muscle group)	Main outcomes (at rest)
Behrens et al. [50]	10 F, 12 M	CG: 23 ± 2 TRAIN: 24 ± 2	Y	8	2 × 1 h	Cycling at 70–90% HRmax	SOL (PF)	VA _{PNS} ↔ H-reflex at rest ↔ H-reflex during MVC ↔ V-wave ↔ RFD ↔
O'Leary et al. [25]	2 F, 8 M	27 ± 6	N	6	3	Cycling high-intensity IT (6–8 × 5 min at Δ50%)	VL (KE)	VA _{PNS} ↔ VA _{TMS} ↔ MEP/Mmax ↔
O'Leary et al. [25]	2 F, 8 M	27 ± 4	N	6	3	Cycling moderate-intensity continuous training (~60–80 min at 90% LT)	VL (KE)	VA _{PNS} ↔ VA _{TMS} ↔ MEP/Mmax ↔
Perot et al. [51]	6 F, 14 M	[19–23]	N	8	2 h	Running at 60% MAV	SOL (PF)	Hmax/Mmax ↑ T-reflex ↑ / ↔
Vila-Cha et al. [52]	18 M	26.1 ± 3.9 ^a	Y	6	3	Cycling increasing from 20–30 min at 50–60% HRR to 40–50 min at 65–75% HRR	VM, VL (KE)	MU discharge rate at 30% MVC ↓ MU conduction velocity ↑
Vila-Cha et al. [44]	2 F, 11 M	24.0 ± 2.6 ^a	N ^b	3	3	Cycling increasing from 30–40 min at 55–65% HRR to 40–50 min at 65–75% HRR	SOL (PF)	Hmax/Mmax ↑ V-wave ↔ H-reflex excitability threshold ↓

Zeghal et al. [53]	23 M	CG: 23.9 ± 2.0 TRAIN: 25.2 ± 2.3	Y	8	3	Low-force concentric and isometric contractions	RF, VL, VM (KE)	$VAP_{NS} \leftrightarrow VAM_{MS}$
Zeghal et al. [54]	16 M	23.6 ± 2.6	Y	8	2–3	Running short IT (80–100% MAV) + continuous (60–65% MAV)	RF, VL, VM (KE)	$VAP_{NS} \leftrightarrow VAM_{MS}$

→ not statistically significant, ↑ indicates a statistically significant increase, ↓ indicates a statistically significant decrease, $\Delta 50\%$ halfway between lactate threshold and maximal oxygen uptake, CG control group, F female, $Hmax$ maximal Hoffmann reflex, $HRmax$ maximal heart rate, HRR heart rate reserve, IT interval training, KE knee extensors, LT lactate threshold, M male, MAP maximal aerobic velocity, MEP motor-evoked potential, $Mmax$ M wave amplitude or area, MVC isometric maximal voluntary contraction, MU motor unit, PF plantar flexors, RF rectus femoris, RFD rate of force development, SOL soleus, SP silent period, TRAIN training group, T-reflex T-response after Achilles tendon tap (stretch reflex), VAP_{NS} voluntary activation assessed via peripheral nerve stimulation, VAT_{TMS} cortical voluntary activation assessed via transcranial magnetic stimulation, VL vastus lateralis, VM vastus medialis

^aAll subjects, including a group that had performed strength training

^bThis study also included a strength training group

training increased the normalized H-reflex response. However, this was not the case with appropriate statistical analysis (ANCOVA). Alternative explanations for the lack of significant change in the H-reflex response in this latter study [50] were that subjects only trained 2 times/week and training was performed as cycling where SOL muscle activation is relatively low compared to the knee-extensor muscles. This could explain the difference with transversal studies where there has been a higher dose of endurance training for several years. Thus, it is possible that (1) a sustained period of regular aerobic exercise is necessary to induce alterations in H-reflex responses and (2) running training has stronger effects on spinal reflex responses than cycling training [50].

To the best of our knowledge, only four studies have examined CNS outcomes using TMS after endurance training [25, 50, 53, 54]. Although these studies found significant increases in endurance performance after 6–8 weeks of various types of endurance training (running vs cycling, continuous vs interval training, local muscle endurance), none of them found significant changes in VA, MEP, or SP measured in resting conditions after training. The effects of resistance training on corticospinal excitability is unclear as some studies showed reductions or no change [38, 57] or increases [58–60] in MEP responses.

It has been shown that 6 weeks of strength and endurance training elicit similar increases in muscle fiber conduction velocity measured at 30% MVC but opposite changes in MU discharge rates. Indeed, MU discharge rate was found to increase after strength training and decrease after endurance training [52]. It is important to note that this was not tested during MVC but at 30% MVC. Short-term endurance training has no effect on maximal RFD or muscle activation at the onset of contraction [50]. However, endurance training performed in addition to power training can limit the development of explosivity (e.g., [61]), as developed in detail elsewhere in this book.

Training Interventions: Effects on CNS During a Fatiguing Exercise

Endurance training is known to increase performance, yet the time to task failure (or other type of performance index) does not provide information regarding neural or muscular contributions to the improved resistance to fatigue. This last section will only focus on that aspect. One of the first longitudinal studies to investigate the effect of endurance training on neural adaptations was performed by Cafarelli et al. [62]. This study showed that after training, a smaller additional recruitment of MUs occurred during a 20-min cycling exercise compared to pre-training because of attenuated muscle fatigue, in line with the correlation that we found between the change in RMS and muscle fatigue during a cycling exercise [63]. The smaller MU recruitment was accompanied by a reduction in force sensation. Since this initial study, only three very recent (2015–2017) experiments have examined the issue of the change in neuromuscular fatigue after a period of endurance training. A summary of subject characteristics and training protocols for these three studies can be found in Table 4.1. The fatiguing tasks for these studies are described as follows.

Behrens et al. [50] performed a fatiguing task consisting of dynamic plantar flexion in isotonic mode of a Cybex dynamometer at 40% isometric MVC at a frequency of 35 contractions/min. Only fatigue at isotime compared to pre-training was considered post-training, and cycling performance was not measured. In Zghal et al. [53], subjects were asked to sustain a low-intensity isometric muscle action (15% of maximal isometric force) until task failure. Post-training, subjects performed a fatiguing exercise until task failure and one at isotime compared to pre-training. Even more interesting is O’Leary et al. [25], where adaptations were quantified at post-training during cycling trials at both absolute exercise intensity (based on pre-training $\text{VO}_{2\text{max}}$) and relative exercise intensity (based on post-training $\text{VO}_{2\text{max}}$). Importantly, only O’Leary et al. [25] investigated fatigue during a task specific to the training performed. Below, we differentiate the effects of training (1) for a given workload (i.e., at isotime) and (2) at task failure.

1. *For a given workload.* Surprisingly, Behrens et al. [50] showed that although some neuromuscular parameters tended to be improved in the endurance-trained group compared to controls following fatiguing exercise (e.g., isometric MVC, normalized V-wave, and peak twitch torque), none reached statistical significance. However, a comparison of the changes in isometric MVC after the fatiguing protocol before and after the training with a paired t-test indicated a significant improvement in fatigue resistance. The two other protocols found significant reductions of fatigue indices. Both Zghal et al. [53] and O’Leary et al. [25] demonstrated that endurance training could delay the time course of central fatigue. The investigators attributed these findings to the reduction in inhibitory afferent feedback from exercising muscles due to an improved muscle oxidative metabolism, i.e., less peripheral fatigue as demonstrated in the two studies. Importantly, the effects of endurance training on the rapid component of VO_2 kinetics could also play a role in minimizing peripheral fatigue as we recently showed [64]. In addition to the reduction of muscle fatigue after training, it has been suggested that the sensitivity of muscle afferents may be reduced (i.e., up-regulation of their threshold) in response to physical training such that central fatigue may be reduced and/or delayed after training. However, no direct evidence currently supports this hypothesis [53]. Neither of these two investigations found any excitability or inhibitory adaptations of the corticospinal pathway following training but Zghal et al. [53] found that the increase in SP duration with fatigue was abolished at isotime after training (SPs were not measured in [25]). It has also been reported that under fatiguing conditions, motor unit conduction velocity declines less during a fatiguing task (30% MVC to task failure) after 6 weeks of endurance training when compared to pre-training [65].
2. *At task failure.* Peripheral fatigue was greater in both O’Leary et al. [25] and Zghal et al. [53] after training. Interestingly, the greater peripheral fatigue at task failure only occurred after the high-intensity interval training protocol and not after the low-intensity continuous one in O’Leary et al. [25]. Two adaptations within the nervous system could explain the greater peripheral fatigue at task failure after training: (1) the up-regulation in the III-IV afferent firing threshold

suggested above [53] that would result in greater tolerance to metabolic disturbances and translate into an accumulation of greater peripheral fatigue and/or (2) improvement of sensorimotor system tolerance to noxious inhibitory signals, i.e., better pain tolerance (e.g., to acidosis) by the central nervous system. In this regard, one of the authors of this book chapter proposed a “flush model” to describe performance regulation in endurance and ultra-endurance exercise [30]. Improved sensorimotor system tolerance would represent a reduction of the “security reserve” in the brain, which is influenced by acceptable levels of peripheral fatigue for the subject (among other factors).

Contrary to peripheral fatigue, central fatigue at task failure either decreases [25] or is maintained [53] after training. In fact, O’Leary et al. [25] demonstrated that 6 weeks of high-intensity interval training significantly attenuated the exercise-induced reduction in VA_{PNS} . Although these investigators found a significant improvement in time to task failure following both interval and continuous training at absolute exercise intensity, they did not observe any change in corticospinal excitability (MEPs) or inhibition (SPs) or in supraspinal voluntary activation (VA_{TMS}) following the two modes of training. Besides the possible up-regulation of group III-IV afferents, O’Leary et al. [25] speculated that adaptations in central mechanisms (improved handling of serotonin [66], mitigated cerebral ammonia uptake [67], improved cerebral oxygenation [68], and enhanced spinal reflex excitability [44]) may also occur. A limitation of O’Leary et al. [25] is that participants needed to move from the cycle-ergometer to the isometric chair for post-exercise assessments. This process resulted in a time-delay to the neuromuscular assessment which could possibly have reduced the magnitude of corticospinal responses [13] (see section “Tools Used to Assess Neural Adaptations” on methodological considerations).

In summary, central fatigue induced by endurance exercise has been extensively investigated over the last 15 years and has been found to play a major role in neuromuscular fatigue, especially with prolonged running, even if the assessment tools available to date have not fully allowed for complete understanding of fatigue etiology. On the contrary, neural responses to endurance training are surprisingly under-investigated. For instance, only one study has investigated the effects of training on fatigue during a task specific to the type of training performed. Similar to muscle adaptations, most neural changes are specific to endurance training when compared to explosive or strength training. Yet the literature regarding spinal excitability (H-reflex) and cortical excitability/inhibition (TMS parameters) in the unfatigued state is rather uninformative. After training, central fatigue is reduced for a given absolute load, probably related to the reduction in inhibitory afferent feedback since peripheral fatigue is reduced as expected, even if lower sensitivity of group III and IV afferents may also play a role. Although no changes in corticospinal excitability or inhibition or supraspinal voluntary activation were found after exercise to task failure, peripheral fatigue is greater (especially when training includes interval training) but central fatigue is attenuated when measured with traditional nerve stimulation techniques. These training adaptations could benefit endurance/ultra-endurance performance, especially since the longer the event, the greater the amount

of central fatigue that develops. Further longitudinal studies, in particular studies examining changes in neuromuscular function post-training with state-of-the-art techniques, are needed to better understand how the central nervous system adapts to chronic, low-intensity exercise.

References

- Burton C, Saey D, Saglam M, Langer D, Gosselink R, Janssens W, Decramer M, Maltais F, Troosters T. Effectiveness of exercise training in patients with COPD: the role of muscle fatigue. *Eur Respir J.* 2012;40:338–44.
- Gathercole RJ, Stellingwerff T, Sporer BC. Effect of acute fatigue and training adaptation on countermovement jump performance in elite snowboard cross athletes. *J Strength Cond Res.* 2015;29:37–46.
- Millet GY, Martin V, Martin A, Verges S. Electrical stimulation for testing neuromuscular function: from sport to pathology. *Eur J Appl Physiol.* 2011;111:2489–500.
- Belanger AY, McComas AJ. Extent of motor unit activation during effort. *J Appl Physiol Respir Environ Exerc Physiol.* 1981;51:1131–5.
- Todd G, Taylor JL, Gandevia SC. Measurement of voluntary activation of fresh and fatigued human muscles using transcranial magnetic stimulation. *J Physiol.* 2003;551:661–71.
- McNeil CJ, Butler JE, Taylor JL, Gandevia SC. Testing the excitability of human motoneurons. *Front Hum Neurosci.* 2013;7:152.
- Taylor JL, Gandevia SC. Noninvasive stimulation of the human corticospinal tract. *J Appl Physiol (1985).* 2004;96:1496–503.
- Taylor JL, Gandevia SC. Transcranial magnetic stimulation and human muscle fatigue. *Muscle Nerve.* 2001;24:18–29.
- Yacyshyn AF, Woo EJ, Price MC, McNeil CJ. Motoneuron responsiveness to corticospinal tract stimulation during the silent period induced by transcranial magnetic stimulation. *Exp Brain Res.* 2016;234:3457–63.
- Temesi J, Rupp T, Martin V, Arnal PJ, Feasson L, Verges S, Millet GY. Central fatigue assessed by transcranial magnetic stimulation in ultratrail running. *Med Sci Sports Exerc.* 2014;46:1166–75.
- Doyle-Baker D, Temesi J, Medsky ME, Holash RJ, Millet GY. An innovative ergometer to measure neuromuscular fatigue immediately after cycling. *Med Sci Sports Exerc.* 2018;50(2):375–87.
- Froyd C, Millet GY, Noakes TD. The development of peripheral fatigue and short-term recovery during self-paced high-intensity exercise. *J Physiol.* 2013;591:1339–46.
- Mira J, Lapole T, Souron R, Messonnier L, Millet GY, Rupp T. Cortical voluntary activation testing methodology impacts central fatigue. *Eur J Appl Physiol.* 2017;117(9):1845–57.
- Taylor JL, Allen GM, Butler JE, Gandevia SC. Supraspinal fatigue during intermittent maximal voluntary contractions of the human elbow flexors. *J Appl Physiol.* 2000;89:305–13.
- Millet GY, Martin V, Lattier G, Ballay Y. Mechanisms contributing to knee extensor strength loss after prolonged running exercise. *J Appl Physiol.* 2003;94:193–8.
- Jubeau M, Rupp T, Perrey S, Temesi J, Wuyam B, Levy P, Verges S, Millet GY. Changes in voluntary activation assessed by transcranial magnetic stimulation during prolonged cycling exercise. *PLoS One.* 2014;9:e89157.
- Sidhu SK, Bentley DJ, Carroll TJ. Locomotor exercise induces long-lasting impairments in the capacity of the human motor cortex to voluntarily activate knee extensor muscles. *J Appl Physiol.* 2009;106:556–65.
- Klass M, Roelands B, Levenez M, Fontenelle V, Pattyn N, Meeusen R, Duchateau J. Effects of noradrenaline and dopamine on supraspinal fatigue in well-trained men. *Med Sci Sports Exerc.* 2012;44:2299–308.

19. Lepers R, Maffiuletti NA, Rochette L, Brugniaux J, Millet GY. Neuromuscular fatigue during a long-duration cycling exercise. *J Appl Physiol.* 2002;92:1487–93.
20. Martin V, Kerhervé H, Messonnier LA, Banfi JC, Geysant A, Bonnefoy R, Féasson L, Millet GY. Central and peripheral contributions to neuromuscular fatigue induced by a 24-h treadmill run. *J Appl Physiol.* 2010;108:1224–33.
21. Millet GY, Tomazin K, Verges S, Vincent C, Bonnefoy R, Boisson RC, Gergele L, Feasson L, Martin V. Neuromuscular consequences of an extreme mountain ultra-marathon. *PLoS One.* 2011;6:e17059.
22. Place N, Lepers R, Deley G, Millet GY. Time course of neuromuscular alterations during a prolonged running exercise. *Med Sci Sports Exerc.* 2004;36:1347–56.
23. Temesi J, Arnal PJ, Rupp T, Feasson L, Cartier R, Gergele L, Verges S, Martin V, Millet GY. Are females more resistant to extreme neuromuscular fatigue? *Med Sci Sports Exerc.* 2015;47:1372–82.
24. Sidhu SK, Cresswell AG, Carroll TJ. Motor cortex excitability does not increase during sustained cycling exercise to volitional exhaustion. *J Appl Physiol (1985).* 2012;113:401–9.
25. O’Leary TJ, Collett J, Howells K, Morris MG. Endurance capacity and neuromuscular fatigue following high- vs moderate-intensity endurance training: a randomized trial. *Scand J Med Sci Sports.* 2017;27(12):1648–61.
26. Racinais S, Girard O, Micallef JP, Perrey S. Failed excitability of spinal motoneurons induced by prolonged running exercise. *J Neurophysiol.* 2007;97:596–603.
27. Sidhu SK, Weavil JC, Mangum TS, Jessop JE, Richardson RS, Morgan DE, Amann M. Group III/IV locomotor muscle afferents alter motor cortical and corticospinal excitability and promote central fatigue during cycling exercise. *Clin Neurophysiol.* 2017;128:44–55.
28. Weavil JC, Sidhu SK, Mangum TS, Richardson RS, Amann M. Fatigue diminishes motoneuronal excitability during cycling exercise. *J Neurophysiol.* 2016;116:1743–51.
29. Goodall S, Gonzalez-Alonso J, Ali L, Ross EZ, Romer LM. Supraspinal fatigue after normoxic and hypoxic exercise in humans. *J Physiol.* 2012;590:2767–82.
30. Millet GY. Can neuromuscular fatigue explain running strategies and performance in ultra-marathons?: the flush model. *Sports Med.* 2011;41:489–506.
31. Millet GY, Lepers R. Alterations of neuromuscular function after prolonged running, cycling and skiing exercises. *Sports Med.* 2004;34:105–16.
32. Millet GY, Martin V, Maffiuletti NA, Martin A. Neuromuscular fatigue after a ski skating marathon. *Can J Appl Physiol.* 2003;28:434–45.
33. Millet GY, Lepers R, Maffiuletti NA, Babault N, Martin V, Lattier G. Alterations of neuromuscular function after an ultramarathon. *J Appl Physiol.* 2002;92:486–92.
34. Avela J, Kyrolainen H, Komi P. Altered reflex sensitivity after repeated and prolonged passive muscle stretching. *J Appl Physiol.* 1999;86:1283–91.
35. Coffey VG, Hawley JA. The molecular bases of training adaptation. *Sports Med.* 2007;37:737–63.
36. Egan B, Zierath JR. Exercise metabolism and the molecular regulation of skeletal muscle adaptation. *Cell Metab.* 2013;17:162–84.
37. Aagaard P, Simonsen EB, Andersen JL, Magnusson P, Dyhre-Poulsen P. Neural adaptation to resistance training: changes in evoked V-wave and H-reflex responses. *J Appl Physiol (1985).* 2002;92:2309–18.
38. Carroll TJ, Riek S, Carson RG. The sites of neural adaptation induced by resistance training in humans. *J Physiol.* 2002;544:641–52.
39. Van Cutsem M, Duchateau J, Hainaut K. Changes in single motor unit behaviour contribute to the increase in contraction speed after dynamic training in humans. *J Physiol.* 1998;513(Pt 1):295–305.
40. Lattier G, Millet GY, Maffiuletti NA, Babault N, Lepers R. Neuromuscular differences between endurance-trained, powertrained, and sedentary subjects. *J Strength Cond Res.* 2003;17:514–21.
41. Garrandas F, Colson SS, Pensini M, Seynnes O, Legros P. Neuromuscular fatigue profile in endurance-trained and power-trained athletes. *Med Sci Sports Exerc.* 2007;39:149–58.

42. Cohen R, Mitchell C, Dotan R, Gabriel D, Klentrou P, Falk B. Do neuromuscular adaptations occur in endurance-trained boys and men? *Appl Physiol Nutr Metab.* 2010;35:471–9.
43. Häkkinen K, Keskinen KL. Muscle cross-sectional area and voluntary force production characteristics in elite strength- and endurance-trained athletes and sprinters. *Eur J Appl Physiol Occup Physiol.* 1989;59:215–20.
44. Vila-Cha C, Falla D, Correia MV, Farina D. Changes in H reflex and V wave following short-term endurance and strength training. *J Appl Physiol (1985).* 2012;112:54–63.
45. Maffiuletti NA, Martin A, Babault N, Pensini M, Lucas B, Schieppati M. Electrical and mechanical H(max)-to-M(max) ratio in power- and endurance-trained athletes. *J Appl Physiol (1985).* 2001;90:3–9.
46. Koceja DM, Davison E, Robertson CT. Neuromuscular characteristics of endurance- and power-trained athletes. *Res Q Exerc Sport.* 2004;75:23–30.
47. Earles DR, Dierking JT, Robertson CT, Koceja DM. Pre- and post-synaptic control of motor-neuron excitability in athletes. *Med Sci Sports Exerc.* 2002;34:1766–72.
48. Kumpulainen S, Avela J, Gruber M, Bergmann J, Voigt M, Linnamo V, Mrachacz-Kersting N. Differential modulation of motor cortex plasticity in skill- and endurance-trained athletes. *Eur J Appl Physiol.* 2015;115:1107–15.
49. Kyrolainen H, Komi PV. Stretch reflex responses following mechanical stimulation in power- and endurance-trained athletes. *Int J Sports Med.* 1994;15:290–4.
50. Behrens M, Weippert M, Wassermann F, Bader R, Bruhn S, Mau-Moeller A. Neuromuscular function and fatigue resistance of the plantar flexors following short-term cycling endurance training. *Front Physiol.* 2015;6:145.
51. Perot C, Goubel F, Mora I. Quantification of T- and H-responses before and after a period of endurance training. *Eur J Appl Physiol Occup Physiol.* 1991;63:368–75.
52. Vila-Cha C, Falla D, Farina D. Motor unit behavior during submaximal contractions following six weeks of either endurance or strength training. *J Appl Physiol (1985).* 2010;109:1455–66.
53. Zghal F, Cottin F, Kenoun I, Rebai H, Moalla W, Dogui M, Tabka Z, Martin V. Improved tolerance of peripheral fatigue by the central nervous system after endurance training. *Eur J Appl Physiol.* 2015;115:1401–15.
54. Zghal F, Martin V, Thorkani A, Arnal PJ, Tabka Z, Cottin F. Effects of endurance training on the maximal voluntary activation level of the knee extensor muscles. *Eur J Appl Physiol.* 2014;114:683–93.
55. de Haan A, Gerrits KH, de Ruiter CJ. Counterpoint: the interpolated twitch does not provide a valid measure of the voluntary activation of muscle. *J Appl Physiol (1985).* 2009;107:355–7; discussion 357–8.
56. Shield A, Zhou S. Assessing voluntary muscle activation with the twitch interpolation technique. *Sports Med.* 2004;34:253–67.
57. Jensen JL, Marstrand PC, Nielsen JB. Motor skill training and strength training are associated with different plastic changes in the central nervous system. *J Appl Physiol (1985).* 2005;99:1558–68.
58. Goodwill AM, Pearce AJ, Kidgell DJ. Corticomotor plasticity following unilateral strength training. *Muscle Nerve.* 2012;46:384–93.
59. Griffin L, Cafarelli E. Transcranial magnetic stimulation during resistance training of the tibialis anterior muscle. *J Electromyogr Kinesiol.* 2007;17:446–52.
60. Weier AT, Pearce AJ, Kidgell DJ. Strength training reduces intracortical inhibition. *Acta Physiol (Oxf).* 2012;206:109–19.
61. Häkkinen K, Alen M, Kraemer WJ. Neuromuscular adaptations during concurrent strength and endurance versus strength training. *Eur J Appl Physiol.* 2003;89:42–52.
62. Cafarelli E, Liebesman J, Kroon J. Effect of endurance training on muscle activation and force sensation. *Can J Physiol Pharmacol.* 1995;73:1765–73.
63. Decorte N, Lafaix PA, Millet GY, Wuyam B, Verges S. Central and peripheral fatigue kinetics during exhaustive constant-load cycling. *Scand J Med Sci Sports.* 2012;22:381–91.

64. Temesi J, Mattioni Maturana F, Peyrard A, Piucco T, Murias JM, Millet GY. The relationship between oxygen uptake kinetics and neuromuscular fatigue in high-intensity cycling exercise. *Eur J Appl Physiol.* 2017;117:969–78.
65. Vila-Cha C, Falla D, Correia MV, Farina D. Adjustments in motor unit properties during fatiguing contractions after training. *Med Sci Sports Exerc.* 2012;44:616–24.
66. Jakeman PM, Hawthorne JE, Maxwell SR, Kendall MJ, Holder G. Evidence for downregulation of hypothalamic 5-hydroxytryptamine receptor function in endurance-trained athletes. *Exp Physiol.* 1994;79:461–4.
67. Nybo L, Dalsgaard MK, Steensberg A, Moller K, Secher NH. Cerebral ammonia uptake and accumulation during prolonged exercise in humans. *J Physiol.* 2005;563:285–90.
68. Rooks CR, Thom NJ, McCully KK, Dishman RK. Effects of incremental exercise on cerebral oxygenation measured by near-infrared spectroscopy: a systematic review. *Prog Neurobiol.* 2010;92:134–50.



Physiological and Molecular Adaptations to Strength Training

5

Juha P. Ahtiainen

Resistance exercise training (RT) can be functionally defined as the progressive overload of a skeletal muscle that is characterized by high muscle contraction force and anaerobic ATP resynthesis. Long-term RT elicits a range of physiological adaptations that contribute to changes in muscle function. Specifically, RT stimulates adaptive machinery responsible for increased maximal contractile force output that is primarily promoted by the combined effect of enhanced muscle activation and muscle fiber hypertrophy [1]. Skeletal muscles play an essential role in locomotion and in the control of whole body metabolism and, hence, RT is widely employed by athletes to improve sport-specific performance, by general population to promote health, lean body mass and general fitness, and in rehabilitation to prevent loss of muscle mass and strength in pathological states [2, 3].

Skeletal muscle can exhibit remarkable plasticity in response to RT. Adjustments within the muscle milieu to mechanical and metabolic demands of RT act to attenuate cellular stress during subsequent exercise sessions [4]. The major morphological adaptation that is specific to RT is a marked increase in muscle cross-sectional area (CSA) of exercised muscles. However, the design of the RT program (i.e., volume, intensity, and frequency of RT sessions, mode of muscle actions used, progression, periodization, variety of RT stimulus, and integration of RT to other fitness training) specifically influences the subsequent chronic physiological adaptations [5]. Also factors such as heredity, sex, biological age, exercise training history, health status and possible medication, diet and nutritional supplements, personal lifestyle and habitual physical activity/inactivity, other physical and psychological stressors (e.g., work-related) and coping with mental stress, training adherence as well as environmental factors can influence chronic outcomes of RT [4, 6].

J. P. Ahtiainen

Neuromuscular Research Center, Faculty of Sport and Health Sciences,
University of Jyväskylä, Jyväskylä, Finland
e-mail: Juha.ahtiainen@jyu.fi

Changes in Muscle Size

Increases in skeletal muscle size (i.e., hypertrophy) are the most striking adaptations that occur in response to RT. Muscle hypertrophy is detectable after few weeks from the beginning of the regular RT and proceeds in a linear manner at least for the first few months of training [1]. Typically, on average 6–9% increases in muscle size are observed in quadriceps muscles following few months of RT in previously untrained individuals [7]. Reaching the individual maximum in muscle mass gains, however, may require several years of systematic RT.

In research, greater hypertrophy is typically observed in upper body muscles compared to lower extremity muscles, possibly due to higher locomotive activity in leg muscles that may reduce the potential for further muscular responses induced by the exercise stimulus [1]. Age and sex may not have substantial effects on the initial RT-induced muscle hypertrophy [1, 8, 9]. However, in women and in older individuals muscle hypertrophy may remain only modest over the years of systematic RT when their responses are compared to those observed in younger adult men. RT-induced muscle hypertrophy occurs specifically in trained muscles and is depending on the design of the RT program. In an untrained state, various kinds of training regimens can induce muscle hypertrophy during the first months of training [10]. For maximizing muscle growth by long-term RT, however, the RT program should principally include multiple sets per exercise with 6–12 heavy repetitions per set and relatively short rest intervals between the sets. Furthermore, several different kinds of exercises should be employed per muscle group in the context of split training routine [5, 11, 12].

Changes in Myofiber Size and Fiber-Type Transitions

Skeletal muscle hypertrophy induced by RT occurs through an increased protein content of individual muscle fibers. Most of the skeletal muscle fiber cytoplasm is occupied by myofibrils with the most abundant proteins being myosin and actin filaments. Thus, RT-induced fiber hypertrophy is primarily a result of the biosynthesis and accumulation of new contractile myofilaments, with concomitant expansion of fiber volume [13–15]. The possible mechanism of fiber growth is an increased CSA and proliferation of myofibrils that results in increased contractile material arranged in parallel and, consequently, an increase in force production capacity. These increases appear especially in fast-twitch type II fibers following RT [1].

Skeletal myofibers develop distinct phenotypic characteristics during the postnatal period, and therefore the distribution of fiber types is genetically determined. Muscle fibers are characterized as type 1 (slow-twitch) and 2A and 2X (fast-twitch) according to the predomination of their myosin heavy chain (MHC) polymorphisms. Although the fiber-type profile is genetically established, fibers may be remodeled throughout the life span by diverse physiological stimuli such as the training status [16]. Many human studies have demonstrated that prolonged RT promotes the conversion of muscle fibers from the glycolytic type 2X fibers to the

more oxidative type 2A fibers, whereas the proportion of type I fibers remains rather unchanged [17]. During fiber-type transformation, the expression of MHC isoforms and mitochondrial density, oxidative phosphorylation (OXPHOS) activity, vasculature, and fatigue resistance are switched accordingly. The ability to “shift” skeletal muscle fibers from a more glycolytic fiber to a more oxidative fiber is critical for energy availability to support skeletal muscle contractile activity during the exercise [18].

Changes in Muscle Architecture

Muscle architecture is defined as the structural arrangement of muscle fibers and connective tissue elements within the muscle relative to the line of force generation at the macroscopic level. Muscle architecture is an important determinant of muscle’s mechanical function by affecting the force–velocity relationship [19]. Key components of this relationship are fiber length and pennation angle. Muscle fascicles are bundles of muscle fibers and the angle in which they attach to tendon or aponeurosis (i.e., pennation angle) can be investigated by ultrasound techniques *in vivo*. Physiological CSA (i.e., the area of the cross section of a muscle perpendicular to its fibers) is closely related to the force produced by the muscle and is largely determined by the pennation angle. On the other hand, muscle velocity is proportional to muscle fiber length [20].

Several studies have shown that RT-induced structural remodeling of the contractile machinery can increase pennation angles to a certain extent in the hypertrophied muscles [21]. These architectural changes in trained muscles affect the manner how force is transmitted from contracting muscle fibers to tendons and bones. RT-induced increases in pennation angles allows greater contractile material deposition (i.e., addition of sarcomeres in parallel) that further increases physiological CSA and, consequently, enabling an increase in the force-generating capacity of the muscle. Mathematically, extensive increases in pennation angle can negatively affect force production of the contracting muscle due to unfavorable arrangement of muscle fibers relative to the axis of force generation to tendon. Thus, when pennation angle increases by excessive hypertrophy, force produced per physiological CSA may decrease [22]. On the other hand, increases in myofibrillar size without changes in muscle architecture (i.e., increase in myofibrillar packing density or lateral force transmission) may explain changes in specific tension (i.e., force exerted by the fibers per unit of physiological CSA). That may partly explain why initial strength gains by RT can be achieved without measurable increase in muscle CSA [22, 23].

Satellite Cells and Myonuclei Addition

Skeletal muscle satellite cells are quiescent myogenic precursor cells, located adjacent to muscle beneath the basal lamina but outside the sarcolemma. The role of satellite cells in muscle regeneration is well established. Satellite cells can be

activated in response to traumatic lesions requiring muscle regeneration. Once activated, satellite cells proliferate and/or fuse together with preexisting fibers to regenerate muscle tissue [24].

Also, increased muscle activity during exercise can induce activation and proliferation of satellite cells. Subsequent fusion with an existing myofiber results in the addition of a myonucleus to the fiber syncytium, thereby increasing the total number of myonuclei. The number of myonuclei is a critical determinant of protein synthesis capacity by providing the amount of DNA necessary to sustain gene transcription [25]. The proposed role of the satellite cells in muscle hypertrophy revolves around the concept of a myonuclear domain, meaning that a single myonucleus supports a certain volume of cytoplasm [24, 26]. Myofibers are composed of many myonuclear domains and the myonuclear domain size is considered as virtually constant. Satellite cells provide a source for new myonuclei at a rate sufficient to maintain an almost constant myonuclei to cytoplasmic ratio during skeletal muscle hypertrophy in response to chronic RT. Indeed, several studies have demonstrated that muscle fiber hypertrophy is accompanied by a concomitant increase in satellite cell and/or myonuclear content during chronic RT in humans [25].

It appears, however, that at least modest muscle hypertrophy can be achieved without the addition of new myonuclei. Thus, the existing myonuclei may have the intrinsic ability to increase their RNA and protein synthesis capacity to such an extent that additional myonuclei are not required to support initial muscle fiber growth [2, 27]. However, there may exist a ceiling size of the myonuclear domain area beyond which a fiber will not be able to continue hypertrophy extensively unless more myonuclei are incorporated into the growing fiber [24]. Furthermore, it has been suggested that satellite cells occasionally need to fuse to the muscle fibers to maintain adult muscle mass. It is currently not well known whether other circulating stem cell populations with myogenic potential, together with satellite cells, are activated during the RT-induced hypertrophic response [25].

Activation of satellite cells and their myonuclear addition has been proposed to play a pivotal role in the phenomenon of “muscle memory” in RT that may be very long lasting in humans. According to the suggested theory, previously untrained fibers recruit myonuclei from activated satellite cells to support hypertrophic growth. During the subsequent detraining and muscle atrophy, myonuclei are protected against the elevated apoptotic activity and the higher number of myonuclei is retained. When muscles are subjected to hypertrophic re-training, muscles grow faster compared to initial RT period. However, convincing evidence of this theory is still lacking in humans [28].

Connective Tissue Adaptations to Resistance Training

Collagen-rich connective tissue constructs tendons and ligaments. In addition, connective tissue exists around and within skeletal muscle. Tendons play a main role in transmitting contractile force to bone and producing elastic energy, while ligaments stabilize joints preventing excessive movements that could damage the joint. Intramuscular connective tissue contributes to passive stiffness in the musculature

and force transmission between muscle fibers. Adaptations in the connective tissues occurs specifically only in structures that are exposed to loading [29, 30].

As skeletal muscles become stronger by RT, intramuscular connective tissues as well as tendons and ligaments also adapt to support increased muscular strength by increasing CSA [31, 32]. The turnover and, thus, renewal of tissue is somewhat slower in connective tissue in the musculoskeletal system compared to that of contractile proteins in the skeletal muscle cells itself. Therefore, tendons appear to hypertrophy at a somewhat slower rate compared to muscles by RT [33, 34]. However, increases in tendon stiffness can occur before tendon hypertrophy. That is possibly due to adaptations in internal structures of the tendon, e.g., modulation of cross-link composition between collagen molecules that improve mechanical properties of the tendon [35, 36]. Increased tendon stiffness may enhance the utilization of elastic energy during stretch shortening cycles and increase the rate of force development during the explosive (fast) muscle actions [33, 37].

Bone mass, density, and architecture are modified to sustain strains produced by the mechanical load. Osteocytes are involved in the turnover of bony matrix through various mechanosensory mechanisms. Bone adapts to external stress specifically at the loaded sites when the magnitude of peak strain is adequate. The most effective intervention for improving bone mineral density (BMD) appears to be exercise characterized by relatively large loading magnitudes and rates. Long-term RT of sufficient intensity and volume has been shown to increase BMD [38–41].

Metabolic Adaptations to Resistance Training

Heavy resistance exercise (i.e., several sets with submaximal loads and short rest periods between the sets) can induce acute decrease in ATP, phosphocreatine (PCr), and glycogen storages and marked increase in the concentration of blood lactate, indicating a high rate of anaerobic glycolysis. Consequently, depleted glycogen storages may partly induce post-exercise muscle fatigue [42–44].

Depending of the exercise-induced myofibrillar disruptions and volume of the loading protocol used and the content of carbohydrates in diet, glycogen storages may be replenished within a couple of days following exercise [45–48]. As a result of chronic RT, the activity of anaerobic enzymes (e.g., creatine phosphokinase, myokinase, and phosphofructokinase) has been shown to increase. Furthermore, intramuscular PCr and glycogen concentrations increase [49, 50]. Chronic RT may also increase skeletal muscle oxidative capacity [51, 52]. These adaptations may lead to improvements in energy metabolism and especially in glycolytic capacity in trained muscle by long-term RT [2].

Skeletal muscle is the main tissue for glucose disposal accounting for up to 80% of insulin-mediated glucose uptake in the postprandial state. During the resistance exercise bout, glucose uptake increases significantly in loaded muscles [51, 53]. Research evidence suggests that chronic RT is effective in improving insulin sensitivity when the intensity is above 50% of 1RM and adaptations occur predominantly locally in the trained skeletal muscles [54, 55]. One of the main mechanisms behind RT-induced muscular adaptations of improving insulin sensitivity is thought to be

an increased glucose transport into the myocytes by increased glucose transporter type four (GLUT 4) production, which is the primary transporter facilitating diffusion of circulating glucose into the skeletal muscle cells [56, 57].

Capillary growth likely occurs in parallel with enlargement of muscle fibers and, thus, capillary density is predominantly maintained in hypertrophied muscles with RT [58]. Mitochondrial content is mainly maintained or reduced following RT [59]. Chronic RT may induce no change or improvements in blood pressure [60–62] and blood lipid profile, of which reductions in LDL cholesterol appears to be a recurrent finding with RT [63–65]. In terms of cardiac morphological changes, resistance-trained athletes may have normal internal diameters but significantly thicker left ventricular wall, referred as to a concentric hypertrophy, although the research findings are not consistent [66–69]. Generally, long-term RT is beneficial for body composition by inducing increases in fat-free mass and decreases in fat mass, which may result in an increased resting metabolic rate [70–72].

Molecular Adaptations to Resistance Training

Skeletal muscle demonstrates a remarkable malleability to respond and adapt to contractile activity. The physiological stress by a resistance exercise bout is thought to disrupt cellular homeostasis. Cells react to stress by altering cellular functions to restore homeostasis during and after the exercise bout. Repeated disruptions of homeostasis, followed by sufficient recovery, generate gradually structural and functional adaptations in muscle tissue associated with long-term RT (“progressive overload principle”) [73, 74].

From a molecular perspective, RT adaptations are based on the accumulation of specific proteins that alter cellular properties. Remodeling of skeletal muscle starts by loading-specific stimuli that affect the activation of a complex network of intracellular signaling pathways. These signals mediate alterations in enzyme activities, gene expression, and protein biosynthesis, which finally will modulate muscle proteome (Fig. 5.1). Thus, the functional outcomes of RT, such as muscle mass gains and metabolic improvements, are coupled to the specificity of molecular responses [2, 75]. Although acknowledging that the molecular network regulating skeletal muscle adaptations to RT is vast and affected by numerous factors, this chapter only briefly reviews a few mechanisms that have been suggested to be key players in adaptation to RT in humans.

Stimuli for Muscle Adaptations to Resistance Training

Mechanical Stress

The mechanical tensile stress (stretch) is one important stressor associated with RT. All forms of muscular activity, whether eccentric or concentric, result in tension (force) through the active muscle(s). Tension associated with RT disturbs the

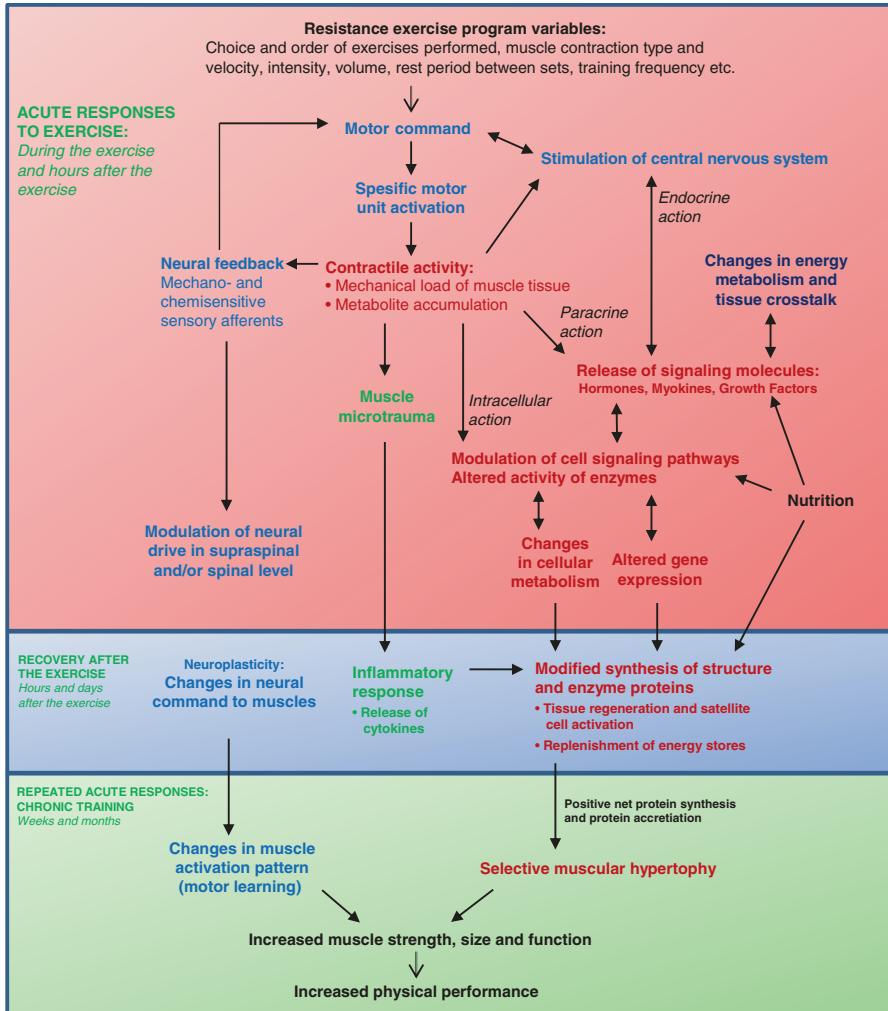


Fig. 5.1 Schematic overview of physiological stimuli by resistance exercise, leading to adaptive responses. Depending on program variables, resistance exercise results in a specific milieu of mechanical and metabolic stimuli within the contracting muscle as well as a systemic and local release of signaling molecules that lead to the activation of networks of signaling pathways and altered activity of cellular enzymes. These resistance exercise stimuli, together with nutrient availability, induce protein synthesis and tissue regeneration following exercise. By chronic resistance training, positive net protein synthesis leads to muscle hypertrophy

integrity of skeletal muscle, causing mechanochemically transduced molecular and cellular responses (mechanotransduction), favoring anabolism in myofibers and satellite cells. Mechanical stress can induce intracellular responses also independently of growth factors [76–79].

Mechanical stress induced by high force contractions during the resistance exercise is sensed in loaded muscles by various mechanisms. Mechanical stress induces the release of growth factors, such as IGF-I and hepatocyte growth factor (HGF), from the extracellular matrix. HGF can interact with satellite cells and activate signaling events leading to satellite cell proliferation [80–82]. Muscle contractions transiently disrupt the sarcolemma (the lipid bilayer that surrounds a muscle cell) integrity, which increases the concentration of membrane lipid phosphatidic acid (PA), leading to the activation of signaling pathways inducing hypertrophy [83–85]. Mechanical stress generated in sarcomeres is transferred to the extracellular matrix via costameres, which is a protein complex that connects peripheral myofibrillls via the z-disks with the sarcolemma. The costamere comprises a dystrophin/glycoprotein complex and focal adhesion complex, which includes the transmembrane receptor integrin. Activation of integrin can induce hypertrophic signal transduction pathways through focal adhesion kinases (FAK) [86–90]. The acute increase in intracellular hydration (cell swelling) may occur during the resistance exercise due to lactate accumulation, contributing to the osmotic gradient in skeletal muscle. Increased intracellular pressure may threaten the structural integrity of the cell membrane and, thus, initiate anabolic intracellular signaling response via activation of integrin and focal adhesion proteins [91–93]. Titin is a flexible intrasarcomeric protein that contributes to force transmission and defines the passive stiffness of skeletal muscle. Titin is a likely candidate to sense alterations of mechanical load and interact with diverse cellular signaling pathways inducing hypertrophy [94, 95]. Stretch activated channels (SACs) are calcium and sodium permeable channels which open due to mechanical stress to the sarcolemma. SACs may act as mechanosensor by allowing an influx of calcium ion (Ca^{2+}) into the myofiber that activates Ca^{2+} -dependent hypertrophic intracellular signaling pathways [96–98].

Metabolic Stress

In addition to mechanical stress, also metabolic stress associated with RT can promote muscle adaptations [99]. A high rate of ATP turnover during muscle contractions and consequent accumulation of AMP, the release of Ca^{2+} from the sarcoplasmic reticulum, and local hypoxia in exercising muscles may stimulate energy-sensing signaling pathways regulating energy metabolism during the resistance exercise [2, 74, 76]. Generally, metabolic stress increases during resistance exercise in an intensity/volume-dependent manner. Presumably, high metabolic stress together with high mechanical strain could be achieved by a hypertrophy-oriented resistance exercise protocol of 6–12 repetitions per set with each set performed until failure, and with relatively short rest periods between the sets [12, 100].

Hypoxia Local tissue hypoxia may occur during resistance exercise. Hypoxia is a major cellular stressor and oxygen sensing is well established in the regulation of adaptive processes in cells [101]. HIF-1 is considered as the master regulator of signal transduction pathways sensitive to the changes in intracellular partial pressure of

oxygen (PiO_2). Activation of HIF-1 induces transcription of target genes involved in promotion of glucose metabolism and glycolysis, erythropoiesis, and angiogenesis [2, 74].

REDOX State Skeletal muscle significantly generates reactive oxygen species (ROS), reactive nitrogen species (RNS), and nitric oxide (NO) during contractile activity. The generation of ROS is dependent on cellular antioxidant capacity and ROS regulates its own defense by promoting cellular antioxidants to maintain redox balance at rest and during the exercise [102, 103]. During resistance exercise, ROS production is likely increased, and it has been suggested to be an important signal in muscle remodeling to a more oxidative phenotype [104, 105]. In the context of human muscle hypertrophic responses to RT, NO may mediate the activation of satellite cells and ROS, if not expressed excessively, mediate activation of several intracellular signaling pathways, such as IGF-I and Mitogen-Activated Protein Kinase (MAPK) cascades, that could be required for muscle growth [82, 106, 107].

Calcium Flux Calcium facilitates the cross-bridge interaction between myosin and actin filaments during myofibrillar contraction. During muscle contractions, amplitude and duration of calcium oscillations depends on the level of force output by the muscle. Alterations of intracellular Ca^{2+} concentrations in myofibers modulate signaling activity of calcineurin- and calmodulin-dependent protein kinase (CaMKII). Ca^{2+} signaling influences glucose transport, lipid uptake and oxidation, and regulates activity-dependent muscle gene expressions that alter fiber-type distribution by promoting slow fiber formation [108, 109].

Myofibrillar Disruptions and Inflammation Processes

Resistance exercise results at least to some extent in localized muscular damage, of the loaded muscles, depending on the volume and intensity of the exercise and the training history of the participant. Regular RT typically causes mild muscle damage (myofibrillar disruptions) and full recovery normally occurs within a few days [110]. Misalignment of the myofibrils and Z-line streaming are common characteristic following resistance exercise, especially if the training regimen involves predominantly eccentric muscle actions. It has been proposed that due to the specific neural activation strategy for eccentric contractions, as compared to concentric, fewer motor units are recruited for a given load. This would result in a greater requirement of force per active motor unit, predisposing recruited muscle fibers to disrupt especially following unaccustomed eccentric exercise [111–113]. Eccentric training, however, has been shown to be especially effective in promoting muscle hypertrophy and strength gains [114].

Resistance exercise-induced myofibrillar disruptions are likely caused by physical stress upon the muscle fibers (i.e., mechanical stress) and the result of metabolic deficiencies, possibly through the loss of Ca^{2+} homeostasis (i.e., metabolic stress) [110]. Exercise-induced myofibrillar disruptions may elicit a local acute inflammatory

response to promote clearance of damaged tissue and muscle regeneration. Inflammatory responses result in movement of fluid, plasma proteins and leukocytes to the site of cellular disruption that is manifested as delayed onset of muscle soreness, muscle stiffness and swelling, and transient decrease of force-generating capacity in loaded muscles [115–117].

The infiltration of immune cells to the damaged muscles may be observed within 2–3 days following injury. The inflammatory response promotes clearance of damaged tissue and the regeneration of the damaged muscle fibers. The acute inflammatory response after the exercise includes infiltration of neutrophils and local release of proinflammatory cytokines, such as IL-1, IL-6, and TNF-alpha, which mediate protein breakdown [118]. Released cytokines may also stimulate proliferation of satellite cells [119]. Subsequent secondary inflammation includes a significant infiltration of monocytes (i.e., precursors to macrophages) within the damaged muscle fiber to induce further phagocytic activity. Eventually, muscle tissue remodeling occurs during the regenerative phase following the exercise [110, 120].

Systemic and Local Mediators of Muscle Plasticity: Hormones, Growth Factors, and Myokines

Systemic hormones such as testosterone, growth hormone (GH), insulin, insulin-like growth factor (IGF-1), and cortisol can affect muscle mass and growth throughout life span. Depending on acute program variables, resistance exercise can elicit transient post-exercise increase in circulating hormone concentrations [121, 122]. Endocrine responses during the exercise may be primarily due to regulation of whole body energy metabolism providing glucose and free fatty acids for energy in working muscles [123, 124]. Hormones can induce their cellular effects through receptor interactions and systemic elevations of circulating hormones presumably increase the likelihood of interactions with receptors located within the muscle tissue and, thus, potentially effects on the responses of RT [122]. However, normal physiological fluctuations in hormones appear to play a preserving, rather than stimulatory, role in the regulation of muscle size [125]. In many studies, resting hormonal concentrations have not shown a significant change during RT despite increases in muscle strength and hypertrophy [121, 122]. However, changes in testosterone and cortisol concentrations may reflect in some cases changes in training load and, thus, overall stress and recovery status in athletes [126].

The anabolic effects of IGF-I in skeletal muscle have been clearly demonstrated but systemic IGF-I has only a limited influence on the hypertrophic response. However, local (autocrine/paracrine) expressions of growth factors, such as IGF-I, within the loaded muscles in response to resistance exercise play probably an important role in skeletal muscle hypertrophy. IGF-I induces proliferation of satellite cells and enhances contractile protein accumulation in myofibers by activating IGF-I receptors in the cell membrane [24]. In contrast to IGF-I, myostatin is a major negative regulator of skeletal muscle growth. Myostatin is classified as a “myokine,” i.e., it is produced and secreted by contracting muscle fibers, and subsequently exert

auto-, para-, and/or endocrine effects. Myostatin inhibits satellite cell activation, repress expression of myogenic regulatory factors and promote proteolysis. Myostatin effects target cells through the Smad2/3 signaling cascade by binding to Activin type II receptors [76]. In addition to myostatin and IGF-I, many other extracellular signaling molecules may potentially modulate skeletal muscle phenotype during resistance training [127–131].

Amino Acids

Protein availability is a potent modulator of acute molecular responses to resistance exercise. Essential amino acids, especially the branched-chain amino acid leucine, can independently stimulate signaling pathways that subsequently increase protein synthesis rates. Thus, essential amino acids not only act as a substrate but also a signal to promote protein synthetic responses [109, 132]. Dietary protein intake appears to stimulate protein synthesis in a dose-dependent and saturable manner. Ingestion of 20 g of an isolated high-quality protein source, or 30 g of protein as part of a mixed meal, has been recommended to achieve maximal protein synthetic response [133, 134].

Regulation of Protein Synthesis and Degradation

A bout of resistance exercise results in an increased rate of protein synthesis during recovery and a proportionately smaller and briefer increase in the protein degradation rate [135, 136]. An acute bout of resistance training increases skeletal muscle protein turnover for up to 48 h after completion of exercise [137]. Increases in protein synthesis are suggested to be a result of an increased efficiency of translation per molecule of RNA [138]. The positive net protein synthetic response following resistance exercise results in an accretion of muscle protein over time [139, 140]. Protein synthesis must exceed protein breakdown for an extended period (i.e., few weeks) until RT-induced muscle size changes are detectable [141]. It seems that unaccustomed exercise bouts lead to exaggerated local and systemic stress responses (e.g., dysregulated redox balance) and, thus, induce increases in protein synthesis [75]. However, repeated bouts of exercise blunt protein synthetic response, resulting in an attenuated increase in protein synthesis in the trained state [142, 143].

mTOR Signaling The most well-described mechanism by which dietary protein and exercise modulates skeletal muscle protein synthesis and subsequently fiber hypertrophy is the mechanistic target of rapamycin complex 1 (mTORC1) signaling pathway [144, 145]. The activation of mTORC1 is mediated via insulin/IGF-1 receptor activation by hormones and growth factors and the activation of the downstream phosphatidyl inositol-3 kinase (PI3K)—Akt pathway [146]. mTORC1 can be activated also independently of Akt via contractile activity (mechanotransduction) and essential amino acid provision [147–149].

Activation of mTORC1 triggers downstream signaling through p70 ribosomal S6 kinase (p70 S6K1), that is a key regulator of protein synthesis through canonical pathways of protein translation and ribosome biogenesis [150, 151]. p70 S6K1 exerts its effect through ribosomal protein S6 (rpS6), eukaryotic elongation factor 2 kinase (eEF2), and eukaryotic initiation factor 4E-binding protein (4E-BP1), which collectively increases mRNA translational efficiency and ultimately protein synthesis for cellular hypertrophy [152, 153]. Increases in resistance exercise volume have been shown to induce a pronounced activation of mTOR signaling proteins [154–157] (Fig. 5.2).

AMPK Signaling The high rate of ATP turnover during the resistance exercise leads to a cellular energy deficit and increases in the AMP/ATP ratio. AMP-activated protein kinase (AMPK) senses the increase in energy turnover when muscle tissue is activated and acts as a signal transducer for metabolic adaptations [158, 159]. Acute exercise increases AMPK enzymatic activity in an intensity-dependent manner, reflecting effects of exercise on ATP turnover. Furthermore, contraction-induced Ca^{2+} release and ROS production leads to the activation of AMPK. As expected, resistance exercise has been shown to acutely increase AMPK activity in skeletal muscle [160–162].

Overall, AMPK activation acts to conserve ATP by inhibiting biosynthetic and anabolic pathways, while simultaneously stimulating catabolic pathways to restore cellular energy stores. In skeletal muscle during the exercise, AMPK activation modulates cellular metabolism acutely through phosphorylation of metabolic enzymes that suppresses glycogen and protein synthesis, but promotes lipid metabolism and glucose uptake [158, 159, 163]. Protein synthesis is an energy-consuming process and, in agreement with the role as an energy sensor, activation of AMPK can suppress protein synthesis by inhibiting directly mTORC1 activity or indirectly through mTOR upstream kinase tuberin (TSC2) activation [161, 164, 165]. AMPK can also inhibit protein synthesis through activation of eukaryotic translation elongation factor 2 kinase (eEF2K), leading to inhibition of protein translation by eEF2 [4, 166]. Like AMPK, also energy sensors REDD1 (regulated in DNA damage and development 1) that is activated by ATP depletion and hypoxia can inhibit mTORC1 and subsequently protein synthesis [4, 167]. Chronic AMPK activation alters metabolic gene expression and induces mitochondrial biogenesis, leading to promotion of an oxidative muscle phenotype. The long-term regulatory actions are mediated via direct phosphorylation of transcription factors and the transcriptional coactivator PGC-1 α [168, 169].

Protein degradation by the ubiquitin-proteasome system is regulated via muscle-specific E3 ubiquitin ligases, muscle atrophy F box (atrogin-1/MAFbx) and muscle RING finger 1 (MuRF1). They are involved in ubiquitination of specific proteins that are transferred to the 26S proteasome for subsequent degradation [170]. For example, MuRF1-dependent ubiquitination regulates the degradation of contractile proteins, such as myosin heavy chains [171]. Transcriptional upregulation of atrogin-1/MAFbx and MuRF1 are increased by activation of the forkhead box O

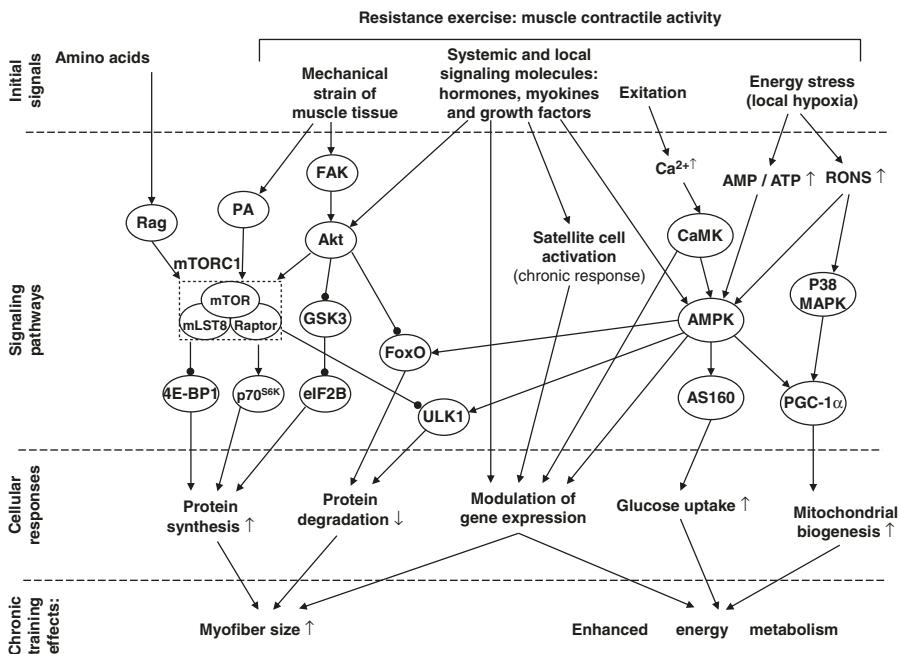


Fig. 5.2 Simplified overview of mTOR and AMPK signaling pathways regulating skeletal muscle size and function by resistance exercise. Putative resistance exercise-induced stimuli (amino acids and contractile activity induced mechanic and metabolic stress, and release of systemic and local signaling molecules), activate specific intracellular signaling networks (including, but not limited to mTOR and AMPK signaling) that mediate acute and chronic skeletal muscle responses to resistance exercise training. Stimulation of the signaling pathways depends on the resistance exercise program variables used [154–157, 187–189]. 4E-BP1 eukaryotic initiation factor 4E-binding protein 1, Akt protein kinase B, AMPK AMP-activated protein kinase, AS160 Akt substrate of 160 kDa, CaMK calmodulin-dependent protein kinase, eIF2B eukaryotic initiation factor 2B, FAK focal adhesion kinase, FoxO forkhead box protein, GSK3 glycogen synthase kinase 3, mTORC1 mammalian/mechanistic target of rapamycin complex 1, p38 MAPK p38 mitogen-activated protein kinase, p70S6K ribosomal S6 kinase 1, PA phosphatidic acid, PGC-1 α peroxisome-proliferator-activated receptor gamma, coactivator 1, Rag Ras-related small GTPase, RONS reactive oxygen and nitrogen species, ULK1 Unc-51-like kinase 1. Arrows denote activation, oval arrows denote inhibition

(FOXO) family of transcription factors [172]. Anabolic and energy sensitive processes regulate the ubiquitin-proteasome pathway activity. Akt, an upstream mediator of mTORC1 activity, inactivate FOXOs and, thus, inhibits proteolysis. Contrarily, AMPK activation promotes FOXOs activity [109, 173]. Also, inflammatory response via the NF- κ B pathway and myostatin promote proteolysis through ubiquitin-proteasome system [174–177].

Autophagy refers to a process of non-selective degradation of cytosolic components by the lysosome. Autophagy is beneficial to maintain cellular homeostasis at rest as well as during the exercise and post-exercise recovery [106, 178]. Resistance

exercise may induce certain damage to loaded myofibers and autophagy enables removal of damaged organelles and proteins through the lysosomes. It appears that adaptation to exercise training is reliant on proper activation of autophagy, and acute physical exercise has been shown to be a potent inducer of autophagy in skeletal muscle [179–182]. Activity of autophagy is regulated through unc-51-like kinase 1 (ULK1). Activated mTORC1 can inhibit autophagy while AMPK stimulates autophagy by regulation of ULK1 activity [161, 178, 183, 184]. Besides the autophagy-lysosomal system, non-lysosomal proteases like the calcium-dependent calpain family and caspase class of proteins are involved in proteolysis [104, 185, 186]. For example, the sarcomeric damage caused by exercise initiates a calpain-mediated degradation of disrupted sarcomeric filaments, such as titin [94].

Summary

The aim of RT is to provide an overload stimulus across the muscle to generate specific molecular responses, promoting adaptive changes in skeletal muscle mass and metabolic function. The conversion of intra- and extracellular signals generated during muscle contractions to subsequent physiological adaptations involves a cascade of stimuli that affect specific signaling pathways regulating exercise-induced satellite cell activation, gene expression, and/or protein turnover rate by proteosynthesis and proteolysis [24, 109, 125].

RT-induced skeletal muscle hypertrophy appears to be significantly controlled by the activity of the translational machinery, where mTORC1 acts as the master regulator. Several signaling pathways have an integrated effect on mTORC1 activity, of which autocrine/paracrine growth factors, mechanical and metabolic stress and amino acid availability appears to be the most prominent [2, 74, 76]. However, RT-induced skeletal muscle adaptation is a complex process involving various cellular responses and many signal transduction pathways. Cellular signaling pathways comprise complex networks that are operative in constantly altering cellular milieu, making it difficult to connect specific signaling responses and changes in gene and protein expression to certain metabolic responses after a resistance exercise bout, let alone to long-term adaptations to RT [190, 191]. In addition to the transcriptional and translational signaling networks involved with skeletal muscle plasticity, epigenetic modifications of DNA that may affect exercise-induced gene expression, or post-transcriptional silencing of genes by miRNAs, comprise additional levels of control on adaptations to RT [192–196].

To entirely understand the adaptive changes that myofibers undergo in response to RT in humans, aspects of the neuromuscular system (e.g., neural drive to muscles), musculoskeletal system (e.g., force transmission from muscles to tendons and bones), and cardiovascular system (e.g., muscle capillary network) should be taken into consideration. Furthermore, RT-induced adaptations generally affect the entire body, thus, adaptations in musculature should be viewed in the context of the cross-talk between tissues and organs in a whole body [197–200].

References

1. Folland JP, Williams AG. The adaptations to strength training: morphological and neurological contributions to increased strength. *Sports Med.* 2007;37:145–68.
2. Egan B, Zierath JR. Exercise metabolism and the molecular regulation of skeletal muscle adaptation. *Cell Metab.* 2013;17:162–84.
3. Westcott WL. Resistance training is medicine: effects of strength training on health. *Curr Sports Med Rep.* 2012;11:209–16.
4. Fyfe JJ, Bishop DJ, Stepto NK. Interference between concurrent resistance and endurance exercise: molecular bases and the role of individual training variables. *Sports Med.* 2014;44:743–62.
5. American College of Sports Medicine. American College of Sports Medicine position stand. Progression models in resistance training for healthy adults. *Med Sci Sports Exerc.* 2009;41:687–708.
6. Murach KA, Bagley JR. Skeletal muscle hypertrophy with concurrent exercise training: contrary evidence for an interference effect. *Sports Med.* 2016;46:1029–39.
7. Wernbom M, Augustsson J, Thomeé R. The influence of frequency, intensity, volume and mode of strength training on whole muscle cross-sectional area in humans. *Sports Med.* 2007;37:225–64.
8. Ahtiainen JP, Walker S, Peltonen H, Holviala J, Sillampää E, Karavirta L, et al. Heterogeneity in resistance training-induced muscle strength and mass responses in men and women of different ages. *Age (Dordr).* 2016;38:10.
9. Hubal MJ, Gordish-Dressman H, Thompson PD, Price TB, Hoffman EP, Angelopoulos TJ, et al. Variability in muscle size and strength gain after unilateral resistance training. *Med Sci Sports Exerc.* 2005;37:964–72.
10. Konopka AR, Harber MP. Skeletal muscle hypertrophy after aerobic exercise training. *Exerc Sport Sci Rev.* 2014;42:53–61.
11. Hackett DA, Johnson NA, Chow C. Training practices and ergogenic aids used by male body-builders. *J Strength Cond Res.* 2013;27:1609–17.
12. Schoenfeld BJ. The mechanisms of muscle hypertrophy and their application to resistance training. *J Strength Cond Res.* 2010;24:2857–72.
13. Lüthi JM, Howald H, Claassen H, Rösler K, Vock P, Hoppeler H. Structural changes in skeletal muscle tissue with heavy-resistance exercise. *Int J Sports Med.* 1986;7:123–7.
14. Alway SE, MacDougall JD, Sale DG, Sutton JR, McComas AJ. Functional and structural adaptations in skeletal muscle of trained athletes. *J Appl Physiol.* 1988;64:1114–20.
15. MacDougall JD, Elder GC, Sale DG, Moroz JR, Sutton JR. Effects of strength training and immobilization on human muscle fibres. *Eur J Appl Physiol Occup Physiol.* 1980;43:25–34.
16. Schiaffino S, Sandri M, Murgia M. Activity-dependent signaling pathways controlling muscle diversity and plasticity. *Physiology (Bethesda).* 2007;22:269–78.
17. Fry AC. The role of resistance exercise intensity on muscle fibre adaptations. *Sports Med.* 2004;34:663–79.
18. Yan Z, Okutsu M, Akhtar YN, Lira VA. Regulation of exercise-induced fiber type transformation, mitochondrial biogenesis, and angiogenesis in skeletal muscle. *J Appl Physiol.* 2011;110:264–74.
19. Narici M, Franchi M, Maganaris C. Muscle structural assembly and functional consequences. *J Exp Biol.* 2016;219:276–84.
20. Lieber RL, Ward SR. Skeletal muscle design to meet functional demands. *Philos Trans R Soc Lond B Biol Sci.* 2011;366:1466–76.
21. Franchi MV, Reeves ND, Narici MV. Skeletal muscle remodeling in response to eccentric vs. concentric loading: morphological, molecular, and metabolic adaptations. *Front Physiol.* 2017;8:447.
22. Degens H, Erskine RM, Morse CI. Disproportionate changes in skeletal muscle strength and size with resistance training and ageing. *J Musculoskelet Neuronal Interact.* 2009;9:123–9.

23. Erskine RM, Jones DA, Maffulli N, Williams AG, Stewart CE, Degens H. What causes in vivo muscle specific tension to increase following resistance training? *Exp Physiol.* 2011;96:145–55.
24. Favier FB, Benoit H, Freyssenet D. Cellular and molecular events controlling skeletal muscle mass in response to altered use. *Pflugers Arch.* 2008;456:587–600.
25. Blaauw B, Reggiani C. The role of satellite cells in muscle hypertrophy. *J Muscle Res Cell Motil.* 2014;35:3–10.
26. Allen DL, Roy RR, Edgerton VR. Myonuclear domains in muscle adaptation and disease. *Muscle Nerve.* 1999;22:1350–60.
27. Snijders T, Nederveen JP, McKay BR, Joannis S, Verdijk LB, van Loon LJ, et al. Satellite cells in human skeletal muscle plasticity. *Front Physiol.* 2015;6:283.
28. Gundersen K. Muscle memory and a new cellular model for muscle atrophy and hypertrophy. *J Exp Biol.* 2016;219:235–42.
29. Magnusson SP, Hansen P, Kjaer M. Tendon properties in relation to muscular activity and physical training. *Scand J Med Sci Sports.* 2003;13:211–23.
30. Magnusson SP, Langberg H, Kjaer M. The pathogenesis of tendinopathy: balancing the response to loading. *Nat Rev Rheumatol.* 2010;6:262–8.
31. Reeves ND, Maganaris CN, Narici MV. Effect of strength training on human patella tendon mechanical properties of older individuals. *J Physiol (Lond).* 2003;548:971–81.
32. Kongsgaard M, Reitelseder S, Pedersen TG, Holm L, Aagaard P, Kjaer M, et al. Region specific patellar tendon hypertrophy in humans following resistance training. *Acta Physiol (Oxf).* 2007;191:111–21.
33. Magnusson SP, Narici MV, Maganaris CN, Kjaer M. Human tendon behaviour and adaptation, in vivo. *J Physiol (Lond).* 2008;586:71–81.
34. Wiesinger H, Kösters A, Müller E, Seynnes OR. Effects of increased loading on in vivo tendon properties: a systematic review. *Med Sci Sports Exerc.* 2015;47:1885–95.
35. Kongsgaard M, Kovanen V, Aagaard P, Doessing S, Hansen P, Laursen AH, et al. Corticosteroid injections, eccentric decline squat training and heavy slow resistance training in patellar tendinopathy. *Scand J Med Sci Sports.* 2009;19:790–802.
36. Kubo K, Kanehisa H, Fukunaga T. Effects of resistance and stretching training programmes on the viscoelastic properties of human tendon structures in vivo. *J Physiol (Lond).* 2002;538:219–26.
37. Kubo K, Morimoto M, Komuro T, Yata H, Tsunoda N, Kanehisa H, et al. Effects of plyometric and weight training on muscle-tendon complex and jump performance. *Med Sci Sports Exerc.* 2007;39:1801–10.
38. Maïmoun L, Sultan C. Effects of physical activity on bone remodeling. *Metab Clin Exp.* 2011;60:373–88.
39. Hawkins SA, Schroeder ET, Wiswell RA, Jaque SV, Marcell TJ, Costa K. Eccentric muscle action increases site-specific osteogenic response. *Med Sci Sports Exerc.* 1999;31:1287–92.
40. Bolam KA, van Uffelen JGZ, Taaffe DR. The effect of physical exercise on bone density in middle-aged and older men: a systematic review. *Osteoporos Int.* 2013;24:2749–62.
41. Martyn-St James M, Carroll S. Effects of different impact exercise modalities on bone mineral density in premenopausal women: a meta-analysis. *J Bone Miner Metab.* 2010;28:251–67.
42. Knuiman P, Hopman MTE, Mensink M. Glycogen availability and skeletal muscle adaptations with endurance and resistance exercise. *Nutr Metab (Lond).* 2015;12:59.
43. Essén-Gustavsson B, Tesch PA. Glycogen and triglyceride utilization in relation to muscle metabolic characteristics in men performing heavy-resistance exercise. *Eur J Appl Physiol Occup Physiol.* 1990;61:5–10.
44. Tesch PA, Colliander EB, Kaiser P. Muscle metabolism during intense, heavy-resistance exercise. *Eur J Appl Physiol Occup Physiol.* 1986;55:362–6.
45. Pascoe DD, Costill DL, Fink WJ, Robergs RA, Zachwieja JJ. Glycogen resynthesis in skeletal muscle following resistive exercise. *Med Sci Sports Exerc.* 1993;25:349–54.
46. Beelen M, Burke LM, Gibala MJ, van Loon LJC. Nutritional strategies to promote postexercise recovery. *Int J Sport Nutr Exerc Metab.* 2010;20:515–32.

47. Doyle JA, Sherman WM, Strauss RL. Effects of eccentric and concentric exercise on muscle glycogen replenishment. *J Appl Physiol.* 1993;74:1848–55.
48. Ivy JL. Regulation of muscle glycogen repletion, muscle protein synthesis and repair following exercise. *J Sports Sci Med.* 2004;3:131–8.
49. MacDougall JD, Ward GR, Sale DG, Sutton JR. Biochemical adaptation of human skeletal muscle to heavy resistance training and immobilization. *J Appl Physiol Respir Environ Exerc Physiol.* 1977;43:700–3.
50. Tesch PA, Alkner BA. Acute and chronic muscle metabolic adaptations to strength training. In: Komi PV, editor. *Strength and power in sport.* 2nd edition. Oxford: Blackwell Science Ltd; 2003. p. 265–80.
51. Pesta DH, Goncalves RLS, Madiraju AK, Strasser B, Sparks LM. Resistance training to improve type 2 diabetes: working toward a prescription for the future. *Nutr Metab (Lond).* 2017;14:24.
52. LeBrasseur NK, Walsh K, Arany Z. Metabolic benefits of resistance training and fast glycolytic skeletal muscle. *Am J Physiol Endocrinol Metab.* 2011;300:3.
53. Sylow L, Kleinert M, Richter EA, Jensen TE. Exercise-stimulated glucose uptake—regulation and implications for glycaemic control. *Nat Rev Endocrinol.* 2017;13:133–48.
54. Colberg SR, Sigal RJ, Fernhall B, Regensteiner JG, Blissmer BJ, Rubin RR, et al. Exercise and type 2 diabetes: the American College of Sports Medicine and the American Diabetes Association: joint position statement. *Diabetes Care.* 2010;33:147.
55. Mann S, Beedie C, Balducci S, Zanuso S, Allgrove J, Bertiato F, et al. Changes in insulin sensitivity in response to different modalities of exercise: a review of the evidence. *Diabetes Metab Res Rev.* 2014;30:257–68.
56. Holten MK, Zacho M, Gaster M, Juel C, Wojtaszewski JFP, Dela F. Strength training increases insulin-mediated glucose uptake, GLUT4 content, and insulin signaling in skeletal muscle in patients with type 2 diabetes. *Diabetes.* 2004;53:294–305.
57. Strasser B, Pesta D. Resistance training for diabetes prevention and therapy: experimental findings and molecular mechanisms. *Biomed Res Int.* 2013;2013:805217.
58. Hellsten Y, Nyberg M. Cardiovascular adaptations to exercise training. *Compr Physiol.* 2015;6:1–32.
59. Groennebaek T, Vissing K. Impact of resistance training on skeletal muscle mitochondrial biogenesis, content, and function. *Front Physiol.* 2017;8:713.
60. Lemes ÍR, Ferreira PH, Linares SN, Machado AF, Pastre CM, Netto J. Resistance training reduces systolic blood pressure in metabolic syndrome: a systematic review and meta-analysis of randomised controlled trials. *Br J Sports Med.* 2016.
61. Cornelissen VA, Fagard RH, Coeckelberghs E, Vanhees L. Impact of resistance training on blood pressure and other cardiovascular risk factors: a meta-analysis of randomized, controlled trials. *Hypertension.* 2011;58:950–8.
62. Strasser B, Siebert U, Schobersberger W. Resistance training in the treatment of the metabolic syndrome: a systematic review and meta-analysis of the effect of resistance training on metabolic clustering in patients with abnormal glucose metabolism. *Sports Med.* 2010;40:397–415.
63. Mann S, Beedie C, Jimenez A. Differential effects of aerobic exercise, resistance training and combined exercise modalities on cholesterol and the lipid profile: review, synthesis and recommendations. *Sports Med.* 2014;44:211–21.
64. Gordon B, Chen S, Durstine JL. The effects of exercise training on the traditional lipid profile and beyond. *Curr Sports Med Rep.* 2014;13:253–9.
65. Tambalis K, Panagiotakos DB, Kavouras SA, Sidossis LS. Responses of blood lipids to aerobic, resistance, and combined aerobic with resistance exercise training: a systematic review of current evidence. *Angiology.* 2009;60:614–32.
66. Mihl C, Dassen WRM, Kuipers H. Cardiac remodelling: concentric versus eccentric hypertrophy in strength and endurance athletes. *Neth Heart J.* 2008;16:129–33.
67. Spence AL, Naylor LH, Carter HH, Buck CL, Dembo L, Murray CP, et al. A prospective randomised longitudinal MRI study of left ventricular adaptation to endurance and resistance exercise training in humans. *J Physiol (Lond).* 2011;589:5443–52.

68. Santoro A, Alvino F, Antonelli G, Caputo M, Padeletti M, Lisi M, et al. Endurance and strength Athlete's heart: analysis of myocardial deformation by speckle tracking echocardiography. *J Cardiovasc Ultrasound*. 2014;22:196–204.
69. Utomi V, Oxborough D, Whyte GP, Somauroo J, Sharma S, Shave R, et al. Systematic review and meta-analysis of training mode, imaging modality and body size influences on the morphology and function of the male athlete's heart. *Heart*. 2013;99:1727–33.
70. Fleck SJ, Kraemer WJ. Designing resistance training programs. Champaign: Human Kinetics; 2014. p. 109–15.
71. St-Onge M, Gallagher D. Body composition changes with aging: the cause or the result of alterations in metabolic rate and macronutrient oxidation? *Nutrition*. 2010;26:152–5.
72. Sparti A, DeLamy JP, de la Bretonne JA, Sander GE, Bray GA. Relationship between resting metabolic rate and the composition of the fat-free mass. *Metab Clin Exp*. 1997;46:1225–30.
73. Hawley JA. Molecular responses to strength and endurance training: are they incompatible? *Appl Physiol Nutr Metab*. 2009;34:355–61.
74. Hoppeler H. Molecular networks in skeletal muscle plasticity. *J Exp Biol*. 2016;219:205–13.
75. Petriz BA, Gomes CPC, Almeida JA, de Oliveira GP, Ribeiro FM, Pereira RW, et al. The effects of acute and chronic exercise on skeletal muscle proteome. *J Cell Physiol*. 2017;232:257–69.
76. Blaauw B, Schiaffino S, Reggiani C. Mechanisms modulating skeletal muscle phenotype. *Compr Physiol*. 2013;3:1645–87.
77. Toigo M, Boutellier U. New fundamental resistance exercise determinants of molecular and cellular muscle adaptations. *Eur J Appl Physiol*. 2006;97:643–63.
78. Rindom E, Vissing K. Mechanosensitive molecular networks involved in transducing resistance exercise-signals into muscle protein accretion. *Front Physiol*. 2016;7:547.
79. Philp A, Hamilton DL, Baar K. Signals mediating skeletal muscle remodeling by resistance exercise: PI3-kinase independent activation of mTORC1. *J Appl Physiol*. 2011;110:561–8.
80. Sheehan SM, Allen RE. Skeletal muscle satellite cell proliferation in response to members of the fibroblast growth factor family and hepatocyte growth factor. *J Cell Physiol*. 1999;181:499–506.
81. Tatsumi R, Anderson JE, Nevoret CJ, Halevy O, Allen RE. HGF/SF is present in normal adult skeletal muscle and is capable of activating satellite cells. *Dev Biol*. 1998;194:114–28.
82. Tatsumi R. Mechano-biology of skeletal muscle hypertrophy and regeneration: possible mechanism of stretch-induced activation of resident myogenic stem cells. *Anim Sci J*. 2010;81:11–20.
83. Wang X, Devaiah SP, Zhang W, Welti R. Signaling functions of phosphatidic acid. *Prog Lipid Res*. 2006;45:250–78.
84. You J, Lincoln HC, Kim C, Frey JW, Goodman CA, Zhong X, et al. The role of diacylglycerol kinase ζ and phosphatidic acid in the mechanical activation of mammalian target of rapamycin (mTOR) signaling and skeletal muscle hypertrophy. *J Biol Chem*. 2014;289:1551–63.
85. Bond P. Phosphatidic acid: biosynthesis, pharmacokinetics, mechanisms of action and effect on strength and body composition in resistance-trained individuals. *Nutr Metab (Lond)*. 2017;14:12.
86. Malik RK, Parsons JT. Integrin-dependent activation of the p70 ribosomal S6 kinase signaling pathway. *J Biol Chem*. 1996;271:29785–91.
87. Flück M, Carson JA, Gordon SE, Ziemiecki A, Booth FW. Focal adhesion proteins FAK and paxillin increase in hypertrophied skeletal muscle. *Am J Physiol*. 1999;277:152.
88. Crossland H, Kazi AA, Lang CH, Timmons JA, Pierre P, Wilkinson DJ, et al. Focal adhesion kinase is required for IGF-I-mediated growth of skeletal muscle cells via a TSC2/mTOR/S6K1-associated pathway. *Am J Physiol Endocrinol Metab*. 2013;305:183.
89. Kosek DJ, Bamman MM. Modulation of the dystrophin-associated protein complex in response to resistance training in young and older men. *J Appl Physiol*. 2008;104:1476–84.
90. Klossner S, Durieux A, Freyssenet D, Flueck M. Mechano-transduction to muscle protein synthesis is modulated by FAK. *Eur J Appl Physiol*. 2009;106:389–98.
91. Sjøgaard G. Water and electrolyte fluxes during exercise and their relation to muscle fatigue. *Acta Physiol Scand Suppl*. 1986;556:129–36.

92. Schliess F, Richter L, vom Dahl S, Häussinger D. Cell hydration and mTOR-dependent signalling. *Acta Physiol (Oxf)*. 2006;187:223–9.
93. Lambert IH, Hoffmann EK, Pedersen SF. Cell volume regulation: physiology and pathophysiology. *Acta Physiol (Oxf)*. 2008;194:255–82.
94. Krüger M, Kötter S. Titin, a central mediator for hypertrophic signaling, exercise-induced mechanosignaling and skeletal muscle remodeling. *Front Physiol*. 2016;7:76.
95. Lange S, Xiang F, Yakovenko A, Vihola A, Hackman P, Rostkova E, et al. The kinase domain of titin controls muscle gene expression and protein turnover. *Science*. 2005;308: 1599–603.
96. Al-Shanti N, Stewart CE. Ca²⁺/calmodulin-dependent transcriptional pathways: potential mediators of skeletal muscle growth and development. *Biol Rev Camb Philos Soc*. 2009;84:637–52.
97. Spangenburg EE, McBride TA. Inhibition of stretch-activated channels during eccentric muscle contraction attenuates p70S6K activation. *J Appl Physiol*. 2006;100:129–35.
98. Butterfield TA, Best TM. Stretch-activated ion channel blockade attenuates adaptations to eccentric exercise. *Med Sci Sports Exerc*. 2009;41:351–6.
99. Ferche B, García-Ramos A, Morales-Artacho AJ, Padial P. Resistance training using different hypoxic training strategies: a basis for hypertrophy and muscle power development. *Sports Med Open*. 2017;3:12.
100. Pearson SJ, Hussain SR. A review on the mechanisms of blood-flow restriction resistance training-induced muscle hypertrophy. *Sports Med*. 2015;45:187–200.
101. Scott BR, Slattery KM, Sculley DV, Dascombe BJ. Hypoxia and resistance exercise: a comparison of localized and systemic methods. *Sports Med*. 2014;44:1037–54.
102. Jackson MJ, Pye D, Palomero J. The production of reactive oxygen and nitrogen species by skeletal muscle. *J Appl Physiol*. 2007;102:1664–70.
103. Powers SK, Talbert EE, Adhihetty PJ. Reactive oxygen and nitrogen species as intracellular signals in skeletal muscle. *J Physiol (Lond)*. 2011;589:2129–38.
104. Powers SK, Duarte J, Kavazis AN, Talbert EE. Reactive oxygen species are signalling molecules for skeletal muscle adaptation. *Exp Physiol*. 2010;95:1–9.
105. Jackson MJ, Vasilaki A, McArdle A. Cellular mechanisms underlying oxidative stress in human exercise. *Free Radic Biol Med*. 2016;98:13–7.
106. Ferraro E, Giannìoli AM, Chiandotto S, Spoletini I, Rosano G. Exercise-induced skeletal muscle remodeling and metabolic adaptation: redox signaling and role of autophagy. *Antioxid Redox Signal*. 2014;21:154–76.
107. Steinbacher P, Eckl P. Impact of oxidative stress on exercising skeletal muscle. *Biomolecules*. 2015;5:356–77.
108. Wright DC, Geiger PC, Han D, Jones TE, Holloszy JO. Calcium induces increases in peroxisome proliferator-activated receptor gamma coactivator-1alpha and mitochondrial biogenesis by a pathway leading to p38 mitogen-activated protein kinase activation. *J Biol Chem*. 2007;282:18793–9.
109. Margolis LM, Rivas DA. Implications of exercise training and distribution of protein intake on molecular processes regulating skeletal muscle plasticity. *Calcif Tissue Int*. 2015;96:211–21.
110. Tee JC, Bosch AN, Lambert MI. Metabolic consequences of exercise-induced muscle damage. *Sports Med*. 2007;37:827–36.
111. Douglas J, Pearson S, Ross A, McGuigan M. Eccentric exercise: physiological characteristics and acute responses. *Sports Med*. 2017;47:663–75.
112. Proske U, Morgan DL. Muscle damage from eccentric exercise: mechanism, mechanical signs, adaptation and clinical applications. *J Physiol (Lond)*. 2001;537:333–45.
113. Duchateau J, Enoka RM. Neural control of lengthening contractions. *J Exp Biol*. 2016;219:197–204.
114. Roig M, O'Brien K, Kirk G, Murray R, McKinnon P, Shadgan B, et al. The effects of eccentric versus concentric resistance training on muscle strength and mass in healthy adults: a systematic review with meta-analysis. *Br J Sports Med*. 2009;43:556–68.

115. Paulsen G, Mikkelsen UR, Raastad T, Peake JM. Leucocytes, cytokines and satellite cells: what role do they play in muscle damage and regeneration following eccentric exercise? *Exerc Immunol Rev.* 2012;18:42–97.
116. Hyldahl RD, Hubal MJ. Lengthening our perspective: morphological, cellular, and molecular responses to eccentric exercise. *Muscle Nerve.* 2014;49:155–70.
117. Howatson G, van Someren KA. The prevention and treatment of exercise-induced muscle damage. *Sports Med.* 2008;38:483–503.
118. Kerksick CM, Willoughby D, Kouretas D, Tsatsakis A. Intramuscular responses with muscle damaging exercise and the interplay between multiple intracellular networks: a human perspective. *Food Chem Toxicol.* 2013;61:136–43.
119. Peake JM, Neubauer O, Della Gatta PA, Nosaka K. Muscle damage and inflammation during recovery from exercise. *J Appl Physiol.* 2017;122:559–70.
120. Tidball JG. Regulation of muscle growth and regeneration by the immune system. *Nat Rev Immunol.* 2017;17:165–78.
121. Gonzalez AM, Hoffman JR, Stout JR, Fukuda DH, Willoughby DS. Intramuscular anabolic signaling and endocrine response following resistance exercise: implications for muscle hypertrophy. *Sports Med.* 2016;46:671–85.
122. Kraemer WJ, Ratamess NA. Hormonal responses and adaptations to resistance exercise and training. *Sports Med.* 2005;35:339–61.
123. Hansen D, Meeusen R, Mullens A, Dendale P. Effect of acute endurance and resistance exercise on endocrine hormones directly related to lipolysis and skeletal muscle protein synthesis in adult individuals with obesity. *Sports Med.* 2012;42:415–31.
124. McMurray RG, Hackney AC. Interactions of metabolic hormones, adipose tissue and exercise. *Sports Med.* 2005;35:393–412.
125. Marcotte GR, West DWD, Baar K. The molecular basis for load-induced skeletal muscle hypertrophy. *Calcif Tissue Int.* 2015;96:196–210.
126. Crewther BT, Cook C, Cardinale M, Weatherby RP, Lowe T. Two emerging concepts for elite athletes: the short-term effects of testosterone and cortisol on the neuromuscular system and the dose-response training role of these endogenous hormones. *Sports Med.* 2011;41:103–23.
127. Catoire M, Kersten S. The search for exercise factors in humans. *FASEB J.* 2015;29:1615–28.
128. Lightfoot AP, Cooper RG. The role of myokines in muscle health and disease. *Curr Opin Rheumatol.* 2016;28:661–6.
129. Huh JY. The role of exercise-induced myokines in regulating metabolism. *Arch Pharm Res.* 2018;41:14–29.
130. Oh K, Lee DS, Kim WK, Han BS, Lee SC, Bae K. Metabolic adaptation in obesity and type II diabetes: myokines, adipokines and hepatokines. *Int J Mol Sci.* 2016;18:8.
131. Zanou N, Gailly P. Skeletal muscle hypertrophy and regeneration: interplay between the myogenic regulatory factors (MRFs) and insulin-like growth factors (IGFs) pathways. *Cell Mol Life Sci.* 2013;70:4117–30.
132. Moro T, Ebert SM, Adams CM, Rasmussen BB. Amino acid sensing in skeletal muscle. *Trends Endocrinol Metab.* 2016;27:796–806.
133. Jäger R, Kerksick CM, Campbell BI, Cribb PJ, Wells SD, Skwiat TM, et al. International Society of Sports Nutrition Position Stand: protein and exercise. *J Int Soc Sports Nutr.* 2017;14:20.
134. Morton RW, McGlory C, Phillips SM. Nutritional interventions to augment resistance training-induced skeletal muscle hypertrophy. *Front Physiol.* 2015;6:245.
135. Biolo G, Maggi SP, Williams BD, Tipton KD, Wolfe RR. Increased rates of muscle protein turnover and amino acid transport after resistance exercise in humans. *Am J Physiol.* 1995;268:514.
136. Kumar V, Atherton P, Smith K, Rennie MJ. Human muscle protein synthesis and breakdown during and after exercise. *J Appl Physiol.* 2009;106:2026–39.
137. Phillips SM, Tipton KD, Aarsland A, Wolf SE, Wolfe RR. Mixed muscle protein synthesis and breakdown after resistance exercise in humans. *Am J Physiol.* 1997;273:99.

138. Chesley A, MacDougall JD, Tarnopolsky MA, Atkinson SA, Smith K. Changes in human muscle protein synthesis after resistance exercise. *J Appl Physiol.* 1992;73:1383–8.
139. Atherton PJ, Smith K. Muscle protein synthesis in response to nutrition and exercise. *J Physiol (Lond).* 2012;590:1049–57.
140. Rennie MJ, Wackerhage H, Spangenburg EE, Booth FW. Control of the size of the human muscle mass. *Annu Rev Physiol.* 2004;66:799–828.
141. Seynnes OR, de Boer M, Narici MV. Early skeletal muscle hypertrophy and architectural changes in response to high-intensity resistance training. *J Appl Physiol.* 2007;102:368–73.
142. Kim PL, Staron RS, Phillips SM. Fasted-state skeletal muscle protein synthesis after resistance exercise is altered with training. *J Physiol (Lond).* 2005;568:283–90.
143. Tang JE, Perco JG, Moore DR, Wilkinson SB, Phillips SM. Resistance training alters the response of fed state mixed muscle protein synthesis in young men. *Am J Physiol Regul Integr Comp Physiol.* 2008;294:172.
144. Bodine SC, Stitt TN, Gonzalez M, Kline WO, Stover GL, Bauerlein R, et al. Akt/mTOR pathway is a crucial regulator of skeletal muscle hypertrophy and can prevent muscle atrophy in vivo. *Nat Cell Biol.* 2001;3:1014–9.
145. Drummond MJ, Fry CS, Glynn EL, Dreyer HC, Dhanani S, Timmerman KL, et al. Rapamycin administration in humans blocks the contraction-induced increase in skeletal muscle protein synthesis. *J Physiol (Lond).* 2009;587:1535–46.
146. Deldicque L, Theisen D, Francaux M. Regulation of mTOR by amino acids and resistance exercise in skeletal muscle. *Eur J Appl Physiol.* 2005;94:1–10.
147. Goberdhan DCI, Wilson C, Harris AL. Amino acid sensing by mTORC1: intracellular transporters mark the spot. *Cell Metab.* 2016;23:580–9.
148. Bond P. Regulation of mTORC1 by growth factors, energy status, amino acids and mechanical stimuli at a glance. *J Int Soc Sports Nutr.* 2016;13:8.
149. Jacobs BL, Goodman CA, Hornberger TA. The mechanical activation of mTOR signalling: an emerging role for late endosome/lysosomal targeting. *J Muscle Res Cell Motil.* 2014;35:11–21.
150. Ma XM, Blenis J. Molecular mechanisms of mTOR-mediated translational control. *Nat Rev Mol Cell Biol.* 2009;10:307–18.
151. Proud CG. Signalling to translation: how signal transduction pathways control the protein synthetic machinery. *Biochem J.* 2007;403:217–34.
152. Goodman CA. The role of mTORC1 in regulating protein synthesis and skeletal muscle mass in response to various mechanical stimuli. *Rev Physiol Biochem Pharmacol.* 2014;166:43–95.
153. Ben-Sahra I, Manning BD. mTORC1 signaling and the metabolic control of cell growth. *Curr Opin Cell Biol.* 2017;45:72–82.
154. Ahtiainen JP, Walker S, Silvennoinen M, Kyröläinen H, Nindl BC, Häkkinen K, et al. Exercise type and volume alter signaling pathways regulating skeletal muscle glucose uptake and protein synthesis. *Eur J Appl Physiol.* 2015;115:1835–45.
155. Burd NA, Holwerda AM, Selby KC, West DWD, Staples AW, Cain NE, et al. Resistance exercise volume affects myofibrillar protein synthesis and anabolic signalling molecule phosphorylation in young men. *J Physiol (Lond).* 2010;588:3119–30.
156. Hulmi JJ, Walker S, Ahtiainen JP, Nyman K, Kraemer WJ, Häkkinen K. Molecular signalling in muscle is affected by the specificity of resistance exercise protocol. *Scand J Med Sci Sports.* 2012;22:240–8.
157. Terzis G, Spengos K, Mascher H, Georgiadis G, Manta P, Blomstrand E. The degree of p70 S6k and S6 phosphorylation in human skeletal muscle in response to resistance exercise depends on the training volume. *Eur J Appl Physiol.* 2010;110:835–43.
158. Kjøbsted R, Hingst JR, Fentz J, Foretz M, Sanz M, Pehmøller C, et al. AMPK in skeletal muscle function and metabolism. *FASEB J.* 2018;32(4):1741–77.
159. Mounier R, Théret M, Lantier L, Foretz M, Viollet B. Expanding roles for AMPK in skeletal muscle plasticity. *Trends Endocrinol Metab.* 2015;26:275–86.

160. Vissing K, McGee SL, Farup J, Kjølhede T, Vendelbo MH, Jessen N. Differentiated mTOR but not AMPK signaling after strength vs endurance exercise in training-accustomed individuals. *Scand J Med Sci Sports.* 2013;23:355–66.
161. Jessen N, Sundelin EIO, Møller AB. AMP kinase in exercise adaptation of skeletal muscle. *Drug Discov Today.* 2014;19:999–1002.
162. Morales-Alamo D, Calbet JAL. AMPK signaling in skeletal muscle during exercise: role of reactive oxygen and nitrogen species. *Free Radic Biol Med.* 2016;98:68–77.
163. Baar K. Using molecular biology to maximize concurrent training. *Sports Med.* 2014;44(Suppl 2):117.
164. Bolster DR, Crozier SJ, Kimball SR, Jefferson LS. AMP-activated protein kinase suppresses protein synthesis in rat skeletal muscle through down-regulated mammalian target of rapamycin (mTOR) signaling. *J Biol Chem.* 2002;277:23977–80.
165. Dreyer HC, Fujita S, Cadena JG, Chinkes DL, Volpi E, Rasmussen BB. Resistance exercise increases AMPK activity and reduces 4E-BP1 phosphorylation and protein synthesis in human skeletal muscle. *J Physiol (Lond).* 2006;576:613–24.
166. Norman S, Browne G, Krause U, Patel J, Vertommen D, Bertrand L, et al. Activation of AMP-activated protein kinase leads to the phosphorylation of elongation factor 2 and an inhibition of protein synthesis. *Curr Biol.* 2002;12:1419–23.
167. Gordon BS, Steiner JL, Williamson DL, Lang CH, Kimball SR. Emerging role for regulated in development and DNA damage 1 (REDD1) in the regulation of skeletal muscle metabolism. *Am J Physiol Endocrinol Metab.* 2016;311:157.
168. Lira VA, Benton CR, Yan Z, Bonen A. PGC-1alpha regulation by exercise training and its influences on muscle function and insulin sensitivity. *Am J Physiol Endocrinol Metab.* 2010;299:145.
169. Thirupathi A, de Souza CT. Multi-regulatory network of ROS: the interconnection of ROS, PGC-1 alpha, and AMPK-SIRT1 during exercise. *J Physiol Biochem.* 2017;73:487–94.
170. Sandri M. Signaling in muscle atrophy and hypertrophy. *Physiology (Bethesda).* 2008;23:160–70.
171. Clarke BA, Drujan D, Willis MS, Murphy LO, Corpina RA, Burova E, et al. The E3 Ligase MuRF1 degrades myosin heavy chain protein in dexamethasone-treated skeletal muscle. *Cell Metab.* 2007;6:376–85.
172. Bodine SC, Baehr LM. Skeletal muscle atrophy and the E3 ubiquitin ligases MuRF1 and MAFbx/atroglin-1. *Am J Physiol Endocrinol Metab.* 2014;307:469.
173. Léger B, Cartomi R, Praz M, Lamon S, Dériaux O, Crettenand A, et al. Akt signalling through GSK-3beta, mTOR and Foxo1 is involved in human skeletal muscle hypertrophy and atrophy. *J Physiol (Lond).* 2006;576:923–33.
174. Murton AJ, Constantin D, Greenhaff PL. The involvement of the ubiquitin proteasome system in human skeletal muscle remodelling and atrophy. *Biochim Biophys Acta.* 2008;1782:730–43.
175. Bilodeau PA, Coyne ES, Wing SS. The ubiquitin proteasome system in atrophying skeletal muscle: roles and regulation. *Am J Physiol Cell Physiol.* 2016;311:392.
176. McCarthy JJ, Esser KA. Anabolic and catabolic pathways regulating skeletal muscle mass. *Curr Opin Clin Nutr Metab Care.* 2010;13:230–5.
177. Turner MD, Nedjai B, Hurst T, Pennington DJ. Cytokines and chemokines: at the crossroads of cell signalling and inflammatory disease. *Biochim Biophys Acta.* 2014;1843:2563–82.
178. Vainshtein A, Hood DA. The regulation of autophagy during exercise in skeletal muscle. *J Appl Physiol.* 2016;120:664–73.
179. Masiero E, Agatea L, Mammucari C, Blaauw B, Loro E, Komatsu M, et al. Autophagy is required to maintain muscle mass. *Cell Metab.* 2009;10:507–15.
180. Grumati P, Coletto L, Schiavonato A, Castagnaro S, Bertaggia E, Sandri M, et al. Physical exercise stimulates autophagy in normal skeletal muscles but is detrimental for collagen VI-deficient muscles. *Autophagy.* 2011;7:1415–23.
181. Tam BT, Siu PM. Autophagic cellular responses to physical exercise in skeletal muscle. *Sports Med.* 2014;44:625–40.

182. Martin-Rincon M, Morales-Alamo D, Calbet JAL. Exercise-mediated modulation of autophagy in skeletal muscle. *Scand J Med Sci Sports.* 2018;28(3):772–81.
183. Alers S, Löffler AS, Wesselborg S, Stork B. Role of AMPK-mTOR-Ulk1/2 in the regulation of autophagy: cross talk, shortcuts, and feedbacks. *Mol Cell Biol.* 2012;32:2–11.
184. Mihaylova MM, Shaw RJ. The AMPK signalling pathway coordinates cell growth, autophagy and metabolism. *Nat Cell Biol.* 2011;13:1016–23.
185. Baar K, Nader G, Bodine S. Resistance exercise, muscle loading/unloading and the control of muscle mass. *Essays Biochem.* 2006;42:61–74.
186. Pasikatos SM, Carbone JW. Assessment of skeletal muscle proteolysis and the regulatory response to nutrition and exercise. *IUBMB Life.* 2014;66:478–84.
187. McKendry J, Pérez-López A, McLeod M, Luo D, Dent JR, Smeuninx B, et al. Short inter-set rest blunts resistance exercise-induced increases in myofibrillar protein synthesis and intracellular signalling in young males. *Exp Physiol.* 2016;101:866–82.
188. Mitchell CJ, Churchward-Venne TA, West DWD, Burd NA, Breen L, Baker SK, et al. Resistance exercise load does not determine training-mediated hypertrophic gains in young men. *J Appl Physiol.* 2012;113:71–7.
189. Popov DV, Lysenko EA, Bachinin AV, Miller TF, Kurochkina NS, Kravchenko IV, et al. Influence of resistance exercise intensity and metabolic stress on anabolic signaling and expression of myogenic genes in skeletal muscle. *Muscle Nerve.* 2015;51:434–42.
190. McGlory C, Phillips SM. Exercise and the regulation of skeletal muscle hypertrophy. *Prog Mol Biol Transl Sci.* 2015;135:153–73.
191. Smiles WJ, Hawley JA, Camera DM. Effects of skeletal muscle energy availability on protein turnover responses to exercise. *J Exp Biol.* 2016;219:214–25.
192. Hitachi K, Tsuchida K. Role of microRNAs in skeletal muscle hypertrophy. *Front Physiol.* 2013;4:408.
193. Kirby TJ, McCarthy JJ. MicroRNAs in skeletal muscle biology and exercise adaptation. *Free Radic Biol Med.* 2013;64:95–105.
194. Rasmussen M, Zierath JR, Barrès R. Dynamic epigenetic responses to muscle contraction. *Drug Discov Today.* 2014;19:1010–4.
195. Sharples AP, Stewart CE, Seaborne RA. Does skeletal muscle have an ‘epi’-memory? The role of epigenetics in nutritional programming, metabolic disease, aging and exercise. *Aging Cell.* 2016;15:603–16.
196. Silva GJJ, Bye A, El Azzouzi H, Wisloff U. MicroRNAs as important regulators of exercise adaptation. *Prog Cardiovasc Dis.* 2017;60:130–51.
197. Schnyder S, Handschin C. Skeletal muscle as an endocrine organ: PGC-1 α , myokines and exercise. *Bone.* 2015;80:115–25.
198. Neuffer PD, Bamman MM, Muoio DM, Bouchard C, Cooper DM, Goodpaster BH, et al. Understanding the cellular and molecular mechanisms of physical activity-induced health benefits. *Cell Metab.* 2015;22:4–11.
199. Hoffman NJ. Omics and exercise: global approaches for mapping exercise biological networks. *Cold Spring Harb Perspect Med.* 2017;7.
200. Giudice J, Taylor JM. Muscle as a paracrine and endocrine organ. *Curr Opin Pharmacol.* 2017;34:49–55.



Neural Adaptations to Strength Training

6

Simon Walker

The purpose of this chapter is to introduce the effects of strength training on the function of the neural system. For comprehensive background knowledge concerning the structure and function of each part of the neural and muscular systems, it is advisable to consult anatomy and physiology textbooks. However, as can be seen from Fig. 6.1, muscle and nerve do not work in isolation but as an interlinked and interactive unit. The end-point of the neural system can be considered to be the neuromuscular junction (the point where motoneuron and muscle fiber are joined). The start-point of the neural system is more difficult to define but for simplicity perhaps it should be regarded as the motor cortex. Consequently, it might be preferable to think of the system as a whole and use the term “neuromuscular” rather than “neural” when discussing the acute and chronic responses to strength training in the following sections.

Neural Effectors of Force Production

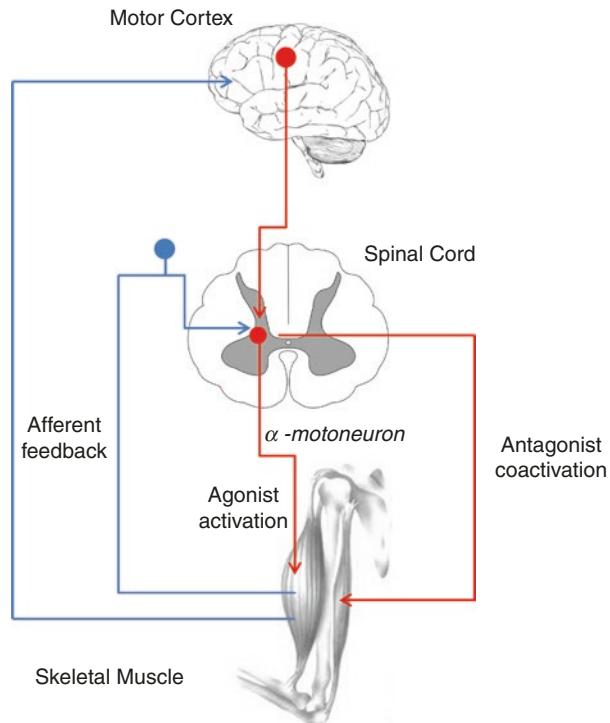
The resultant force production of skeletal muscle(s) is dependent upon many different system and tissue properties, for example musculotendinous properties, such as muscle size and fiber type as well as tendon stiffness. Overall force production is naturally a sum of all the parts of the neuromuscular-tendinous system. Nevertheless, there are specific elements within the neural system that control and manipulate the functioning of muscle(s) for the body's specific needs at any moment in time.

Firstly, let us address the end-point of the neural system and smallest entity of the neuromuscular system, the motor unit. A motor unit consists of an alpha (α -)

S. Walker

Neuromuscular Research Center, Faculty of Sport and Health Sciences,
University of Jyväskylä, Jyväskylä, Finland
e-mail: Simon.walker@jyu.fi

Fig. 6.1 Schematic representation of the parts of the neural system that influence force production (adapted from Moritani [1]. Chapter 3, Strength and Power in Sport)



motoneuron and all of the muscle fibers it innervates. Motor units can be classified by their properties, as identified by Burke [2], as slow (also known as Type I), fast fatigue resistant (Type IIa), or fast fatigable (Type IIx). Consequently, the type and number of motor unit(s) activated would influence force production. Furthermore, recruitment of motor units is governed by the “size principle” [3]. This principle states that the smallest α -motoneurons (and motor units) are recruited first and an orderly recruitment, relative to size, occurs thereafter. This would appear a good strategy since the smaller motor units are also the ones that are most difficult to fatigue and can withstand long contraction durations. When gradually increasing force production, most muscles fully recruit all motor units between 50 and 95% of maximum force production [4–6]. During fast contractions, the level of force required to recruit a specific motor unit is lowered [7]. In other words, larger (the so-called high-threshold) motor units are recruited at a lower force level (i.e., more readily recruited) when the contraction is performed as fast as possible rather than during a slow contraction.

Force production is also regulated by the rate at which a motor unit is activated. In simple terms, how often an electrical discharge passes along the α -motoneuron (i.e., motor unit action potential). This is known as firing rate (also known as discharge rate, firing frequency or rate coding). As has been clearly demonstrated during gradually increasing force contractions (the so-called ramp contractions),

already recruited motor units increase their firing rate as the force level increases [7, 8]. Firing rate patterns appear to be reversed during fast contractions showing an initial burst of high firing rate followed by lowered rates once a certain level of force is attained [7, 9], but recruitment still follows the size principle. Differences in the interaction between motor unit recruitment and firing rate may be dependent upon the muscle in question, with small muscles seemingly more reliant on firing rate to modulate force production while large force-producing muscles rely more on recruitment [10]. Nevertheless, ultimately, neural control of force production is reliant upon motor unit recruitment and firing rate whose combination determines the final signal presented to the muscle.

Prior to the α -motoneuron, there are many upstream regulators that influence both/either the recruitment and firing rate of motor units. Afferent feedback (identified by blue lines in Fig. 6.1) from muscular contraction influences forthcoming signals at the cortex and spinal cord. At the spinal level, afferent feedback from muscle spindles sensing stretch within muscle fibers serves to enhance (i.e., excitatory), while feedback from Golgi tendon organs sensing tension within the muscle-tendon junction serve to dampen (i.e., inhibitory), signals sent to the α -motoneuron. Also, Renshaw cells act as a negative feedback system that responds to activation of the α -motoneuron. These regulators allow the neural system to constantly monitor and modulate force production.

Initiation of descending drive (identified by red lines in Fig. 6.1), the signal sent down the spinal cord, originates in the cortex. A convergence of signals from the premotor cortex, cerebellum, and other cortex centers influence the output of the motor cortex to the spinal cord. Various feedback sources contribute to the modulation of descending drive (Fig. 6.1) during continuing contractions. A greater level of descending drive is possible through either enhanced excitation or reduced inhibition (or combination of both) within the cortex. Assuming that the effects of all other regulators of the neural system (mentioned above) are constant then a greater descending drive would lead to greater force production. It should be remembered, however, that greater descending drive may also influence the level of antagonist coactivation simultaneously [11].

Finally, force production of agonist and synergist muscles is also affected by the level of coactivation of antagonist muscles, which may be considered as the brake applied during voluntary contraction. It is thought that coactivation is necessary to stabilize the joint for both effective movement and to act in a protective manner, and also in the case of multi-joint movement to facilitate fluid motion and coordination between muscles/joints (e.g., running and jumping). During simple single-joint movement, the level of antagonist coactivation may vary between different populations, for example, older individuals tend to demonstrate greater coactivation of antagonists than young adults [12]. Despite many experimental studies, only a handful have shown evidence that strength training reduces antagonist coactivation [13–16]. Due to this uncertainty, and in the interests of brevity, the following sections will focus on modulation of agonist activation during strength training.

Acute Responses During a Strength Training Session

Following the law of specificity, it is of great importance to understand the mechanisms of acute fatigue during strength training as this/these part(s) of the neuromuscular system are susceptible to adaptation given long-term exposure [17]. Upon reading this chapter, it should become apparent that there is a remarkable commonality between the challenged and failing parts of the neuromuscular system during a specific strength training program and their improvements over a training period. The vast majority of our (earlier) understanding on acute neuromuscular fatigue has originated from controlled experiments using electrical stimulation techniques (particularly in animals), or voluntary isometric intermittent or prolonged contractions in humans. Consulting the work of scholars such as Brenda Bigland-Ritchie, Simon Gandevia, Janet Taylor, Roger Enoka, and Jacques Duchateau to name a few would help to attain knowledge from highly controlled experiments. However, this chapter will focus on applied scientific studies utilizing strength training typically performed in gyms.

At this point, it is perhaps prudent to outline (rather simplistically) the typical type of strength training programs studied in the literature. Maximum strength or neural strength training is comprised of high external load (>85% 1-RM), multiple sets (3–5 per exercise) of low repetitions (1–5) and long inter-set rest periods (3–5 min). Hypertrophic strength training typically uses medium external load (60–85% 1-RM), multiple sets (2–4 per exercise), and several repetitions (8–12) and brief inter-set rest periods (1–3 min). Power training aims to perform each action with the maximum possible acceleration but the external load (0–80% 1-RM), number of sets (2–6 per exercise) and repetitions (2–10), and inter-set rest period (2–6 min) can vary greatly. The names of each type of strength training are derived from the primary goals of each program.

In terms of studying the acute effects of strength training on neural processes, the majority of studies have utilized surface EMG. The inherent weaknesses of this methodology make identifying the mechanism(s) of acute fatigue inconclusive (as explained by [18]), but it is one of the simplest and least invasive methods available. To the author's knowledge, the first studies investigating neuromuscular fatigue during strength training were performed by Häkkinen in the 1990s with athletes as subjects [19, 20]. Here, both maximum strength (20 sets of 1 rep at 100% 1-RM) and hypertrophic (10 sets of 10 reps at 70% 1-RM) training sessions led to decreases in maximal strength (~24% vs. ~47% in men and in ~21% vs. ~29% women, respectively) immediately after the session and both led to decreased EMG amplitude (with the exception of maximum strength in women for some unknown reason). One interesting study that compared three work-matched but different types of strength training was performed by McCaulley et al. [21]. Large acute decreases in maximal strength occurred during maximum strength and hypertrophic sessions, but EMG amplitude only decreased during the maximum strength session. Power sessions specifically influence initial EMG amplitude [22], as discussed later. The lack of reduced EMG amplitude during hypertrophic sessions is a common observation, especially in untrained/non-athlete populations [23, 24].

This has led to some interpreting the data that fatigue within the neural system does not occur during hypertrophic sessions and that the cause of the reduced strength is situated purely within the muscle. However, when inspecting changes in the frequency component of the EMG signal, as well as the amplitude, it becomes apparent that changes do occur [23, 24, 25]. Hypertrophic strength training leads to a reduced median frequency, whereas maximum strength training does not (as depicted in Fig. 6.2a, [24]). Since median frequency is purported to represent the average conduction velocity of the firing motor units [28], the data might be interpreted as demonstrating maintained motor unit recruitment but reduced firing rate during maximum strength sessions. A more complex situation to interpret is the lowered EMG median frequency during hypertrophic sessions (Fig. 6.2a).

There are several hypotheses for this phenomenon, one being slowing of the conduction velocity of the action potential due to fatigue/damage within the muscle. One other possibility for the reduced median frequency could be that there was greater synchronization in motor unit recruitment [29]. Motor unit synchronization has been shown to increase EMG amplitude [30]. Therefore, it may be that increased motor unit synchronization and consequent increase in EMG amplitude negates the otherwise expected reduction in EMG amplitude due to reduced motor unit recruitment and/or firing rate. This speculation may be plausible given that athletes have a greater level of motor unit synchronization than untrained populations [31, 32]. Furthermore, strength athletes have demonstrated reduced EMG amplitude during and after

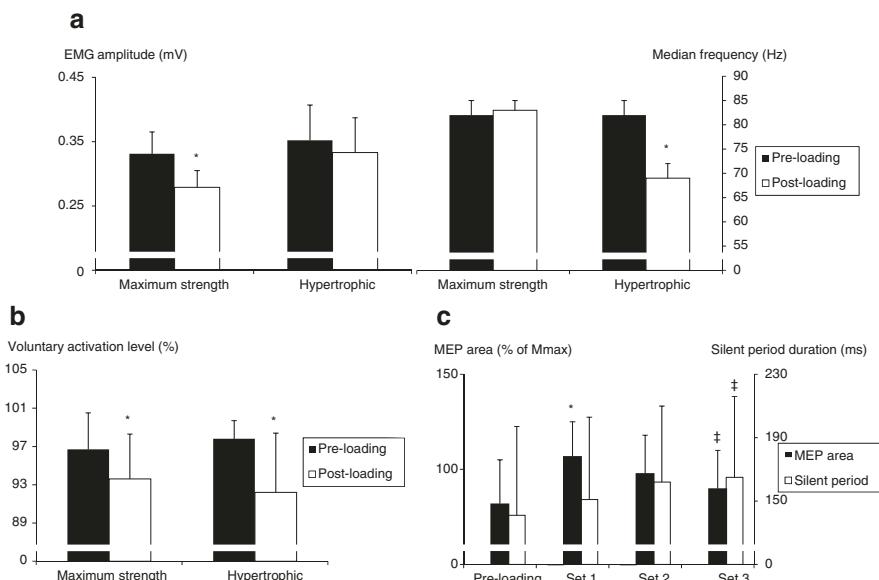


Fig. 6.2 Fatigue-induced changes after a single strength training session in (a) EMG amplitude and median frequency (mean \pm SE) [24], (b) voluntary activation level (mean \pm SD) [26], and (c) Motor Evoked Potential (MEP) area and silent period length (mean \pm SD) [27] during maximum isometric force production

hypertrophic sessions [19, 33] which (in-line with this hypothesis) may be due to an already higher level of motor unit synchronization and no great potential to further synchronize firings.

Nevertheless, perhaps the clearest method to demonstrate fatigue within the neural system during strength training sessions is to use (electrical or magnetic) stimulation methods. Merton [34] used the interpolated twitch technique to demonstrate the inability of the human to maximally activate their skeletal muscles. Briefly, if superimposing a high-intensity electrical stimulation to the innervating nerve or directly to the activated muscle during a maximum voluntary contraction induces an increase in the measured force, then the muscle was not performing to its potential and the deficit was located within the neural system. This method has shown that fatigue within the neural system exists during hypertrophic strength sessions as demonstrated by a reduction in voluntary activation level ([26], Fig. 6.2b).

Another method to detect fatigue within the neural system is to utilize Transcranial Magnetic Stimulation (TMS) directly to the motor cortex and measure the response at the muscle. In an interesting study by Ruotsalainen et al. [27], measurement of the Motor Evoked Potential (MEP) in the EMG signal of the biceps brachii after each set of a $3 \times 10\text{-RM}$ (i.e., Hypertrophic) bicep curl session showed an initial increase concomitant to muscular fatigue after set 1 (Fig. 6.2c). It could be suggested that corticospinal excitability (i.e., the efficacy of all parts of the cortical and spinal network mentioned above) increased in order to possibly overcome the inability of the musculature to produce the required force level to sustain performance. This initial increase was then followed by a progressive decrease after each set. The decreases in MEP size set-to-set were matched by an elongation of the silent period following the stimulation (Fig. 6.2c). This likely represents fatigue-induced cortical inhibition, which could account for a reduction in descending drive following (hypertrophic) strength training sessions. For more information regarding neural fatigue and the potential mechanisms that cause such fatigue, recent work by Carroll and colleagues [35] is worth consulting.

Finally, to briefly address the effects of a Power training session, it is worth noting that the reductions in both force and EMG amplitude during the initial ~ 100 ms of contraction were greater than the reductions of maximum force and EMG amplitude [22]. This finding was contrasted by similar reductions of all time-points during isometric action following a maximum strength session. These findings highlight that the manifestation of fatigue during Power training, where the aim is to accelerate the load as fast as possible, specifically affect the initiation of contraction. These findings seem to give clues as to the specific training-induced adaptations from various strength training programs.

Neural Adaptations to Strength Training

As noted in the first section of this chapter, simplistically, greater motor unit recruitment and/or firing rate of agonist and synergists would increase force production. Therefore, greater force production could be due to; (1) greater descending drive

from the cortex and/or (2) greater spinal motoneuron excitability and/or reduced inhibition influencing descending drive [36]. In this section, studies using various methods to estimate and quantify these potential adaptations during strength training will be presented.

The amplitude of the surface EMG signal is taken to be a gross measure of motor unit recruitment and firing rate of those motor units that are within the pick-up area of the electrodes. This has led authors to utilize surface EMG as an indication of neural adaptation to strength training. Over the past 3–4 decades, many studies have shown increases in EMG amplitude during maximum force production from 8 to 21 weeks of strength training in various populations [37–42] but particularly previously untrained individuals. Also, rate of EMG rise or average EMG amplitude over the initial period of force production (e.g., 50–100 ms) has been shown to increase during fast contractions [37, 38, 43, 44]. Nevertheless, use of surface EMG to infer neural adaptation is fraught with pitfalls. Specific methodological constraints and confounding factors as highlighted by Farina et al. [18] suggest that other mechanisms other than neural adaptation could account for increases in EMG amplitude, particularly during maximum force production.

One physiological, but muscular adaptation, which could affect the EMG signal is the propagation of the action potential [45] and another is the level of motor unit synchronization [30]. This last point is interesting since strength-trained individuals have shown a greater level of synchronization than non-trained controls [31, 32]. Whether increased motor unit synchronization aids strength development is debatable [30, 46], but it highlights a limitation of the method in assessing neural adaptation.

Indwelling or intramuscular EMG electrodes have been used by some groups to quantify motor unit activity patterns before and after strength training. In particular, early increases (<6 weeks training) in firing rate have been demonstrated in several populations during maximum [47, 48] and rapid force production [9]. Furthermore, increased firing rate at the beginning of fast contractions was accompanied by improved rate of force development [9]. These findings may help to explain the observed increases in EMG during the initial part of the force-time curve of fast contractions following Power training [37, 38, 43, 44], as mentioned above.

Perhaps a more direct and non-invasive method to assess neural adaptation is peripheral nerve/muscle stimulation. The twitch interpolation technique has demonstrated increases in voluntary activation level in several muscles [42, 48] due to strength training, in both young and older subjects (Fig. 6.3a). While these findings could infer greater motor unit recruitment and/or firing rate, these findings likely reflect greater firing rate given the above-mentioned evidence from intramuscular EMG and that most muscles' motor units are fully recruited below 95% of maximum force.

Other studies have used peripheral stimulation to quantify H-reflex and V-wave amplitude before and after strength training. Submaximal electrical stimulation to a peripheral nerve induces an artificial reflex response recorded by surface EMG, known as the Hoffmann- or H-reflex. Conversely, a maximal electrical stimulation elicits a compound action potential (i.e., M-wave) that concomitantly abolishes the H-reflex response in a resting condition. The V-wave is the voluntary equivalent of

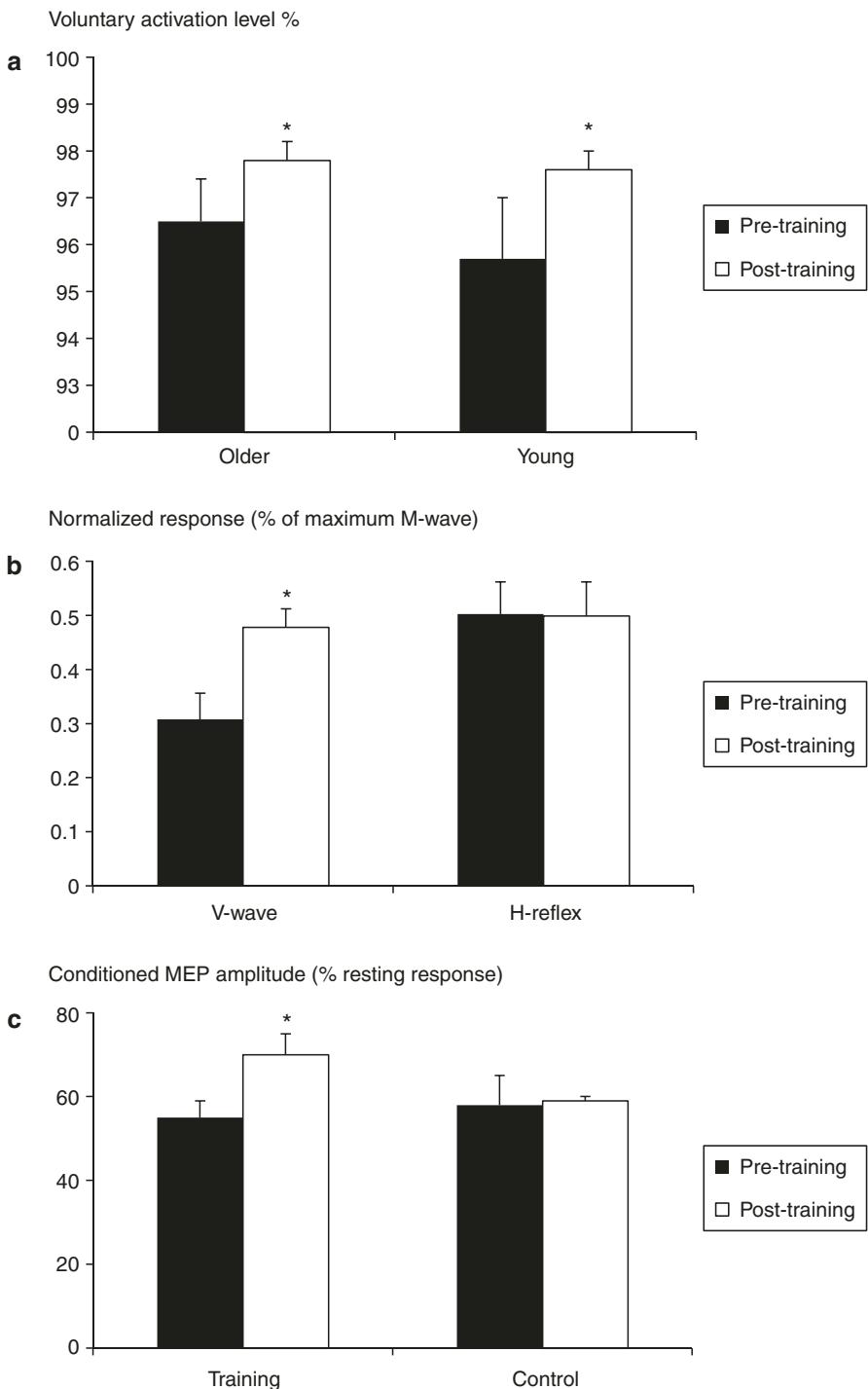


Fig. 6.3 Strength training-induced increases in (a) voluntary activation level (mean \pm SE) [48], (b) V-wave amplitude (mean \pm SD) [37, 38], and (c) conditioned MEP amplitude (mean \pm SE) [49]

the H-reflex, and voluntary drive must surpass the M-wave abolishment to be observable in the EMG signal. Hence, it is a measure of overall efferent output from the motoneuron pool [37, 38] and an increase in V-wave (normalized to the maximum M-wave) represents an increase in descending drive. Possibly due to methodological considerations (e.g., the proximity of the muscle to the spinal cord) distal muscles, such as the triceps surae, have been utilized to demonstrate training-induced adaptations to strength training using this method. Strength training has been accompanied by increases in V-wave responses after only 3 weeks [50] and 14 weeks ([37, 38], Fig. 6.3b) of training in healthy young subjects and in older individuals [51]. These studies combined this method with resting H-reflex stimulation to show that changes in spinal excitability did not occur as a consequence of training, which supports the previously stated hypothesis that neural adaptations are largely a result of supraspinal changes.

TMS stimulation of the motor cortex to measure neural adaptation has led to mixed findings. While Kidgell et al. [52] and Weier et al. [49] observed greater MEP size following training (possibly indicating greater descending drive), Lee et al. [53] did not. In support of reduced corticospinal inhibition due to strength training, Latella et al. [54] observed shortened silent periods in both the trained and untrained rectus femoris muscles. Furthermore, reduced intracortical inhibition was observed following 4 weeks of hypertrophic squat training ([49], Fig. 6.3c). Therefore, although there has been limited study of corticospinal excitability/inhibition during strength training, it may be that a training-induced decrease in the level of inhibition is the most likely candidate for the improved descending drive.

Finally, it should be noted that the use of stimulation methods have also largely been limited to being induced under a constant force level, either maximal or submaximal. Therefore, the potential role of training-induced supraspinal adaptations that increase motor unit firing rate has not been investigated fully. But current evidence perhaps enables us to speculate that inhibitory mechanisms at both the supraspinal and spinal level are suppressed after strength training, which allows greater descending drive and ultimately greater motor unit firing rates. These neural adaptations may well account for improved performance after short-duration strength training. Future investigations may look to other methods to assess cortical functioning during rapid contractions and new insights may be attained.

Summary

The neural system controls force production through an intricate and complex system that has many levels of control. Each element of this system is capable of increasing (i.e., facilitating) or decreasing (i.e., inhibiting) force output. Ultimately, the sum of these different effectors results in a specific recruitment pattern consisting of motor unit recruitment and motor unit firing rate. Increasing either or both motor unit recruitment and/or firing rate will lead to an increase in force output assuming that the muscle and tendon are able to transmit this force in a similarly effective manner. Performing a single session of strength training will challenge various elements of the neural system leading to acute modifications in the ability

of the system to recruit motor units and/or limit their firing rate. Training is a repetitive stimulus that fatigues these parts of the neural system and these specifically adapt to be able to increase motor unit recruitment and/or firing rate. However, as this chapter highlights, there is still work to be done in order to fully understand which parts of the system are fatigued during a single strength training session and also which parts adapt during training.

References

1. Moritani T. Motor unit and motoneurone excitability during explosive movement. In: Komi PV, editor. Strength and power in sport. 2nd ed. Oxford: Blackwell Science Ltd; 2003. p. 27–49.
2. Burke RE. Motor unit types of cat triceps surae muscle. *J Physiol*. 1967;193(1):141–60.
3. Henneman E, Somjen G, Carpenter DO. Functional significance of cell size in spinal motoneurons. *J Neurophysiol*. 1965;28:560–80.
4. Grillner S, Udo M. Recruitment in the tonic stretch reflex. *Acta Physiol Scand*. 1971;81(4):571–3.
5. Kulkilka CG, Clamann HP. Comparison of the recruitment and discharge properties of motor units in human brachial biceps and adductor pollicis during isometric contractions. *Brain Res*. 1981;219(1):45–55.
6. Oya T, Riek S, Cresswell AG. Recruitment and rate coding organization for soleus motor units across entire range of voluntary isometric plantar flexions. *J Physiol*. 2009;587(19):4737–48.
7. Desmedt JE, Godaux E. Ballistic contractions in fast or slow human muscles: discharge patterns of single motor units. *J Physiol*. 1978;285:185–96.
8. Milner-Brown HS, Stein RB, Yemm R. The orderly recruitment of human motor units during voluntary isometric contraction. *J Physiol*. 1973;230(2):359–70.
9. Van Cutsem M, Duchateau J, Hainaut K. Changes in single motor unit behavior contribute to the increase in contraction speed after dynamic training in humans. *J Physiol*. 1998;513(1):295–305.
10. Seki K, Narusawa M. Firing rate modulation of human motor units in different muscles during isometric contraction with various forces. *Brain Res*. 1996;719(1–2):1–7.
11. Mullany H, O’Malley M, St Clair Gibson A, Vaughan C. Agonist-antagonist common drive during fatiguing knee extension efforts using surface electromyography. *J Electromyogr Kinesiol*. 2002;12(5):375–84.
12. Klein CS, Rice CL, Marsh GD. Normalized force, activation, and coactivation in the arm muscles of young and old men. *J Appl Physiol*. 2001;91(3):1341–9.
13. Carolan B, Cafarelli E. Adaptations in coactivation after isometric resistance training. *J Appl Physiol*. 1992;73(3):911–7.
14. Häkkinen K, Kallinen M, Izquierdo M, Jokelainen K, Lassila H, Mälkiä E, Kraemer WJ, Newton RU, Alen M. Changes in agonist-antagonist EMG, muscle CSA, and force during strength training in middle-aged and older people. *J Appl Physiol*. 1998;84(4):1314–49.
15. Häkkinen K, Alen M, Kallinen M, Newton RU, Kraemer WJ. Neuromuscular adaptation during prolonged strength training, detraining and re-strength-training in middle-aged and elderly people. *Eur J Appl Physiol*. 2000;83(1):51–62.
16. Tillin NA, Pain MT, Folland JP. Short-term unilateral resistance training affects the agonist-antagonist but not the force-agonist activation relationship. *Muscle Nerve*. 2011;43(3):375–84.
17. Enoka RM, Duchateau J. Muscle fatigue: what, why and how it influences muscle function. *J Physiol*. 2008;586(1):11–23.
18. Farina D, Merletti R, Enoka RM. The extraction of neural strategies from the surface EMG. *J Appl Physiol*. 2014;117(11):1215–30.

19. Häkkinen K. Neuromuscular fatigue in males and females during strenuous heavy resistance loading. *Electromyogr Clin Neurophysiol.* 1994;34(4):205–14.
20. Häkkinen K. Neuromuscular fatigue and recovery in male and female athletes during heavy resistance exercise. *Int J Sports Med.* 1993;14(2):53–9.
21. McCaulley GO, McBride JM, Cormie P, Hudson MB, Nuzzo JL, Quindry JC, Triplett TN. Acute hormonal and neuromuscular responses to hypertrophy, strength and power type resistance exercise. *Eur J Appl Physiol.* 2009;105(5):695–704.
22. Linnamo V, Häkkinen K, Komi PV. Neuromuscular fatigue and recovery in maximal compared to explosive strength loading. *Eur J Appl Physiol.* 1998;77(1–2):176–81.
23. Izquierdo M, Ibañez J, Calbet JA, González-Izal M, Navarro-Amézqueta I, Granados C, Malanda A, Idoate F, González-Badillo JJ, Häkkinen K, Kraemer WJ, Tirapu I, Gorostiaga EM. Neuromuscular fatigue after resistance training. *Int J Sports Med.* 2009;30(8):614–23.
24. Walker S, Davis L, Avela J, Häkkinen K. Neuromuscular fatigue during dynamic maximal strength and hypertrophic resistance loadings. *J Electromyogr Kinesiol.* 2012;22(3):356–62.
25. Gonzalez-Izal M, Malanda A, Navarro-Amezqueta I, Gorostiaga EM, Mallor F, Ibanez J, Izquierdo M. EMG spectral indices and muscle power fatigue during dynamic contractions. *J Electromyogr Kinesiol.* 2010;20(2):233–8.
26. Walker S, Peltonen H, Avela J, Häkkinen K. Neuromuscular fatigue in young and older men using constant or variable resistance. *Eur J Appl Physiol.* 2013;113(4):1069–79.
27. Ruotsalainen I, Ahtiainen JP, Kidgell DJ, Avela J. Changes in corticospinal excitability during an acute bout of resistance exercise in the elbow flexors. *Eur J Appl Physiol.* 2014;114(7):1545–53.
28. Solomonow M, Baten C, Smit J, Baratta R, Hermens H, D'Ambrosia R, Shoji H. Electromyogram power spectra frequencies associated with motor unit recruitment strategies. *J Appl Physiol (1985).* 1990;68(3):1177–85.
29. Weytjens JL, van Steenberghe D. The effects of motor unit synchronization on the power spectrum of the electromyogram. *Biol Cybern.* 1984;51(2):71–7.
30. Yao W, Fluglevand RJ, Enoka RM. Motor-unit synchronization increases EMG amplitude and decreases force steadiness of simulated contractions. *J Neurophysiol.* 2000;83(1):441–52.
31. Milner-Brown HS, Stein RB, Lee RG. Synchronization of human motor units: possible roles of exercise and supraspinal reflexes. *Electromyogr Clin Neurophysiol.* 1975;38(3):245–54.
32. Semmler JG, Nordstrom MA. Motor unit discharge and force tremor in skill- and strength-trained individuals. *Exp Brain Res.* 1998;119(1):27–38.
33. Ahtiainen JP, Häkkinen K. Strength athletes are capable to produce greater muscle activation and neural fatigue during high-intensity resistance exercise than nonathletes. *J Strength Cond Res.* 2009;23(4):1129–34.
34. Merton PA. Voluntary strength and fatigue. *J Physiol.* 1954;123(3):553–64.
35. Carroll TJ, Taylor JL, Gandevia SC. Recovery of central and peripheral neuromuscular fatigue after exercise. *J Appl Physiol.* 2017;122(5):1068–76.
36. Aagaard P, Thorstensson A. Neuromuscular aspects of exercise-adaptive responses evoked by strength training. In: Kjaer M, Krosgaard M, Magnusson P, editors. *Textbook of sports medicine: basic science and clinical aspects of sports injury and physical activity.* Chichester: Wiley; 2003. p. 70–106.
37. Aagaard P, Simonsen EB, Andersen JL, Magnusson P, Dyhre-Poulsen P. Neural adaptations to resistance training: changes in evoked V-wave and H-reflex responses. *J Appl Physiol.* 2002;92(6):2309–18.
38. Aagaard P, Simonsen EB, Andersen JL, Magnusson P, Dyhre-Poulsen P. Increase rate of force development and neural drive of human skeletal muscle following resistance training. *J Appl Physiol.* 2002;93(4):1318–26.
39. Häkkinen K, Komi PV. Electromyographic changes during strength training and detraining. *Med Sci Sports Exerc.* 1983;15(6):455–60.

40. Narici MV, Roi GS, Landoni L, Minetti AE, Cerretelli P. Changes in force, cross-sectional area and neural activation during strength training and detraining of the human quadriceps. *Eur J Appl Physiol.* 1989;59(4):310–9.
41. Suetta C, Aagaard P, Rosted A, Jakobsen AK, Duus B, Kjaer M, Magnusson SP. Training-induced changes in muscle CSA, muscle strength, EMG, and rate of force development in elderly subjects after long-term unilateral disuse. *J Appl Physiol.* 2004;97(5):1954–61.
42. Walker S, Blazevich AJ, Haff GG, Tufano JJ, Newton RU, Häkkinen K. Greater gains after training with accentuated eccentric than traditional isoinertial loads in already strength-trained men. *Front Physiol.* 2016;7:149.
43. Häkkinen K, Komi PV, Alen M. Effect of explosive type strength training on isometric force- and relaxation-time, electromyographic and muscle fibre characteristics of leg extensor muscles. *Acta Physiol Scand.* 1985;125(4):587–600.
44. Tillin NA, Pain MT, Folland JP. Short-term training for explosive strength causes neural and mechanical adaptations. *Exp Physiol.* 2012;97(5):630–41.
45. Arabadzhiev TI, Dimitrov VG, Dimitrov GV. The increase in surface EMG could be a misleading measure of neural adaptation during early gains in strength. *Eur J Appl Physiol.* 2014;114(8):1645–55.
46. Kidgell DJ, Sale MV, Semmler JG. Motor unit synchronization measured by cross-correlation is not influenced by short-term training of a hand muscle. *Exp Brain Res.* 2006;175(4):745–53.
47. Christie A, Kamen G. Short-term training adaptations in maximal motor unit firing rates and afterhyperpolarization duration. *Muscle Nerve.* 2010;41(5):651–60.
48. Knight CA, Kamen G. Adaptations in muscular activation of the knee extensor muscles with strength training in young and older adults. *J Electromyogr Kinesiol.* 2001;11(6):405–12.
49. Weier AT, Pearce AJ, Kidgell DJ. Strength training reduces intracortical inhibition. *Acta Physiol.* 2012;206(2):109–19.
50. Vila-Cha C, Falla D, Correia MV, Farina D. Changes in H reflex and V wave following short-term endurance and strength training. *J Appl Physiol.* 2012;112(1):54–63.
51. Unhjem R, Lundestad R, Fimland MS, Mosti MP, Wang E. Strength training-induced responses in older adults: attenuation of descending neural drive with age. *Age.* 2015;37(3):9784.
52. Kidgell DJ, Stokes MA, Castricum TJ, Pearce AJ. Neurophysiological responses after short-term strength training of the biceps brachii muscle. *J Strength Cond Res.* 2010;24(11):3123–32.
53. Lee M, Gandevia SC, Carroll TJ. Short-term strength training does not change cortical voluntary activation. *Med Sci Sports Exerc.* 2009;41(7):1452–60.
54. Latella C, Kidgell DJ, Pearce AJ. Reduction in corticospinal inhibition in the trained and untrained limb following unilateral leg strength training. *Eur J Appl Physiol.* 2012;112(8):3097–107.

Part II

The Interference Effect



Proposed Mechanisms Underlying the Interference Effect

7

Stian Ellefsen and Keith Baar

Introduction to the Interference Effect

In 1980, Dr. Hickson [1] published a seminal paper on concurrent training, comparing the effects of endurance training and strength training alone with those of concurrent training on aerobic capacity and leg strength in humans [1]. Since then, the assumption has been that there is an interference effect between the two training modalities, also known as the concurrent training, or interference, effect [2]. The interference effect can be further broken down into the acute interference effect, whereby the residual fatigue from the first bout decreases the subsequent performance of the second bout [3], and the chronic effect (the focus of this review), whereby the adaptation to endurance or strength is modified by the participation in the other form of training [4]. In short, performing the two exercise modalities in proximity of each other over an extended period of time may decrease the effects of strength training on muscle strength [1], mass [5], and power [4], with no apparent negative effects on outcomes of endurance training [1], which indeed is likely to benefit from concurrent training [6]. Animal studies have consistently attributed this impairment to activation and deactivation of specific molecular switches and cellular signaling pathways [2, 7]. Over the decades, it has become increasingly clear that the universality of the interference effect is questionable in humans, with an

S. Ellefsen

Section of Sports Sciences, Inland Norway University of Applied Sciences,
Lillehammer, Norway

Innlandet Hospital Trust, Brumunddal, Norway

K. Baar (✉)

Departments of Neurobiology, Physiology and Behavior and Physiology and Membrane Biology, University of California, Davis, Davis, CA, USA

Functional Molecular Biology Lab, University of California, Davis, Davis, CA, USA
e-mail: kbaar@ucdavis.edu

increasing bulk of evidence suggesting that its presence and extent depends on training status, type of muscle being trained, endurance training modality and protocol [2, 7]. This may explain data from human muscle biopsies, which often end up negative for proxy markers of an interference effect [8, 9].

In a meta-analysis from 2012 [4], Wilson and colleagues attempted to draw a definitive conclusion from the human studies investigating the interference effects of concurrent training. Their conclusions were that concurrent training leads to increases in strength and muscle mass that were not statistically less than strength training alone, suggesting that endurance training does not impose a generic interference effect on strength adaptations [4]. The analysis only reached statistical significance when looking at muscle power, which was lower in the concurrent group than those who completed strength alone [4]. In a subset of analyses, different modes of endurance training were associated with different degrees of interference, with running but not cycling impairing increases in lower body strength and muscle mass. Lastly, the degree of interference was associated with the volume of endurance training, showing a negative correlation with both frequency and average duration of endurance workout. In a sense, Wilson et al. [4] summarized what we already suspected: if you train at a high enough frequency, intensity, and duration, endurance exercise inhibits strength development. Therefore, in high-level athletes, an interference may exist, but in recreational athletes who only train 3–6 times a week, the effect seems to be equivocal [10]. Further, since the response to training varies with age, gender, training status, and genetics, observing a statistically significant concurrent training effect in a small cohort is difficult. By contrast, when training >6 times a week at high intensities, there is a decrease in both strength [1] and hypertrophy [5] when strength and endurance training are performed together.

The Interference Effect and Hypertrophy

The molecular mechanism underlying the interference effect has been an area of research interest for almost 15 years [11]. By 1999, complex 1 of the mechanistic target of rapamycin (mTORC1) had been identified as one of the key molecular components of the hypertrophic response to resistance exercise [12]. In 2003, the AMP-activated protein kinase (AMPK) was shown to directly inactivate mTORC1 and limit growth in cells [11]. Since AMPK had previously been shown to be activated by endurance exercise [13], the logical hypothesis was that when activated by endurance exercise, AMPK would shut down mTORC1 and reduce muscle hypertrophy. In agreement with this hypothesis, old animals that showed increased AMPK activity hypertrophied less following overload [14] and the pharmacological AMPK activator 5-aminoimidazole-4-carboxamide-1-4-riboside (AICAR) could prevent the activation of mTORC1 following resistance exercise [15]. These data seemed to confirm that the concurrent training effect was the result of a simple molecular switch: strength exercise activated mTORC1, endurance activated AMPK, and when performed together AMPK shut off mTORC1 reduced muscle hypertrophy [16].

Unfortunately, this simple relationship did not translate into human muscle. When Apro and colleagues began to look for an acute inhibition of mTORC1

signaling in human muscle after concurrent training they found that neither steady-state cycling for 30 min at 70% of VO_{2max} [9], nor five 4-min intervals at 85% of VO_{2max} with 3 min rest in between [8] inhibited the activation of mTORC1 following resistance exercise in moderate trained persons. The high intensity interval training, which activated AMPK, did decrease mTORC1 activity marginally, but this did not reach statistical significance, suggesting that a simple relationship where AMPK activation during endurance exercise blocked mTORC1 activation by resistance exercise was not the mechanism underlying the interference effect.

In hindsight, there were many clues that this simple mechanism was not sufficient. First, in models of concurrent training, such as overload hypertrophy in rodents, it is the $\alpha 1$ isoform of AMPK that is upregulated [17] and only when $\alpha 1$ AMPK is knocked out does skeletal muscle mass increase further with overload [18]. This suggests that it is the $\alpha 1$ isoform of AMPK that can block hypertrophy. Second, endurance exercise activates primarily the $\alpha 2$ isoform of AMPK [19, 20], suggesting that endurance exercise does not activate the isoform of AMPK that blocks growth. If these data are combined with those of Thomson et al. [15], who injected rats with AICAR (that activates all forms of AMPK) and blocked mTORC1 activation, the conclusion would be that activation of $\alpha 1$ AMPK may block mTORC1 activation and growth, or at least is activated concomitant with a secondary factor that does block growth.

The question then is: what is it that activates $\alpha 1$ AMPK and inhibits mTORC1 and is it a causal relationship between AMPK and mTORC1 or merely a correlation? mTORC1 is activated not only by resistance exercise but by amino acids as well [21]. The activation of mTORC1 by amino acids is particularly sensitive to the amino acid leucine (Fig. 7.1). Leucine is important since it directly activates mTORC1 through a molecular process where it binds to a protein named sestrin [22, 23]. When bound to leucine, sestrin no longer inhibits recruitment of mTOR to its activator Rheb [24]. Therefore, leucine binding to sestrin initiates the activation of mTORC1. Interestingly, overexpression of sestrin is associated with an increase in AMPK phosphorylation, while at the same time exerting its negative effect on mTORC1 [25]. Also, removal of $\alpha 1$ AMPK prevents sestrin from inhibiting mTORC1 [25]. Together, these observations suggest that regulation of sestrin activity provides a mechanism for simultaneously regulating mTORC1 and AMPK activity, with increased sestrin impairing muscle growth. So, how can sestrin activity be regulated in muscle cells? The most compelling link is that, in many cells, sestrin gene expression is regulated by the tumor suppressor protein p53 [25, 26]. p53 is known to be activated following endurance exercise [27–29], but also through cellular stressors such as fasting, immobilization, shifts in redox state, age, and excessive growth signaling [29–32]. p53 activation induces upregulation of sestrin [25, 26], and with greater amounts of sestrin in muscle, it becomes harder for leucine-rich protein to activate mTORC1, resulting in impaired growth. This represents a possible mechanism behind the interference effect. Consistent with this hypothesis, it takes more protein in each meal to increase muscle protein synthesis and maintain or grow muscle when a person is in a caloric deficit [33, 34], in bed for a period of unloading [35], or older [36, 37], all of which are associated with increased p53 activity [30–32]. Such a mechanism would argue that there is nothing unique about the concurrent training effect, rather that any

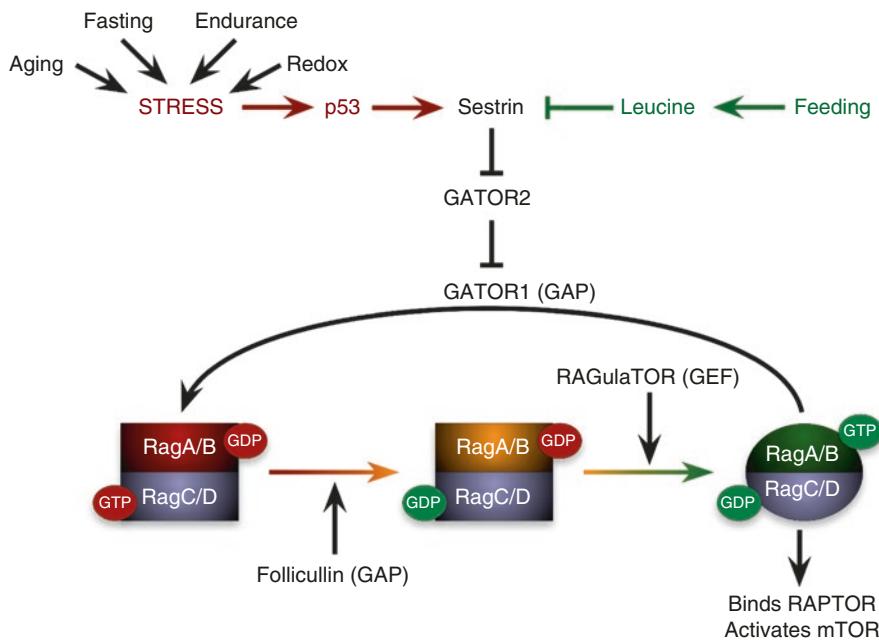


Fig. 7.1 Schematic representing the activation of mTORC1 by leucine. Here, feeding leucine-rich protein results in the inhibition of sestrin and activation of the GATOR2 complex. When activated, GATOR2 prevents GATOR1 from activating the GTPase activity of RagA/B resulting in GTP loading and recruitment of mTOR to its activator Rheb resulting in mTORC1 activation. In the presence of stress from a variety of sources, p53 is stabilized and increases sestrin levels, making it harder for leucine-rich protein to activate mTORC1

significant stress would result in a decrease in mTORC1 signaling in response to feeding, resulting in poorer muscle growth.

Beyond sestrin, p53 activation could limit muscle hypertrophy by regulating ribosome mass. Ribosome mass is positively related to the amount of muscle hypertrophy that occurs with training [38]. p53 is one of the better characterized regulators of ribosome biogenesis (Fig. 7.2). In response to stress, p53 protein is stabilized and disrupts the interaction between the ribosomal transcriptional regulators: upstream binding factor (UBF) and selectivity factor (SL1) [39]. With less interaction between UBF and SL1, the activity of polymerase I, which transcribes the ribosomal RNAs, decreases [39]. Intuitively, this would reduce muscle growth by lowering the capacity for protein translation. Consistent with a role of p53 in regulating ribosome mass, older individuals, who have more p53 activity [31], show less ribosome biogenesis and muscle hypertrophy than young individuals following resistance exercise [40].

A mechanism where the stress induced by endurance exercise underlies the interference effect would also explain why greater training volume and intensity result in greater interference. Greater training volumes and intensities would increase redox and metabolic stress within the working muscles, resulting in greater increases in p53 activity, greater sestrin activity, more difficulty activating mTORC1 in response to feeding, and lower ribosome mass resulting in lower rates of protein synthesis. Consistent with this

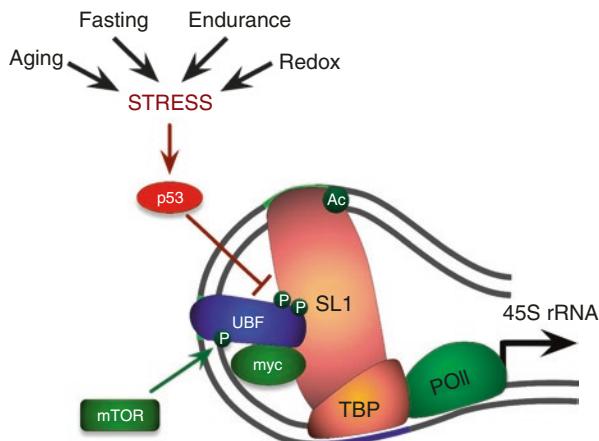


Fig. 7.2 Schematic representing the effect of stress on ribosome biogenesis. Stress from either endurance exercise, fasting, shifts in redox state, or aging can increase p53. Secondary to the increase in p53, there is destabilization of the interaction between the essential transcription factors SL1 and UBF resulting in a decrease in polymerase I activity and a decrease in production of the 45S pre-ribosomal RNA

model, equal workloads (whether low or high intensity) result in similar p53 activation [27], and increasing the metabolic stress of training by reducing carbohydrate availability results in a further increase in p53 activity [28]. This suggests that the greater the metabolic stress the greater the p53 activation and the greater the interference effect, consistent with the training data from human studies.

The Interference Effect and Muscle Power

Even though the greatest amount of attention has been paid to the limits of muscle growth, the strongest component of the interference effect is its effect on power [4]. Power is the product of force and velocity and is therefore determined by muscle cross-sectional area, the neural activation of the muscle, the isoform of myosin heavy chain expressed in the muscle, and the ability to transmit force from the myosin and actin within each sarcomere through the tendon to the bone [41]. Therefore, in theory each of these factors may show an interference effect. We discussed the potential interference effect on cross-sectional area above; however, one important aspect of the interference effect on muscle size was not discussed: the effect on fiber type. Strength training preferentially increases the amount of Type II myosin heavy chain protein in muscle [42]. Even though the number of fast fibers does not change with training, muscle growth preferential occurs through addition of Type IIa myosin heavy chain protein in existing fibers, both by increasing their cross-sectional area and by transforming IIx fibers into IIa fibers [43]. This increases the Type II myosin area and increases strength and power [5, 43, 44]. In contrast to strength training, endurance and strength performed together results in greater hypertrophy of Type I fibers [45], while simultaneously limiting growth in Type II fibers [46].

The resulting muscle would have a greater proportion of slow myosin and may therefore show a lower power than muscle trained exclusively for strength. Accordingly, muscles from athletes completing endurance training or combined endurance and strength training may demonstrate lower power than muscles from athletes trained exclusively for strength or power [47]. As for neural adaptations, strength training generally alters neural functions to facilitate activation of a greater number of muscle fibers [48]. This increases the potential for activating Type II muscle fibers during maximal efforts, providing increased muscle strength and power. These adaptations may be prone to the interference effect, as suggested by studies showing impaired alterations in voluntary activation, EMG, or rate of force development after concurrent training [49, 50]. The interference may also be ascribed residual fatigue from the endurance training, compromising the quality of strength training. However, it is beyond the scope of this chapter to elaborate on potential neurological mechanisms. Lastly, endurance exercise might exert interference by altering the microarchitecture of muscle [51]. Here, there is far less information as to how different types of training result in shifts in force transfer proteins in the muscle, within the extracellular matrix of the muscle, as well as in the tendons and therefore whether this contributes to the interference effect cannot be determined at this point.

Summary

Even though there is good empirical data for an interference effect with high volume or high intensity endurance training, the molecular mechanism has proven difficult to establish. The mechanism presented here, whereby the chronic metabolic stress of high intensity and high volume endurance exercise results in the activation of p53 and this leads to an increase in sestrin and a decrease in ribosome biogenesis, would explain much of the experimental data in the literature. Importantly, this mechanism would not only apply to the interference of endurance in the adaptation to strength training, but would also explain the difficulty in increasing muscle mass and strength in caloric restriction, unloading, and aging. Such a broadly applicable mechanism would prove easier to target using timed training and nutrition and may even prove to be a target for the development of new drugs to fight muscle wasting.

Acknowledgements This work was supported by a project grant to KB from the National Institute on Aging of the National Institutes of Health under award number R01AG045375.

References

1. Hickson RC. Interference of strength development by simultaneously training for strength and endurance. *Eur J Appl Physiol Occup Physiol*. 1980;45(2–3):255–63. <https://doi.org/10.1007/bf00421333>.
2. Baar K. Using molecular biology to maximize concurrent training. *Sports Med*. 2014;44(Suppl 2):S117–25. <https://doi.org/10.1007/s40279-014-0252-0>.
3. Doma K, Deakin GB. The acute effects intensity and volume of strength training on running performance. *Eur J Sport Sci*. 2014;14(2):107–15. <https://doi.org/10.1080/17461391.2012.726653>.

4. Wilson JM, Marin PJ, Rhea MR, Wilson SM, Loenneke JP, Anderson JC. Concurrent training: a meta-analysis examining interference of aerobic and resistance exercises. *J Strength Cond Res.* 2012;26(8):2293–307. <https://doi.org/10.1519/JSC.0b013e31823a3e2d>. National Strength & Conditioning Association.
5. Kraemer WJ, Patton JF, Gordon SE, Harman EA, Deschenes MR, Reynolds K, et al. Compatibility of high-intensity strength and endurance training on hormonal and skeletal muscle adaptations. *J Appl Physiol.* 1995;78(3):976–89.
6. Berryman N, Maurel DB, Bosquet L. Effect of plyometric vs. dynamic weight training on the energy cost of running. *J Strength Cond Res.* 2010;24(7):1818–25. <https://doi.org/10.1519/JSC.0b013e3181def1f5>.
7. Fyfe JJ, Bishop DJ, Stepto NK. Interference between concurrent resistance and endurance exercise: molecular bases and the role of individual training variables. *Sports Med.* 2014;44(6):743–62. <https://doi.org/10.1007/s40279-014-0162-1>.
8. Apro W, Moberg M, Hamilton DL, Ekblom B, van Hall G, Holmberg HC, Blomstrand E. Resistance exercise-induced S6K1 kinase activity is not inhibited in human skeletal muscle despite prior activation of AMPK by high-intensity interval cycling. *Am J Physiol Endocrinol Metab.* 2015;308(6):E470–81. <https://doi.org/10.1152/ajpendo.00486.2014>.
9. Apro W, Wang L, Ponten M, Blomstrand E, Sahlin K. Resistance exercise induced mTORC1 signaling is not impaired by subsequent endurance exercise in human skeletal muscle. *Am J Physiol Endocrinol Metab.* 2013;305(1):E22–32. <https://doi.org/10.1152/ajpendo.00091.2013>.
10. Coffey VG, Hawley JA. Concurrent exercise training: do opposites distract? *J Physiol.* 2017;595(9):2883–96. <https://doi.org/10.1113/JP272270>.
11. Inoki K, Zhu T, Guan KL. TSC2 mediates cellular energy response to control cell growth and survival. *Cell.* 2003;115(5):577–90.
12. Baar K, Esser K. Phosphorylation of p70(S6k) correlates with increased skeletal muscle mass following resistance exercise. *Am J Physiol.* 1999;276(1 Pt 1):C120–7.
13. Winder WW, Hardie DG. Inactivation of acetyl-CoA carboxylase and activation of AMP-activated protein kinase in muscle during exercise. *Am J Physiol.* 1996;270(2 Pt 1):E299–304.
14. Thomson DM, Gordon SE. Diminished overload-induced hypertrophy in aged fast-twitch skeletal muscle is associated with AMPK hyperphosphorylation. *J Appl Physiol.* 2005;98(2):557–64.
15. Thomson DM, Fick CA, Gordon SE. AMPK activation attenuates S6K1, 4E-BP1, and eEF2 signaling responses to high-frequency electrically stimulated skeletal muscle contractions. *J Appl Physiol.* 2008;104(3):625–32. <https://doi.org/10.1152/japplphysiol.00915.2007>.
16. Atherton PJ, Babraj J, Smith K, Singh J, Rennie MJ, Wackerhage H. Selective activation of AMPK-PGC-1alpha or PKB-TSC2-mTOR signaling can explain specific adaptive responses to endurance or resistance training-like electrical muscle stimulation. *FASEB J.* 2005;19(7):786–8.
17. McGee SL, Mustard KJ, Hardie DG, Baar K. Normal hypertrophy accompanied by phosphorylation and activation of AMP-activated protein kinase alpha1 following overload in LKB1 knockout mice. *J Physiol.* 2008;586(6):1731–41. <https://doi.org/10.1113/jphysiol.2007.143685>.
18. Mounier R, Lantier L, Leclerc J, Sotiropoulos A, Pende M, Daegelen D, et al. Important role for AMPKalpha1 in limiting skeletal muscle cell hypertrophy. *FASEB J.* 2009;23(7):2264–73. <https://doi.org/10.1096/fj.08-119057>.
19. Lee-Young RS, Koufogiannis G, Canny BJ, McConell GK. Acute exercise does not cause sustained elevations in AMPK signaling or expression. *Med Sci Sports Exerc.* 2008;40(8):1490–4. <https://doi.org/10.1249/MSS.0b013e318173a037>.
20. Wojtaszewski JF, Nielsen P, Hansen BF, Richter EA, Kiens B. Isoform-specific and exercise intensity-dependent activation of 5'-AMP-activated protein kinase in human skeletal muscle. *J Physiol.* 2000;528(Pt 1):221–6.
21. Bar-Peled L, Sabatini DM. Regulation of mTORC1 by amino acids. *Trends Cell Biol.* 2014;24(7):400–6. <https://doi.org/10.1016/j.tcb.2014.03.003>.

22. Saxton RA, Knockenhauer KE, Wolfson RL, Chantranupong L, Pacold ME, Wang T, et al. Structural basis for leucine sensing by the Sestrin2-mTORC1 pathway. *Science*. 2016;351(6268):53–8. <https://doi.org/10.1126/science.aad2087>.
23. Wolfson RL, Chantranupong L, Saxton RA, Shen K, Scaria SM, Cantor JR, Sabatini DM. Sestrin2 is a leucine sensor for the mTORC1 pathway. *Science*. 2016;351(6268):43–8. <https://doi.org/10.1126/science.aab2674>.
24. Bar-Peled L, Chantranupong L, Cherniack AD, Chen WW, Ottina KA, Grabiner BC, et al. A Tumor suppressor complex with GAP activity for the Rag GTPases that signal amino acid sufficiency to mTORC1. *Science*. 2013;340(6136):1100–6. <https://doi.org/10.1126/science.1232044>.
25. Budanov AV, Karin M. p53 target genes sestrin1 and sestrin2 connect genotoxic stress and mTOR signaling. *Cell*. 2008;134(3):451–60. <https://doi.org/10.1016/j.cell.2008.06.028>.
26. Deng W, Cha J, Yuan J, Haraguchi H, Bartos A, Leishman E, et al. p53 coordinates decidua sestrin 2/AMPK/mTORC1 signaling to govern parturition timing. *J Clin Invest*. 2016;126(8):2941–54. <https://doi.org/10.1172/JCI87715>.
27. Bartlett JD, Hwa Joo C, Jeong TS, Louhelainen J, Cochran AJ, Gibala MJ, et al. Matched work high-intensity interval and continuous running induce similar increases in PGC-1alpha mRNA, AMPK, p38, and p53 phosphorylation in human skeletal muscle. *J Appl Physiol*. 2012;112(7):1135–43. <https://doi.org/10.1152/japplphysiol.01040.2011>.
28. Bartlett JD, Louhelainen J, Iqbal Z, Cochran AJ, Gibala MJ, Gregson W, et al. Reduced carbohydrate availability enhances exercise-induced p53 signaling in human skeletal muscle: implications for mitochondrial biogenesis. *Am J Physiol Regul Integr Comp Physiol*. 2013;304(6):R450–8. <https://doi.org/10.1152/ajpregu.00498.2012>.
29. Tachtsis B, Smiles WJ, Lane SC, Hawley JA, Camera DM. Acute endurance exercise induces nuclear p53 abundance in human skeletal muscle. *Front Physiol*. 2016;7:144. <https://doi.org/10.3389/fphys.2016.00144>.
30. Aquilano K, Baldelli S, Pagliei B, Cannata SM, Rotilio G, Ciriolo MR. p53 orchestrates the PGC-1alpha-mediated antioxidant response upon mild redox and metabolic imbalance. *Antioxid Redox Signal*. 2013;18(4):386–99. <https://doi.org/10.1089/ars.2012.4615>.
31. Edwards MG, Anderson RM, Yuan M, Kendziora CM, Weindrich R, Prolla TA. Gene expression profiling of aging reveals activation of a p53-mediated transcriptional program. *BMC Genomics*. 2007;8:80. <https://doi.org/10.1186/1471-2164-8-80>.
32. Fox DK, Ebert SM, Bongers KS, Dyle MC, Bullard SA, Dierdorff JM, et al. p53 and ATF4 mediate distinct and additive pathways to skeletal muscle atrophy during limb immobilization. *Am J Physiol Endocrinol Metab*. 2014;307(3):E245–61. <https://doi.org/10.1152/ajpendo.00010.2014>.
33. Arete JL, Burke LM, Camera DM, West DW, Crawshaw S, Moore DR, et al. Reduced resting skeletal muscle protein synthesis is rescued by resistance exercise and protein ingestion following short-term energy deficit. *Am J Physiol Endocrinol Metab*. 2014;306(8):E989–97. <https://doi.org/10.1152/ajpendo.00590.2013>.
34. Garthe I, Raastad T, Refsnes PE, Koivisto A, Sundgot-Borgen J. Effect of two different weight-loss rates on body composition and strength and power-related performance in elite athletes. *Int J Sport Nutr Exerc Metab*. 2011;21(2):97–104.
35. English KL, Mettler JA, Ellison JB, Mamerow MM, Arentson-Lantz E, Pattarini JM, et al. Leucine partially protects muscle mass and function during bed rest in middle-aged adults. *Am J Clin Nutr*. 2016;103(2):465–73. <https://doi.org/10.3945/ajcn.115.112359>.
36. De Bandt JP. Leucine and mammalian target of rapamycin-dependent activation of muscle protein synthesis in aging. *J Nutr*. 2016;146(12):2616S–24S. <https://doi.org/10.3945/jn.116.234518>.
37. Yang Y, Breen L, Burd NA, Hector AJ, Churchward-Venne TA, Josse AR, et al. Resistance exercise enhances myofibrillar protein synthesis with graded intakes of whey protein in older men. *Br J Nutr*. 2012;108(10):1780–8. <https://doi.org/10.1017/S0007114511007422>.
38. Stec MJ, Kelly NA, Many GM, Windham ST, Tugge SC, Bamman MM. Ribosome biogenesis may augment resistance training-induced myofiber hypertrophy and is required for

- myotube growth in vitro. *Am J Physiol Endocrinol Metab.* 2016;310(8):E652–61. <https://doi.org/10.1152/ajpendo.00486.2015>. ajpendo 00486 02015.
39. Zhai W, Comai L. Repression of RNA polymerase I transcription by the tumor suppressor p53. *Mol Cell Biol.* 2000;20(16):5930–8.
40. Stec MJ, Mayhew DL, Bamman MM. The effects of age and resistance loading on skeletal muscle ribosome biogenesis. *J Appl Physiol.* 2015;119(8):851–7. <https://doi.org/10.1152/japplphysiol.00489.2015>.
41. Hughes DC, Wallace MA, Baar K. Effects of aging, exercise, and disease on force transfer in skeletal muscle. *Am J Physiol Endocrinol Metab.* 2015;309(1):E1–E10. <https://doi.org/10.1152/ajpendo.00095.2015>.
42. Kosek DJ, Kim JS, Petrella JK, Cross JM, Bamman MM. Efficacy of 3 days/wk resistance training on myofiber hypertrophy and myogenic mechanisms in young vs. older adults. *J Appl Physiol.* 2006;101(2):531–44. <https://doi.org/10.1152/japplphysiol.01474.2005>.
43. Staron RS, Leonardi MJ, Karapondo DL, Malicky ES, Falkel JE, Hagerman FC, Hikida RS. Strength and skeletal muscle adaptations in heavy-resistance-trained women after detraining and retraining. *J Appl Physiol.* 1991;70(2):631–40. <https://doi.org/10.1152/jappl.1991.70.2.631>.
44. Verdijk LB, Gleeson BG, Jonkers RA, Meijer K, Savelberg HH, Dendale P, van Loon LJ. Skeletal muscle hypertrophy following resistance training is accompanied by a fiber type-specific increase in satellite cell content in elderly men. *J Gerontol A Biol Sci Med Sci.* 2009;64(3):332–9. <https://doi.org/10.1093/gerona/gln050>.
45. Kazior Z, Willis SJ, Moberg M, Apro W, Calbet JA, Holmberg HC, Blomstrand E. Endurance exercise enhances the effect of strength training on muscle fiber size and protein expression of Akt and mTOR. *PLoS One.* 2016;11(2):e0149082. <https://doi.org/10.1371/journal.pone.0149082>.
46. Aagaard P, Andersen JL, Bennekou M, Larsson B, Olesen JL, Crameri R, et al. Effects of resistance training on endurance capacity and muscle fiber composition in young top-level cyclists. *Scand J Med Sci Sports.* 2011;21(6):e298–307. <https://doi.org/10.1111/j.1600-0838.2010.01283.x>.
47. Sleivert GG, Backus RD, Wenger HA. Neuromuscular differences between volleyball players, middle distance runners and untrained controls. *Int J Sports Med.* 1995;16(6):390–8. <https://doi.org/10.1055/s-2007-973026>.
48. Gandevia SC. Spinal and supraspinal factors in human muscle fatigue. *Physiol Rev.* 2001;81(4):1725–89.
49. Eklund D, Pulverenti T, Bankers S, Avela J, Newton R, Schumann M, Häkkinen K. Neuromuscular adaptations to different modes of combined strength and endurance training. *Int J Sports Med.* 2015;36(02):120–9. <https://doi.org/10.1055/s-0034-1385883>.
50. Häkkinen K, Alen M, Kraemer WJ, Gorostiaga E, Izquierdo M, Rusko H, et al. Neuromuscular adaptations during concurrent strength and endurance training versus strength training. *Eur J Appl Physiol.* 2003;89(1):42–52. <https://doi.org/10.1007/s00421-002-0751-9>.
51. Hughes DC, Ellefson S, Baar K. Adaptations to endurance and strength training. *Cold Spring Harb Perspect Med.* 2018;8(6):a029769. <https://doi.org/10.1101/cshperspect.a029769>.



Molecular Adaptations to Concurrent Strength and Endurance Training

8

Eduardo O. De Souza

Introduction

Both strength and endurance training regimens induce distinct skeletal muscle adaptations [1, 2]. It has been suggested that when performed in conjunction with a high frequency, volume, and intensity, conflicting adaptations may occur. If not implemented properly, concurrent strength and endurance training (CT) may result in reduced strength training (ST) adaptations [3–5]. The negative interaction between ST and endurance training (ET) has been defined as the interference effect. The advancements in technology have increased our understanding of the molecular mechanisms behind the exercise-induced adaptations to both strength and endurance stimuli. The molecular basis of muscular adaptation in response to different training regimens is very complex. It involves increases in the expression and/or activity of genes and proteins in order to increase contractile tissue (i.e., muscle hypertrophy) or mitochondrial content [6, 7]. Furthermore, there is considerable cross-talking and redundancy between signaling pathways that control exercise-induced adaptations, which is beyond the scope of this chapter (for further readings, see [6, 8, 9]). The following sections will review the acute and chronic molecular responses induced by CT, and how they are related to the interference effect and morphological changes.

E. O. De Souza

Department of Health Sciences and Human Performance, University of Tampa,
Tampa, FL, USA

e-mail: edesouza@ut.edu

Molecular Interference Hypothesis

ST-induced muscle hypertrophy is the cumulative effect of multiple training sessions that have resulted in a net positive balance between the rate of muscle protein synthesis (MPS) and muscle protein breakdown (MPB) [10]. Despite the complexity of the protein synthesis process, it is regulated through signaling pathways that enhance mRNA translation [11]. The mammalian or mechanistic target of rapamycin complex 1 (mTORC1) is a key kinase controlling protein synthesis and muscle hypertrophy [12, 13]. The role of mTOR controlling other kinases involved in protein synthesis is explained in Chap. 5.

On the other hand, ET-induced adaptions are attributed to increases in mitochondrial function and content within the skeletal muscles that ultimately results in improved oxidative capacity and endurance performance [14–16]. Even though ET has been shown to activate multiple signals (Fig. 8.1), [17]. The peroxisome-proliferator-activated receptor γ co-activator-1 α (PGC-1 α) has been referred to as a key driver of mitochondrial biogenesis [18]. PGC-1 α is a transcriptional co-activator that induces mitochondrial biogenesis. It activates different transcription factors that modulate gene expression resulting in the encoding of mitochondrial proteins [19, 20]. Even though multiple signals can modulate PGC-1 α , it has been suggested that AMP-activated protein kinase (AMPK) is one of the major contributors as it controls the transcription and activity of PGC-1 α [21–23].

AMPK also plays an important role in cellular energy metabolism during exercise and nutrient deprivation [24]. Furthermore, AMPK has been referred to as a sensor for cellular energy status as it is activated by increases in cellular AMP:ATP ratio. Once activated, AMPK blunts the biosynthetic process that demands ATP consumption and stimulates an energy generating process in order to reestablish cellular energy levels [25]. In fact, animal model studies have demonstrated that AMPK activation can inhibit mTORC1 activity, its downstreams and blunts MPS and skeletal muscle hypertrophy [25–27].

In this regard, the greater energy demands and the different signaling pathways involved with CT compared to a single mode regimen create a conflicting environment within the skeletal muscle. Therefore, a molecular hypothesis has been put forward to explain the reduced training adaptation after CT [26]. In this hypothetical model referred to AMPK-Akt switch hypothesis, the AMPK phosphorylates tuberous sclerosis complex-2 (TSC2). TSC2 switches off the mTORC1-signaling cascade, ultimately decreasing the potential for muscle fiber hypertrophy after CT regimen [26] (Fig. 8.1).

Acute Molecular Responses of Concurrent Exercise

When analyzing the current literature in molecular responses to CT, the reader needs to consider multiple factors, as there is an important disparity in the experimental study designs (Table 8.1). For example, demographics, intra-individual responses, training status, exercise mode and volume, and nutrient availability will

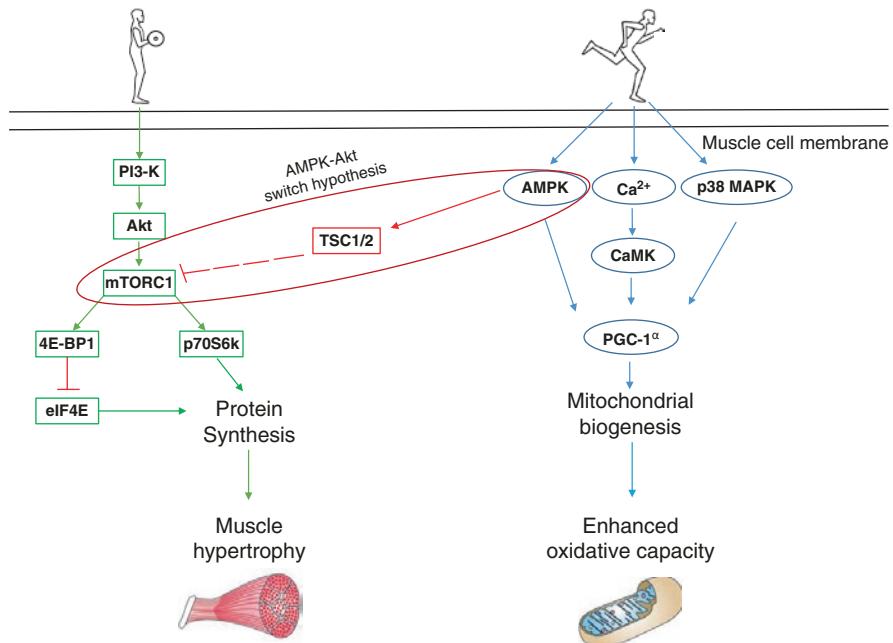


Fig. 8.1 Schematic diagram summarizing signaling pathways activated by strength (ST) and endurance training (ET) and the AMPK-Akt switch hypothesis. ST induces an increase in the activity of protein kinase B (Akt), mammalian target of rapamycin complex 1 (mTORC1), that modulates rates of protein synthesis through phosphorylation of eukaryotic initiation factor 4E-binding protein (4E-BP1) that promotes dissociation between 4E-BP1 and eukaryotic initiation factor 4E- (eIF4E) and activation of 70 kDa ribosomal protein kinase (p70S6K). ET activates signaling cascade that regulates metabolic process and mitochondrial biogenesis that comprises adenosine-monophosphate-activated protein kinase (AMPK), p38 mitogen-activated protein kinase (MAPK), calmodulin-dependent protein kinase (CaMK) and proliferator-activated receptor-gamma coactivator 1-alpha (PGC-1^α). In the Akt-AMPK switch hypothesis model, AMPK activated by ET may inhibit mTORC1 signaling cascade through tuberous sclerosis complex (TSC) blunting ST-induced protein synthesis. Figure was adapted from: Hawley, JA. (2009) Molecular adaptations to strength and endurance: Are they incompatible? Atherton et al. (2005). Selective activation of AMPK-PGC-1 or PKB-TSC2-mTOR signaling can explain specific adaptive responses to endurance or resistance training-like electrical muscle stimulation. Coffey and Hawley (2017). Concurrent exercise training: do opposites distract?

all affect the acute molecular responses. Furthermore, the muscle sampling time can significantly impact how the selected molecular markers will respond at the transcriptional level (i.e., gene expression) and the translational level (i.e., protein signaling and myofibrillar and sarcoplasmic synthetic rates).

Coffey and Hawley [7] have suggested that training status and intra-individual responses are the primary factors modulating the molecular cascades induced by CT [7]. These researchers investigated the effect of training background on acute molecular responses to strength exercise (SE) and endurance exercise (EE) in athletes with different training experience (i.e., either strength or endurance). In one experimental

Table 8.1 Summary of studies designs that investigate the acute molecular responses to concurrent exercise

Study	Training status	Study design	Nutrient availability	Sampling time	Exercise regimens	Recovery between exercise	CT order	Conclusions
Lundberg et al. [36]	Recreationally trained EE, 2–3×/week or SE 1–2×/week for more than a year	Intra-subject, unilateral cross-over, one leg performed SE, and the contralateral the CE	EE was performed 1 h after breakfast (1.01 g CHO/kg BM, 0.31 g protein/kg BM, and 0.24 g fat/kg BM), SE was performed 3 h after lunch (2.02 g CHO/kg BM, 0.62 g protein/kg BM, and 0.49 g fat/kg BM)	Baseline, 15 min and 3 h after SE	SE Unilateral leg-press and leg-extension, 2 × 7 each at maximal effort	~42 min, 40 min unilateral cycling ergometer at 70% of W_{\max} , then workload was increased by 20 W until exhaustion	EE→SE	Performing SE 6 h after EE did not compromise signaling of mTOR-related proteins
Babcock et al. [32]	Recreationally active, college-aged males, EE 2×/week and SE 2×/week for >3 months	Intra-subject, unilateral cross-over, one leg performed SE, and the contralateral the CE	Experimental sessions were performed 2 h after subjects received standardized breakfast (500 kcal: 90–100 g of carbohydrates, 8–12 g of protein, and 4–8 g of fat)	Baseline, 96 h after exercise regimens	4 × 10 unilateral leg-extension at 75% of IRM followed by unilateral leg-press 4 × 10 at the same intensity 75%.	90 min of cycle ergometer exercise at 60% of W_{\max}	10 min	CE attenuates the satellite cell response to SE alone, and does so by preferentially blunting increases in MHC I satellite cell content

Coffey et al. [30]	Regular CT (>3×/week)	Randomized cross-over, all the participants performed two CT experimental sessions	Experimental sessions were performed after 10-h overnight fasting	Baseline, 0, 15 min and 3 h after sessions	8×5 at 80%, leg-extension exercise	10×6 s, all-out sprints, cycling ergometer against 0.75 Nm torque $^{-1}$ kg $^{-1}$	15 min	Both orders were performed	Repeated sprints impair anabolic response induced by SE and enhance catabolic responses
Coffey et al. [31]		Randomized cross-over, all participants performed two CT experimental sessions	Experimental sessions were performed after 10-h overnight fasting	Baseline, 0, 15 min and 3 h after sessions	8×5 at 80% of 1RM, leg-extension exercise	30 min at 70% of $\dot{V}O_{2\text{peak}}$, cycling ergometer	15 min	Both orders were performed	CE produce suboptimal signaling responses associated with single mode exercises
Wang et al. [33]	Recreationally active	Randomized cross-over, all participants completed the two experimental sessions	Experimental sessions were performed after 12-h overnight fast	Baseline, 1 and 3 h after exercise	6 sets at 70, 75, 80, 80, 75, 70% of 1RM. Participants were oriented to complete maximal reps as possible up to 15 on the leg-press exercise	60 min continuous cycling at 65% $\dot{V}O_{2\text{max}}$ (3-min rest allowed after 30 min)	15 min	EE→SE	Performing SE after EE augmented signaling of mitochondrial biogenesis
Pugh et al. [35]	Healthy untrained males	Counterbalanced cross-over design	2 h prior the experimental sessions, a breakfast was provided (1803 kJ, 55% carbohydrate; 29% fat and 16% protein)		4×8 at 70% of 1RM on leg-extension exercise	10×1 min at 90% HR_{max}	2 min after the last SE set	SE→EE	CE utilizing low volume and high intensity EE does not attenuate anabolic protein signaling and mRNA expression, or exacerbates marker of protein breakdown in fed state

(continued)

Table 8.1 (continued)

Study	Training status	Study design	Nutrient availability	Sampling time	Exercise regimens	Recovery between exercise	CT order	Conclusions
Donges et al. [39]	Sedentary middle-aged men	Randomized cross-over, all participants completed three experimental sessions, SE, however, CE comprised 50% volume of SE and EE alone	Sessions were performed after 10-h overnight fast and subjects received 20 g of whey protein immediately after the experimental session	Baseline, 1 and 4 h after exercise	SE EE 40 min of continuous cycle ergometer at 55% of $\dot{V}O_{2\text{peak}}$ or 20-min for CE	None	SE→EE	When providing 20 g of whey protein immediately after the training sessions, CE performed with 50% less training volume is effective as SE stimulating both myofibrillar and mitochondrial protein synthesis fractions
Apro et al. [43]	Moderately trained male	Randomized cross-over, all participants completed three experimental sessions	Sessions were performed after ~10.5 h overnight fast	Baseline, 1 h and 3 h after	10 × 10 on leg-press exercise (4 × 10 at 85% of IRM, 4 × 12 at 75% of IRM, and two sets to failure at 65% of IRM	30 min at 70% of $\dot{V}O_{2\text{max}}$	EE→SE	EE-induced elevation in AMPK does not blunt anabolic signalling pathway after subsequent SE

Table 8.1 (continued)

Carrithers et al. [38]	Moderately active	Intra-subject, unilateral cross-over, one leg performed SE, and the contralateral the CE	Sessions were performed after 10.5–14.5 h overnight fast	Baseline, immediately and 3 h after exercise, unilateral leg-press and leg extension, and a fourth set to failure	3×10 at 80% of 1RM for each exercise, unilateral leg-press and leg extension, and a fourth set to failure	90 min at 60% of their peak power while maintaining a cadence of 60 rpm.	30 min	EE→SE	While it was reported that CE does not suppress post-SE myofibrillar protein synthesis. There were no differences across time and conditions, which may suggest that exercise stimulus was not sufficient to alter the protein turnover
Lambert et al. [37]	Overweight/obese individuals	Parallel group repeated measures design with acute and chronic assessments, where each group performed one of three acute sessions: SE, CE, and CE aquatic which EE was performed in aquatic treadmill	Sessions were performed after 12 h overnight fast	Baseline and 24 h after exercise	3×12 at 60% of 1RM for each exercise, leg-press, leg-curl, and leg-extension	Time to complete 250 kcal at 60% of $\dot{V}O_{2\max}$	None	SE→EE	CE utilizing aquatic treadmill elicited greater myofibrillar protein synthesis responses compared to SE and conventional CE (i.e., EE performed on land treadmill)

SE strength exercise, EE endurance exercise, CE concurrent exercise, BM body mass, CHO carbohydrate, W Watts, W_{\max} peak power output, IRM one repetition maximum, $\dot{V}O_{2\max}$ peak oxygen uptake, $\dot{V}O_{2\max}$ maximum oxygen uptake, $\dot{V}O_{2\max}$ maximum heart rate, KJ kilojoules

session, the athletes underwent their typical exercise regimen. In the following session, they switched, undertaking the unfamiliar exercise regimen. The authors found that AMPK^(Thr172) phosphorylation increased after EE in strength-trained but not in endurance-trained individuals. On the other hand, AMPK^(Thr172) and p70S6K^(Thr389) increased after SE in the endurance athletes but not in strength-trained individuals [28]. It is important to point out that AMPK has been elevated after SE in untrained individuals [29]. This suggests that AMPK may not be exclusively activated by EE. Therefore, the main takeaway is that training background diminishes sensitivity to specific molecular responses associated with single mode exercise.

Regarding acute molecular responses to concurrent strength and endurance exercises (CE), conflicting results have been observed. While previous research has demonstrated that CE can decrease the anabolic signaling pathways and myogenic factors when compared to SE [30–32], other studies have demonstrated that CE produced similar and/or favorable responses on endurance [33] and anabolic signaling pathways [34–36] and on MPS [37–39].

For example, Lundberg et al. [36] found favorable results on selected gene expression and protein signaling after CE compared to SE in recreationally active males. They reported that PGC-1 α and VEGF (i.e. an angiogenic factor) gene expression were higher in CE compared to SE. Regarding gene expression of MuRF-1 and Atrogin-1 that are considered to be the major modulators of MPB. While, MuRF-1 demonstrated a similar decrease across conditions. Atrogin-1 decreased over time only in CE. Myostatin, which inhibits protein synthesis demonstrated lower mRNA levels in CE. The authors also reported favorable results in mTOR-p70SK6 axis. There was a significant exercise effect, in which mTOR^(Ser2448) and p70S6K^(Thr389) phosphorylation were higher in CT. These findings are well in line with previous studies and suggest that a bout of CE can increase anabolic signaling pathways in an acute setting [34] with higher or no suppression on MPS [37–39].

Nevertheless, some researchers have pointed out an important and inherent limitation when comparing the results of studies that have investigated single mode exercise versus CE [7]. Those authors stated that CE often has imposed a greater contractile stimulus to the skeletal muscle as during a CE session typically more work is performed by combining the two single mode exercises [7]. This additional work may stimulate protein signaling and MPS to a greater extent compared to single mode exercises. In order to address this issue, Donges and colleagues [39] had sedentary middle-aged men to perform single modes of SE and EE, as well as a CE session, which had 50% less volume than each single mode exercise session (i.e., all sessions were matched for volume). The authors found differences in protein signaling that may indicate favorable responses to SE. They also reported that mitochondrial protein synthetic rate increased in a similar fashion between the three exercise regimens. In addition, MPS was similar for both SE and CE and they were both greater than in EE alone [39]. However, one important factor to consider is that the participants consumed 20 g of whey protein isolate immediately after exercise. This was done in order to maximize the anabolic potential in response to exercise regimens. However, this makes it impossible to verify if CE and SE sessions modulated protein synthetic responses in a different fashion.

The above-mentioned contention is supported by different evidences: (1) studies have demonstrated that 20 g of protein is sufficient to maximize MPS after SE [40, 41], and (2) it has been demonstrated that whey protein ingestion after CE produced greater MPS and attenuated markers of MPB compared to CE + placebo [42]. In addition, other studies that have investigated the effects of CE on protein synthetic responses did not provide conclusive findings. For example, when EE comprised aquatic treadmill and the work performed was the double than SE alone (i.e., 500 vs. 250kcal, respectively), MPS favored to CE in overweight/obese individuals [37]. Another study suggested that MPS after CE was not suppressed when compared to SE, as both regimens demonstrated similar rates of protein synthesis. Nonetheless, neither exercise regimen demonstrated significant increases in MPS compared to baseline [38], further suggesting that the exercise regimens did not produce enough strain to stimulate anabolic responses. Therefore, more research needs to be done assessing the effects of CE and SE on protein synthetic responses before any general conclusions can be drawn.

On the other hand, some studies have suggested that CE may attenuate acute anabolic signaling and myogenic responses [30–32]. While this data may suggest some acute interference, it is important to point out that studies demonstrating that are limited [30–32]. Coffey et al. [30] submitted recreationally trained individuals to perform two different orders of CE (i.e., SE→EE and EE→SE). In general, the authors reported modest changes in protein signaling phosphorylation regardless of the exercise order. However, p70S6K^(Thr389) was elevated to the greatest extent when the strength bout was performed before sprints bouts. The authors also investigated the selected genes associated with myogenesis and proteolysis activity. The gene expression of insulin-like growth factor I (IGF-I) and MyoD did not demonstrate any order effects other than an inhibited gene expression of IGF-1. In regard to the marker of proteolysis, Atrogin-1 demonstrated no significant differences, whereas MuRF-1 gene expression was elevated 3-h post the CE regardless of the exercise order [30]. In another study, the authors also found results that suggested some acute interference. They observed a significant reduction in the mTOR^{Ser2448} phosphorylation levels when EE was performed after SE, but not in the opposite order [31].

These findings from Coffey and colleagues [30, 31] suggest that EE hampered anabolic signaling pathways in response to SE. Furthermore, it seems that CE exacerbates proteolytic gene expression in the acute fashion in recreational trained individuals. These two studies performed by Coffey et al. [30, 31] demonstrate strong ecological validity (i.e., real-world generalizability) as the study design represents well how different athletes and trained individuals perform CE. However, these studies also have inherent limitations: The lack of a positive control condition (i.e., strength exercise alone) makes it difficult to conclude whether CE produced interference on the translational signaling pathways and proteolytic markers. Moreover, analyzing selected mRNA expression may not reflect the protein levels in response to CE. Although nutrient availability might be a potential candidate for the outcomes reported by the authors, there is conflicting evidence from other studies [43, 44]. These studies involved trained participants performing CE after 9–10 h of fasting, and they did not report negative effects on anabolic signaling pathways [43, 44].

Other potential mediators in the molecular adaptations to exercise are satellite cells. Satellite cells function as donors of new myonuclei for the muscle fiber and are considered to be myogenic precursors. They play an important role in muscle regeneration, repair and possibly also aid in muscle hypertrophy as a response to ST [45]. In fact, one study has demonstrated that those individuals considered high responders for muscle fiber hypertrophy demonstrated a greater satellite cell number after the training period [46].

To date, only one study has investigated the acute effects of CE on satellite cells [32]. Babcock et al. [32] submitted recreationally active individuals to different exercise regimens. While SE increased satellite cell density more than CE in type II muscle fibers. It is important to mention that the elevated baseline satellite cell count for CE may have decreased the potential for additional increases following CE. However, satellite cells increased by 46% after SE, 7% after EE, and 8% after CE in muscle fiber type I. These results are interesting, as it has been consistently demonstrated that the interference effect at a morphological level (i.e., muscle hypertrophy) occurred primarily among muscle fiber type I [3, 4, 47]. In addition, the findings by Babcock et al. [32] suggested that the addition of ET suppressed the increase of satellite cells induced by SE. Again, this should be interpreted cautiously as EE alone might activate satellite cells for muscle remodeling as well [48, 49]. Thus, more studies are necessary in order to elucidate the effects of CE on satellite cells activation.

In light of incongruences in study designs, the anabolic molecular responses seem to be very similar between SE and CE. Furthermore, AMPK downregulating mTORC1 has been consistently demonstrated in animal models [25, 26]. However, the proposed hypothesis for the interference effect at the molecular level in which AMPK switches off mTORC1 has not been confirmed in human studies. In fact, studies have demonstrated that increases in AMPK phosphorylation induced by EE did not blunt mTORC1-signaling pathway or MPS responses [43]. In addition, satellite cells and markers of MPB emerge as potential factors explaining the acute molecular interference in CE. However, only one study has investigated the effects of SE and CE on satellite cells population. Also, scrutinizing mRNA expression may not be representative of protein content and it is difficult to differentiate whether those changes are associated with MPB or greater protein turnover. Although these acute studies have shed some light on the variation of molecular responses to CE, it remains unclear on how this may translate to chronic molecular and morphological adaptations induced by CE.

Chronic Molecular Adaptations to Concurrent Training

Chronic adaptations to ST and ET are likely a result of cumulative changes in gene expression, acute signaling, and protein synthesis/breakdown. This ultimately leads to changes in the phenotype, morphology, and functionality of skeletal muscle [5, 6, 50–52]. Even though skeletal muscle displays a remarkable ability to adapt to different exercise stimuli, it has been demonstrated that CT may negatively affect the adaptations induced by ST in isolation (i.e., muscle hypertrophy, strength, and power) [3,

4, 53–56]. From a molecular standpoint, it has been suggested that the conflicting adaptations are a result of distinct signaling responses induced by ST and ET [26, 57, 58] (Fig. 8.1). As previously mentioned, the signaling cascade activated by ET can inhibit the anabolic stimulus of ST compromising long-term adaptations induced by ST. While the number of studies investigating the acute responses to concurrent exercise are low, there are even fewer studies available on the chronic effects of CT [34, 36, 37, 56, 59–61]. Additionally, there are significant differences in the chronic experimental designs, which should be taken into account when attempting to make comparisons between investigations (Table 8.2). Nevertheless, this section will address the methodological differences between these studies and extrapolate the chronic effects of CT on molecular adaptations and morphological changes based off of a comprehensive analysis of the available literature on the topic.

Regarding the molecular makers associated with ET adaptations, one study found no significant changes on PGC-1 α and VEGF mRNA expression after 5 weeks of CT and ST [62]. On the other hand, another study from the same researchers reported that after 5 weeks of training, CT induced a significant reduction on PGC-1 α mRNA expression. In addition, VEGF mRNA expression was higher in CT than ST [34]. There may be some methodological discrepancies that could explain the different findings in these investigations. First off, mRNA is relatively short-lived and unstable, and Lundberg et al. [62] performed the muscle biopsies 72 h after the last training session that may have diminished the ability to detect significant changes on those selected genes [63]. Conversely, Fernandez-Gonzalo et al. [34] performed muscle biopsies 3 h post ST regimen, nevertheless there was a significant group effect (i.e., CT greater than ST) probably because of the higher levels of PGC-1 α at baseline for CT regimen.

In addition, PGC-1 α mRNA increased in response to ET, ST, and CT regimens, while PGC-1 α 4 increased only after ST and CT. Moreover, CT demonstrated the greatest increase in PGC-1 α 4 compared to all the other groups [60]. These results suggest that other PGC-1 α isoforms might be associated with the long-term adaptations induced by CT. Different from PGC-1 α that is associated with mitochondrial changes inducing oxidative capacity improvements, PGC-1 α 4 is associated with increases in muscle size [60, 64]. Therefore, more research is necessary in order to elucidate the role of different PGC-1 α isoforms on exercise-induced adaptation.

Another issue that limits our understanding on molecular adaptations to CT is that only a few studies have compared the long-term effects of CT to ET in isolation on protein signaling responses. We [59] investigated the effects of ST, ET, and CT on basal AMPK^(Thr172) phosphorylation [59]. After 8 weeks of training, the intermittent ET regimen was the only group to demonstrate significant increases in AMPK^(Thr172) when compared to baseline levels. On the other hand, Wilkinson et al. [52] reported that after 10 weeks of either continuous ET or ST in isolation, both training regimens increased AMPK^(Thr172). However, AMPK^(Thr172) returned to baseline levels 4 h later on both regimens. Importantly, ET was the only group that significantly increased mitochondrial protein synthetic rates above resting values. In agreement with the acute data, those results suggest that AMPK^(Thr172) might not be specific to exercise modalities [65].

Table 8.2 Summary of study designs that investigate the chronic molecular and morphological adaptations to concurrent training

Study	Training status	Study design	Nutrient availability	Sampling time	Training regimens	Recovery between regimens	Conclusions
Lundborg et al. [62]	Recreationally trained involved in team sports activities	Intra-subject, unilateral repeated measures design, one leg	Biopsies were performed 2 h after subjects receiving a standardized breakfast.	Pre-training, 72 h after the last training session	ST 2 days/ week—12 sessions: 4 × 7 at unilateral knee extensions in the flywheel ergometer at maximal effort	CT Only as part of CT regimen: continuous ~42 min, 40 min unilateral cycling ergometer at 70% of V_{max} , then workload was increased by 20 W until exhaustion	5 weeks of CT and ST produced similar molecular adaptations on markers of ET adaptation and protein breakdown. Muscle volume increase was greater in CT regimen than ST. Muscle fiber CSA increase was not different between CT and ST.

Fernandez-Gonzalo et al. [34]	Recreationally trained individuals involved in team sports activities	Intra-subject, unilateral repeated measures design, one leg performed ST, and the contralateral the CT regimen. Five weeks training period	EE was performed 1 h after breakfast (1.01 g CHO/kg BM, 0.31 g protein/kg BM and 0.24 g fat/kg BM), SE was performed 3 h after lunch (2.02 g CHO/kg BM, 0.62 g protein/kg BM and 0.49 g fat/kg BM)	Pre-training and 3 h after the last training session. Pre-test biopsies were performed prior ST, 6 h after completion of ET	2 days/week—12 sessions: 4 × 7 at unilateral knee extensions in the flywheel ergometer at maximal effort	Only as part of CT regimen: continuous ~42 min, 40 min unilateral cycling ergometer at 70% of W_{max} then workload was increased by 20 W until exhaustion	3 days/week—15 sessions. ET followed by ST	6 h	5-week training blunts the overall interference of greater anabolic response observed in acute fashion after CT in untrained muscle, which suggests that ET acts synergistically with ST only during short-term training.
Ruas et al. [60]	Sedentary	Parallel group repeated measures design. Participants were randomly assigned to C, ET, ST, or CT groups. Eight weeks training period	Not mentioned	Pre-training, 48 h after the last training session	Whole body routine, (week-1, light-weight, 4 days/week), (week-2, 2 × 8–10RM, 4 days/week), (week-3, 3 × 8–10RM, 4 days/week), (week 4–8, 4 × 8–10RM, 4 days/week)	Continuous stationary cycling at 65% of $\dot{V}O_{2\text{max}}$, (week-1, 30 min, 3 days/week), (week-2, 45 min, 4 days/week), (week 3–8, 60 min 5 days/week)	Not mentioned	8 weeks of CT augments mRNA gene expression associated with muscle size (e.g., PGC1α4) compared to ST and ET.	

(continued)

Table 8.2 (continued)

Study	Training status	Study design	Nutrient availability	Sampling time	Training regimens	Recovery between regimens	Conclusions
Lambert et al. [37]	Overweight/obese individuals	Parallel group repeated measures design.	Sessions were performed after 12 h overnight fast	Baseline and 24 h after exercise	ST Whole body routine, 2 days/week. Week 1–6, 3 × 12 at 60% of 1RM. Week 8–12, 3 × 8 at 75% of 1RM.	CT Only as part of CT regimens. 3 days/week Continuous exercise Week 1–6, 250 kcal at 60–85 of $\text{VO}_{2\text{max}}$. Week 8–12, 500 kcal at 85% of $\text{VO}_{2\text{max}}$.	None Progression of the ET and ST was the same. However, CT regimens performed three sessions of ET. ST was performed followed by ET regimes

De Souza et al. [59] and De Souza et al. [56]	Recreationally active individuals involved in team sports activities	Parallel group repeated measures design. Participants were randomly assigned to C, ET, ST, and CT groups. Eight weeks training period	Biopsies were performed 2 h after subjects receiving a standardized breakfast, (~311 kcal; 63.5% CHO, 21.8% protein, and 14.7% fat	Baseline and 48 h after exercise	Lower body routine (leg-press, knee extension and knee-flexion. 2 days/week.	Interval training, week 1–2: 20 × 1 min at 80 of $\nu\text{VO}_{2\text{max}}$, week 3–4: 20 × 1 min at 85–90% of $\nu\text{VO}_{2\text{max}}$, week 5–6: 20 × 1 min at 95% of $\nu\text{VO}_{2\text{max}}$, week 7–8: 20 × 1 min at 95–100% of $\nu\text{VO}_{2\text{max}}$

(continued)

Table 8.2 (continued)

Study	Training status	Study design	Nutrient availability	Sampling time	Training regimens	Recovery between regimens	Conclusions
Lundberg et al. [66]	Moderately trained involved in recreational team sports activities	Intra-subject, unilateral repeated measures design, one leg	Biopsies were performed 2 h after subjects receiving a liquid formula (1.01 g carbohydrates/kg bw, 0.31 g protein/kg bw, and 0.24 g fat/kg bw). The liquid formulas contained 6.3 g protein (0.55 g leucine), 20.2 g carbohydrates, and 4.9 g fat per 100 ml	Baseline, 3 h after the first training session, 72 h after last training session	ST 2 days/ week—12 sessions: 4 × 7 at knee extensions in the flywheel ergometer at maximal effort	Only as part of CT regimen: continuous ~42 min, 40 min unilateral cycling ergometer at 70% of W_{\max} , then workload was increased by 20 W until exhaustion	3 days/ week—15 sessions. ET followed by ST CT 15 min

	Fyfe et al. [61]	Recreationally involved in endurance and/or strength training at least twice a week for >30 min	Parallel group repeated measures design Participants were randomly assigned to HIT+ST, MICT+ST, or ST groups.	Biopsies were performed overnight fast	Baseline and 1 and 3 h after first and last training session	3 days/week—24 sessions: $3-4 \times 4-14RM$ at ~65–90% of 1RM whole-body routine- 3 lower body exercise per training session (e.g., day 1 and MICT+ST, or ST groups. Eight weeks training period	Only as part of CT regimen: HIT: 5–10 × 2 min intervals at 120–150 of lactate threshold; MICT: 15–33 min at 80–100% of lactate threshold	3 days/week. Two concurrent training regimes (HIT and MICT). ET followed by ST	10 min	8 weeks of CT regimens favored adaptations on selected molecular markers indicating ribosome biogenesis and translational capacity. However, CT diminished chronic anabolic signaling and produced interference on muscle fiber CSA type I development.
--	---------------------	---	---	--	--	--	--	---	--------	---

ST strength training. ET endurance training. CT concurrent training. C control. CHO carbohydrate, BM body mass. W Watts, W_{\max} peak power output, $VO_{2\max}$ maximum oxygen uptake, CSA cross-sectional area, $VO_{2\max}$ maximum oxygen uptake, LTM land-treadmill, ATM aquatic-treadmill, MICT moderate-intensity continuous training

Nevertheless, the great debate is whether the AMPK-Akt switch hypothesis explains the chronic interference effect, and how CT and ST influence molecular parameters that control MPS and MPB. Currently, the chronic studies have demonstrated similar effects of ST and CT on AMPK phosphorylation levels [59, 61, 66]. Interestingly, different CT regimens produced an interference in ST-induced adaptations regardless of ET intensity employed (i.e., continuous or intermittent). The ST demonstrated the greatest AMPK activation compared with CT regimens after the last training session. Which suggests that rather than placing more energy stress on the muscle cell, chronic CT would allow muscles to be less susceptible to energy homeostasis perturbation induced by exercise [61]. While it is attractive to rule out that AMPK may help explain the interference effect, more evidence on how AMPK would respond during CT-induced interference effect are indeed warrant. To date, it is important to note that AMPK switching off mTORC1 has not been confirmed in chronic CT studies even when interference effect was reported [61].

In addition, the chronic studies, which have investigated the effects of CT on molecular and morphological adaptations have demonstrated that CT can enhance [34, 37, 62, 66], blunt [56], or produce a similar magnitude of muscle hypertrophy [59]. Importantly, as only few studies have investigated the chronic effect of CT on anabolic and MPB markers [34, 56, 60, 62], no clear pattern emerges in regard to the chronic molecular adaptations. Interestingly, while studies have suggested that CT can be more “catabolic” in an acute fashion [30], some chronic training studies have not confirmed this [34, 62]. For example, CT regimen was the only condition to demonstrate significant reductions in gene expression associated with protein breakdown, whereas ST regimen was the only one to demonstrate a significant reduction on Myostatin gene expression [34]. In fact, the effects of CT on Myostatin gene expression are scarce and controversial. For example, Lundberg and colleagues [62] did not report any significant changes on Myostatin levels. Similarly, our own study [56] also failed to report significant changes in Myostatin mRNA levels after 8 weeks of CT and ST. However, the SMAD-7 mRNA that negatively modulates the Myostatin gene expression significantly increased in both training regimens [56]. Ruas and colleagues [60], on the other hand, found that Myostatin mRNA expression was reduced only in ST and CT groups. Notwithstanding Myostatin is an important negative regulator of muscle mass, it is noteworthy to mention that Myostatin cannot differentiate muscle hypertrophy levels in humans [67]. Further studies are required in order to elucidate the long-term effects of CT and ST on proteolytic markers. The differences between protocols and the lack of data limit our understanding of the molecular markers that are associated with MPB in humans.

In regard to the chronic effects of CT on anabolic responses, the studies have demonstrated conflicting results as well [34, 37, 59]. Lambert et al. [37] is the only study that investigated the long-term effects of CT and ST on MPS. These researchers submitted overweight/obese individuals to three different training regimens. One CT group performed ST combined with ET on land treadmill (ST + LTM), while another CT group performed ST combined with ET on aquatic treadmill (ST + ATM), and the third group consisted of single mode ST. After a 12-week

training period, ST + ATM demonstrated the highest mean for myofibrillar protein synthetic rate, but no significant differences between groups. In addition, ST + ATM demonstrated the greatest lean body mass gains when compared to other two groups. Furthermore, Fernandez-Gonzalo et al. [34] did not report within or between groups on selected anabolic protein signaling (e.g., mTOR^{Ser2448}, rp6^{Ser235/236}, eEF2^{Thr56}), while p70S6^{Thr389} increased in similar fashion in CT and ST regimens. As part of this study was published elsewhere, the authors also reported that the CT leg demonstrated greater increases in muscle volume (i.e., CT: 13.6; ST: 7.8%) and muscle fiber cross-sectional area (i.e., CT: 17.0%; ST: 9.0%) [62]. Collectively, those studies provide evidence that CT might produce an additional effect on muscle hypertrophy with similar molecular adaptations between regimens.

Conversely, two other studies combined suggest that ST favors muscle hypertrophy and CT induced a down-regulation in the basal phosphorylation of Akt/mTORC1/p70S6K [56, 59]. De Souza et al. [59] reported that ST and CT increased p70S6K protein content. In addition, they found a significant group by time interaction which the ST group was the only group to increase basal Akt^(Ser473) and demonstrated a strong trend to towards significant p70S6K^(Thr389) phosphorylation. In the second study using the same sample, the authors found that ST was the only group that significantly increased cross-sectional area of type I and IIA, whereas the CT blunted muscle hypertrophy across the whole spectrum of fibers [56]. These two studies suggest that the interference effect might be associated with down-regulation of Akt/mTORC1/p70^{S6K} signaling cascade.

These outcomes should be cautiously interpreted. In fact, some studies have demonstrated that ET can activate anabolic signaling pathways and MPS, specifically with cycling ergometer exercise in untrained individuals [68–71]. In addition, one review reported that several studies found significant increases in muscle size after ET utilizing a cycling ergometer modality in untrained individuals [64]. Interestingly, the studies that have demonstrated favorable chronic adaptations to CT were in untrained and/or physically active participants and it was used cycling ergometer modality [34, 62, 66]. Due to the subject's low training status, they are more sensitive to activate anabolic signaling pathways and demonstrated longer MPS responses [28]. Therefore, adding this ET stimulus with a greater resistance component to their short-term and low-volume ST scheme can make these CT regimens more anabolic than performing ST alone. Another important factor to be considered is the exercise mode, while it remains to be determined, evidence has suggested that ET performed with treadmill can be more detrimental to muscle hypertrophy during CT [72]. Even though Lambert et al. [37] used treadmill mode, they reported that utilizing the aquatic-treadmill exercise demonstrated greater acute MPS than the land treadmill. This culminated in greater lean body mass in the aquatic-treadmill group after the CT period. This is likely due to the increased resistance and reduced fatigue of the ATM modality. On the contrary, higher intensity interval training performed with the standard land treadmill demonstrated lower basal anabolic signaling which culminated in blunted muscle hypertrophy [56, 59].

However, an elegant study performed by Fyfe et al. [61] partially corroborates with the aforementioned findings. These authors were the first to investigate ribosome

biogenesis markers (i.e., gene expression and RNA content), and anabolic signaling in response to ST and CT regimens performed on a cycle ergometer in trained individuals. In a scenario which CT regimens produced attenuation in muscle fiber type I hypertrophy. The selected acute and chronic changes indicating ribosome biogenesis and translational capacity favored CT regimens regardless of the intensity (i.e., continuous and high-intensity). Nevertheless, the anabolic signaling in response to last training session was different. For example, mTOR phosphorylation was increased post-1 h only in ST and it was increased post-3 h only in the CT regimen which used high intensity ET. Still, changes in p70S6K^{Thr389} and rps6^{Ser235/236} were greater for ST when compared with both CT regimens. These findings suggest that (1) there is a disconnect between makers of ribosome biogenesis/translational efficiency and muscle fiber hypertrophy, (2) the chronic repetition of the training stimulus may allow skeletal muscles to be more mode-specific, and (3) CT performed on cycle ergometer can impair training-induced muscle hypertrophy even in individuals who were undergoing ST and/or ET for at least 1 year prior the beginning of the study.

Summary

In conclusion, the molecular basis of CT and the interference effect are incompletely depicted, which may be attributed to limitations/differences on previous investigations. Accordingly, all the disparities between study designs make the understanding of the molecular basis that control muscle hypertrophy in response to CT complex. In addition, it has been neglected that even for a high volume, frequency, and intensity CT regimen, it took 7–8 weeks to observe any interference effect [5]. Therefore, chronic studies aiming to scrutinize the effects of CT on molecular responses and the interference effect need to be longer in duration. Since we do not have convincing evidence supporting AMPK as a key factor regulating the interference effect, chronic studies should search for alternative pathways that may hamper myofibrillar protein synthesis when one undergoes CT. For example, the sirtuin family of NAD⁺-dependent deacetylases (SIRT) and Ca2+/calmodulin-independent kinase II (CaMKII) can inhibit anabolic signaling pathways as well. In addition, advances in technology that allow researchers to investigate specific protein synthetic rates of contractile proteins (i.e., actin and myosin) are required to depict a better picture of the different anabolic training effects and to draw more specific conclusions. Those concerns suggest that further mechanistic studies are warranted to maximize the benefits of CT for special populations and to avoid the interference effect for athletic population.

References

1. Fluck M, Hoppeler H. Molecular basis of skeletal muscle plasticity—from gene to form and function. *Rev Physiol Biochem Pharmacol.* 2003;146:159–216. PubMed PMID: 12605307. Epub 2003/02/28

2. Stefanetti RJ, Lamon S, Wallace M, Vendelbo MH, Russell AP, Vissing K. Regulation of ubiquitin proteasome pathway molecular markers in response to endurance and resistance exercise and training. *Pflugers Arch.* 2015;467(7):1523–37. PubMed PMID: 25104573. Epub 2014/08/12
3. Kraemer WJ, Patton JF, Gordon SE, Harman EA, Deschenes MR, Reynolds K, et al. Compatibility of high-intensity strength and endurance training on hormonal and skeletal muscle adaptations. *J Appl Physiol* (1985). 1995;78(3):976–89. PubMed PMID: 7775344. Epub 1995/03/01
4. Putman CT, Xu X, Gillies E, MacLean IM, Bell GJ. Effects of strength, endurance and combined training on myosin heavy chain content and fibre-type distribution in humans. *Eur J Appl Physiol.* 2004;92(4–5):376–84. PubMed PMID: 15241691. Epub 2004/07/09
5. Hickson RC. Interference of strength development by simultaneously training for strength and endurance. *Eur J Appl Physiol Occup Physiol.* 1980;45(2–3):255–63. PubMed PMID: 7193134. Epub 1980/01/01
6. Coffey VG, Hawley JA. The molecular bases of training adaptation. *Sports Med.* 2007;37(9):737–63. PubMed PMID: 17722947. Epub 2007/08/29
7. Coffey VG, Hawley JA. Concurrent exercise training: do opposites distract? *J Physiol.* 2017;595(9):2883–96. PubMed PMID: 27506998. Pubmed Central PMCID: PMC5407958. Epub 2016/08/11
8. Egan B, Hawley JA, Zierath JR. SnapShot: exercise metabolism. *Cell Metab.* 2016;24(2):342–e1. PubMed PMID: 27508878. Epub 2016/08/11
9. Egan B, Zierath JR. Exercise metabolism and the molecular regulation of skeletal muscle adaptation. *Cell Metab.* 2013;17(2):162–84. PubMed PMID: 23395166. Epub 2013/02/12
10. Phillips SM, Parise G, Roy BD, Tipton KD, Wolfe RR, Tamopolsky MA. Resistance-training-induced adaptations in skeletal muscle protein turnover in the fed state. *Can J Physiol Pharmacol.* 2002;80(11):1045–53. PubMed PMID: 12489923. Epub 2002/12/20
11. Nader GA. Molecular determinants of skeletal muscle mass: getting the “AKT” together. *Int J Biochem Cell Biol.* 2005;37(10):1985–96. PubMed PMID: 16125108. Epub 2005/08/30
12. Bodine SC. mTOR signaling and the molecular adaptation to resistance exercise. *Med Sci Sports Exerc.* 2006;38(11):1950–7. PubMed PMID: 17095929. Epub 2006/11/11
13. Bodine SC, Stitt TN, Gonzalez M, Kline WO, Stover GL, Bauerlein R, et al. Akt/mTOR pathway is a crucial regulator of skeletal muscle hypertrophy and can prevent muscle atrophy in vivo. *Nat Cell Biol.* 2001;3(11):1014–9. PubMed PMID: 11715023. Epub 2001/11/21
14. Holloszy JO. Regulation by exercise of skeletal muscle content of mitochondria and GLUT4. *J Physiol Pharmacol.* 2008;59 Suppl 7:5–18. PubMed PMID: 19258654. Epub 2009/03/11
15. Hood DA. Mechanisms of exercise-induced mitochondrial biogenesis in skeletal muscle. *Appl Physiol Nutr Metab.* 2009;34(3):465–72. PubMed PMID: 19448716. Epub 2009/05/19
16. Hood DA, Uggucioni G, Vainshtein A, D’Souza D. Mechanisms of exercise-induced mitochondrial biogenesis in skeletal muscle: implications for health and disease. *Compr Physiol.* 2011;1(3):1119–34. PubMed PMID: 23733637. Epub 2011/07/01
17. Baar K. Using molecular biology to maximize concurrent training. *Sports Med.* 2014;44 Suppl 2:S117–25. PubMed PMID: 25355186. Pubmed Central PMCID: PMC4213370. Epub 2014/10/31
18. Jornayvaz FR, Shulman GI. Regulation of mitochondrial biogenesis. *Essays Biochem.* 2010;47:69–84. PubMed PMID: 20533901. Pubmed Central PMCID: PMC3883043. Epub 2010/06/11
19. Irrcher I, Adhiketty PJ, Joseph AM, Ljubicic V, Hood DA. Regulation of mitochondrial biogenesis in muscle by endurance exercise. *Sports Med.* 2003;33(11):783–93. PubMed PMID: 12959619. Epub 2003/09/10
20. Hawley JA. Molecular responses to strength and endurance training: are they incompatible? *Appl Physiol Nutr Metab.* 2009;34(3):355–61. PubMed PMID: 19448698. Epub 2009/05/19
21. Baar K, Wende AR, Jones TE, Marison M, Nolte LA, Chen M, et al. Adaptations of skeletal muscle to exercise: rapid increase in the transcriptional coactivator PGC-1. *FASEB J.* 2002;16(14):1879–86. PubMed PMID: 12468452. Epub 2002/12/07

22. Jager S, Handschin C, St-Pierre J, Spiegelman BM. AMP-activated protein kinase (AMPK) action in skeletal muscle via direct phosphorylation of PGC-1alpha. *Proc Natl Acad Sci U S A.* 2007;104(29):12017–22. PubMed PMID: 17609368. Pubmed Central PMCID: PMC1924552. Epub 2007/07/05
23. Jorgensen SB, Richter EA, Wojtaszewski JF. Role of AMPK in skeletal muscle metabolic regulation and adaptation in relation to exercise. *J Physiol.* 2006;574(Pt 1):17–31. PubMed PMID: 16690705. Pubmed Central PMCID: PMC1817795. Epub 2006/05/13
24. Dasgupta B, Ju JS, Sasaki Y, Liu X, Jung SR, Higashida K, et al. The AMPK beta2 subunit is required for energy homeostasis during metabolic stress. *Mol Cell Biol.* 2012;32(14):2837–48. PubMed PMID: 22586267. Pubmed Central PMCID: PMC3416196. Epub 2012/05/16
25. Bolster DR, Crozier SJ, Kimball SR, Jefferson LS. AMP-activated protein kinase suppresses protein synthesis in rat skeletal muscle through down-regulated mammalian target of rapamycin (mTOR) signaling. *J Biol Chem.* 2002;277(27):23977–80. PubMed PMID: 11997383. Epub 2002/05/09
26. Atherton PJ, Babraj J, Smith K, Singh J, Rennie MJ, Wackerhage H. Selective activation of AMPK-PGC-1alpha or PKB-TSC2-mTOR signaling can explain specific adaptive responses to endurance or resistance training-like electrical muscle stimulation. *FASEB J.* 2005;19(7):786–8. PubMed PMID: 15716393. Epub 2005/02/18
27. Thomson DM, Gordon SE. Diminished overload-induced hypertrophy in aged fast-twitch skeletal muscle is associated with AMPK hyperphosphorylation. *J Appl Physiol* (1985). 2005;98(2):557–64. PubMed PMID: 15465886. Epub 2004/10/07
28. Coffey VG, Zhong Z, Shield A, Canny BJ, Chibalin AV, Zierath JR, et al. Early signaling responses to divergent exercise stimuli in skeletal muscle from well-trained humans. *FASEB J.* 2006;20(1):190–2. PubMed PMID: 16267123. Epub 2005/11/04
29. Dreyer HC, Fujita S, Cadena JG, Chinkes DL, Volpi E, Rasmussen BB. Resistance exercise increases AMPK activity and reduces 4E-BP1 phosphorylation and protein synthesis in human skeletal muscle. *J Physiol.* 2006;576(Pt 2):613–24. PubMed PMID: 16873412. Pubmed Central PMCID: PMC1890364. Epub 2006/07/29
30. Coffey VG, Jemiolo B, Edge J, Garnham AP, Trappe SW, Hawley JA. Effect of consecutive repeated sprint and resistance exercise bouts on acute adaptive responses in human skeletal muscle. *Am J Physiol Regul Integr Comp Physiol.* 2009;297(5):R1441–51. PubMed PMID: 19692661. Epub 2009/08/21
31. Coffey VG, Pilegaard H, Garnham AP, O'Brien BJ, Hawley JA. Consecutive bouts of diverse contractile activity alter acute responses in human skeletal muscle. *J Appl Physiol* (1985). 2009;106(4):1187–97. PubMed PMID: 19164772. Epub 2009/01/24
32. Babcock L, Escano M, D'Lugos A, Todd K, Murach K, Luden N. Concurrent aerobic exercise interferes with the satellite cell response to acute resistance exercise. *Am J Physiol Regul Integr Comp Physiol.* 2012;302(12):R1458–65. PubMed PMID: 22492813. Epub 2012/04/12
33. Wang L, Mascher H, Psilander N, Blomstrand E, Sahlin K. Resistance exercise enhances the molecular signaling of mitochondrial biogenesis induced by endurance exercise in human skeletal muscle. *J Appl Physiol* (1985). 2011;111(5):1335–44. PubMed PMID: 21836044. Epub 2011/08/13
34. Fernandez-Gonzalo R, Lundberg TR, Tesch PA. Acute molecular responses in untrained and trained muscle subjected to aerobic and resistance exercise training versus resistance training alone. *Acta Physiol (Oxf).* 2013;209(4):283–94. PubMed PMID: 24112827. Epub 2013/10/12
35. Pugh JK, Faulkner SH, Jackson AP, King JA, Nimmo MA. Acute molecular responses to concurrent resistance and high-intensity interval exercise in untrained skeletal muscle. *Physiol Rep.* 2015;3(4). PubMed PMID: 25902785. Pubmed Central PMCID: PMC4425969. Epub 2015/04/24
36. Lundberg TR, Fernandez-Gonzalo R, Gustafsson T, Tesch PA. Aerobic exercise alters skeletal muscle molecular responses to resistance exercise. *Med Sci Sports Exerc.* 2012;44(9):1680–8. PubMed PMID: 22460475. Epub 2012/03/31
37. Lambert BS, Shimkus KL, Fluckey JD, Riechman SE, Greene NP, Cardin JM, et al. Anabolic responses to acute and chronic resistance exercise are enhanced when combined with aquatic

- treadmill exercise. *Am J Physiol Endocrinol Metab.* 2015;308(3):E192–200. PubMed PMID: 25425002. Epub 2014/11/27
38. Carrithers JA, Carroll CC, Coker RH, Sullivan DH, Trappe TA. Concurrent exercise and muscle protein synthesis: implications for exercise countermeasures in space. *Aviat Space Environ Med.* 2007;78(5):457–62. PubMed PMID: 17539438. Epub 2007/06/02
39. Donges CE, Burd NA, Duffield R, Smith GC, West DW, Short MJ, et al. Concurrent resistance and aerobic exercise stimulates both myofibrillar and mitochondrial protein synthesis in sedentary middle-aged men. *J Appl Physiol (1985).* 2012;112(12):1992–2001. PubMed PMID: 22492939. Epub 2012/04/12
40. Moore DR, Robinson MJ, Fry JL, Tang JE, Glover EI, Wilkinson SB, et al. Ingested protein dose response of muscle and albumin protein synthesis after resistance exercise in young men. *Am J Clin Nutr.* 2009;89(1):161–8. PubMed PMID: 19056590. Epub 2008/12/06
41. Witard OC, Jackman SR, Breen L, Smith K, Selby A, Tipton KD. Myofibrillar muscle protein synthesis rates subsequent to a meal in response to increasing doses of whey protein at rest and after resistance exercise. *Am J Clin Nutr.* 2014;99(1):86–95. PubMed PMID: 24257722. Epub 2013/11/22
42. Camera DM, West DW, Phillips SM, Rerecich T, Stellingwerff T, Hawley JA, et al. Protein ingestion increases myofibrillar protein synthesis after concurrent exercise. *Med Sci Sports Exerc.* 2015;47(1):82–91. PubMed PMID: 24870574. Epub 2014/05/30
43. Apro W, Moberg M, Hamilton DL, Ekblom B, van Hall G, Holmberg HC, et al. Resistance exercise-induced S6K1 kinase activity is not inhibited in human skeletal muscle despite prior activation of AMPK by high-intensity interval cycling. *Am J Physiol Endocrinol Metab.* 2015;308(6):E470–81. PubMed PMID: 25605643. Epub 2015/01/22
44. Apro W, Wang L, Ponten M, Blomstrand E, Sahlin K. Resistance exercise induced mTORC1 signaling is not impaired by subsequent endurance exercise in human skeletal muscle. *Am J Physiol Endocrinol Metab.* 2013;305(1):E22–32. PubMed PMID: 23632629. Epub 2013/05/02
45. Blaauw B, Reggiani C. The role of satellite cells in muscle hypertrophy. *J Muscle Res Cell Motil.* 2014;35(1):3–10. PubMed PMID: 24505026. Epub 2014/02/08
46. Petrella JK, Kim JS, Mayhew DL, Cross JM, Bamman MM. Potent myofiber hypertrophy during resistance training in humans is associated with satellite cell-mediated myonuclear addition: a cluster analysis. *J Appl Physiol (1985).* 2008;104(6):1736–42. PubMed PMID: 18436694. Epub 2008/04/26
47. McCarthy JP, Pozniak MA, Agre JC. Neuromuscular adaptations to concurrent strength and endurance training. *Med Sci Sports Exerc.* 2002;34(3):511–9. PubMed PMID: 11880817. Epub 2002/03/07
48. Abreu P, Mendes SV, Ceccatto VM, Hirabara SM. Satellite cell activation induced by aerobic muscle adaptation in response to endurance exercise in humans and rodents. *Life Sci.* 2017;170:33–40. PubMed PMID: 27888112. Epub 2016/11/27
49. Joanisse S, Gillen JB, Bellamy LM, McKay BR, Tarnopolsky MA, Gibala MJ, et al. Evidence for the contribution of muscle stem cells to nonhypertrophic skeletal muscle remodeling in humans. *FASEB J.* 2013;27(11):4596–605. PubMed PMID: 23928822. Pubmed Central PMCID: PMC3804745. Epub 2013/08/10
50. Blaauw B, Schiaffino S, Reggiani C. Mechanisms modulating skeletal muscle phenotype. *Compr Physiol.* 2013;3(4):1645–87. PubMed PMID: 24265241. Epub 2013/11/23
51. Fyfe JJ, Bishop DJ, Stepto NK. Interference between concurrent resistance and endurance exercise: molecular bases and the role of individual training variables. *Sports Med.* 2014;44(6):743–62. PubMed PMID: 24728927. Epub 2014/04/15
52. Wilkinson SB, Phillips SM, Atherton PJ, Patel R, Yarasheski KE, Tarnopolsky MA, et al. Differential effects of resistance and endurance exercise in the fed state on signalling molecule phosphorylation and protein synthesis in human muscle. *J Physiol.* 2008;586(15):3701–17. PubMed PMID: 18556367. Pubmed Central PMCID: PMC2538832. Epub 2008/06/17
53. Hakkinen K, Alen M, Kraemer WJ, Gorostiaga E, Izquierdo M, Rusko H, et al. Neuromuscular adaptations during concurrent strength and endurance training versus strength training. *Eur J Appl Physiol.* 2003;89(1):42–52. PubMed PMID: 12627304. Epub 2003/03/11

54. Docherty D, Sporer B. A proposed model for examining the interference phenomenon between concurrent aerobic and strength training. *Sports Med.* 2000;30(6):385–94. PubMed PMID: 11132121. Epub 2000/12/29
55. Dudley GA, Djamil R. Incompatibility of endurance- and strength-training modes of exercise. *J Appl Physiol* (1985). 1985;59(5):1446–51. PubMed PMID: 4066574. Epub 1985/11/01
56. De Souza EO, Tricoli V, Aoki MS, Roschel H, Brum PC, Bacurau AV, et al. Effects of concurrent strength and endurance training on genes related to myostatin signaling pathway and muscle fiber responses. *J Strength Cond Res.* 2014;28(11):3215–23. PubMed PMID: 24832980. Epub 2014/05/17
57. Nader GA. Concurrent strength and endurance training: from molecules to man. *Med Sci Sports Exerc.* 2006;38(11):1965–70. PubMed PMID: 17095931. Epub 2006/11/11
58. Baar K. Training for endurance and strength: lessons from cell signaling. *Med Sci Sports Exerc.* 2006;38(11):1939–44. PubMed PMID: 17095927. Epub 2006/11/11
59. De Souza EO, Tricoli V, Roschel H, Brum PC, Bacurau AV, Ferreira JC, et al. Molecular adaptations to concurrent training. *Int J Sports Med.* 2013;34(3):207–13. PubMed PMID: 23044732. Epub 2012/10/10
60. Ruas JL, White JP, Rao RR, Kleiner S, Brannan KT, Harrison BC, et al. A PGC-1alpha isoform induced by resistance training regulates skeletal muscle hypertrophy. *Cell.* 2012;151(6):1319–31. PubMed PMID: 23217713. Pubmed Central PMCID: PMC3520615. Epub 2012/12/12
61. Fyfe JJ, Bishop DJ, Bartlett JD, Hanson ED, Anderson MJ, Garnham AP, et al. Enhanced skeletal muscle ribosome biogenesis, yet attenuated mTORC1 and ribosome biogenesis-related signalling, following short-term concurrent versus single-mode resistance training. *Sci Rep.* 2018;8(1):560. PubMed PMID: 29330460. Pubmed Central PMCID: 5766515. Epub 2018/01/14. eng
62. Lundberg TR, Fernandez-Gonzalo R, Gustafsson T, Tesch PA. Aerobic exercise does not compromise muscle hypertrophy response to short-term resistance training. *J Appl Physiol* (1985). 2013;114(1):81–9. PubMed PMID: 23104700. Epub 2012/10/30
63. Cunha TF, Moreira JB, Paixao NA, Campos JC, Monteiro AW, Bacurau AV, et al. Aerobic exercise training upregulates skeletal muscle calpain and ubiquitin-proteasome systems in healthy mice. *J Appl Physiol* (1985). 2012;112(11):1839–46. PubMed PMID: 22461440. Epub 2012/03/31
64. Konopka AR, Harber MP. Skeletal muscle hypertrophy after aerobic exercise training. *Exerc Sport Sci Rev.* 2014;42(2):53–61. PubMed PMID: 24508740. Pubmed Central PMCID: PMC4523889. Epub 2014/02/11
65. Vissing K, McGee S, Farup J, Kjolhede T, Vendelbo M, Jessen N. Differentiated mTOR but not AMPK signalling after strength vs endurance exercise in training-accustomed individuals. *Scand J Med Sci Sports.* 2013;23(3):355–66. PubMed PMID: 23802289. Epub 2013/06/27
66. Lundberg TR, Fernandez-Gonzalo R, Tesch PA. Exercise-induced AMPK activation does not interfere with muscle hypertrophy in response to resistance training in men. *J Appl Physiol* (1985). 2014;116(6):611–20. PubMed PMID: 24408998. Epub 2014/01/11
67. Kim JS, Petrella JK, Cross JM, Bamman MM. Load-mediated downregulation of myostatin mRNA is not sufficient to promote myofiber hypertrophy in humans: a cluster analysis. *J Appl Physiol* (1985). 2007;103(5):1488–95. PubMed PMID: 17673556. Epub 2007/08/04
68. Mascher H, Ekblom B, Rooyackers O, Blomstrand E. Enhanced rates of muscle protein synthesis and elevated mTOR signalling following endurance exercise in human subjects. *Acta Physiol (Oxf).* 2011;202(2):175–84. PubMed PMID: 21385328. Epub 2011/03/10
69. Mascher H, Andersson H, Nilsson PA, Ekblom B, Blomstrand E. Changes in signalling pathways regulating protein synthesis in human muscle in the recovery period after endurance exercise. *Acta Physiol (Oxf).* 2007;191(1):67–75. PubMed PMID: 17488244. Epub 2007/05/10
70. Benziene B, Burton TJ, Scanlan B, Galuska D, Canny BJ, Chibalin AV, et al. Divergent cell signaling after short-term intensified endurance training in human skeletal muscle. *Am J Physiol Endocrinol Metab.* 2008;295(6):E1427–38. PubMed PMID: 18827172. Epub 2008/10/02

71. Di Donato DM, West DW, Churchward-Venne TA, Breen L, Baker SK, Phillips SM. Influence of aerobic exercise intensity on myofibrillar and mitochondrial protein synthesis in young men during early and late postexercise recovery. *Am J Physiol Endocrinol Metab.* 2014;306(9):E1025–32. PubMed PMID: 24595306. Pubmed Central PMCID: PMC4010655. Epub 2014/03/07
72. Wilson JM, Marin PJ, Rhea MR, Wilson SM, Loenneke JP, Anderson JC. Concurrent training: a meta-analysis examining interference of aerobic and resistance exercises. *J Strength Cond Res.* 2012;26(8):2293–307. PubMed PMID: 22002517. Epub 2011/10/18



Effects of Endurance-, Strength-, and Concurrent Training on Cytokines and Inflammation

9

Jorming Goh, Chin Leong Lim, and Katsuhiko Suzuki

Introduction

The immune system maintains physiological homeostasis and health by protecting the body from the harmful effects of antigens (molecules that induce an immune response), including microbes, pathogens, stress-related insults, and soft tissue damage. This system monitors antigenic insults using a two-tier response against antigens of varying complexity and novelty [1].

The first line of defence against foreign bodies involves the innate or non-adaptive immune system, which responds to foreign particles in the body using a generic mechanism. The protective mechanisms under this immune system include surface barriers (e.g., skin and mucosa surface), localized inflammation, phagocytosis by monocytes and granulocytes, and cytotoxicity by binding natural killer (NK) cells to the major histocompatibility complexes (MHC) of tumour or virus-infected cells. The second line of defence, known as the adaptive immune system, is activated against antigens that are not neutralized by the innate immune system. The immune cells in this system can recognize unique features in the antigen and modify its own morphology and functions to form new antibodies that target and neutralize specific novel antigens. These characteristics of the adaptive immune system allow

J. Goh (✉)

Ageing Research Institute for Society and Education (ARISE), Nanyang Technological University, Singapore, Singapore

Exercise Medicine and Physiology Laboratory, Lee Kong Chian School of Medicine, Nanyang Technological University, Singapore, Singapore
e-mail: gohjm@ntu.edu.sg

C. L. Lim

Exercise Medicine and Physiology Laboratory, Lee Kong Chian School of Medicine, Nanyang Technological University, Singapore, Singapore

K. Suzuki

Faculty of Sport Sciences, Waseda University, Tokyo, Japan

the body to mount an antibody-response against novel antigens, and the new antibodies become a permanent component of the immune surveillance system in the body. This system is activated about 24–48 h after an antigenic insult and is driven by lymphocyte subset cells, i.e. T cells (cytotoxic T and T-helper cells) as well as B cells and immunoglobulin (Ig)G, IgA, IgM, and IgE [2].

Besides antigenic insults, the state of the immune system is also influenced by acute and prolonged physical stressors, such as endurance-, strength-, and sports training and occupational tasks (e.g., military and physical labour) [3–6]. Prolonged exposure to these stressors can lead to suppression of immune functions and skeletal muscle damage that triggers the inflammatory response. The inflammatory response is part of the tissue protection and repair functions in the immune system and is driven primarily by cytokines and chemokines. Cytokines and chemokines are intercellular signalling molecules that modulate inflammation and immune responses, usually in an autocrine or paracrine manner at extremely low concentrations [7]. In the context of exercise, the inflammatory response can involve intricate cellular signalling between different immune and non-immune cells (e.g. skeletal muscle), leading to the secretion and uptake of cytokines and chemokines and the downstream mobilization of leukocytes into the systemic circulation and inflammatory sites in the body. These inflammatory responses can also activate tissue resident immune cells and change their functional responses. Cytokines are generally classified as being pro- or anti-inflammatory, based on their effects on cellular or immune pathways and the plasma concentrations of anti-inflammatory cytokines (e.g. IL-1ra, IL-4, IL-10) and chemokines (e.g. IL-8) are typically upregulated after a bout of exercise ([7, 8]).

Intense exercise can increase the number of circulating leukocytes (0.5–2.6-fold), monocytes (0.2–2.5-fold), granulocytes (0.3–4-fold) and neutrophils (0.8–2.6-fold) during and >1 h after exercise [3, 9–11]. Lymphocytes also increased by up to one-fold during exercise, but lymphocyte counts can be downregulated to below baseline concentrations (−19%–−60%) for up to 6 h after an intense bout of exercise [3, 9, 10]. The increase in immune cell counts during exercise is due to the effects of hemodynamic shear stress, which demarginates (detaches) immune cells that have adhered to blood vessel walls, as well as from the lungs, liver and spleen, into systemic circulation [12]. Neutrophils are also mobilized from the bone marrow 1–3 h after exercise [11]. Elevated concentrations of exercise-induced catecholamines also bind to β_2 -adrenergic receptors on leukocytes which also contribute to their mobilization into systemic circulation [13]. The decrease in post-exercise lymphocyte count is accompanied by reduced concentrations in NK cells (−60% to −80%), B cells (−8% to −40%), T-cells (−14% to −50%), T-helper (−5% to −52%) and cytotoxic T (−40% to −60%) cells [10, 14–18]. The suppression in post-exercise immune cell count is due to the inter-compartmental shift of lymphocyte subtype cells, from central circulation to peripheral organs [4, 5], and is related to exercise intensity and volume, but not to the type of exercise [4, 5, 10, 14, 19–21]. The post-exercise mobilization of immune cells into peripheral organs such as the liver, lungs and skeletal muscle may be instrumental in initiating tissue remodelling, which can contribute to the metabolic and phenotypic changes in these organs.

Successful long-term adaptation to exercise training is predicated on the body's ability to mount and regulate an immune response appropriately during intense

exercise, including the modulation of the cytokine and chemokine responses. Failure of the immune system to properly regulate these responses, as a consequence of excessive training load or sub-optimal recovery, may suppress immune functions, compromise athletic performance and increase the risks of respiratory infections. This phenomenon is known as over-reaching when the effects are more transient, lasting days or weeks, and can progress to an over-trained state when the malaise lasts for months. In a previous study conducted in a small group ($N = 10$) of well-trained cyclists and triathletes [22], 28 days of continuous, intensified endurance training comprising primarily (~75–80%) of cycling, with the remaining time spent on running, swimming and weight lifting, did not result in changes in resting leukocyte cell counts across days 1, 14, 28 and 30. Differences in immune cell counts are actually observed between elite athletes and the reference adult populations when such outcomes are measured across a longer span of time. A cross-sectional study that tracked elite athletes from 14 sports (937 women, 1310 men) for 10 years demonstrated that well-trained and elite endurance athletes present with ~16% lower resting leukocyte and neutrophil counts compared to the general healthy population [23]. Of note, Horn's study detected clinical neutropenia (defined as $<2.0 \times 10^9/L$) in 17% and 16% of cyclists and triathletes, respectively, and 5% from the total athlete sample pool. It is unknown whether the athletes in the study experienced symptoms of over-training, as training diaries and medical visits were not documented. Nevertheless, exposures to a single bout of intense exercise and to an extended period of high training load (particularly endurance-type exercise) can induce immune suppression and increase the risks of infections. These research findings have important practical implications on the well-being of athletes who are exposed to prolonged high training loads. Sports and health professionals can contribute to the well-being of athletes by being aware of, and by taking precautions against the effects of prolonged intense training on the immune system.

This chapter aims to introduce the key concepts and research findings in exercise and immune health in active healthy populations. This topic has been reviewed in greater depth elsewhere, which readers can refer to for further reading [6, 13, 24–26]. Our primary focus is to summarize the current knowledge of exercise-induced immune response in endurance, strength and combined (concurrent) endurance and strength training. Specifically, we will describe exercise-induced cytokine responses, and how such inflammatory responses modulate infection risk and tissue homeostasis in healthy populations engaging in different modes of exercise.

Models of Exercise Immunology Research

“Open Window” and “J-Curve” Models of Exercise-Induced Immunosuppression

Interest in exercise immunology research has grown since the 1980s, with more than 3500 peer-reviewed publications currently in this domain of study [6]. Much of the bases for exercise immunology research in the last 30 years were influenced by the classical “open window” and the “J-curve” models. The “open window” model

suggests that immune functions can be suppressed for 3–72 h after an intense bout of exercise [27]. During this “open window” period, viruses that are dormant in the cells may be reactivated to cause an infection. Exposing the host to repeated bouts of exercise during this open window period would further suppress the immune system and increase the risk of having an infection [28, 29]. Scholars also subscribe to the concept of the “J” curve model (Fig. 9.1), suggesting that prolonged intense training is associated with a high risk of infection, followed by sedentary individuals with an average risk of infection, and lastly, individuals participating in moderate-intensity training having the lowest risk of infection [30, 31].

Both the “open window” and “J-curve” models were instrumental in the development of exercise immunology research, but recent evidence suggest that the concepts behind these classical models may be challenged.

Contrary to the classical models, recent data suggest that the risks of exercise-induced URTI can differ between athletes competing in international and national competitions [6]. The incidence of URTI, monitored over four training and competitive seasons (4 years), was 35–65% lower in international-level than in national-level swimmers [32]. In a mixed group of elite endurance athletes (cross-country skiers, biathletes, runners), data retrieved from 3 to 16 years of training logs showed that the number of self-reported sick days was inversely related to training volume [33]. Increasing training load by 20% for 2 weeks also did not alter immune response in endurance athletes before, during, and 2 h after running in warm and humid conditions [34]. These observations challenged the central doctrine proposed by the classical J-curve and open window models and led some scholars to suggest that besides lifestyle factors, the immune system in the higher performing athletes may be genetically selected to better tolerate exercise-induced stresses [6].

“Tissue Injury” Model of Exercise-Induced Immunosuppression

Another model to explain exercise-induced immune suppression is the “tissue injury” hypothesis [35]. This model proposes that tissue damage resulting from repetitive mechanical trauma during intense exercise training, combined with an

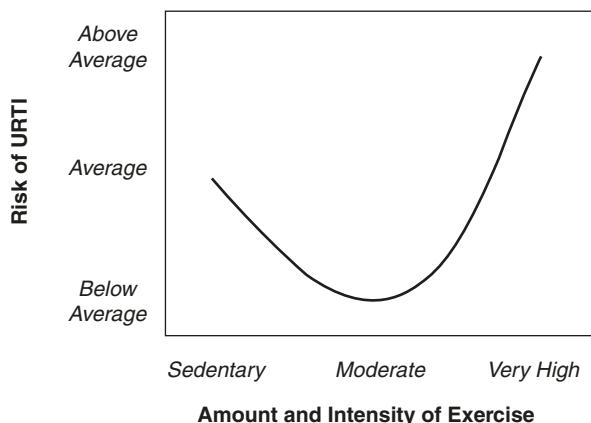


Fig. 9.1 “J-curve” model depicting the risks of developing URTI based on the volume and intensity of exercise training

accumulation of sub-optimal recovery can induce a pro-inflammatory response involving cytokines typically produced by T-helper (Th)1 cells, including interleukin (IL)-2, IL-6, interferon (IFN)- γ , and tumour necrosis factor (TNF)- α . The first wave of Th1 cytokine response is followed by a persistent anti-inflammatory cytokine response involving cytokines produced by Th2 cells, i.e. IL-4, IL-5, IL-10, and IL-13. The Th2 cytokine response is the host response to restore homeostasis and prevent further tissue damage by dampening the pro-inflammatory (Th1) cytokine response [36].

Adding to the concept of the tissue injury model is the current appreciation of the immunoregulatory role of endogenous stress molecules termed “alarmins”, which have been shown to respond to cellular insults, including oxidative stress, hypoxia, cellular necrosis, etc. [37]. Briefly, these alarmins, which include the prototypical danger protein, high mobility group box (HMGB) protein 1, are normally sequestered in either the nuclear or extracellular compartments of a cell. When cells experience stress or undergo necrosis, these alarmins are mobilized and released into the systemic circulation, where they behave like cytokines by binding to pattern recognition receptors (PRRs) on target cells [38]. Importantly, the release of alarmins can initiate signalling cascades for the ensuing cytokine and chemokine responses [39]. Few human studies have explored the role of alarmins in exercise-induced muscle damage but it is attractive to speculate that they may play a role in the immunoregulatory process in acute and long-term exercise.

Exercise-induced cytokine responses drive the recruitment of immune cells into the damaged muscle milieu, and neutrophils are the earliest immune cells to be recruited, followed by monocytes [40]. Gene and protein expression levels of exercise-induced chemokines, such as CX₃CL1, were upregulated after an acute bout of cycle ergometry [41], which in turn, may recruit circulating monocytes into the skeletal muscle microenvironment for remodelling and repair. These monocytes differentiate into skeletal muscle macrophages and cross-talk with myogenic precursor cells [42], which are essentially muscle-specific stem cells. Discrete macrophage populations within the skeletal muscle milieu, such as M1 and M2 cells, phagocytose damaged myofibres, secrete mitogenic factors, and participate in angiogenesis and matrix remodelling, which contributes to muscle cell regeneration [40].

The lingering presence of Th2 cytokines can also be a sign of unresolved chronic inflammation, which can suppress cell-mediated immune function against infections, including the downregulation of respiratory burst in neutrophils by IL-10 [43]. This Th2 response was observed during months of intense training in infection-prone high-performance athletes, who had fourfold higher circulating concentrations of the anti-inflammatory Th2 cytokines, particularly IL-10, compared with athletes free from infections [44]. In summary, the “tissue injury” model suggests that increased susceptibility to colds or allergies in athletes may be due to an imbalanced inflammatory response, partly due to the combination of sub-optimal recovery, high training load, and acute increase in training load or frequency. These imbalanced inflammatory responses can contribute to, and also be the consequences of the over-reaching/over-training phenomena in a positive feedback loop.

Immune Responses to Endurance Exercise (Acute and Chronic)

Acute Endurance Exercise

Acute endurance exercise is associated with leukocytosis [3, 9, 10] in healthy individuals, which is also modulated by their interactions with cytokines and chemokines. The magnitude of this cytokine response is influenced by the mode, duration, and intensity of exercise. Many acute exercise studies involving long duration and high-intensity exercises, such as marathons [45, 46], the Ironman triathlon [47], and long distance cycling (164 km road race; [48]) typically showed an increase in pro-(IL-1 β , IL-6, IL-8) and anti-inflammatory (IL-1ra, IL-10) cytokines.

Similar outcomes in cytokine response have been demonstrated with other exercise studies that are of lower intensities or shorter duration. For example, cycling 30 min to 3 h at 60–65% VO₂ max [49], 80% VO₂ peak [50], 90% of second ventilatory threshold [51] and 70% VO₂ max [52] resulted in increased systemic circulating concentrations of IL-1 β , IL-1ra, IL-6, IL-8, IL-10, and TNF- α . These findings of enhanced pro- and anti-inflammatory cytokine responses are corroborated in other studies conducted in runners [53–55].

Transcriptional levels of inflammatory genes are also enhanced after endurance exercise in peripheral blood mononuclear cells (PBMCs) [56, 57] and neutrophils [54], suggesting that these immune cells may be the source of circulating cytokines and chemokines after exercise. In healthy men, running (80% VO₂ max) till exhaustion elicited an upregulation of 450 genes and down-regulation of 150 genes involved in stress (e.g. heat shock protein family A (HSPA1A)) and inflammatory responses (e.g. matrix metalloproteinase (MMP)-9) [56]. A less intense exercise bout comprising cycling at 80% VO₂ peak for 30 min changed transcriptional output of 311 genes in PBMCs after exercise [57], wherein HSP70 was upregulated by >3.5-fold. Interestingly, the gene encoding the anti-inflammatory cytokine, IL-1ra, was upregulated by 1.5-fold during recovery, which paralleled the nearly 1.5-fold increase in circulating IL-1ra concentration at the same time point.

Despite the variations in temporal responses of individual pro-inflammatory and anti-inflammatory cytokines among different studies, the consensus is that acute endurance exercise stimulates an inflammatory response, which is necessary to mobilize leukocytes for tissue repair.

Chronic Endurance Exercise

The chronic effects of endurance exercise training have also been investigated in national-level athletes [58] and healthy individuals participating in 8 [59, 60] or 12 weeks [61] of endurance exercise training. In the young (18 years) athletic population, long-term participation (~ 8 year) in endurance exercise training was associated with a downregulation of pro-inflammatory cytokine gene expression (IL-8, IL-15) and chemokines (CXCL8, CXCL1) in PBMCs [58]. In healthy men and women training 4 days weekly for 8 weeks in aerobic activities (e.g. treadmill

running, cycling for 30–40 min) showed a decrease in inducible TNF- α response (24 h post-exercise), but only in participants stratified to the high-intensity (55–80% of HR_{max}) condition, compared with the moderate-intensity (55–60% of HR_{max}) condition [61]. In another study, running 3 times weekly for 8 weeks at 50–75% VO₂ max did not show changes in TNF- α concentrations immediately after exercise [60]. These discrepancies may be explained by the different exercise protocols, as well as time course for blood taking.

Immune Responses to Strength Training (Acute and Chronic)

Acute Strength Exercise

Whereas the effects of endurance training on inflammatory responses are well documented, fewer studies on strength training and inflammatory paradigms have been conducted in healthy populations. In general, the leukocyte response to acute resistance exercise is similar to that in endurance exercise. For example, a single bout of resistance exercise (10 repetitions of squats at 65% 1-repetition maximum (RM)) performed by healthy middle-aged men (46.9 ± 1.2 years) until volitional fatigue enhanced leukocytosis [17]. Acute enhancement in leukocytosis was also observed in other resistance exercise studies with younger volunteers [62–64]. These studies also demonstrated increased systemic concentrations of IL-6 [62], TNF- α [62, 64], and chemokines, e.g. monocyte chemotactic protein (MCP)-1 [64]. The increased concentration of MCP-1 in the systemic circulation after resistance exercise supports the recruitment of monocytes [64] into skeletal muscle, such as CD14⁺⁺CD16⁻ monocytes, which are the primary immune cells that secrete IL-10 [65].

The extent of total muscle fibre recruitment *via* the manipulation of the number of sets or repetitions to shift the emphasis between a hypertrophic and a maximal all-out effort contraction can result in differences in leukocytosis and cytokine responses after an acute bout of resistance exercise [63]. Increased leukocytosis was observed immediately after acute hypertrophic bout of exercise (leg press with 5 sets of 10 reps at 80% of 1RM). Comparatively, an increased leukocyte count was only observed after 30 min after the maximal bout of leg press (15 sets of 1 rep at 100% of 1RM). The chemokine, MCP-1, and anti-inflammatory cytokine, IL-1ra, decreased and increased, respectively, after the hypertrophic bout, but no changes were observed in these inflammatory markers after the maximal bout [63]. This intriguing study suggests that the recruitment of immune cells into the circulation, possibly for skeletal muscle remodelling may occur differently, depending on the degree of muscle fibre recruitment, and whether the contractions are brief or sustained.

Chronic Strength Exercise

The inflammatory response to short-term resistance exercise training varies, depending on the frequency, intensity, and duration of training. Three sessions of resistance

training weekly at moderate- (45–55% of 1RM) or high-intensity (80–90% of 1RM) over 6 weeks had no effect on systemic IL-6 and IL-1 β concentrations in young healthy men [66]. However, moderate-intensity training (60% of 1RM) performed for 8 weeks by college-aged males resulted in higher systemic IL-8 concentrations than in either the control or high-intensity training groups [67]. High-intensity resistance training (80% of 1RM) also resulted in higher concentrations of serum soluble TNF receptor (sTNFR1), IL-1ra and IL-8 in healthy men and women (36 ± 2 years) [68]. However, the low-intensity training (range of 20–40% of 1RM) showed decreased concentration of serum IL-6 after 9 weeks of training [68]. In contrast, 12 weeks of high-intensity resistance exercise (80% of 1RM; 2 days/week) had no effect on systemic concentration of IL-1 β , IL-2, IL-6, and TNF- α in healthy young men and women [69].

In a different study conducted in young healthy men [70], the authors investigated the effects of 12 weeks of resistance training on systemic cytokine and chemokine responses to two acute bouts of leg press exercise: either a hypertrophic (5 sets × 10 repetitions at 60% of 1RM) or power-type (10 sets of 5 repetitions at 60% of 1RM) exercise tests were completed by the participants. In the untrained state, serum IL-1 β , plasma IL-6, and resistin all increased immediately after either type of exercise. After 12 weeks of resistance training however, only plasma IL-1ra was increased after both exercise protocols, while plasma MCP-1 was increased only at 24 and 48 h.

These seemingly disparate findings on resistance training and inflammation may be due to different subject characteristics and exercise regimes. The extent of eccentric and concentric muscle action in resistance training may determine the remodelling process in skeletal muscle. Eccentric muscle action, but not concentric action resulted in increased MCP-1 and skeletal muscle stem cells [71] within skeletal muscle of young men. Hence, it is possible that resistance exercises that employ more concentric actions may elicit a different pattern of inflammatory cytokine and chemokine production, which may not result in extensive skeletal muscle damage and remodelling.

Immune Responses to Concurrent Strength and Endurance Exercise

Compared with research into the immune responses to endurance or strength exercise alone, considerably fewer studies have been conducted to determine the immune response to concurrent strength and endurance exercise. Therefore, a critical gap exists in the knowledge-base on how healthy individuals respond to combined strength and endurance exercises, given that many recreational and elite athletes perform some kind of combined training.

Acute Concurrent Exercise

Current research evidence suggests that combining both endurance and strength exercises acutely upregulates IL-1 β , IL-6, TNF- α , and TNF-R1 gene expression

in skeletal muscle, and these gene expression levels return to resting levels 48 h after the exercise session [72]. These responses differ from performing endurance or resistance exercises independently, where the gene expression for the same set of cytokines remained elevated [72] In recreational weight-lifters, concurrent exercise performed in either order (strength-endurance or endurance-strength) resulted in increased systemic concentration of IL-6, but concentration of TNF- α was increased only in the endurance-strength condition [73].

Chronic Concurrent Exercise

Long-term concurrent training appears to have varied immune responses, depending on the structure of the programme. For middle-aged men, 12 weeks of concurrent training resulted in lower plasma concentrations of TNF- α and IL-6 [72], but 16 weeks of concurrent training showed no changes in resting plasma concentrations of these two cytokines [74, 75]. In another training study that spanned 24 weeks, healthy young men were stratified into two interventional and one control groups [76] where one group of subjects performed concurrent endurance and resistance training in the same session, 2–3 times per week, and the second intervention group performed alternating days of endurance and resistance training, 4–5 times per week. Performing concurrent endurance and resistance exercises in the same sessions or on alternate days resulted in a decrease in plasma leptin, resistin, and C-reactive protein (CRP). However, only subjects performing concurrent training on alternate days presented with decreased plasma IL-6, MCP-1, and TNF- α .

It is noteworthy that many authors have investigated concurrent endurance and resistance exercises using different modes of exercises, which makes the interpretation of the results difficult to generalize. In the study by Donges et al. [72], the authors implemented cycle exercise (55% of peak aerobic workload) as the endurance component, and leg extension exercise (8 sets of 8 repetitions at 70% maximal strength) as the strength component, whereas Libardi and colleagues [74, 75] used walking and running (55–85% of VO_2 peak) for endurance training combined with whole-body resistance exercises (3 sets of 8–10 repetitions). Finally, Ihalainen and colleagues [70, 76] employed a combination of cycle exercise (performed below and above anaerobic threshold) and whole-body resistance training with an emphasis on lower limb strength training.

The aforementioned studies illustrate a large diversity in study design, subject demographics, and immune outcomes regarding the science of concurrent training. Notwithstanding these disparate findings, some observations are still worth noting. For instance, it would appear that the amount of muscle mass recruited during training may be a factor that affects the immune responses to concurrent exercise training. In addition, the manipulation of rest and implementation of concurrent training sessions either within the same day or on alternate days may affect the dynamics of cytokine and chemokine response, as seen from the reduced MCP-1, IL-6, and TNF- α responses with alternating days of training, but not with same-day sessions [76].

This also suggests that the extent of leukocyte recruitment for skeletal muscle remodelling may be affected by such manipulations as well.

Finally, compared with younger men (18–35 years), older men (65–85 years) demonstrated an accentuated TNF- α response both at baseline and after 12 weeks of concurrent training [77], suggesting that in addition to exercise frequency, intensity, duration, and order (endurance-strength or strength-endurance), the age of individuals participating in concurrent exercise will influence their immune responses.

Summary

In this chapter, we have covered the general scope of exercise immunology and discussed the three models of immune responses to exercise that shape the prevailing research trends in our field. We have also presented immune responses to endurance, resistance, and concurrent exercise training, both in terms of acute exposures and short-term periods. The implications of immune responses on clinical or performance outcomes after resistance and concurrent exercise training are less clear and warrant further research.

In summary, a translational implication of exercise-induced inflammation in healthy individuals and athletes, is that intensified endurance training can lead to over-reaching or over-training symptoms, which increase the risk of developing acute URTIs. As such, the pro- and anti-inflammatory cytokine balance might determine the host defence to infection as well as tissue damage following exercise and training. Further research is necessary in the future and may entail the understanding of cross-talk between immune cells and their putative target organs/tissues.

References

1. Janeway CA, Travers P, Walport M, Shlomchik M. Immune biology. New York: Garland Publishing; 2001. p. 12, 69–87, 360–375, 683.
2. Mackinnon LT. Advances in exercise immunology, vol. 314. Champaign IL: Human Kinetics; 1999. p. 33.
3. Lim CL, Byrne C, Chew SA, Mackinnon LT. Leukocyte subset responses during exercise under heat stress with carbohydrate or water intake. *Aviat Space Environ Med*. 2005;76:726–32.
4. Nieman DC. Exercise effects on systemic immunity. *Immunol Cell Biol*. 2000a;78:496–501.
5. Nieman DC. Is infection risk linked to exercise workload? *Med Sci Sports Exerc*. 2000b;32(Suppl):S406–11.
6. Walsh NP, Samuel JO. Exercise, immune function and respiratory infection: an update on the influence of training and environmental stress. *Immunol Cell Biol*. 2016;94:132–9.
7. Suzuki K, Nakaji S, Yamada M, Totsuka M, Sato K, Sugawara K. Systemic inflammatory response to exhaustive exercise. *Cytokine kinetics. Exerc Immunol Rev*. 2002;8:6–48.
8. Lancaster GI, Jentjens RL, Moseley L, Jeukendrup AE, Gleeson M. Effect of pre-exercise carbohydrate ingestion on plasma cytokine, stress hormone, and neutrophil degranulation responses to continuous, high-intensity exercise. *Int J Sport Nutr Exerc Metab*. 2003;13:436–53.
9. Nieman DC, Buckley KS, Henson DA, Warren BJ, Suttles J, Ahle JC, Nehlsen-Cannarella SL. Immune function in marathon runners versus sedentary controls. *Med Sci Sports Exerc*. 1995a;27:986–92.

10. Nieman DC, Nehlsen-Cannarella SL, Donohue KM, Chritton DBW, Haddock BL, Stout RW, Lee JW. The effects of acute moderate exercise on leukocyte and lymphocyte subpopulations. *Med Sci Sports Exerc.* 1991;23:578–85.
11. Suzuki K, Totsuka M, Nakaji S, Yamada M, Kudoh S, Liu Q, Sugawara K, Yamaya K, Sato K. Endurance exercise causes interaction among stress hormones, cytokines, neutrophil dynamics, and muscle damage. *J Appl Physiol.* 1999;87:1360–7.
12. Simpson RJ, Kunz H, Agha N, Graff R. Exercise and the regulation of immune functions. *Prog Mol Biol Transl Sci.* 2015;135:355–80.
13. Peake J, Neubauer O, Walsh NP, Simpson RJ. Recovery of the immune system after exercise. *J Appl Physiol.* 2017;122:1077–87.
14. Gabriel H, Schwarz L, Steffens G, Kindermann W. Immunoregulatory hormones, circulating leukocyte and lymphocyte subpopulations before and after endurance exercise of different intensities. *Int J Sports Med.* 1992;13:359–66.
15. Henson DA, Nieman DC, Parker JCD, Rainwater MK, Butterworth DE, Warren BJ, Utter AC, Davies JM, Fagoaga OR, Nehlsen-Cannarella SL. Carbohydrate supplementation and lymphocyte proliferative response to long endurance running. *Int J Sports Med.* 1998;19:574–80.
16. Nehlsen-Cannarella SL, Nieman DC, Balk-Lamberton AJ, Markoff PA, Chritton DBW, Gusewitch G, Lee JW. The effects of moderate exercise training on immune response. *Med Sci Sports Exerc.* 1991;23:64–70.
17. Nieman DC, Henson DA, Sampson CS, Herring JL, Suttles J, Conley M, Stone MH, Butterworth DE, JM D. The acute immune response to exhaustive resistance exercise. *Int J Sports Med.* 1995b;16:322–8.
18. Nieman DC, Simandl S, Henson DA, Warren BJ, Suttles J, Davis JM, Buckley KS, Ahle JC, Butterworth DE, Fagoaga OR, Nehlsen-Cannarella SL. Lymphocyte proliferative response to 2.5 hours of running. *Int J Sports Med.* 1995c;16:404–8.
19. Kargotich S, Keast D, Goodman C, Crawford GPM, Morton AR. The influence of blood volume changes on leukocyte and lymphocyte subpopulations in elite swimmers following interval training of varying intensities. *Int J Sports Med.* 1997;18:373–80.
20. Nieman DC. Immune response to heavy exertion. *J Appl Physiol.* 1997;82:1385–94.
21. Tvede N, Kappel M, Halkjær-Kristensen J, Galbo H, Pedersen BK. The effects of light, moderate, and severe bicycle exercise on lymphocyte subsets, natural and lymphokine killer cells, lymphocyte proliferative response and interleukin 2 production. *Int J Sports Med.* 1993;15:275–82.
22. Ndon JA, Snyder AC, Foster C, Wehrenberg WB. Effects of chronic intense exercisetraining on the leukocyte response to acute exercise. *Int J Sports Med.* 1992;13:176–82.
23. Horn PL, Pyne DB, Hopkins WG, Barnes CJ. Lower white blood cell counts in elite athletes training for highly aerobic sports. *Eur J Appl Physiol.* 2010;110:925–32.
24. Gleeson M, Pyne DB. Respiratory inflammation and infection in high performance athletes. *Immunol Cell Biol.* 2016;94:124–31.
25. Walsh NP, Gleeson M, Pyne DB, Nieman D, Dhabhar FS, Shephard RJ, Oliver SJ, Bermon S, Kajeniene A. Position statement part II: maintaining immune health. *Exerc Immunol Rev.* 2011a;17:64–103.
26. Walsh NP, Gleeson M, Shephard RJ, Gleeson M, Wood JA, Bishop NC, Fleshner M, Green C, Pedersen BK, Hoffman-Goetz L, Rogers CJ, Northoff GH, Abbassi A, Simon P. Position statement part I: immune function and exercise. *Exerc Immunol Rev.* 2011b;17:6–63.
27. Pedersen BK, Rohde T, Zacho M. Immunity in athletes. *J Sports Med Phys Fitness.* 1996;36:236–45.
28. Mackinnon LT. Overtraining effects on immunity and performance in athletes. *Immunol Cell Biol.* 2000;78:502–9.
29. Smith LL. Overtraining, excessive exercise, and altered immunity. *Sports Med.* 2003;33:347–64.
30. Nieman DC. Exercise, immunology and nutrition. *World Rev Nutr Diet.* 2001;90:89–101.
31. Nieman DC, Nehlsen-Cannarella SL. The immune response to exercise. *Semin Hematol.* 1994;31:166–79.

32. Hellard P, Avalos M, Guimaraes F, Toussaint JF. Training-related risk of common illness in elite swimmers over a 4-year period. *Med Sci Sports Exerc.* 2015;47:698–707.
33. Martensson S, Nordebo K, Malm C. High training volumes are associated with a low number of self-reported sick days in elite endurance athletes. *J Sports Sci Med.* 2014;13:929–33.
34. Lim CL, Pyne DB, Horn P, Kalz A, Saunders P, Peake J, Suzuki K, Wilson G, Mackinnon LT. The effects of increased endurance training load on biomarkers of heat tolerance during intense exercise in the heat. *Appl Physiol Nutr Metab.* 2009;34:616–24.
35. Smith LL. Tissue trauma: the underlying cause of overtraining syndrome? *J Strength Cond Res.* 2004;18(1):185–93.
36. Suzuki K, Nakaji S, Kurakake S, Totsuka M, Sato K, Kuriyama T, Fujimoto H, Shibusawa K, Machida K, Sugawara K. Exhaustive exercise and type-1/type-2 cytokine balance in special focus on interleukin-12 p40/p70. *Exerc Immunol Rev.* 2003a;9:48–57.
37. Oppenheim JJ, Yang D. Alarmins: chemotactic activators of immune responses. *Curr Opin Immunol.* 2005;17:359–65.
38. Hung YL, Suzuki K. The pattern recognition receptors and lipopolysaccharides (LPS)-induced systemic inflammation. *Int J Res Stud Med Health Sci.* 2017;7:1–7.
39. Yang D, Han Z, Oppenheim JJ. Alarmins and immunity. *Immunol Rev.* 2017;280:41–56.
40. Juban G, Chazaud B. Metabolic regulation of macrophages during tissue repair: insights from skeletal muscle regeneration. *FEBS Lett.* 2017. doi: <https://doi.org/10.1002/1873-3468.12703>.
41. Strömberg A, Rullman E, Jansson E, Gustafsson T. Exercise-induced upregulation of endothelial adhesion molecules in human skeletal muscle and number of circulating cells with remodeling properties. *J Appl Physiol.* 2017;122:1145–54.
42. Saclier M, Yacoub-Youssef H, Mackey AL, Arnold L, Ardjoune H, Magnan M, Sailhan F, Chelly J, Pavlath GK, Mounier R, Kjaer M, Chazaud B. Differentially activated macrophages orchestrate myogenic precursor cell fate during human skeletal muscle regeneration. *Stem Cells.* 2013;31:384–96.
43. Dang PM, Elbim C, Marie JC, Chiandotto M, Gougerot-Pocidalo MA, El-Benna J. Anti-inflammatory effect of interleukin-10 on human neutrophil respiratory burst involves inhibition of GM-CSF-induced p47PHOX phosphorylation through a decrease in ERK1/2 activity. *FASEB J.* 2006;20:1504–6.
44. Gleeson M, Bishop N, Oliveira M, McCauley T, Tauler P, Muhamad AS. Respiratory infection risk in athletes: association with antigen-stimulated IL-10 production and salivary IgA secretion. *Scand J Med Sci Sports.* 2012;22:410–7.
45. Suzuki K, Nakaji S, Yamada M, Liu Q, Kurakake S, Okamura N, Kumae T, Umeda T, Sugawara K. Impact of a competitive marathon race on systemic cytokine and neutrophil responses. *Med Sci Sports Exerc.* 2003b;35:348–55.
46. Suzuki K, Yamada M, Kurakake S, Okamura N, Yamaya K, Liu Q, Kudoh S, Kowatari K, Nakaji S, Sugawara K. Circulating cytokines and hormones with immunosuppressive but neutrophil-priming potentials rise after endurance exercise in humans. *Eur J Appl Physiol.* 2000;81:281–7.
47. Suzuki K, Peake J, Nosaka K, Okutsu M, Abbiss CR, Surriano R, Bishop D, Quod MJ, Lee H, Martin DT, Laursen PB. Changes in markers of muscle damage, inflammation and HSP70 after an Ironman Triathlon race. *Eur J Appl Physiol.* 2006;98:525–34.
48. Luk HY, Levitt DE, Lee EC, Ganio MS, McDermott BP, Kupchak BR, McFarlin BK, Hill DW, Armstrong LE, Vingren JL. Pro- and anti-inflammatory cytokine responses to a 164-km road cycle ride in a hot environment. *Eur J Appl Physiol.* 2016;116:2007–15.
49. Moldoveanu AI, Shephard RJ, Shek PN. Exercise elevates plasma levels but not gene expression of IL-1beta, IL-6, and TNF-alpha in blood mononuclear cells. *J Appl Physiol.* 2000;89:1499–504.
50. Zaldivar F, Wang-Rodriguez J, Nemet D, Schwindt C, Galassetti P, Mills PJ, Wilson LD, Cooper DM. Constitutive pro- and anti-inflammatory cytokine and growth factor response to exercise in leukocytes. *J Appl Physiol.* 2006;100:1124–33.
51. Kakanis MW, Peake J, Bremu EW, Simmonds M, Gray B, Marshall-Gradisnik SM. T helper cell cytokine profiles after endurance exercise. *J Interf Cytokine Res.* 2014;34:699–706.

52. Ulven SM, Foss SS, Skjølvik AM, Stadheim HK, Myhrstad MC, Raael E, Sandvik M, Narverud I, Andersen LF, Jensen J, Holven KB. An acute bout of exercise modulates the inflammatory response in peripheral blood mononuclear cells in healthy young men. *Arch Physiol Biochem.* 2015;121:41–9.
53. Landers-Ramos RQ, Jenkins NT, Spangenburg EE, Hagberg JM, Prior SJ. Circulating angiogenic and inflammatory cytokine responses to acute aerobic exercise in trained and sedentary young men. *Eur J Appl Physiol.* 2014;114:1377–84.
54. Neubauer O, Sabapathy S, Lazarus R, Jowett JB, Desbrow B, Peake JM, Cameron-Smith D, Haseler LJ, Wagner KH, Bulmer AC. Transcriptome analysis of neutrophils after endurance exercise reveals novel signaling mechanisms in the immune response to physiological stress. *J Appl Physiol.* 2013;114:1677–88.
55. Sugama K, Suzuki K, Yoshitani K, Shiraiishi K, Miura S, Yoshioka H, Mori Y, Kometani T. Changes of thioredoxin, oxidative stress markers, inflammation and muscle/renal damage following intensive endurance exercise. *Exerc Immunol Rev.* 2015;21:130–42.
56. Buttner P, Mosig S, Lechtermann A, Funke H, Mooren FC. Exercise affects the gene expression profiles of human white blood cells. *J Appl Physiol.* 2007;102:26–36.
57. Connolly PH, Caiozzo VJ, Zaldivar F, Nemet D, Larson J, Hung SP, Heck JD, Hatfield GW, Cooper DM. Effects of exercise on gene expression in human peripheral blood mononuclear cells. *J Appl Physiol.* 2004;97:1461–9.
58. Liu D, Wang R, Grant AR, Zhang J, Gordon PM, Wei Y, Chen P. Immune adaptation to chronic intense exercise training: new microarray evidence. *BMC Genomics.* 2017;18(1):29. <https://doi.org/10.1186/s12864-016-3388-5>.
59. Elmer DJ, Laird RH, Barberio MD, Pascoe DD. Inflammatory, lipid, and body composition responses to interval training or moderate aerobic training. *Eur J Appl Physiol.* 2016;116:601–9.
60. Jahromi AS, Zar A, Ahmadi F, Krstrup P, Ebrahim K, Hovanloo F, Amani D. Effects of endurance training on the serum levels of tumour necrosis factor- α and interferon- γ in sedentary men. *Immune Netw.* 2014;14:255–9.
61. Sloan RP, Shapiro PA, Demeersman RE, McKinley PS, Tracey KJ, Slavov I, Fang Y, Flood PD. Aerobic exercise attenuates inducible TNF production in humans. *J Appl Physiol.* 2007;103:1007–11.
62. Brunelli DT, Caram K, Nogueira FR, Libardi CA, Prestes J, Cavaglieri CR. Immune responses to an upper body tri-set resistance training session. *Clin Physiol Funct Imaging.* 2014;34:64–71.
63. Ihala J, Walker S, Paulsen G, Häkkinen K, Kraemer WJ, Hämäläinen M, Vuolteenaho K, Moilanen E, Mero AA. Acute leukocyte, cytokine and adipocytokine responses to maximal and hypertrophic resistance exercise bouts. *Eur J Appl Physiol.* 2014;114:2607–16.
64. Wells AJ, Hoffman JR, Jajtner AR, Varanoske AN, Church DD, Gonzalez AM, Townsend JR, Boone CH, Baker KM, Beyer KS, Mangine GT, Oliveira LP, Fukuda DH, Stout JR. Monocyte recruitment after high-intensity and high-volume resistance exercise. *Med Sci Sports Exerc.* 2016;48:1169–78.
65. Ziegler-Heitbrock HW, Ströbel M, Kieper D, Fingerle G, Schlunck T, Petersmann I, Ellwart J, Blumenstein M, Haas JG. Differential expression of cytokines in human blood monocyte subpopulations. *Blood.* 1992;79:503–11.
66. Sheikholeslami Vatani D, Ahmadi S, Ahmadi Dehrashid K, Gharibi F. Changes in cardiovascular risk factors and inflammatory markers of young, healthy, men after six weeks of moderate or high intensity resistance training. *J Sports Med Phys Fitness.* 2011;51:695–700.
67. Yeo NH, Woo J, Shin KO, Park JY, Kang S. The effects of different exercise intensity on myokine and angiogenesis factors. *J Sports Med Phys Fitness.* 2012;52:448–54.
68. Forti LN, Van Roie E, Njemini R, Coudryzer W, Beyer I, Delecluse C, Bautmans I. Effects of resistance training at different loads on inflammatory markers in young adults. *Eur J Appl Physiol.* 2017;117:511–9.
69. Rall LC, Roubenoff R, Cannon JG, Abad LW, Dinarello CA, Meydani SN. Effects of progressive resistance training on immune response in aging and chronic inflammation. *Med Sci Sports Exerc.* 1996;28:1356–65.

70. Ihälainen J, Ahtiainen JP, Walker S, Paulsen G, Selänne H, Hämäläinen M, Moilanen E, Peltonen H, Mero AA. Resistance training status modifies inflammatory response to explosive and hypertrophic resistance exercise bouts. *J Physiol Biochem*. 2017a;73:595–604.
71. Hyldahl RD, Olson T, Welling T, Groscost L, Parcell AC. Satellite cell activity is differentially affected by contraction mode in human muscle following a work-matched bout of exercise. *Front Physiol*. 2014;5(485) <https://doi.org/10.3389/fphys.2014.00485>.
72. Donges CE, Duffield R, Smith GC, Short MJ, Edge JA. Cytokine mRNA expression responses to resistance, aerobic, and concurrent exercise in sedentary middle-aged men. *Appl Physiol Nutr Metab*. 2014;39:130–7.
73. Inoue DS, Panissa VL, Monteiro PA, Gerosa-Neto J, Rossi FE, Antunes BM, Franchini E, Cholewa JM, Gobbo LA, Lira FS. Immunometabolic responses to concurrent training: the effects of exercise order in recreational weightlifters. *J Strength Cond Res*. 2016;30:1960–7.
74. Libardi CA, Souza GV, Gáspari AF, Dos Santos CF, Leite ST, Dias R, Frollini AB, Brunelli DT, Cavaglieri CR, Madruga VA, Chacon-Mikahil MP. Effects of concurrent training on interleukin-6, tumour necrosis factor-alpha and C-reactive protein in middle-aged men. *J Sports Sci*. 2011;29:1573–81.
75. Libardi CA, De Souza GV, Cavaglieri CR, Madruga VA, Chacon-Mikahil MP. Effect of resistance, endurance, and concurrent training on TNF- α , IL-6, and CRP. *Med Sci Sports Exerc*. 2012;44:50–6.
76. Ihälainen JK, Schumann M, Eklund D, Hämäläinen M, Moilanen E, Paulsen G, Häkkinen K, Mero AA. Combined aerobic and resistance training decreases inflammation markers in healthy men. *Scand J Med Sci Sports*. 2017b; <https://doi.org/10.1111/sms.12906>.
77. Stewart LK, Flynn MG, Campbell WW, Craig BA, Robinson JP, Timmerman KL, McFarlin BK, Coen PM, Talbert E. The influence of exercise training on inflammatory cytokines and C-reactive protein. *Med Sci Sports Exerc*. 2007;39:1714–9.



Immediate Effects of Endurance Exercise on Subsequent Strength Performance

10

Thomas W. Jones and Glyn Howatson

The Acute and Chronic Hypotheses

The order in which strength and endurance training are performed within a concurrent training regimen can vary. Previous work has employed strength training prior [1–3] and subsequent to [4–7] endurance exercise. As the focus of much work into concurrent training is the inhibition of strength development, it is important to understand the influence of any prior endurance exercise on strength-type performance.

Within the concurrent training paradigm there exist the acute and chronic hypotheses pertaining to the “interference effect”. The chronic hypothesis suggests that the trained muscle is placed under conflicting training stimuli during a longitudinal concurrent training programme, as the muscle is attempting to adapt simultaneously to both strength and endurance training [8]. This chapter will however not focus on the chronic effect, but rather the acute effect of endurance exercise on subsequent strength performance. The acute hypothesis, that was initially proposed by Craig et al. [9], relates to the inhibition of strength development resulting from endurance (in this case running) training carried out immediately prior to the strength training. In other words, simply performing strength and endurance training concurrently may not inhibit strength development; rather, that endurance loading immediately prior to strength training results in diminished quality, volume, and intensity of strength training due to residual fatigue. It was proposed that this residual fatigue resulting from prior endurance training might compromise the ability of the trained muscles to develop adequate muscular tension during strength training [9]. Consequently, the ability of muscle to generate a sufficient stimulus to complete the strength session could be compromised and hence reduce the potential for a positive

T. W. Jones (✉) · G. Howatson
Department Sport, Exercise and Rehabilitation, Northumbria University,
Newcastle upon Tyne, UK
e-mail: Thomas2.jones@northumbria.ac.uk

adaptive response. Despite the acute hypothesis being related to acute concurrent training, it still has relevance in longitudinal training scenarios. If strength performance is repeatedly reduced as a result of prior endurance training, it is likely that the magnitude of strength development will be inhibited [1, 2] when compared with strength training performed in isolation.

The acute hypothesis, like many aspects of concurrent training, is equivocal. Interestingly, much of the research reported reduced strength performance, whereas some other studies (3 out of 25 studies) reported that a prior bout of endurance training does not affect strength performance (summary presented in Table 10.1). As such, it is conceptually possible that any negative effect of prior endurance activity on subsequent strength performance may be dependent on modality, intensity, and duration of both the endurance and strength training.

Endurance Exercise-Induced Fatigue

Fatigue is an extremely broad term and is attributable to numerous physiological processes. Fatigue mechanisms can generally be subdivided into central and peripheral origins. Peripheral fatigue results from impaired processes at, or distal to the neuromuscular junction, whereas central fatigue is caused by impaired processes within the central nervous system (CNS) [38] (Fig. 10.1). In applied sport and exercise science, fatigue can be defined as an exercise-induced impairment in the ability to produce muscular force [16, 38] and sustain increased force in the presence of an increased perception of effort [39]. The fatiguing effect of endurance-type exercise has received substantial attention in scientific literature and is well documented [33, 40–44] and there is a great deal of research available pertaining to the effect of endurance loading on subsequent performance in an acute setting [8, 15, 17, 24, 31, 34, 37].

It has been frequently reported that central and/or peripheral fatigue following endurance exercise cause acute declines in contractile strength (Table 10.1). Previous research has also indicated that the contributions of central and peripheral fatigue are largely dependent on the volume and intensity of exercise performed. For example, during sustained higher intensity contractions of an isolated muscle group, peripheral fatigue appears to be the dominant factor contributing to fatigue. However, the contribution from central mechanisms increases as the exercise task increases in duration [16, 45, 46]. Consequently, it is reasonable to suggest that it is the central, rather than peripheral, factors that contribute to fatigue and hence to the decrement in strength performance that is often observed when endurance exercise acutely precedes strength training. However, it is also plausible that peripheral mechanisms make some contribution to any reduction of strength performance in the short term following higher intensity lower volume endurance loading. Consequently, any impaired strength performance and contributions from central and/or peripheral fatigue appear to be dependent on the endurance exercise and the nature of subsequent strength session and recovery (or “relief period”) between endurance and strength stimuli.

Table 10.1 Summary of research that assessed strength performance following endurance exercise

Reference	Subjects ^a	END modality	END volume and intensity	Relief duration	ST modality	ST loading/assessment	Impact of END loading on strength performance
Jones et al. [10]	Strength-trained males	Treadmill running	30 min 70% $\nu\dot{V}O_{2\max}$	None	Back squat Deadlift Bench press Prone row Military press	5 × 6 80% 1RM	↓
Thomas et al. [11]	Male semi-professional soccer players	Simulated soccer match	90 min	None 24 h 48 h 72 h	Knee extension	MVC	↓
Eklund et al. [7]	Recreationally active females	Cycle ergometry	30 min 65% W_{\max}	None	Leg press	1RM	↓
García-Pinillos et al. [12]	Trained endurance runners (males and females)	Running	MSFT	None	CMJ	Max effort	↑
Jones et al. [13]	Strength-trained males	Cycle ergometry	30 min 70% $p\dot{V}O_{2\max}$	10 min	Leg press Knee extension	5 × 6 80% 1RM	=
García-Pinillos et al. [14]	Experienced recreational male long-distance runners	Running on track	4 × 3 × 400 m	None	CMJ	Max effort	↑
Panissa et al. [15]	Physically active males	Treadmill running Cycle ergometry	15 × 1 min 50% I_{\max}	None	Half squat on smith machine	4 sets to failure 80% 1RM	↓

(continued)

Table 10.1 (continued)

Reference	Subjects ^a	END modality	END volume and intensity	Relief duration	ST modality	ST loading/assessment	Impact of END loading on strength performance
Thomas et al. [16]	Well-trained male cyclists	Cycle ergometry	Time trial of: 4 km 20 km 40 km	None	Knee extension	MVC	↓
De Salles Painelli et al. [17]	Recreationally strength-trained males	Treadmill running	5 km continuous 90% anaerobic threshold velocity or 5 km intermittent 1:1 min work periods $\nu \dot{V} O_{2\max}$	10 min	Leg press Bench press	1 RM 4 sets to failure 80% 1RM	↓
Latorre-Román et al. [18]	Sub-elite male long-distance runners	Running on track	4 × 3 × 400 m	None	CMJ	Max effort	↑
Schumann et al. [19]	Physically active males	Cycle ergometry	30 min 65% MAP	None	Isometric leg press	MVC	↓
Taipale et al. [20]	Recreationally endurance trained males and females	Running on track	60 min 80% $\nu \dot{V} O_{2\max}$	None	Isometric leg press CMJ	MVC Max effort	↓
Tan et al. [21]	Strength-trained males	Elliptical ergometer (lower limbs only)	30 min 70% age predicted HR _{max}	10 min	Back squat Bench press	3 sets to failure 75% 1RM	↓
Reed et al. [22]	Strength-trained males	Cycle ergometry	45 min 75% HR _{max}	None	Back squat Bench press	6 sets to failure 80% 1RM	↓

Taipale and Häkkinen [23]	Recreationally endurance trained males and females	Running on track	60 min between LT and RCT	None	Isometric leg press	MVC RFD	↓
Panissa et al. [24]	Variety of athletes	Treadmill running	5 km intermittent 1:1 min $\nu \dot{V} O_{2\max}$	30 min 60 min 4 h 8 h 24 h	Half squat on smith machine	4 sets to failure 80% 1RM	↓
Boullosa et al. [25]	Male and female experienced endurance athletes	Running on track	Incremental protocol to exhaustion (mean speed = 18.9 km h ⁻¹ , mean time = 1476 s)	None	CMI	Max effort	↑
de Araújo Ruas et al. [26]	Strength-trained males	Cycle ergometry	30 min OBLA	None	Leg press	10RM To failure	↓
Boullosa and Tuimil [27]	Male distance athletes	Running on track	Incremental protocol to exhaustion (mean speed = 20.8 km h ⁻¹ , mean time = 3222 s)	None	CMI	Max effort	↑
Lemos et al. [28]	Physically active elderly women	Treadmill running	20 min 60% HR _{max} or 20 min 80% HR _{max}	2 min	Leg press Knee extension Leg curl	10RM To failure	↓
de Souza et al. [29]	Physically active males	Treadmill running	5 km continuous anaerobic threshold velocity or 5 km 1:1 min $\nu \dot{V} O_{2\max}$	10 min	Inclined leg press Bench press	80% 1RM To failure	↓

(continued)

Table 10.1 (continued)

Reference	Subjects ^a	END modality	END volume and intensity	Relief duration	ST modality	ST loading/assessment	Impact of END loading on strength performance
Vurimaa et al. [30]	Male long and middle distance athletes	Treadmill running	Maximal run: Incremental to exhaustion Tempo run: 40 min at 80% $\dot{V} O_{2\max}$ Intermittent run: 40 min 2 min on, 2 min off at 100% $\dot{V} O_{2\max}$	None	CMI Half squat	Max effort 10 reps at 35% 1RM	↑
Goto et al. [5]	Recreationally strength-trained males	Cycle ergometry	60 min 50% $\dot{V} O_{2\max}$	15 min	Isometric knee extension	MVC	=
Sporer & Wenger [31]	Active males	Cycle ergometry	6 × 3 min 95–100% $p \dot{V} O_{2\max}$ or 36 min 70% $p \dot{V} O_{2\max}$	4 h 8 h 24 h	Leg press Bench press	4 sets to failure 75% 1RM	↓
Bentley et al. [32]	Trained male cyclists	Cycle ergometry	30 min 80% $\dot{V} O_{2\max}$	None 6 h	Isometric knee extension	MVC	↓
Lepers et al. [33]	Trained male cyclists	Cycle ergometry	2 h 65% MAP	None	Knee extension	MVC	↓
Leveritt et al. [34]	Strength-trained males	Cycle ergometry	50 min 70–100% critical power	8 h 32 h	Isokinetic Isometric Isotonic knee extension	5 MVC between 1.04 and 8.37 rad s ⁻¹	=

Leveritt and Abernethy [8]	Recreationally active males and 1 female	Cycle ergometry	5 min intervals 40, 60, 80% peak $\dot{V}O_2$ 2 min peak $\dot{V}O_2$	30 min	Ioinertial squats Isokinetic knee extension	3 MVC 5 MVC MVC	↓
Bentley et al. [35]	Male-trained cyclists	Cycle ergometry	30 min Lactate threshold	6 h 24 h	Isokinetic knee extension $60^\circ s^{-1}$ $120^\circ s^{-1}$ $180^\circ s^{-1}$ concentric squat jump	MVC	↓
Abernethy et al. [36]	Active males and females	Cycle ergometry	150 min 35% $p \dot{V}O_{2\max}$ or 5×5 min 40, 60, 80 and 100% $p \dot{V}O_{2\max}$	60 min 4 h	Isokinetic knee extension 0.52 and 5.20 rad s^{-1}	MVC between 0.52 and 5.20 rad s^{-1}	↓
Jacobs et al. [37]	Male athletes (runners) and physical education students	Treadmill running Cycle ergometry	Treadmill running: 75 min Max velocity that could be maintained Cycle ergometry: 30 min 70% $\dot{V}O_{2\max}$	1 h 2 h	Isokinetic knee extension	50 MVC	↓

^a As described in individual studies, *CMJ* countermovement jump, *END* endurance training, *HR_{max}* maximum heart rate, *I_{max}* maximal intensity attained on incremental test, *LT* lactate threshold, *MAP* maximal aerobic power, *MSFT* multistage fitness test *MVC* maximal voluntary contraction, *OBLA* onset of blood lactate accumulation, *p* $\dot{V}O_{2\max}$, power output at $\dot{V}O_{2\max}$; *RCT* respiratory compensation threshold, *RFD* rate of force development, *RM* repetition maximum, *ST* strength training, *TT* time trial, *v* $\dot{V}O_{2\max}$, velocity at $\dot{V}O_{2\max}$; *W_{max}* maximal workload

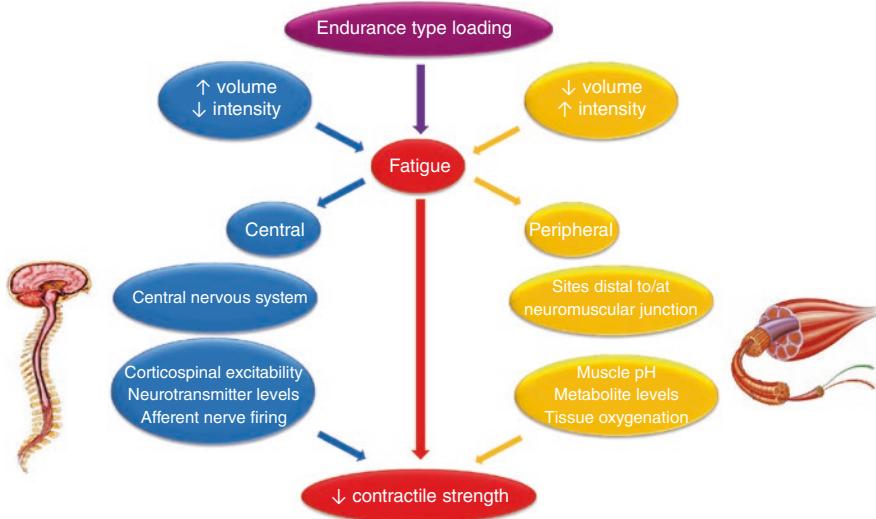


Fig. 10.1 Schematic representation of central and peripheral fatigue mechanisms

Relief Period Between Endurance and Strength Loadings

The “relief period” refers to the time period between endurance and strength loadings. In the available body of peer reviewed literature, relief periods range from strength performance being assessed immediately following endurance loading to assessments conducted 72 h post-endurance loading. It appears that the duration of the relief period may influence the presence of any impairment in strength performance following endurance loading.

Reduced strength performance is observed when the relief between endurance and strength training is shorter (≤ 60 min; Table 10.1). Additionally, reduced strength performance has been observed following longer relief periods of 2, 4, 6, and 8 h [31, 32, 36, 37]; in fact, impaired maximal voluntary contractions (MVC) have also been reported following relief periods of 24, 48, and 72 h [11]. This latter impairment [18], however was observed following a 90-min simulated soccer match (where the exercise stimulus is a combination of both metabolic and mechanical stressors) and represents a very different stimulus to other research. Other studies tend to employ volumes of between 30 and 60 min and intensities of 70–80% heart rate max (HR_{max}), $\dot{V}O_{2\max}$, or similar (Table 10.1). Studies which assess strength performance following relief durations of <8 h and ≥ 8 h only report strength performance to be decremented within 8 h of endurance exercise [19, 24, 31, 35]. In addition, elite kayakers have been reported to separate strength and endurance training sessions by 6–8 h to allow full glycogen restoration [1], which resulted in greater strength increases than those who performed endurance and strength training in closer proximity. Collectively, these data indicate that impairments in strength

performance are likely for ≤ 8 h following endurance loading. As such, if the primary aim of the session is for the individual to perform high quality strength training, in which the neuromuscular system is challenged by high force and/or velocity-based movements the scheduling of strength and endurance stimuli should be considered. If strength training must be conducted in close proximity to endurance training, it is perhaps more appropriate for the session to focus on fibre hypertrophy or strength endurance. Additional caveats to these considerations include the stage of the periodised plan and the training status of the individual. For instance, if the session takes place early in an individual's periodised plan or the individual has limited strength training experience and is unable to produce high levels of contractile force, the aforementioned considerations need not be made.

Modality, Volume, and Intensity of Endurance and Strength Loading

As previously stated, the research tends to employ endurance volumes of between 30 and 60 min at intensities of 70–80% HR_{max} , $\dot{V}O_{2max}$, or similar, prior to strength training. The primary endurance training modality employed in these studies is cycle ergometry [7, 8, 15, 16, 19, 22, 26, 31–33, 35–37] with some others [10, 15, 17, 20, 23, 24, 28, 29, 37] employing running (Table 10.1). Thus, at face value, the mode of endurance exercise does not determine the impaired strength performance. This is perhaps surprising as a meta-analysis has indicated that concurrent training with running, but not with cycling results in the inhibition of lower body strength development [47]. It was proposed that this may be attributable to the greater eccentric loading associated with running and possibly the fact cycling involves biomechanical movement patterns with greater similarity to many of the compound lifts employed as measures of lower body strength [48, 49]. However, as previously stated the modality of endurance loading does not appear to influence subsequent strength performance in an acute setting.

Although the presence of any reduced strength performance following endurance exercise appears to be independent of the modality of endurance stimulus, the method and muscle group in which strength is assessed does influence strength impairment. Upper body strength may be unaffected by prior primarily lower-body endurance loading; previous work has reported decreased lower, but not upper, body strength following lower limb endurance activity such as running [17, 29], elliptical training [21], and cycling [22, 31]. Consequently, for such impaired strength performance to occur, the endurance exercise needs to be body part specific; insofar as lower body endurance exercise might influence subsequent lower body strength, but not upper body strength performance. As such, it may be suggested that endurance training modalities such as rowing and arm crank cycling may result in reduced upper body strength performance.

Decremented strength performance has been observed following 15 [15], 20 [28], 30 [7, 10, 19, 21, 26, 32, 35], 36 [31], 45 [22], 60 [20, 23], 75 [37], 90 [11], 120 [33], and 150 min [36] of endurance loading. As such, the volume of endurance

loading does not appear to be a primary determinant for subsequent impairment of strength performance. However, it is possible that the volume of endurance exercise influences the recovery time course of strength performance. Following 90 min of a simulated soccer game, strength (as assessed via knee extension MVC) performance has been reported to be impaired for up to 72 h [11]. As previously stated, following shorter durations of endurance loading strength performance typically returns to “baseline” within 8 h of endurance loading [19, 24, 31, 35]. However, it is also likely that the intensity of the simulated soccer match was a higher intensity than the other endurance exercise.

Few studies directly compared intensities of endurance exercises on subsequent strength-type performance. Lemos et al. [28] observed greater impairments in leg press, knee extension, and leg curl 10 repetition maximum (RM) reps to failure following 20 min of treadmill running at 80% HR_{\max} than the same volume of running at 60% HR_{\max} . Whilst this may indicate that higher intensities of endurance exercise can result in greater reduction of strength performance, it should be noted that this observation was made exclusively in a physically active yet elderly female population. Different responses may have been observed in a more highly trained cohort whom are more accustomed to higher intensity endurance loading, thus a reduction in strength is perhaps less likely. During self-paced endurance exercise, the intensity and volume of the exercise may influence the contributions of central and peripheral fatigue. Following a higher intensity, shorter duration 4 km time trial (TT) impaired strength and peripheral dominant fatigue mechanisms have been observed. Following higher volume and lower intensity TTs of 20 and 40 km impaired strength was still observed yet central fatigue mechanisms were dominant [16]. This finding may suggest an intensity and volume-dependent influence on the neuromuscular underpinnings to fatigue and impaired strength performance following endurance exercise.

Direct comparisons are available between continuous and intermittent endurance exercise [17, 29, 31, 36] and subsequent strength performance. This line of work has yielded equivocal findings, with impaired strength performance being observed following both continuous and intermittent endurance exercises [31, 36], intermittent but not continuous endurance exercise [29] and vice versa [17]. As such, the influence of it may be suggested that it is neither the continuous nor intermittent nature of the endurance exercise, which influences any impaired strength performance. The available evidence based suggests that mode of exercise (intermittent and continuous) is not the determining factor, but rather that engaging in endurance exercise per se results in potential detriments in strength performance. This suggestion is supported by the fact that both de Salles Painelli et al. [17] and de Souza et al. [29] employed identical intermittent and continuous endurance exercises in comparable cohorts, yet de Souza et al. [29] observed strength performance only to be reduced following intermittent endurance exercise, whereas de Salles Painelli et al. [17] reported leg press reps to failure only to be lower following continuous endurance exercise.

As previously discussed, various relief periods, modalities, intensities, and volumes of endurance exercise have been employed in research (Table 10.1). Although some of the aforementioned programme variables appear to influence strength performance following endurance exercise (particularly the relief period), it is also

important to note the method in which strength is assessed can have a noteworthy influence on how strength-type performance is interpreted. Many studies assess subsequent strength performance via reps to failure at a specified relative load [15, 17, 21, 22, 24, 26, 28, 29, 31], others employ more high-intensity measures such as 1–5 RM/MVC [5, 8, 11, 16, 17, 19, 20, 23, 32–36, 50] and few utilise more “realistic” strength training protocols [10, 13]. These measures represent different strength qualities, with reps to failure being indicative of strength endurance, and 1–5 RM/MVC representing maximal strength. Nonetheless, inhibited strength endurance, maximal strength both occur following endurance exercise (Table 10.1). Few studies employed measures of both strength endurance and maximal strength following the same endurance and strength loading protocols. As such, it is difficult to make definitive statements regarding which quality is more susceptible to endurance-induced fatigue. Previously, work has indicated that more explosive, “power”, and/or velocity-based phenotypes are more susceptible to endurance exercise-induced decrements in performance than maximal strength and strength endurance indices [9, 51–53]. This finding is, at least in part, supported by observations that impairments in rate of force development (RFD) in the isometric leg press [23] and countermovement jump height (CMJ) [20] following 60 min of running. As previously stated, upper body strength training following endurance exercise (primarily involving the lower body musculature) remained unimpaired [17, 21, 22, 29, 31]. This may indicate peripheral fatigue at, or distal to the neuromuscular junction, to be a major contributing factor to any decremented in lower body strength performance. Based on these observations, it can be recommended that high velocity and explosive lower body phenotypes should be trained independently from any endurance stimulus.

There is limited evidence to suggest that in acute settings strength performance is not inhibited by prior endurance exercise. Research in which strength performance remains unimpaired post-endurance exercise has assessed strength performance via isolated limb actions such as knee extension [5, 13, 34]. However, in the larger body of evidence, strength performance is reduced following endurance exercise when assessed via multi joint exercises such as squats [8, 10, 15, 21, 22, 24] or leg press [7, 17, 19, 20, 23, 26, 28, 29, 31], which also has a greater applicability to athletes, coaches, and practitioners. Therefore, it is reasonable to suggest that multi joint movements involving large amounts of muscle mass are more susceptible to endurance exercise-induced fatigue than isolated limb single joint movements.

Post-activation Potentiation

Notwithstanding the previous issues relating to strength performance, there is some suggestion that performing an endurance-type stimulus can have a potentiating effect and thus a positive acute effect on strength performance [12, 14, 18, 25, 27, 30]. However, this has been reported almost exclusively in trained endurance athletes. Consequently, it appears that those accustomed to endurance loading are perhaps more fatigue resistant to endurance exercise than strength-trained individuals in the acute period following endurance stimulus. Furthermore, in the case of highly

endurance-trained individuals, a prior bout of endurance loading acts as a warm up or “primer” resulting in improved ability to generate force; the same is not true for those whom are not highly endurance trained.

Summary

The relief duration between endurance and strength-type loadings appears to be the primary determinant for any decrement in strength performance. Typically, acute strength performance returns to baseline ≥ 8 h following endurance exercise and therefore if strength sessions follow endurance, then a period of relief of not less than 8 h seems pragmatic to optimise the performance in the strength training.

Reduced strength performance appears to be independent of the endurance modality (cycling or running) and of a continuous or intermittent nature. Impaired strength performance is observed following both; lower volume higher intensity and higher volume lower intensity endurance exercise. Whilst the presence of decremented strength performance appears to be independent of volume and intensity of endurance exercise, the contributions of central and peripheral fatigue are not. Peripheral fatigue mechanisms are dominant following lower volume higher intensity endurance exercise and central fatigue mechanisms are dominant following higher volume lower intensity endurance exercise.

Upper body strength remains unimpaired following lower body endurance exercise. Lower body multi joint movements involving higher muscle mass and velocity based/explosive movements are likely the most susceptible to endurance exercise-induced impairments in strength-type performance (Fig. 10.2).

Implications for Programming

Whilst not recommended practice, due to logistical and scheduling constraints both elite athletes and recreational exercisers will perform strength training subsequent, and in close proximity to, endurance exercise. As detailed in this chapter, this structure will likely lead to some degree of impaired strength performance, particularly when conducted within 8 h of endurance exercise and during lower body lifts that require the engagement of larger volumes of muscle mass. Therefore, if high quality strength training and strength development are the primary aims of the training intervention or macro/meso/micro cycle practitioners seeking to optimise performance during strength training should consider the following:

- Where possible perform strength training ≥ 8 h after any endurance exercise.
- If strength training must be performed in close proximity to lower body endurance exercise, the session should focus on upper body strength development.
- If strength training must be performed in close proximity to lower body endurance exercise, the session should avoid lower body explosive and velocity-based movements and multi joint lifts involving large amounts of muscle mass.

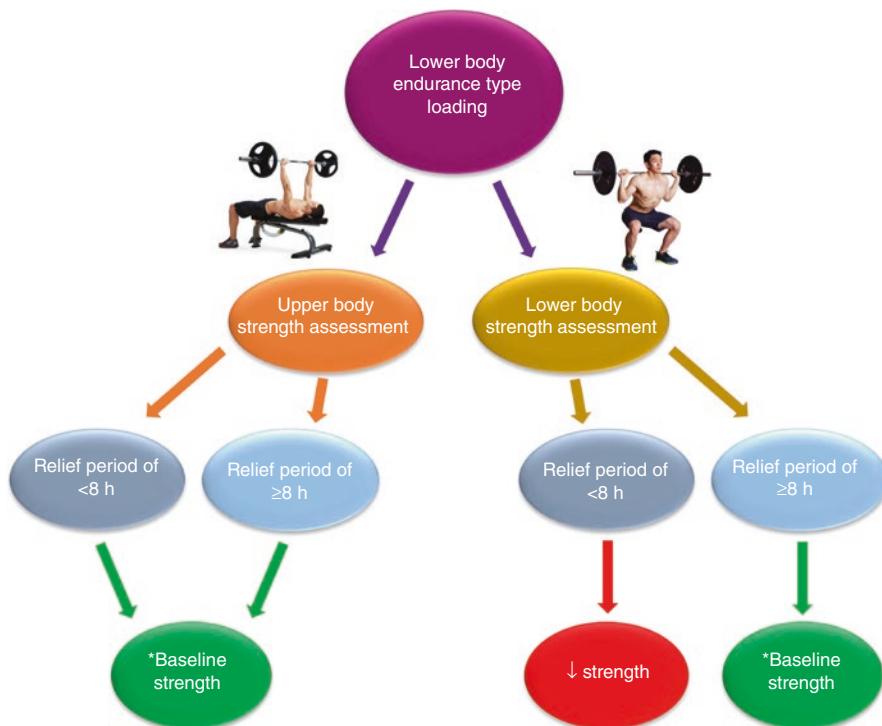


Fig. 10.2 Schematic representation of the “typical” influence of prior endurance loading on subsequent strength performance. Previous work detailed throughout this chapter has indicated that the method by which strength performance is assessed and the relief period are the primary determinants of acute strength performance following endurance loading. *Baseline = prior any endurance loading

It should be noted that it is likely not feasible to implement these evidence-based recommendations year-round, nor is it necessary to. However, during pre-season or pre-competition periods in which practitioners and athletes may be seeking to optimise longer term athletic strength development or enhance velocity-based phenotypes the recommendations here should be considered.

References

1. García-Pallarés J, Sánchez-Medina L, Carrasco L, Díaz A, Izquierdo M. Endurance and neuromuscular changes in world-class level kayakers during a periodized training cycle. *Eur J Appl Physiol*. 2009;106:629–38.
2. Wong P, Chaouachi A, Chamari K, Dellal A, Wisloff U. Effect of preseason concurrent muscular strength and high-intensity interval training in professional soccer players. *J Strength Cond Res*. 2010;24:653–60.
3. Marta C, Marinho DA, Barbosa TM, Izquierdo M, Marques MC. Effects of concurrent training on explosive strength and VO(2max) in prepubescent children. *Int J Sports Med*. 2013;34:888–96.

4. Hendrickson NR, Sharp MA, Alemany JA, et al. Combined resistance and endurance training improves physical capacity and performance on tactical occupational tasks. *Eur J Appl Physiol.* 2010;109:1197–208.
5. Goto K, Higashiyama M, Ishii N, Takamatsu K. Prior endurance exercise attenuates growth hormone response to subsequent resistance exercise. *Eur J Appl Physiol.* 2005;94:333–8.
6. Balabinis CP, Psarakis CH, Moukas M, Vassiliou MP, Behrakis PK. Early phase changes by concurrent endurance and strength training. *J Strength Cond Res.* 2003;17:393–401.
7. Eklund D, Schumann M, Kraemer WJ, Izquierdo M, Taipale RS, Häkkinen K. Acute endocrine and force responses and long-term adaptations to same-session combined strength and endurance training in women. *J Strength Cond Res.* 2016;30:164–75.
8. Leveritt M, Abernethy PJ. Acute effects of high-intensity endurance exercise on subsequent resistance activity. *J Strength Cond Res.* 1999;13:47–51.
9. Craig B, Lucas J, Pohlman R, Stelling H. The effects of running, weightlifting and a combination of both on growth hormone release. *J Strength Cond Res.* 1991;5:198–203.
10. Jones TW, Howatson G, Russell M, French DN. Effects of strength and endurance exercise order on endocrine responses to concurrent training. *Eur J Sport Sci.* 2017;17:326–34.
11. Thomas K, Dent J, Howatson G, Goodall S. Etiology and recovery of neuromuscular fatigue after simulated soccer match play. *Med Sci Sports Exerc.* 2017;49:955–64.
12. García-Pinillos F, Molina-Molina A, Latorre-Román PÁ. Impact of an incremental running test on jumping kinematics in endurance runners: can jumping kinematic explain the post-activation potentiation phenomenon. *Sports Biomech.* 2016;15:103–15.
13. Jones TW, Walshe IH, Hamilton DL, Howatson G, Russell M, Price OJ, Gibson ASC, French DN. Signaling responses after varying sequencing of strength and endurance training in a fed state. *Int J Sports Physiol Perform.* 2016;11:868–75.
14. García-Pinillos F, Soto-Hermoso VM, Latorre-Román PA. Acute effects of extended interval training on countermovement jump and handgrip strength performance in endurance athletes: postactivation potentiation. *J Strength Cond Res.* 2015;29:11–21.
15. Panissa VLG, Tricoli VAA, Julio UF, Ribeiro N, de Azevedo Neto RMA, Carmo EC, Franchini E. Acute effect of high-intensity aerobic exercise performed on treadmill and cycle ergometer on strength performance. *J Strength Cond Res.* 2015;29:1077–82.
16. Thomas K, Goodall S, Stone M, Howatson G, St Clair Gibson A, Ansley L. Central and peripheral fatigue in male cyclists after 4-, 20-, and 40-km time trials. *Med Sci Sports Exerc.* 2015;47:537–46.
17. de Salles Painelli V, Alves VT, Ugrinowitsch C, Benatti FB, Artioli GG, Lancha AH, Gualano B, Roschel H. Creatine supplementation prevents acute strength loss induced by concurrent exercise. *Eur J Appl Physiol.* 2014;114:1749–55.
18. Latorre-Román PÁ, García-Pinillos F, Martínez-López EJ, Soto-Hermoso VM. Concurrent fatigue and postactivation potentiation during extended interval training in long-distance runners. *Motriz Rev Educ Fís.* 2014;20:423–30.
19. Schumann M, Walker S, Izquierdo M, Newton RU, Kraemer WJ, Häkkinen K. The order effect of combined endurance and strength loadings on force and hormone responses: effects of prolonged training. *Eur J Appl Physiol.* 2014;114:867–80.
20. Taipale RS, Schumann M, Mikkola J, Nyman K, Kyröläinen H, Nummela A, Häkkinen K. Acute neuromuscular and metabolic responses to combined strength and endurance loadings: the “order effect” in recreationally endurance trained runners. *J Sports Sci.* 2014;32:1155–64.
21. Tan JG, Coburn JW, Brown LE, Judelson DA. Effects of a single bout of lower-body aerobic exercise on muscle activation and performance during subsequent lower- and upper-body resistance exercise workouts. *J Strength Cond Res.* 2014;28:1235–40.
22. Reed JP, Schilling BK, Murlasits Z. Acute neuromuscular and metabolic responses to concurrent endurance and resistance exercise. *J Strength Cond Res.* 2013;27:793–801.
23. Taipale RS, Häkkinen K. Acute hormonal and force responses to combined strength and endurance loadings in men and women: the “order effect”. *PLoS One.* 2013;8:e55051.

24. Panissa VLG, Ferreira Julio U, Pinto e Silva C, Vidal Andreato L, Hardt F, Franchini E. Effects of interval time between high-intensity intermittent aerobic exercise on strength performance: analysis in individuals with different training background. *J Hum Sport Exerc.* 2012;7:815–25.
25. Boullosa DA, Tuimil JL, Alegre LM, Iglesias E, Lusquiños F. Concurrent fatigue and potentiation in endurance athletes. *Int J Sports Physiol Perform.* 2011;6:82–93.
26. de Araújo Ruas VD, Figueira TR, Denadai BS, Greco CC. Effect of cycling exercise at different pedal cadences on subsequent muscle strength. *J Exerc Sci Fit.* 2011;9:93–9.
27. Boullosa DA, Tuimil JL. Postactivation potentiation in distance runners after two different field running protocols. *J Strength Cond Res.* 2009;23:1560–5.
28. Lemos A, Simão R, Polito M, Salles B, Rhea MR, Alexander J. The acute influence of two intensities of aerobic exercise on strength training performance in elderly women. *J Strength Cond Res.* 2009;23:1252–7.
29. de Souza EO, Tricoli V, Franchini E, Paulo AC, Regazzini M, Ugrinowitsch C. Acute effect of two aerobic exercise modes on maximum strength and strength endurance. *J Strength Cond Res.* 2007;21:1286–90.
30. Vuorimaa T, Virlander R, Kurkilahti P, Vasankari T, Häkkinen K. Acute changes in muscle activation and leg extension performance after different running exercises in elite long distance runners. *Eur J Appl Physiol.* 2006;96:282–91.
31. Sporer BC, Wenger HA. Effects of aerobic exercise on strength performance following various periods of recovery. *J Strength Cond Res.* 2003;17:638–44.
32. Bentley DJ, Smith PA, Davie AJ, Zhou S. Muscle activation of the knee extensors following high intensity endurance exercise in cyclists. *Eur J Appl Physiol.* 2000;81:297–302.
33. Lepers R, Hausswirth C, Maffiuletti N, Brisswalter J, van Hoecke J. Evidence of neuromuscular fatigue after prolonged cycling exercise. *Med Sci Sports Exerc.* 2000;32:1880–6.
34. Leveritt M, MacLaughlin H, Abernethy PJ. Changes in leg strength 8 and 32 h after endurance exercise. *J Sports Sci.* 2000;18:865–71.
35. Bentley DJ, Zhou S, Davie AJ. The effect of endurance exercise on muscle force generating capacity of the lower limbs. *J Sci Med Sport.* 1998;1:179–88.
36. Abernethy PJ. Influence of acute endurance activity on isokinetic strength. *J Strength Cond Res.* 1993;7:141–6.
37. Jacobs I, Kaiser P, Tesch P. Muscle strength and fatigue after selective glycogen depletion in human skeletal muscle fibers. *Eur J Appl Physiol Occup Physiol.* 1981;46:47–53.
38. Gandevia SC. Spinal and supraspinal factors in human muscle fatigue. *Physiol Rev.* 2001;81:1725–89.
39. Enoka RM, Stuart DG. Neurobiology of muscle fatigue. *J Appl Physiol.* 1992;72:1631–48.
40. Amann M. Central and peripheral fatigue: interaction during cycling exercise in humans. *Med Sci Sports Exerc.* 2011;43:2039–45.
41. Decorte N, Lafaix PA, Millet GY, Wuyam B, Verges S. Central and peripheral fatigue kinetics during exhaustive constant-load cycling. *Scand J Med Sci Sports.* 2012;22:381–91.
42. Lepers R, Maffiuletti NA, Rochette L, Brugniaux J, Millet GY. Neuromuscular fatigue during a long-duration cycling exercise. *J Appl Physiol.* 2002;92:1487–93.
43. Place N, Lepers R, Deley G, Millet GY. Time course of neuromuscular alterations during a prolonged running exercise. *Med Sci Sports Exerc.* 2004;36:1347–56.
44. Ross EZ, Middleton N, Shave R, George K, Nowicky A. Corticomotor excitability contributes to neuromuscular fatigue following marathon running in man. *Exp Physiol.* 2007;92:417–26.
45. Bigland-Ritchie B, Kukulka CG, Lippold OC, Woods JJ. The absence of neuromuscular transmission failure in sustained maximal voluntary contractions. *J Physiol.* 1982;330:265–78.
46. Schillings ML, Hoefsloot W, Stegeman DF, Zwarts MJ. Relative contributions of central and peripheral factors to fatigue during a maximal sustained effort. *Eur J Appl Physiol.* 2003;90:562–8.
47. Wilson JM, Marin PJ, Rhea MR, Wilson SMC, Loenneke JP, Anderson JC. Concurrent training: a meta-analysis examining interference of aerobic and resistance exercises. *J Strength Cond Res.* 2012;26:2293–307.

48. Escamilla RF. Knee biomechanics of the dynamic squat exercise. *Med Sci Sports Exerc.* 2001;33:127–41.
49. Gergley JC. Comparison of two lower-body modes of endurance training on lower-body strength development while concurrently training. *J Strength Cond Res.* 2009;23:979–87.
50. Eklund D, Pulverenti T, Bankers S, Avela J, Newton R, Schumann M, Häkkinen K. Neuromuscular adaptations to different modes of combined strength and endurance training. *Int J Sports Med.* 2015;36:120–9.
51. Jones TW, Howatson G, Russell M, French DN. Performance and endocrine responses to differing ratios of concurrent strength and endurance training. *J Strength Cond Res.* 2016;30:693–702.
52. Dudley GA, Djamil R. Incompatibility of endurance- and strength-training modes of exercise. *J Appl Physiol.* 1985;59:1446–51.
53. Häkkinen K, Alen M, Kraemer WJ, et al. Neuromuscular adaptations during concurrent strength and endurance training versus strength training. *Eur J Appl Physiol.* 2003;89:42–52.



Acute Effects of Strength Exercise on Subsequent Endurance Performance

11

Kenji Doma

Introduction

There is a growing body of literature demonstrating the benefits of adding strength training to a progressive endurance training programme [1–3]. Some of the postulated mechanisms that are responsible for optimising endurance development as a result of strength training include changes in muscle fibre type recruitment, increased muscular contractility, a reduction in the proportion of type 2X fibres, and a shift toward muscle phenotypes that are fatigue resistant yet powerful [2, 4]. Although coaches are encouraged to implement strength training for endurance athletes, if appropriate recovery is not accounted for between each mode of training session, carry-over effects of fatigue can be induced from strength training sessions and negatively impact on the ability to perform optimally during subsequent endurance training sessions [5–7].

In fact, a number of studies have previously shown deterioration on indices of performance measures [5–11]. A summary of these findings is presented in Table 11.1. Therefore, continually experiencing strength training-induced fatigue during subsequent endurance training sessions may impair the quality of endurance training sessions and possibly lead to a state of over-reaching, overtraining, or injuries [17, 18], all of which are not beneficial in optimising endurance development. For example, studies have shown that strength training-induced fatigue reduces time-trial performances [13] and time-to-exhaustion [6, 7] whilst increase physiological cost of exercise (e.g. oxygen consumption and heart rate) and rating of perceived exertion at a constant sub-maximal intensity [8, 19]. If endurance athletes are

K. Doma

Division of Tropical Health and Medicine, College of Healthcare Sciences, James Cook University, Townsville, QLD, Australia
e-mail: kenji.doma@jcu.edu.au

Table 11.1 The summary of findings based on studies that have examined the acute effects of a single bout of strength training on subsequent endurance performance

Study	Sample	Training background	Strength training exercises	Endurance performance measures	Results
Deakin [12]	Males (n = 9)	Highly trained cyclists who also had been undertaking strength training	Incline leg press at 6RM for 6 repetition of 4–6 sets	Cycling efficiency test	Significant impairment in cycling efficiency 3 h post strength training
Burt and Twist [13]	Males (n = 7) Females (n = 1)	Recreationally active collegiate students undertaking 2 endurance training sessions per week with no exposure to strength training for 6 months	Plyometric vertical jump exercises for 10 repetitions of 10 sets	Cycling time-trial performance	Significant reduction in cycling distance covered for up to 48 h post plyometric training
Gee et al. [14]	Male (n = 7)	Highly trained club rowers who also had been undertaking strength training	Snatch, clean, back squat, deadlift, bench press, bench pull and weighted sit-ups at 75–85% of 1RM for 5–15 repetitions of 3–4 sets	Rowing time-trial performance	No changes in rowing time-trial performance measures 24 h post strength training
Doma and Deakin [6]	Males (n = 14)	Trained and moderately trained runners with no exposure to strength training for 6 months	Incline leg press, leg extension, and leg curls performed at 6RM for 6 repetitions of 4–6 sets	RE and running TTE	No changes in $\dot{V}O_2$, but significant reduction in running TTE for up to 24 h post strength training
Burt et al. [8]	Males (n = 9)	Healthy individuals partaking in 2–3 endurance sessions per week	Back squats at 80% of body mass for 10 sets of 10 repetitions	Running economy	Significant increase in $\dot{V}O_2$ for up to 48 h post strength training

Doma and Deakin [7]	Males (n = 15)	Moderately trained runners with no exposure to strength training for 6-months	Incline leg press, bench press, and bench pulls performed with a condition at high intensity (3 sets of 6 repetitions at 6RM) and low intensity (3 sets of 20 repetitions with load equated for work)	RE and running TTE	No changes in VO_2 , but significant reduction in running TTE for up to 6 h post strength training following the high intensity strength training session. No changes observed following the low intensity strength training session
Doma et al. [15]	Males (n = 14)	Healthy individuals partaking in 2–3 running sessions per week with no exposure to strength training for 6 months	Back squats, single-leg leg horizontal leg press, leg extension, and leg curls at 6RM for 6 repetitions of 3 sets	RE and running TTE	No changes in VO_2 , but significant increase in RPE during the RE test reduction in running TTE for up to 24 h post strength training
Doma and Deakin [5]	Males (n = 16) Females (n = 8)	Moderately trained runners with no exposure to strength training for 6 months	Incline leg press, leg extension, and leg curls performed at 6RM for 6 repetitions of 4–6 sets	RE and running TTE	No changes in VO_2 , but significant increase in RPE during the RE test and reduction in running TTE for up to 24 h post strength training
Doma et al. [16]	Males (n = 12)	Healthy individuals partaking in 2–3 running sessions per week with no exposure to strength training for 6 months	Back squats, single-leg leg horizontal leg press, leg extension, and leg curls at 6RM for 6 repetitions of 3 sets	RE and running TTE	No changes in VO_2 , but significant increase in RPE during the RE test and reduction in running TTE for up to 24 h post strength training

to train in such a state, they may experience difficulty in covering particular distances, compromise pacing and/or struggle to meet training goals for the session.

Whilst there is strong evidence to suggest that strength training-induced fatigue acutely impairs endurance performance, the magnitude of this phenomenon appears to be dependent on the strength training background, training intensity, and the recovery period following a strength training exercise. Therefore, this chapter will discuss the impact of strength training-induced fatigue on endurance performance and how strength training background and training variables (i.e. intensity, volume, and recovery) may affect this phenomenon. Finally, a number of recommendations are provided for coaches to minimise the carry-over effects of fatigue induced by strength training sessions on subsequent endurance training sessions.

Strength and Endurance Training Background

Strength Training Background

The recovery dynamics following a strength training session is highly dependent on the level of exposure to previous strength exercises [20–23]. The magnitude of muscle damage and neuromuscular fatigue is attenuated following the initial bout of strength exercises in individuals who have not previously been exposed to strength exercises, known as the repeated bout effect (RBE) [24]. In addition, the magnitude of muscle damage and impaired muscular contractility is greater acutely post strength exercises for strength-untrained individuals compared to strength-trained individuals [25]. Therefore, strength training background has a marked influence on the impact of strength training-induced fatigue on subsequent endurance performance. For example, typical lower body strength training sessions (e.g. squats and leg press) at moderate-to-high intensities have been shown to impair running economy measures for up to 48 h post in strength-untrained individuals [8, 15]. However, running economy measures have also been reported to remain unchanged 6–8 h following similar strength training protocols in strength-trained individuals [7, 19].

Based on the RBE phenomenon, individuals with previous strength training exposure may experience less fatigue following strength training. However, this is not to suggest that strength training-induced fatigue is completely avoidable, given that muscle damage and attenuation in muscle function have been observed for up to 48 h following strength training sessions in individuals previously exposed to strength trained [26–28]. Furthermore, studies have shown that running economy measures were still impaired for up to 48 h following two strength training bouts [5] and running time-to-exhaustion impaired for 24 h following three strength training bouts [16]. These findings suggest that muscle damage and neuromuscular fatigue can still occur in strength-trained individuals, and that strength training-induced fatigue is not avoidable despite increasing the number of strength training bouts in strength-untrained individuals, particularly for running performance measures.

Our previous studies have also shown that running time-to-exhaustion was impaired 24 h following a lower body strength training session in moderately

endurance-trained runners despite these participants having been exposed to a flush-out period (i.e. undertaking a number of strength training sessions prior to study commencement to alleviate possible RBE effects during the course of the study) [5, 9]. Accordingly, if incorporating endurance training sessions for individuals with minimal exposure to previous strength training, extra care should be taken for at least 48 h post exercise.

Endurance Training Background

In comparison to strength training background, there has been limited research examining the effects that endurance training background has on the magnitude of acute strength training-induced attenuation on endurance performance. In a study by Skurvydas et al. [29], indirect muscle damage markers (i.e. muscle soreness, creatine kinase [CK], and isokinetic torque) were measured prior to and 48 h following eccentric knee extension exercises separately for endurance-trained and -untrained individuals. The results showed that the magnitude of reduction in isokinetic torque was significantly greater for the untrained individuals compared to their endurance-trained counterparts, despite no differences between groups in muscle soreness and CK. Similarly, Snieckus et al. [30] reported no changes in muscle soreness and CK values between endurance-trained and -untrained individuals, despite a greater reduction in muscle force generation capacity for untrained individuals for up to 48 h following eccentric knee contractions. Collectively, these findings suggest that endurance-trained individuals appear to be more resistant to symptoms of exercise-induced muscle damage (EIMD) with respect to muscle function compared to their untrained counterparts. However, these studies brought about EIMD via isokinetic knee contractions, as opposed to traditional resistance exercises that involve both concentric and eccentric contractions. In addition, neither of these studies [29, 30] compared the effects of EIMD on endurance performance measures (e.g. running economy, running time-to-exhaustion) between endurance-trained and -untrained individuals. Therefore, more research is necessary to make specific recommendations for endurance-untrained individuals when commencing both strength and endurance training simultaneously. Nonetheless, given that we have previously reported associations between reduction in muscle force generation capacity and measures of running performance [5–7, 9, 15, 16], a greater degree of caution should be taken with EIMD for individuals that are both strength and endurance untrained, particularly when commencing a concurrent training programme.

Strength and Endurance Training Intensity

Strength Training Intensity

The neuromuscular characteristics differ substantially during strength training sessions performed between heavy and light loads. For example, strength training

sessions prescribed with heavier loads to optimise muscular strength development (i.e. $\geq 85\%$ of 1RM) will result in greater motor unit recruitment, synchronously at higher frequencies [31]. Alternatively, strength training sessions with lighter loads typically would favour recruitment of fewer motor units in a more sequential manner to sustain contractions for longer [31]. Therefore, greater physiological stress is imposed on the neuromuscular system for each repetition during strength training sessions with heavier loads. In line with this conjecture, Thornton and Pottiger [32] showed greater excess post-exercise oxygen consumption following high intensity strength training (8 repetitions at 85% of 8RM) compared to low intensity strength training (15 repetitions at 45% of 8RM) whilst equating for work volume using 9 typical strength exercises. The authors postulated that high intensity strength training may have resulted in greater motor unit recruitment, thereby causing disturbances to the metabolic system. Whilst Thornton and Pottiger [32] only measured physiological responses at rest, the distinct neuromuscular characteristics between different strength training intensities may have profound effects on the way in which strength training-induced fatigue impacts on subsequent endurance performance.

A study conducted by Deakin [12] examined the acute effects of different strength training intensities on sub-maximal cycling performance in strength-trained participants. The participants performed both high (i.e. 6RM) and low intensity (6 sets of 20 repetitions) lower body strength exercises in a counter-balanced, randomised order. Each strength training bout was equated for work with a cycling efficiency test conducted 3 h post strength exercise. The results showed that the high intensity strength training bout increased the physiological cost of cycling to a greater extent than the low intensity strength training bout. Similarly, we also investigated the impact of strength training intensity whilst equating for strength training work, but on sub-maximal and maximal running performance measures 6 h post strength exercise in strength-trained individuals [7]. The findings showed that neither strength training bout impacted on running economy measures (i.e. running at 90% of anaerobic threshold). However, high intensity strength training impaired running time-to-exhaustion (i.e. running at 110% of anaerobic threshold) despite these measures being unaffected post low intensity strength training.

According to the findings by Deakin [12] and our own study [7], it appears that high intensity strength training sessions may acutely impair indices of endurance performance to a greater extent than that of lower intensity when both intensities are equated for work. More recently, Bartolomei et al. [33] reported greater attenuation in muscle force generation capacity and vertical jump performance measures for 48 h following a bout of low intensity, high volume strength exercise compared to a bout of high intensity, low volume strength exercise in strength-trained individuals. Whilst these findings contradict those of Deakin [12] and [7], the work performed by participants in the study by Bartolomei et al. [33] was approximately double during the bout with high volume, low intensity strength exercises. Furthermore, the physical performance measures were based on muscle force production, which makes reference to indices of endurance performance difficult. Nonetheless, these contradictory findings highlight the importance of equating work when examining the acute effects of strength training intensity in a controlled setting. In addition, the results by Deakin [12] and [7] demonstrate the need to take caution when

undertaking endurance exercises within hours post strength exercises, particularly following high intensity strength exercises. It is also important to note that typical low intensity strength training sessions (e.g. 3–4 sets of 12–15 repetitions at 50–65% of 1RM) may encompass a greater work volume compared to very high intensity strength training sessions (e.g. 4–5 sets of 1–3 repetitions at 90–100% of 1RM). Therefore, appropriate recovery should also be considered following low intensity strength training if undertaken with a very high volume.

Endurance Training Intensity

Acutely following strength training, the intensity of endurance exercises could be manipulated in order to minimise the impact of strength training-induced fatigue on subsequent endurance training sessions. Several studies have shown that attenuation of running performance measures are augmented during periods of strength training-induced fatigue at higher endurance exercise intensities [5, 7, 9]. For example, we showed no effect on running economy measures several hours to days post strength training although running time-to-exhaustion was impaired [7, 15]. These findings have also been confirmed by others following downhill running [34], further demonstrating the increased sensitivity to changes in endurance performance measures at higher intensities during periods of muscular fatigue.

It has been postulated that the attenuation in indices of endurance performance at greater intensities may be due to differences in muscle fibre recruitment patterns [34]. Indeed, type 1 muscle fibres are primarily recruited when exercising below the anaerobic threshold, whereas a greater number of type 2 fibres are recruited at exercise intensities above the anaerobic threshold [35, 36]. Given that strength exercises have been shown to cause greater muscle damage in type 2 as compared to type 1 muscle fibres, it is plausible to assume that the ability recruit type 2 fibres are impaired, and as a result, strength training-induced fatigue may compromise endurance performance at higher intensities. Subsequently, caution should be taken when prescribing endurance training sessions at higher intensities, particularly above the anaerobic threshold, during periods of strength training-induced fatigue. Appropriate progression and periodization of concurrent training programme prescription by incorporating a low intensity endurance training session several hours to days following a strength training session may minimise possible negative effects on endurance performance, thereby optimising the quality of endurance training sessions and eventually chronic cardiorespiratory adaptations.

Recovery Following Strength Training

Appropriate recovery in-between strength and endurance training sessions must be accounted for to minimise the carry-over effects of fatigue from one mode of training to the next, when implementing a concurrent training programme. Indeed, the duration of recovery required in-between each mode of training session is dependent on the training variables, particularly the mode of exercise. A typical endurance training

session with durations of 40–60 min will allow muscular contractility to recover within hours post exercise [37, 38]. In contrast, heavy strength exercises have been shown to impair muscular contractility for up to 96 h post [39, 40], deplete muscle glycogen for up to 6 h post [12] and possibly induce muscle damage from as early as 8 h and up to 72 h post [41], all of which impair indices of endurance performance [42].

Several studies have examined the time course recovery acutely following strength exercises on indices of endurance performance. Whilst research in the acute impact of typical strength training on cycling performance is limited, Deakin [12] did examine sub-maximal cycling performance and muscular contractility 3 h following a high intensity lower body strength training session (i.e. incline leg press) at 6RM in trained cyclists with strength training backgrounds. The results showed impaired sub-maximal cycling performance with a concomitant reduction in muscle force production. Similar trends have been observed in several studies on running performance measures. For example, [19] investigated the acute effects of a whole body strength training session (i.e. bench press, squat, upright row, deadlift, seated row, and abdominal exercises) at 8RM on running economy measures 8 and 24 h post exercise in well-trained distance runners with strength training backgrounds. The results showed that running economy was impaired 8 h post although returned to baseline values by 24 h post. We also showed impaired running economy 6 h following a lower body strength training session (i.e. incline leg press, leg extension, and leg curls) at 6RM in moderately trained runners with strength training experience [9]. Using a similar strength training protocol, running economy was not impaired 24 h post exercise, although a reduction was observed in running time-to-exhaustion (i.e. at 110% of anaerobic threshold) [5, 7] in moderately trained runners with strength training experience. In strength-untrained individuals, typical lower body strength training sessions have been shown to impair running economy measures for 48 h post exercise [15].

According to the above-mentioned findings, at least 8 h of recovery may be required in order to not negatively affect endurance performance measurements following a typical strength training session for endurance athletes with strength training experience. However, several days of recovery may be needed for endurance athletes with minimal background in strength training, or in strength de-trained endurance athletes. Regardless of training background, more than 24 h of recovery may be needed to avoid reduced performance following a strength training session if implementing a high intensity endurance training session (i.e. above anaerobic threshold). However, even though acute impairment of measurements related to endurance performance has been observed, that does not mean that there is no training effect of the sessions.

Summary

In conclusion, strength training-induced fatigue can be sustained for several days post-exercise, which appears to have detrimental effects on endurance performance. Accordingly, when implementing an endurance training session following a strength training session, the following training scenarios may require greater recovery

periods: (1) undertaking a high intensity strength training session (e.g. $\geq 6\text{RM}$) prior to an endurance training session; (2) undertaking a high intensity endurance training session (e.g. above anaerobic thresholds) following a strength training session; (3) strength-untrained individuals; (4) individuals with previous experience in strength training but have not undertaken strength training for several months; and (5) endurance-untrained individuals. The extent to which a bout of strength training may impact on the quality of a subsequent endurance training session may be dependent on the degree of each, or all of these factors. Therefore, it is important to monitor and understand the recovery dynamics of each individual prior to prescribing concurrent training for endurance athletes.

References

1. Balsalobre-Fernandez C, Santos-Concejero J, Grivas GV. Effects of strength training on running economy in highly trained runners: a systematic review with meta-analysis of controlled trials. *J Strength Cond Res.* 2016;30(8):2361–8. <https://doi.org/10.1519/JSC.00000000000001316>.
2. Ronnestad BR, Hansen EA, Raastad T. Strength training improves 5-min all-out performance following 185 min of cycling. *Scand J Med Sci Sports.* 2011;21(2):250–9. <https://doi.org/10.1111/j.1600-0838.2009.01035.x>.
3. Ronnestad BR, Mujika I. Optimizing strength training for running and cycling endurance performance: a review. *Scand J Med Sci Sports.* 2013;24(4):603–12. <https://doi.org/10.1111/sms.12104>.
4. Aagaard P, Andersen JL, Bennekou M, Larsson B, Olesen JL, Crameri R, et al. Effects of resistance training on endurance capacity and muscle fiber composition in young top-level cyclists. *Scand J Med Sci Sports.* 2011;21(6):e298–307. <https://doi.org/10.1111/j.1600-0838.2010.01283.x>.
5. Doma K, Deakin G. The acute effect of concurrent training on running performance over 6 days. *Res Q Exerc Sport.* 2015;86(4):387–96. <https://doi.org/10.1080/02701367.2015.1053104>.
6. Doma K, Deakin GB. The effects of strength training and endurance training order on running economy and performance. *Appl Physiol Nutr Metab.* 2013;38(6):651–6. <https://doi.org/10.1139/apnm-2012-0362>.
7. Doma K, Deakin GB. The acute effects intensity and volume of strength training on running performance. *Eur J Sport Sci.* 2014;14(2):107–15.
8. Burt D, Lamb K, Nicholas C, Twist C. Effects of repeated bouts of squatting exercise on submaximal endurance running performance. *Eur J Appl Physiol Occup Physiol.* 2013;113(2):285–93. <https://doi.org/10.1007/s00421-012-2437-2>.
9. Doma K, Deakin GB. The effects of combined strength and endurance training on running performance the following day. *Int J Sport Health Sci.* 2013;11:1–9.
10. Doncaster GG, Twist C. Exercise-induced muscle damage from bench press exercise impairs arm cranking endurance performance. *Eur J Appl Physiol Occup Physiol.* 2012;112(12):4135–42. <https://doi.org/10.1007/s00421-012-2404-y>.
11. Hayter KJ, Doma K, Schumann M, Deakin G. The comparison of cold-water immersion and cold air therapy on maximal cycling performance and recovery markers following strength exercises. *PeerJ.* 2016;4:e1841. <https://doi.org/10.7717/peerj.1841>.
12. Deakin BD. Concurrent training in endurance athletes: the acute effects on muscle recovery capacity, physiological, hormonal and gene expression responses post-exercise. Doctor of Philosophy, Southern Cross University, Lismore; 2004.
13. Burt DG, Twist C. The effects of exercise-induced muscle damage on cycling time-trial performance. *J Strength Cond Res.* 2011;25(8):2185–92. <https://doi.org/10.1519/JSC.0b013e3181e86148>.

14. Gee TI, French DN, Howatson G, Payton SJ, Berger NJ, Thompson KG. Does a bout of strength training affect 2,000 m rowing ergometer performance and rowing-specific maximal power 24 h later? *Eur J Appl Physiol.* 2011;111(11):2653–62. <https://doi.org/10.1007/s00421-011-1878-3>.
15. Doma K, Schumann M, Sinclair WH, Leicht AS, Deakin GB, Hakkinen K. The repeated bout effect of typical lower body strength training sessions on sub-maximal running performance and hormonal response. *Eur J Appl Physiol Occup Physiol.* 2015;115(8):1789–99. <https://doi.org/10.1007/s00421-015-3159-z>.
16. Doma K, Schumann M, Leicht AS, Heilbronn B, Damas F, Burt D. The repeated bout effect of lower body resistance exercises on running performance across three bouts. *Appl Physiol Nutr Metab.* 2017;42(9):978–85.
17. Aubry A, Hausswirth C, Louis J, Coutts AJ, Le Meyur Y. Functional overreaching: the key to peak performance during the taper? *Med Sci Sports Exerc.* 2014;46(9):1769–77. <https://doi.org/10.1249/MSS.0000000000000301>.
18. Coutts AJ, Wallace LK, Slattery KM. Monitoring changes in performance, physiology, biochemistry, and psychology during overreaching and recovery in triathletes. *Int J Sports Med.* 2007;28(2):125–34. <https://doi.org/10.1055/s-2006-924146>.
19. Palmer CD, Sleivert GG. Running economy is impaired following a single bout of resistance exercise. *J Sci Med Sport.* 2001;4(4):447–59.
20. Clarkson PM, Byrnes WC, Gillisson E, Harper E. Adaptation to exercise-induced muscle damage. *Clin Sci (Lond).* 1987;73(4):383–6.
21. Clarkson PM, Dedrick ME. Exercise-induced muscle damage, repair, and adaptation in old and young subjects. *J Gerontol.* 1988;43(4):M91–6.
22. Clarkson PM, Tremblay I. Exercise-induced muscle damage, repair, and adaptation in humans. *J Appl Physiol (1985).* 1988;65(1):1–6.
23. Ebbeling CB, Clarkson PM. Exercise-induced muscle damage and adaptation. *Sports Med.* 1989;7(4):207–34.
24. Nosaka K, Clarkson PM, McGuiggin ME, Byrne JM. Time course of muscle adaptation after high force eccentric exercise. *Eur J Appl Physiol Occup Physiol.* 1991;63(1):70–6.
25. Newton MJ, Morgan GT, Sacco P, Chapman DW, Nosaka K. Comparison of responses to strenuous eccentric exercise of the elbow flexors between resistance-trained and untrained men. *J Strength Cond Res.* 2008;22(2):597–607. <https://doi.org/10.1519/JSC.0b013e3181660003>.
26. Bird SP, Mabon T, Pryde M, Feebrey S, Cannon J. Triphasic multinutrient supplementation during acute resistance exercise improves session volume load and reduces muscle damage in strength-trained athletes. *Nutr Res.* 2013;33(5):376–87. <https://doi.org/10.1016/j.nutres.2013.03.002>.
27. Chaves CP, Simao R, Miranda H, Ribeiro J, Soares J, Salles B, et al. Influence of exercise order on muscle damage during moderate-intensity resistance exercise and recovery. *Res Sports Med.* 2013;21(2):176–86. <https://doi.org/10.1080/15438627.2012.738439>.
28. Meneghel AJ, Verlengia R, Crisp AH, Aoki MS, Nosaka K, da Mota GR, Lopes CR. Muscle damage of resistance-trained men after two bouts of eccentric bench press exercise. *J Strength Cond Res.* 2014;28(10):2961–6. <https://doi.org/10.1519/JSC.0000000000000494>.
29. Skurvydas A, Brazaitis M, Venckunas T, Kamandulis S, Stanislovaitis A, Zuozia A. The effect of sports specialization on musculus quadriceps function after exercise-induced muscle damage. *Appl Physiol Nutr Metab.* 2011;36(6):873–80. <https://doi.org/10.1139/h11-112>.
30. Snieckus A, Kamandulis S, Venckunas T, Brazaitis M, Volungevicius G, Skurvydas A. Concentrically trained cyclists are not more susceptible to eccentric exercise-induced muscle damage than are stretch-shortening exercise-trained runners. *Eur J Appl Physiol.* 2013;113(3):621–8. <https://doi.org/10.1007/s00421-012-2470-1>.
31. Fisher J, Steele J, Smith D. High- and Low-load resistance training: interpretation and practical application of current research findings. *Sports Med.* 2017;47(3):393–400. <https://doi.org/10.1007/s40279-016-0602-1>.
32. Thornton MK, Potteiger JA. Effects of resistance exercise bouts of different intensities but equal work on EPOC. *Med Sci Sports Exerc.* 2002;34(4):715–22.

33. Bartolomei S, Sadres E, Church DD, Arroyo E, Iii JAG, Varanoske AN, et al. Comparison of the recovery response from high-intensity and high-volume resistance exercise in trained men. *Eur J Appl Physiol.* 2017;117(7):1287–98. <https://doi.org/10.1007/s00421-017-3598-9>.
34. Chen TC, Nosaka K, Lin MJ, Chen HL, Wu CJ. Changes in running economy at different intensities following downhill running. *J Sports Sci.* 2009;27(11):1137–44. <https://doi.org/10.1080/02640410903062027>.
35. Abernethy PJ, Thayer R, Taylor AW. Acute and chronic responses of skeletal muscle to endurance and sprint exercise. A review. *Sports Med.* 1990;10(6):365–89.
36. Gollnick PD, Karlsson J, Piehl K, Saltin B. Selective glycogen depletion in skeletal muscle fibres of man following sustained contractions. *J Physiol.* 1974;241(1):59–67.
37. Bentley DJ, Smith PA, Davie AJ, Zhou S. Muscle activation of the knee extensors following high intensity endurance exercise in cyclists. *Eur J Appl Physiol.* 2000;81(4):297–302. <https://doi.org/10.1007/s004210050046>.
38. Bentley DJ, Zhou S, Davie AJ. The effect of endurance exercise on muscle force generating capacity of the lower limbs. *J Sci Med Sport.* 1998;1(3):179–88.
39. Lentz M, Nielsen JF. Post-exercise facilitation and depression of M wave and motor evoked potentials in healthy subjects. *Clin Neurophysiol.* 2002;113(7):1092–8.
40. Sargeant AJ, Dolan P. Human muscle function following prolonged eccentric exercise. *Eur J Appl Physiol Occup Physiol.* 1987;56(6):704–11.
41. Jakeman JR, Byrne C, Eston RG. Lower limb compression garment improves recovery from exercise-induced muscle damage in young, active females. *Eur J Appl Physiol.* 2010;109(6):1137–44. <https://doi.org/10.1007/s00421-010-1464-0>.
42. Ihsan M, Watson G, Abbiss CR. What are the physiological mechanisms for post-exercise cold water immersion in the recovery from prolonged endurance and intermittent exercise. *Sports Med.* 2016;46(8):1095–109. <https://doi.org/10.1007/s40279-016-0483-3>.



Long-Term Effects of Supplementary Aerobic Training on Muscle Hypertrophy

12

Tommy Lundberg

Introduction

When athletes or recreationally active individuals perform structured strength or aerobic training for an extended period of time (i.e., months to years), in due course, their skeletal muscles will display a distinct phenotype reflecting the primary overload-stimulus imposed. This is manifested in its extremes by, e.g., the marathon runner displaying a slim and fatigue-resistant muscle profile, and the powerlifter or bodybuilder showing extraordinarily large muscles. From a conceptual view, it appears unlikely that the skeletal muscle is capable of achieving the extreme features displayed by the powerlifter and the marathon runner at the same time. As has been made clear in previous chapters, the question has therefore been raised whether one can perform aerobic and strength training simultaneously, without compromising the distinct muscle adaptations that would have occurred with either exercise mode in isolation.

Although the skeletal muscle adaptations outlined in the simplified example above represent classical end-point adaptations to strength and aerobic training, it should be acknowledged that phenotype changes occur along a continuum and several muscle adaptations actually show minor specificity across exercise modes, at least in the short term. For example, whole-muscle and fiber size may to some extent increase in response to aerobic training [1, 2] and fiber type transformation occurs in the same direction regardless of exercise modality [3]. Moreover, high-volume strength training may induce capillary proliferation [4] and increased oxidative enzyme activity and aerobic capacity [5]. These examples highlight that the muscle adaptive response to exercise is complex and occur along a continuum. Thus, given the limited understanding of the mechanisms dictating classical

T. Lundberg

Division of Clinical Physiology, Department of Laboratory Medicine, Karolinska Institutet,
Stockholm, Sweden

e-mail: Tommy.Lundberg@ki.se

adaptations to aerobic and strength training, it is perhaps not surprising that the results of studies exploring muscle hypertrophy in response to concurrent training are somewhat equivocal. The goal of this chapter is to explore the long-term effects of supplementary aerobic training on muscle hypertrophy.

Concurrent Training and Muscle Hypertrophy: The Past

It should be acknowledged that so far, the majority of concurrent training studies have not included the measure of muscle hypertrophy as an outcome variable. Thus, many studies showing incompatibilities between aerobic and strength training have only focused on strength or power development. Also, in several studies, muscle strength has been compromised by additional aerobic training whereas muscle hypertrophy has been unaffected. For example, although the original work of Hickson [6] is often cited in favor for an interference effect in terms of muscle adaptations to concurrent training, that seminal study actually did not report reduced muscle growth in response to the concurrent training regime. The measurement of muscle size was made using a tape-measure to estimate thigh girth, and the increase in this measure did not differ between groups (concurrent training vs. strength training alone) at the end of the training programme. Nonetheless, ever since, numerous studies have investigated the effect of adding aerobic training to a strength training programme with assessments of muscle hypertrophy through various measurements of muscle or fiber size before and after training.

The literature provides large inconsistencies regarding the effects of concurrent training on muscle hypertrophy. Clearly, and as pointed out in several earlier review papers (e.g., [7–10]), these inconsistencies are probably due to differences in study design factors such as study duration, subject population, age and training status, as well as differences in training mode, frequency, intensity, and volume. Indeed, a previous meta-analysis indicated that although there was no statistical difference in the averaged effect size for lower-body muscle hypertrophy between concurrent training and strength training [10], there were some differences when the effect sizes were split for different training variables. More specifically, interference in muscle hypertrophic development was noted when running was selected as the aerobic training modality, or when high training frequencies or long aerobic training workouts were employed. Since then, however, several new studies have been published including review papers challenging the idea of an interference effect on muscle hypertrophy with concurrent training [11].

Concurrent Training and Muscle Hypertrophy: Updating the View

A summary of 23 published studies [3, 6, 12–33] reporting changes in muscle hypertrophy to concurrent training and strength training alone are summarized in Table 12.1. The subject populations in the studies identified have typically been untrained or recreationally active young men, with a few exceptions where studies

Table 12.1 Summary of concurrent training studies measuring muscle hypertrophy compared with strength training alone

Study	Subjects	Training duration and frequency	Order of sessions	Training programme	Hypertrophy measure	Interference (yes/no)	Comment
Hickson [6]	Recreationally trained men and women	5 days/week, 10 weeks	Unclear order. ~2 h between sessions	ST: 3–5 sets × 5 reps in isoinertial leg exercises, 80% of 1RM. AT: Cycling intervals and continuous running	Thigh girth	N	
Nelson et al. [16]	Untrained men	4 days/week, 20 weeks	ST—AT	ST: 3 sets × 6 reps max knee extensions @30 deg/s. AT: 30–60 min continuous cycling	Fiber area	N	Greater increase in AT + ST than ST
Sale et al. [17, 36]	Untrained men and women. Between leg comparison	3 days/week, 22 weeks	AT—ST	ST: 6 × 15–20 reps leg press. AT: 5 × 3 min interval cycling at 90–100% of VO ₂ max	CSA (CT), thigh girth, and fiber area	N	
Craig et al. [18]	Untrained men	3 days/week, 10 weeks	AT—ST	ST: 3 × 6–10 reps of UB and LB exercises including LP and leg curls. AT: continuous running 30–35 min @ 75% MHR	Thigh girth	Y	No interaction reported. Very small increase overall
Volpe et al. [19]	Untrained women	3 days/week, 9 weeks	AT—ST	ST: 2–4 sets of 4–10 reps of LP, extensions, leg curl, calf raise + 6 UB exercises. AT: 20–25 min of running at 75% of predicted MHR	Thigh girth	N	
Kraemer et al. [3]	Trained (army) men	4 days/week, 12 weeks	AT—5–6 h—ST	ST: 3–5 sets of 5–15 reps, 10 UB exercises and 8 isoinertial leg exercises. AT: distance and interval running with aim to maximally stress the aerobic system	Fiber area	Y	Interference in Type 1 and 2C fiber area (no interaction reported)

(continued)

Table 12.1 (continued)

Study	Subjects	Training duration and frequency	Order of sessions	Training programme	Hypertrophy measure	Interference (yes/no)	Comment
McCarthy et al. [20]	Untrained men	3 days/week, 10 weeks	Same session, rotating order	ST: 4 × 5–7 reps, isoinertial strength such as squats, BP, extensions, leg curls, and UB exercises. AT: 50 min continuous cycling @70% HR reserve	Thigh girth	N	
Bell et al. [27]/Putman et al. [28]	Recreationally trained men	3 days/week, ST + AT 6 days/week, 12 weeks	Alternate days	ST: 2–6 sets, 4–12 rep of 4 LB and 4 UB exercises free weights + machines. AT: Cycling, continuous + intervals	Fiber area	Y	Interference in Type 1 fiber area (no interaction reported)
McCarthy et al. [21]	Untrained men	3 days/week, 10 weeks	Same session, rotating order	ST: 3 sets × 5–7 reps of 8 exercises including squats, curls, extensions. AT: continuous cycling	CSA (CT) and fiber area	N	
Häkkinen et al. [22]	Recreationally trained men	2 days/week, ST + AT 4 days/week, 21 weeks	Alternate days	ST: 3–5 sets of 5–15 reps of LP and KE + 4 UB exercises. Aim both maximal strength and explosive strength. AT: First 30 min cycling or walking, then increased cycling at different intensities for 60–90 min	CSA (MRI)	N	
Izquierdo et al. [23]	Untrained older men	2 days/week, 16 weeks	Alternate days	ST: first 8 weeks: 3–4 sets of 10–15 reps @ 50–70% 1RM, last 8 weeks: 3–5 sets × 5–6 reps of LP, KE, BP and 4–5 other UB exercises. AT: Continuous and interval cycling	CSA (ultrasound)	N	
Izquierdo et al. [12]	Untrained middle-aged men	2 days/week, 16 weeks	Alternate days	ST: first 8 weeks: 3–4 sets of 10–15 reps @ 50–70% 1RM, last 8 weeks: 3–5 sets × 5–6 reps of LP, KE, BP and 4–5 other UB exercises. AT: Continuous and interval cycling	CSA (ultrasound)	N	

Sillanpää et al. [13]	Untrained middle-aged men	2 days/week, ST + AT 4 days/week, 21 weeks	Alternate days	ST: whole-body programme including 2 exercises for the leg extensors. AT: 30–60 min continuous cycling	VL + VI thickness (ultrasound)	N	
Ahtiainen et al. [24]	Untrained older men	2 days/week, ST + AT 4 days/week, 21 weeks	Alternate days	ST: whole-body programme including 2 exercises for the leg extensors. AT: 30–60 min continuous cycling	VL thickness and fiber area	N/Y	Interference in Type 2 fiber area (no interaction reported) but not in VL thickness
Karavirta et al. [14]	Untrained older men	2 days/week, ST + AT 4 days/week, 21 weeks	Alternate days	ST: whole-body programme including 2 exercises for the leg extensors. AT: 30–60 min continuous cycling	Fiber area	Y	Interference in 2 fiber area (no interaction reported)
Mikkola et al. [15]	Untrained middle-aged men	2 days/week, ST + AT 4 days/week, 21 weeks	Alternate days	ST: whole-body programme including 2 exercises for the leg extensors. AT: 30–60 min continuous cycling	CSA (MRI)	N	Greater increase in AT + ST than ST
de Souza et al. [25, 26]	Untrained young men	2 days/week, 8 weeks	Same session, rotating order	ST: 3–5 sets of 6–12 RM LP, KE, Knee flexion. AT: Interval training at 80–100% of vVO _{2max}	CSA (MRI) and fiber area	N/Y	Interference in fiber area (no interaction reported) but not whole-muscle MRI
Jones et al. [29]	Recreationally resistance-trained men	3 days/week, 6 weeks	ST—AT	ST: 5 sets of 6 reps at 80% of MVC in isokinetic leg extensions. Unilateral training. AT: 30 min of repeated extensions at 30% of MVC	Thigh girth	Y/N	Interference with 3 days/week but not with 1 day/ week AT
Lundberg et al. [30]	Moderately trained men. Between leg comparison	AT: 3 days/ week, ST: 2 or 3 days/week, 5 weeks	AT—6 h—ST	ST: 4 × 7 sets of flywheel knee extensions. AT: one-legged continuous cycling ~45 min	Volume and CSA (MRI), fiber area	N	Greater increase in AT + ST than ST

(continued)

Table 12.1 (continued)

Study	Subjects	Training duration and frequency	Order of sessions	Training programme	Hypertrophy measure	Interference (yes/no)	Comment
Lundberg et al. [31]	Moderately trained men. Between leg comparison	AT: 3 days/week, ST: 2 or 3 days/week, 5 weeks	AT—15 min—ST	AT: one-legged continuous cycling ~45 min. ST: 4 × 7 sets of flywheel knee extensions	Volume and CSA (MRI)	N	Greater increase in AT + ST than ST
Kazior et al. [32]	Untrained young men	2–4 days/week (progressive increase), 7 weeks	AT—ST	AT: Both continuous and interval cycling sessions. ST: Leg press 4–6 sets × 8–15 reps	Fiber area	N	Greater increase in AT + ST than ST
Terzis et al. [33]	Moderately trained young women	3 days/week, 6 weeks	ST—AT	AT: 30 min low-intensity running 60–70% of MHR. ST: Lower-body power training (ECC half-squats, CMJ jumps, drop-jumps)	Fiber area	Y	Interference in all fiber types
Tsitkanou et al. [34]	Recreationally active young men	2 days/week, 8 weeks	ST—AT	AT: High-intensity cycling 10 sets of 1 min @maximal aerobic power, ST: Leg press and half-squats 4 sets of 6RM	CSA (ultrasound) and fiber area	N	

Note: ST strength training, AT aerobic training, RM repetition maximum, LP leg press, KE knee extension, UB upper body, MHR maximal heart rate, LB lower body, BP bench press, CSA cross-sectional area, CMJ counter movement jump, VO_2 oxygen uptake, ECC eccentric, MVC maximal voluntary contraction, CT computerized tomography, MRI magnetic resonance imaging, VL vastus lateralis, VI vastus intermedius

have looked at women or trained/athletic populations. The study duration has varied between 5 and 22 weeks, and the training frequencies have varied between 2 and 6 days per week (most often with 2 or 3 weekly strength and/or endurance training sessions). In 15 of the studies, the strength and aerobic sessions have been carried out on the same day, typically with only a short rest period in between the sessions. In seven studies, the sessions were scheduled on alternative days.

There Is No Uniform Interference Effect on Muscle Hypertrophy

When summarizing the effect sizes and the relative increase in muscle hypertrophy across all studies, it becomes apparent that there is no general or “global” interference effect on muscle hypertrophy from concurrent training (Fig. 12.1). The global average increase in muscle hypertrophy (i.e., averaging all measurements from all studies) is 14% from strength training alone and 12% with concurrent aerobic and strength training ($P = 0.36$). The average effect size for muscle hypertrophy is 0.76 for strength exercise alone and 0.60 for concurrent exercise ($P = 0.17$). If each study is given the same weight in the analysis (regardless of whether they included several measures of hypertrophy or not), the results are still very similar. Indeed, the majority of the individual studies independently report no difference in the mean hypertrophic response across the two training conditions (Table 12.1, Fig. 12.1). It should be noted that there are as many papers reporting a greater increase in muscle hypertrophy with concurrent training as there are papers showing an interference effect.

An important research design note is that in those studies reporting some kind of interference effect, all except one study used fiber size as the outcome measure of muscle hypertrophy. As the only exception, Craig et al. [18] used the thigh girth to assess muscle hypertrophy pre- and post-training, and the authors noted an increase of 1.8% in the strength group compared with 1.3% increase in the concurrent training group. Even if the author concluded that the increase in the strength group was significant in contrast to the increase in the concurrent group, one must certainly question if this small difference in thigh girth can be meaningful. An important point to make here is that none of the studies showing an interference effect used the most reliable techniques to assess muscle size (i.e., MRI or CT). In some cases, however, these techniques have been used together with fiber size measurements [17, 21, 25, 26, 30]. However, in the study by de Souza et al., the interference effect noted in fiber size measurements were not noted at the whole-muscle level using MRI or CT [25, 26]. It is difficult to elucidate the reason for these conflicting findings but two main hypotheses can be postulated. Since MRI and CT measure whole-muscle anatomical cross-sectional area, it is possible that changes in fiber size accompanied by changes in muscle architecture (i.e., increased pennation angle) will mask early hypertrophic effects that are not detected by either of these techniques. Thus, it could be speculated that with longer training periods, the interference effect would be noted also at the whole-muscle level with CT/MRI imaging. Alternatively, and perhaps even more likely, the conflicting findings on fiber size differences could reflect random effects or

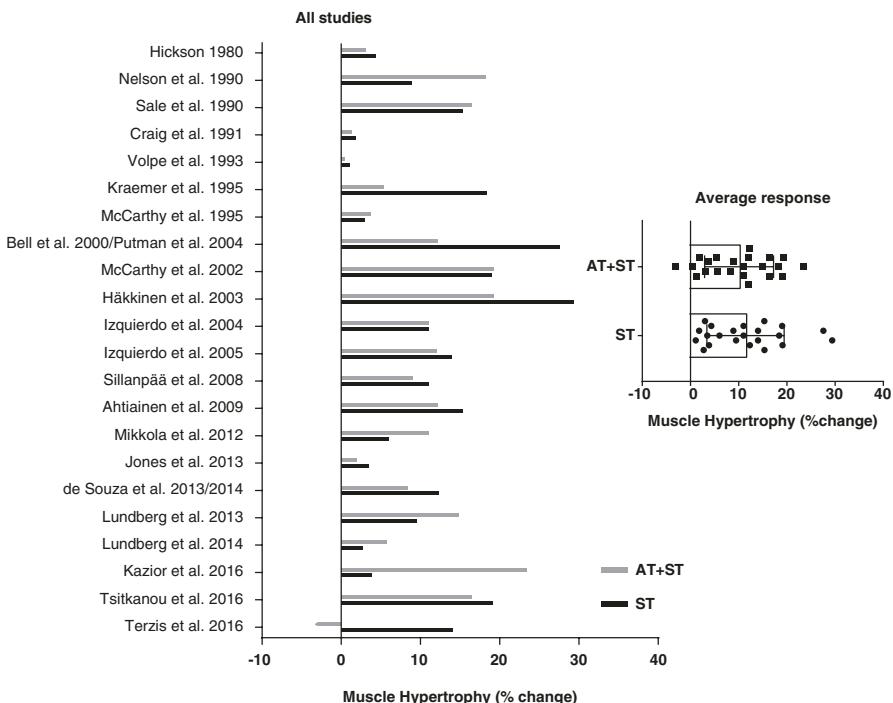


Fig. 12.1 A quantitative summary of the relative increase in muscle hypertrophy in all studies included in Table 12.1. The panel to the left depicts each individual study whereas the right panel shows the average response. *ST* strength training alone, *AT + ST* concurrent aerobic and strength training

type 1 errors that occur due to low sample sizes and a lack of a complete data sets, i.e., all fibers of the entire muscle, which leads to the extreme variance that is associated with measuring fiber size from a small sample of muscle tissue. To complicate this issue further, the statistics used to reach the conclusions in Table 12.1 can sometimes be questioned. Specifically, when one compares two groups across two time points in order to assess if the experimental condition (concurrent training) respond differently than the control condition (strength training), the main outcome statistics should be the interaction effect between group and time. However, in many of the studies shown in Table 12.1, and actually in all of the studies claiming an interference effect, the authors instead have analyzed the effects of each training mode (strength training vs. concurrent training) separately, obviously providing a significant bias.

The Effect of Different Training Variables on the Interference Effect in Muscle Hypertrophy

Training Frequency

Given that there is no general interference effect of concurrent training on hypertrophy, it appears clear that specific programme variables such as training

frequency, volume, and how the sessions are distributed will dictate the outcome of a specific concurrent training regime. Only one study has directly assessed the influence of endurance training frequency on the hypertrophic response to concurrent training. In that study [29], subjects were randomized to an experimental condition of either (a) strength training, (b) concurrent training with the aerobic training carried out 3 days/week, or (c) concurrent training with the aerobic training carried out 1 day/week. The strength training was always performed 3 days/week and the study duration was 6 weeks. The results showed a similar hypertrophic response (limb girth) between strength training alone and concurrent training with low-frequency aerobic training. Interestingly, however, the higher frequency of aerobic training was associated with an interference effect. While these data are the only direct evidence supporting that greater frequencies of aerobic training are negative for the muscle hypertrophic response to strength training, the data summarized in the current chapter also lend slight support to this notion. More specifically, if one divides all the studies in Table 12.1 into two groups split on training frequencies of either >3 days/week or ≤ 3 days/week, there seems to be a tendency for an interference effect with concurrent training with high training frequencies as compared with low frequencies (Fig. 12.2a).

Aerobic Training Modality

Regarding the effect of exercise mode, only four studies in Table 12.1 have selected running as the aerobic exercise modality [3, 6, 18, 33], whereas the remaining studies have studied cycling. Even though there is not enough data to draw firm statistical conclusions on any differential effect on muscle hypertrophy depending on the selected aerobic training mode, it is worth noting that three of the four studies employing running as the aerobic mode actually do show an interference effect (Fig. 12.2b). This strongly suggests that running, as compared with cycling, will exacerbate the risk of an interference effect on muscle hypertrophy. In fact, this may not be surprising since cycling in itself has often, in contrast to running [35], been associated with muscle hypertrophy [2].

Training Distribution

Regarding the distribution of training sessions, i.e., whether it is better to schedule the different training sessions on the same or alternate days, there is no difference in the outcome of muscle hypertrophy between concurrent training and strength training (Fig. 12.2c). This is also supported by Sale et al. [36] reporting that same day (vs. different day) concurrent training did not impede muscle hypertrophy (even though increases in muscle strength were attenuated by same day training). However, it is worth noting that there is a general main effect indicating that overall, training on alternate days gives better end-point results (hypertrophy) for both

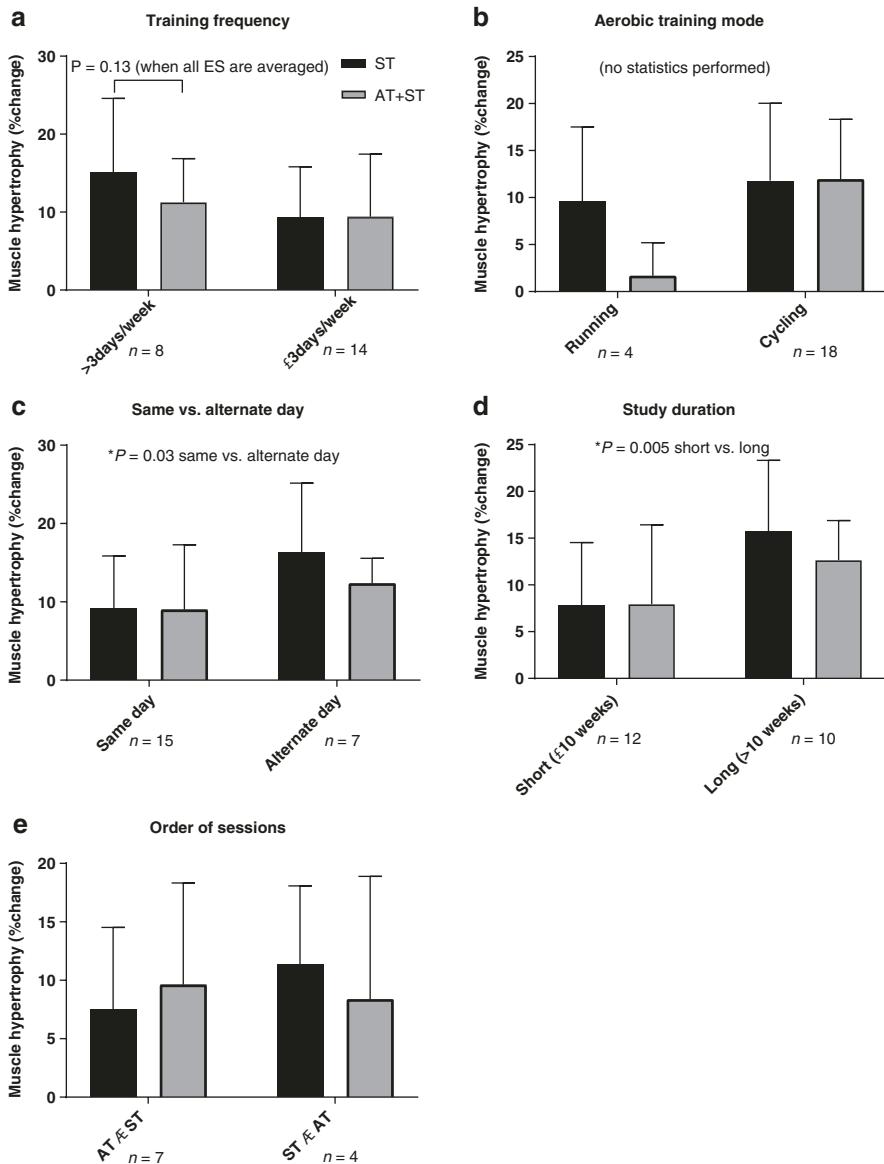


Fig. 12.2 The effect of different training variables on the relative increase in muscle hypertrophy. The indicated sample sizes (*n*) reflects the number of individual studies included in the analysis. *ST* strength training alone, *AT + ST* concurrent aerobic and strength training

strength training and concurrent training (Fig. 12.2c). Similarly, regarding the effect of study duration, longer study durations (>10 weeks) generally produces greater hypertrophy than shorter studies (Fig. 12.2d), but there is no difference between strength training and concurrent training in this regard.

Order of Sessions

There is somewhat limited data to quantify the effect of different orders of the session (i.e., aerobic training before or after strength), but from the 11 studies that have scheduled the aerobic and strength sessions in a specified order on the same day, there seems to be no clear order effect (Fig. 12.2e). In addition to these studies, some investigators have assessed the order effect by comparing two concurrent training groups with opposite order of the exercise modes with no comparison to strength training alone. The collective interpretation from these studies is also that there is no clear order effect on muscle hypertrophy [37, 38]. This notion certainly questions the often purported view that performing aerobic training prior to resistance training would activate molecular signalling pathways that are antagonistic to those induced by subsequent strength training, which in turn would inhibit muscle hypertrophy [8, 39]. Regardless of the order of training sessions, an interesting finding reported by Küüsmaa et al. was that concurrent training in the evening led to larger gains in muscle mass compared with the same training programme in the morning hours [38], suggesting that the timing of the concurrent training session is more important than the order of the different exercise modalities.

Other Factors

Unfortunately, there is not enough data to reliably quantify any effect of trained vs. untrained populations, women vs. men, different intensities during the aerobic training, different length of recovery between sessions, or upper- vs. lower-body muscle groups. There are, however, some preliminary data from individual studies that are worth mentioning. In my laboratory, we carried out two 5-week training studies where the only training variable manipulated between the studies was the length of recovery between the aerobic and strength training carried out on the same day 2–3 days per week. Regardless of whether the recovery was 6 h or 15 min between sessions, muscle hypertrophy was substantially greater following the concurrent training regime in recreationally active young men [30, 31]. Although this indicate that for muscle growth it does not matter if daily sessions are performed combined or with several hours of rest in between, it should be acknowledged that some aspects of strength performance were negatively influenced by the shorter recovery period.

Another study, performed by Rønnestad et al., explored the effects of high-volume aerobic training on the muscle hypertrophic response to resistance training in well-trained cyclists [40]. These cyclists, with limited strength training experience, performed heavy strength training twice a week in addition to high volume (~10 h per week) aerobic training during a 12-week period. A group of non-strength trained individuals performed the same strength training as the cyclists, but without added aerobic (cycling) training. Following the training period, the relative increase in thigh cross-sectional area was greater in the strength training group than in the concurrent training group, suggesting that high volumes of aerobic training impairs

muscle hypertrophy in trained individuals. These results should, however, be viewed with some caution since the strength training group consisted of non-cyclists. This was also why that particular study did not qualify for inclusion in the quantitative summary in this chapter.

Regarding the effect of aerobic training intensity, Fyfe et al. determined the effects of concurrent training incorporating either high-intensity interval training or volume-matched moderate-intensity continuous training [41]. The authors noted that lower-body lean mass increased similarly between the groups of strength training alone and moderate-intensity training + strength training, whilst the hypertrophic response was attenuated in the group incorporating high-intensity aerobic training with the strength training. Although these data indicate that high-intensity may be worse than low-intensity aerobic training for the development of muscle hypertrophy, the effect sizes were rather small and the responses were not reflected in the training-induced changes in strength. Therefore, it remains for future studies to confirm or refute these preliminary observations.

Summary

The collective body of evidence indicates that no universal interference effect of aerobic training on muscle hypertrophy seems to exist when added to a strength training programme. Thus, the effects of concurrent training on muscle hypertrophy ultimately depend on the specific training programme carried out. High training frequencies (>3 days/week regardless of training mode) and the running mode of exercise appear to increase the risk of a compromised hypertrophic response to strength training compared with low training frequencies and the cycling modality. Unfortunately, however, there is a lack of systematic high-powered studies examining the effect of different training variables on the concurrent training effect. Nonetheless, current data suggest that most individuals can accomplish significant muscle hypertrophy with strength training despite concurrently performing aerobic training. From a practical standpoint, it could be recommended that athletes or trained individuals prioritizing gains in muscle mass and strength should choose cycling instead of running as the aerobic modality and avoid high aerobic training frequencies. It remains for future studies to determine for how long an athlete or recreationally active individual can maintain uncompromised hypertrophic development before any (potential) interference effect becomes evident.

References

1. Andersen P, Henriksson J. Capillary supply of the quadriceps femoris muscle of man: adaptive response to exercise. *J Physiol.* 1977;270(3):677–90.
2. Konopka AR, Harber MP. Skeletal muscle hypertrophy after aerobic exercise training. *Exerc Sport Sci Rev.* 2014;42(2):53–61.
3. Kraemer WJ, Patton JF, Gordon SE, Harman EA, Deschenes MR, Reynolds K, et al. Compatibility of high-intensity strength and endurance training on hormonal and skeletal muscle adaptations. *J Appl Physiol.* 1995;78(3):976–89.

4. Schantz P. Capillary supply in hypertrophied human skeletal muscle. *Acta Physiol Scand.* 1982;114(4):635–7.
5. Tesch PA, Thorsson A, Essen-Gustavsson B. Enzyme activities of FT and ST muscle fibers in heavy-resistance trained athletes. *J Appl Physiol.* 1989;67(1):83–7.
6. Hickson RC. Interference of strength development by simultaneously training for strength and endurance. *Eur J Appl Physiol Occup Physiol.* 1980;45(2–3):255–63.
7. Leveritt M, Abernethy PJ. Acute effects of high-intensity endurance exercise on subsequent resistance activity. *J Strength Cond Res.* 1999;13(1):47–51.
8. Baar K. Training for endurance and strength: lessons from cell signaling. *Med Sci Sports Exerc.* 2006;38(11):1939–44.
9. Nader GA. Concurrent strength and endurance training: from molecules to man. *Med Sci Sports Exerc.* 2006;38(11):1965–70.
10. Wilson JM, Marin PJ, Rhea MR, Wilson SM, Loenneke JP, Anderson JC. Concurrent training: a meta-analysis examining interference of aerobic and resistance exercises. *J Strength Cond Res.* 2012;26(8):2293–307.
11. Murach KA, Bagley JR. Skeletal muscle hypertrophy with concurrent exercise training: contrary evidence for an interference effect. *Sports Med.* 2016;46(8):1029–39.
12. Izquierdo M, Hakkinen K, Ibanez J, Kraemer WJ, Gorostiaga EM. Effects of combined resistance and cardiovascular training on strength, power, muscle cross-sectional area, and endurance markers in middle-aged men. *Eur J Appl Physiol.* 2005;94(1–2):70–5.
13. Sillanpaa E, Hakkinen A, Nyman K, Mattila M, Cheng S, Karavirta L, et al. Body composition and fitness during strength and/or endurance training in older men. *Med Sci Sports Exerc.* 2008;40(5):950–8.
14. Karavirta L, Hakkinen A, Sillanpaa E, Garcia-Lopez D, Kauhanen A, Haapasaari A, et al. Effects of combined endurance and strength training on muscle strength, power and hypertrophy in 40–67-year-old men. *Scand J Med Sci Sports.* 2011;21(3):402–11.
15. Mikkola J, Rusko H, Izquierdo M, Gorostiaga EM, Hakkinen K. Neuromuscular and cardiovascular adaptations during concurrent strength and endurance training in untrained men. *Int J Sports Med.* 2012;33(9):702–10.
16. Nelson AG, Arnall DA, Loy SF, Silvester LJ, Conlee RK. Consequences of combining strength and endurance training regimens. *Phys Ther.* 1990;70(5):287–94.
17. Sale DG, MacDougall JD, Jacobs I, Garner S. Interaction between concurrent strength and endurance training. *J Appl Physiol.* 1990;68(1):260–70.
18. Craig BW, Lucas J, Pohlman R, Stelling H. The effects of running, weightlifting and a combination of both on growth hormone release. *J Strength Cond Res.* 1991;5(4):198–203. National Strength & Conditioning Association.
19. Volpe SL, Walberg-Rankin J, Rodman KW, Sebolt DR. The effect of endurance running on training adaptations in women participating in a weight lifting program. *J Strength Cond Res.* 1993;7(2):101–7.
20. McCarthy JP, Agre JC, Graf BK, Pozniak MA, Vailas AC. Compatibility of adaptive responses with combining strength and endurance training. *Med Sci Sports Exerc.* 1995;27(3):429–36.
21. McCarthy JP, Pozniak MA, Agre JC. Neuromuscular adaptations to concurrent strength and endurance training. *Med Sci Sports Exerc.* 2002;34(3):511–9.
22. Häkkinen K, Alen M, Kraemer WJ, Gorostiaga E, Izquierdo M, Rusko H, et al. Neuromuscular adaptations during concurrent strength and endurance training versus strength training. *Eur J Appl Physiol.* 2003;89(1):42–52.
23. Izquierdo M, Ibanez J, Häkkinen K, Kraemer WJ, Larrión JL, Gorostiaga EM. Once weekly combined resistance and cardiovascular training in healthy older men. *Med Sci Sports Exerc.* 2004;36(3):435–43.
24. Ahtiainen JP, Hulmi JJ, Kraemer WJ, Lehti M, Pakarinen A, Mero AA, et al. Strength, [corrected] endurance or combined training elicit diverse skeletal muscle myosin heavy chain isoform proportion but unaltered androgen receptor concentration in older men. *Int J Sports Med.* 2009;30(12):879–87.
25. de Souza EO, Tricoli V, Roschel H, Brum PC, Bacurau AV, Ferreira JC, et al. Molecular adaptations to concurrent training. *Int J Sports Med.* 2013;34(3):207–13.

26. de Souza EO, Tricoli V, Aoki MS, Roschel H, Brum PC, Bacurau AV, et al. Effects of concurrent strength and endurance training on genes related to myostatin signaling pathway and muscle fiber responses. *J Strength Cond Res.* 2014;28(11):3215–23.
27. Bell GJ, Syrotuik D, Martin TP, Burnham R, Quinney HA. Effect of concurrent strength and endurance training on skeletal muscle properties and hormone concentrations in humans. *Eur J Appl Physiol.* 2000;81(5):418–27.
28. Putman CT, Xu X, Gillies E, MacLean IM, Bell GJ. Effects of strength, endurance and combined training on myosin heavy chain content and fibre-type distribution in humans. *Eur J Appl Physiol.* 2004;92(4–5):376–84.
29. Jones TW, Howatson G, Russell M, French DN. Performance and neuromuscular adaptations following differing ratios of concurrent strength and endurance training. *J Strength Cond Res.* 2013;27(12):3342–51.
30. Lundberg TR, Fernandez-Gonzalo R, Gustafsson T, Tesch PA. Aerobic exercise does not compromise muscle hypertrophy response to short-term resistance training. *J Appl Physiol.* 2013;114(1):81–9.
31. Lundberg TR, Fernandez-Gonzalo R, Tesch PA. Exercise-induced AMPK activation does not interfere with muscle hypertrophy in response to resistance training in men. *J Appl Physiol (1985).* 2014;116(6):611–20.
32. Kazior Z, Willis SJ, Moberg M, Apro W, Calbet JA, Holmberg HC, et al. Endurance exercise enhances the effect of strength training on muscle fiber size and protein expression of Akt and mTOR. *PLoS One.* 2016;11(2):e0149082.
33. Terzis G, Spengos K, Methenitis S, Agaard P, Karandreas N, Bogdanis G. Early phase interference between low-intensity running and power training in moderately trained females. *Eur J Appl Physiol.* 2016;116(5):1063–73.
34. Tarando F, Coisne D, Galli E, Rousseau C, Viera F, Bosseau C, Habib G, Lederlin M, Schnell F, Donal E. Left ventricular non-compaction and idiopathic dilated cardiomyopathy: the significant diagnostic value of longitudinal strain. *Int J Cardiovasc Imaging.* 2017;33(1):83–95.
35. Trappe S, Harber M, Creer A, Gallagher P, Slivka D, Minchev K, et al. Single muscle fiber adaptations with marathon training. *J Appl Physiol.* 2006;101(3):721–7.
36. Sale DG, Jacobs I, MacDougall JD, Garner S. Comparison of two regimens of concurrent strength and endurance training. *Med Sci Sports Exerc.* 1990;22(3):348–56.
37. Cadore EL, Izquierdo M, Pinto SS, Alberton CL, Pinto RS, Baroni BM, et al. Neuromuscular adaptations to concurrent training in the elderly: effects of intrasession exercise sequence. *Age.* 2013;35(3):891–903.
38. Küümaa M, Schumann M, Sedliak M, Kraemer WJ, Newton RU, Malinen JP, et al. Effects of morning versus evening combined strength and endurance training on physical performance, muscle hypertrophy, and serum hormone concentrations. *Appl Physiol Nutr Metab.* 2016;41(12):1285–94.
39. Fyfe JJ, Bishop DJ, Stepto NK. Interference between concurrent resistance and endurance exercise: molecular bases and the role of individual training variables. *Sports Med.* 2014;44(6):743–62.
40. Rønnestad BR, Hansen EA, Raastad T. High volume of endurance training impairs adaptations to 12 weeks of strength training in well-trained endurance athletes. *Eur J Appl Physiol.* 2012;112(4):1457–66.
41. Fyfe JJ, Bartlett JD, Hanson ED, Stepto NK, Bishop DJ. Endurance training intensity does not mediate interference to maximal lower-body strength gain during short-term concurrent training. *Front Physiol.* 2016;7:487.

Part III

Training-Methodological Considerations for Concurrent Aerobic and Strength Training



Methodological Considerations for Concurrent Training

13

David J. Bishop, Jon Bartlett, Jackson Fyfe,
and Matthew Lee

Introduction

As highlighted in earlier chapters, there are many studies that suggest performing both endurance and resistance training within the same training program (i.e., concurrent training) can lead to sub-optimal adaptations. However, although these studies provide evidence for interference to resistance training adaptations [i.e., reduced improvements in maximal strength, muscle hypertrophy, or power/rate of force development] with concurrent training [e.g., 1–6], these findings are not universal. For example, some concurrent training studies show no evidence for an interference effect [7, 8], while others suggest only certain adaptations are attenuated (e.g., compromised training-induced improvement in rate of force development, rather than attenuated maximal strength and/or muscle hypertrophy) [9]. On the contrary, there is also evidence for concurrent training further enhancing muscle hypertrophy (although, importantly, not maximal strength) [10–12] or post-exercise cellular signaling responses [13–15] compared with resistance training alone. The equivocal and varied nature of the response to concurrent training suggests the presence and magnitude of the observed interference effects might be related to methodological factors [6, 16]. These factors relate to training program design (i.e., exercise

D. J. Bishop (✉) · J. Bartlett · M. Lee

Institute of Sport and Health, Victoria University, Melbourne, VIC, Australia
e-mail: David.bishop@vu.edu.au

J. Fyfe

Faculty of Health, School of Exercise and Nutrition Sciences, Deakin University, Melbourne Burwood Campus, Burwood, VIC, Australia

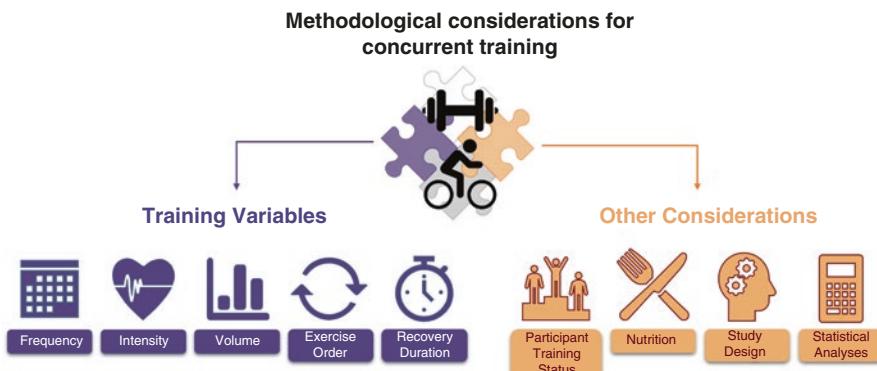


Fig. 13.1 Methodological considerations for concurrent training

frequency, intensity, volume, order, and recovery duration), as well as other factors including participant training status, nutrition, the study design, and statistical analyses used in the research (Fig. 13.1).

Training Program Design

Analysis of the results of studies investigating the *interference effect* suggests there are a number of training variables and other factors that need to be considered in the planning and prescription of concurrent training. Indeed, the volume, intensity, mode, and frequency of previous, current, and future training sessions, plus the exercise order and recovery duration between sessions, are all important factors that may influence the response to concurrent training. Furthermore, consideration of participant training status is critical when designing programs and interpreting concurrent training research, especially in relation to any observed interference effects. The following section outlines how these various methodological aspects should be controlled and/or considered when designing and interpreting concurrent training studies.

Training Status

Training status has been shown to affect the response to a single exercise session and plays an important role in determining subsequent adaptations to training. The concurrent training literature includes studies that have recruited sedentary [13, 17], recreationally trained [18–21], and exercise mode unaccustomed and/or accustomed participants [14, 21–24], with varying training outcomes often reported for different participant groups. For example, untrained participants elicit similar adaptive responses to both single-mode and concurrent training [24–26]. However, as

training is continued over a period of months to years, and the exercise stimulus is progressively increased to further enhance adaptation, the interference effect may become more apparent [27]. This suggests that in the untrained state concurrent training promotes predominantly generic, non-exercise mode-specific adaptations, while those with a greater training history exhibit more selective training responses to divergent stimuli, suggesting participant training status and history is a primary methodological factor to consider in the context of concurrent training.

In addition to sedentary, recreational, and trained participants, professional athletes may have a long training history, spanning several years, which is likely to impact on the planning of, and the adaptive responses to, concurrent training. Furthermore, the different competition schedules between individual and team sports will also impact planning and scheduling. For example, individual pursuit sports, which largely work on 4-year Olympic cycles, with specific yearly competition goals, may target specific phases in a year to develop specific physical qualities. When compared with team sports, in which competition may occur up to 4 times per week, the time available for training becomes a major issue, owing to the heightened need for recovery. From a logistical sense, changes to training schedules can also occur owing to injury management, weather, squad sizes, and available facilities. These “practical” issues, which are particularly prevalent across many sports, are likely to impact upon the acute and chronic adaptive responses to concurrent training.

Training Variables

Although there are many training variables that can be manipulated to influence the training response, the most common are frequency, intensity, and volume of training, as well as session order and the recovery between training sessions. While research evidence is limited, it is likely that these variables (individually and together) can influence the extent of any interference effect.

Frequency

Frequency relates to the number of training sessions (endurance and resistance) performed per week. While there appears to be little relationship between the frequency of resistance training sessions and improvements in running economy [28], $\text{VO}_{2\text{max}}$, or body fat [29], there are greater effects of endurance training frequency on resistance training adaptations. Indeed, performing ≥ 3 sessions of endurance training per week (which also results in a greater training status, and thus potential for greater interference) attenuates resistance training-induced adaptations [1–3, 30]. Conversely, performing ≤ 2 sessions per week appears to have a less negative impact on resistance training adaptations [8, 9, 31], which possibly also relates to the lesser trained status of the individual. As such, the frequency of endurance and resistance training sessions is an important methodological factor when programming concurrent training and when comparing the results of different studies.

Intensity

Training intensity is another important variable that likely influences concurrent training outcomes. This can be considered with respect to both endurance training intensity [e.g., high- vs. low-intensity continuous training, or high-intensity interval training (HIT) vs. moderate-intensity continuous training (MICT)], and resistance training intensity (e.g., high vs. low relative training intensities/loads). Endurance training intensity is a particularly relevant consideration, as higher endurance training intensities are a potent (and potentially time-efficient) stimulus for enhancing aerobic fitness and markers of cardiometabolic health [32]. For these reasons, HIT is often touted as a highly attractive strategy for improving cardiometabolic health and $\text{VO}_{2\text{max}}$, compared with traditional MICT [32, 33]. High-intensity exercise is also highly specific to the demands of many team and individual endurance-based sports, and so training modalities such as HIT often form an integral part of training programs aimed at enhancing performance across a wide range of athletes [34]. Given the popularity and effectiveness of high-intensity endurance training, the potential influence of this on the interference effect during concurrent training is an important consideration.

The intensity of endurance training performed within a concurrent training program may also influence the interference effect. Higher endurance training intensities are known to elicit greater residual fatigue of the trained musculature [35, 36] compared with lower-intensity endurance exercise [37, 38], and this can further attenuate force production capacity for at least 6 h after exercise [35, 36]. As discussed previously, this compromise in force production capacity can also negatively influence subsequent resistance training performance, an effect worsened following higher-intensity endurance exercise [38–40]. It is important to mention, however, that a number of additional variables also likely influence the neuromuscular demands of endurance training sessions, and therefore the likelihood for associated residual fatigue to negatively influence subsequent resistance training performance. Such factors include the endurance training modality (e.g., running vs. cycling), HIT work interval length, running surface (e.g., road, track, grass, or sand), running incline (e.g., hill vs. flat-ground running), and change-of-direction characteristics of running-based HIT [41].

A number of studies have demonstrated an interference effect with concurrent training incorporating a range of endurance training intensities, including low-intensity continuous training [4, 42], high-intensity interval training [43–46], or combinations of training intensities [1–3, 9]. There is, however, a lack of concurrent training studies directly comparing endurance training programs incorporating different training intensities [6, 47]. Such studies are required to determine the potential influence of training intensity on concurrent training outcomes. A study by Silva and colleagues [47] simultaneously investigated the effects of endurance training intensity (i.e., continuous vs. interval training) and modality (i.e., cycling vs. running) on neuromuscular adaptations to 11 weeks of concurrent training in physically active females. No differences for improvements in 1-RM leg press strength from baseline were found between training groups performing either resistance training only (~53%), or concurrent training incorporating either continuous cycling

(~39%), continuous running (~41%), or interval running (~47%). A limitation of that study, however, was that the endurance training protocols were only matched for total exercise duration, and not total work, making it difficult to infer the potential influence of training intensity on maximal strength outcomes [6].

Indeed, one methodological challenge when investigating the role of endurance training intensity in mediating the interference effect is that manipulating training intensity naturally influences total training volume, which in turn may confound study outcomes (*see paragraphs on training frequency and volume*). A potential solution to this problem is to equate the training volume of different endurance training protocols by matching them for total work performed, an approach used for comparing the influence of HIT and MICT on training adaptations [6, 48, 49]. Previous studies have observed attenuated maximal strength development with concurrent training programs incorporating either HIT [1, 43], MICT [4, 42], or combinations of both [2, 3]. Few studies have actually compared the influence of HIT and MICT as the endurance training modality on concurrent training outcomes [6], again making it difficult to determine the importance of endurance training intensity in mediating the interference effect. Fyfe and colleagues [6] compared the influence of work-matched HIT and MICT cycling on concurrent training outcomes, and observed almost identical interference of maximal (1-RM leg press) strength development, although HIT was more detrimental to improvements in various CMJ measures induced by resistance training (e.g., peak velocity and rate of force development) compared with MICT. The results suggested endurance training intensity per se may not be a critical factor for interference to maximal strength development, while higher endurance training intensities may be sub-optimal for the concurrent development of CMJ performance. Further work is required to better define the role endurance training intensity in modulating adaptation to concurrent training.

Volume

While training volume may be considered in the context of training frequency, it can also be depicted by the duration, equal also to work done, of a given training session and/or program. An increase in endurance session duration results in greater fatigue and substrate depletion [50], and therefore a requirement for longer recovery. Wilson et al. [29] observed a relationship between increasing daily endurance training duration and impaired resistance training-induced strength adaptations. This may indicate that increasing endurance training volume via the accumulation of total training time (and associated cumulative fatigue) would also impact on longer-term resistance training adaptations. Indeed, Hickson [2] only reported impaired strength adaptations in the concurrent training group from week 8 onwards of a 10-week training program. In that study, the concurrent group were performing endurance training (both running and cycling) 30–40 min per day 6 days per week—a volume of work that has not been matched in any other concurrent training study—on top of the 5 days per week of resistance training. This volume of training, which induces a large degree of cumulative fatigue, greatly superseded that of the endurance and strength-only training groups. More recently, Donges et al. [17] reported that when

concurrent exercise is matched for total work done with either resistance or endurance exercise performed alone (i.e., 50% of each mode combined), there are comparable increases in myofibrillar protein synthesis following concurrent and resistance exercise, and similar increases in mitochondrial protein synthesis between concurrent and endurance exercise. Taken together, this suggests that in sedentary, untrained participants, both aerobic and resistance exercise elicit a general additive effect on skeletal muscle exercise responses, while those with several weeks of training history are sensitive to both the volume of work done and the divergent exercise modes.

Contrasting that of endurance training, increasing resistance training volume in a concurrent training program through prolonged program duration (i.e., number of weeks) actually improves running economy in recreational ($\leq 55 \text{ mL kg}^{-1} \text{ min}^{-1} \dot{V} \text{ O}_{2\text{max}}$), well-trained ($55\text{--}65 \text{ mL kg}^{-1} \text{ min}^{-1} \dot{V} \text{ O}_{2\text{max}}$), and highly-trained athletes ($\geq 65 \text{ mL kg}^{-1} \text{ min}^{-1} \dot{V} \text{ O}_{2\text{max}}$) [28]. This is particularly important from the perspective of endurance sports, where running economy is a key performance indicator [51]. While the effect of resistance training session duration on concurrent training adaptations is less clear, there is evidence to suggest the ability to complete higher resistance training session volume, following endurance training, is compromised depending on the recovery duration between bouts [52] (see “recovery duration proximity” for detail). Another important “volume” factor to consider is that of accumulating resistance training volume. Given that higher resistance training volume results in greater muscle damage [53], and neuromuscular fatigue [54], it may be speculated that high resistance-training volume over time may impair the magnitude of concurrent training-induced adaptations. Collectively, training volume has varying roles in determining concurrent training adaptations and should be considered as a critical methodological factor when programming both endurance and strength training in a concurrent design, and when comparing the divergent findings in the literature.

Intra-session Exercise Order

Concurrent training offers a time-efficient alternative to single-mode training, particularly if both modes are performed within the same session. However, the acute interference hypothesis suggests residual fatigue and substrate depletion following a single exercise session may hinder the quality and performance of a subsequent bout, and induce unfavorable neuromuscular and molecular milieus, and thus compromise the potential for adaptation [16, 50]. Consequently, the choice of exercise order may be an important consideration for maximizing concurrent training adaptations. However, despite some evidence to support *acute* exercise order-dependent effects on strength [55, 56] and endurance exercise performance [57], as well as neuromuscular [58, 59] and molecular responses [19, 20], more research is needed to determine if, and how, these findings translate to order-dependent training effects. Most training studies to date report comparable gains in dynamic and isometric strength [60–70], power [65], hypertrophy [60, 62, 65, 67, 68], aerobic power and capacity [60, 62, 64, 67, 68], endurance performance [67, 69, 70], speed and agility [69, 70], irrespective of intra-session exercise order. This has been shown in a range of populations, including previously untrained/recreationally active men and women [60–63, 66–68], elite soccer players [69, 70], and elderly men [65]. Nevertheless, applying the existing research to

principles of training prescription, it would be prudent to recommend, where possible, the order in which concurrent endurance and resistance sessions are performed be dictated and periodized by the goals of that period in the training program.

Between-Session Recovery Duration

Increasing the recovery duration between divergent exercise modes might alleviate the potential negative effects of prior exercise on the quality of a subsequent session. Indeed, reductions in force generating capacity [35, 36], isokinetic strength [71, 72], and resistance exercise performance (i.e., number of reps completed) [52, 72] have been reported following endurance exercises of varying intensities and durations. These reductions in neuromuscular function and strength performance remained evident for at least 4–8 h post-endurance exercise, typically returning to baseline by 24 h [35, 36, 52]. Superior strength adaptations have also been observed following concurrent training sessions conducted on alternate days, compared to either same session [45, 73] or twice-daily training [73]. Collectively, these studies suggest that to restore muscle function for optimal strength performance and adaptation, at least 6–24 h recovery between concurrent sessions is warranted.

A greater recovery period between sessions may also benefit muscle growth. Indeed, Wilson et al. [29] reported a greater (albeit non-significant) effect size for hypertrophy when concurrent sessions were performed on alternate days (1.06) compared to the same day (0.80). However, others have shown similar gains in muscle size and mean fiber area regardless of whether sessions were performed on the same or different days [45]. Additional evidence in healthy, recreationally-active individuals suggests muscle hypertrophy and its associated acute molecular responses are not compromised, and are in fact potentiated, following short-term (5-week) training, irrespective of whether sessions are 15 min [12] or 6 h apart [11, 21]. A recent review by Murach and Bagley provides further support for comparable, if not greater, hypertrophic adaptations following concurrent training, compared with resistance-only training, regardless of the duration between modes [74]. Consequently, while muscle growth may not be limited by inter-session recovery duration, reductions in neuromuscular function and strength performance remain evident for 6–24 h. Increasing the rest period between divergent exercise sessions will allow for a greater quality of resistance training, increased force production and muscle fiber recruitment, and a better stimulus for strength adaptations.

Training Periodization

Athletic trainers may wish to manipulate training variables using a periodized approach, to match adaptations and performance with specific training and competition goals throughout a season. Since training variable manipulation clearly influences the interference effect [16, 29], the periodization strategy employed within a concurrent training program may also influence the degree of interference seen. Although studies directly examining the effect of training periodization on concurrent training adaptation are scarce [75, 76], some direct and indirect observations from the literature may provide some insight into the potential importance of concurrent training periodization. For example, given that higher endurance training

volumes or loads are associated with interference to strength training adaptations [29, 77], strategies to minimize endurance training volume during certain training phases may be beneficial. Periodized training approaches, whereby higher volumes/loads of endurance training are “cycled” between higher volumes/loads of strength training, may be useful for promoting improved strength training adaptations. Experimental evidence for the efficacy of this approach for minimizing interference is, however, currently lacking.

Research findings in world-class kayakers favored a block periodization approach, whereby specific endurance and strength components were trained simultaneously over multiple 5-week “blocks,” for improving kayaking performance [75, 76]. Compared with a traditional periodization model, the block periodization approach, which involved a 10% higher workload accumulation in each training block and less than half the total training volume, led to greater improvement in markers of kayaking performance. The authors noted that the choice of fitness component to be emphasized, and manipulation of training intensity in each block, were important considerations for any interference effect to be minimized [75]. Thus, for athletes in individual sports, block periodization may be an appropriate strategy, allowing endurance and strength parameters to be simultaneously developed towards a specific competition or goal. Team sports, however, involve a high frequency of competitive fixtures throughout long seasons, during which athletes are required to maintain high levels of strength, power, and endurance. Therefore, team sport athletes will likely benefit from a combination of different periodization strategies, dictated by the phase in the season, and the competition schedule. These strategies have been reviewed elsewhere [78]. In recreationally-active individuals, one study suggested that training periodization (specifically, endurance training intensity distribution) for this cohort may be less important, as both traditional and polarized distributions of training intensity and volume were equally effective for improving cardiovascular and neuromuscular fitness [79]. Nevertheless, this may reflect the potentially greater importance of endurance training volume, as opposed to training intensity, in mediating the interference effect [6, 29, 77]. Evidently, more research is needed to investigate the application of periodization strategies, with a specific focus on concurrent endurance and strength development, to identify strategies for minimizing interference during concurrent training.

Nutrition

Nutrition is another important methodological consideration, with strong evidence to suggest that nutrient availability can significantly modulate training adaptations [80]. Commencing exercise with low carbohydrate availability enhances metabolic and mitochondrial signaling responses [81, 82] and endurance adaptations [83–86], while protein ingestion (either as whole protein or amino acids) consumed pre- and post-exercise can augment muscle protein synthesis both in combination with and independent of exercise [87, 88]. Additionally, nutrient provision influences the expression of genes and proteins involved in protein breakdown [89], a physiological response regarded as unfavorable to achieving training goals. An equally

important, but less appreciated factor in terms of nutrition support is the effect of energy balance on resistance exercise-induced adaptations [90]. Indeed, Areta et al. [91] reported that following 5 days of energy deficit ($30 \text{ kcal kg FFM}^{-1} \text{ day}^{-1}$), myofibrillar fractional synthetic rate is lower compared with being in energy balance. This suggests that an energy deficit induced by preceding endurance training (higher endurance training volume equates to greater energy deficit), which may exacerbate the endurance signaling response through carbohydrate restriction, may in fact decrease the anabolic response to the subsequent resistance exercise bout. Therefore, the independent effects of nutrient provision on divergent signaling and adaptive responses are important methodological considerations for those trying to maximize responses to both ends of the adaptation continuum.

To date, the majority of exercise-nutrition research has been conducted in single-mode exercise only [92]. Furthermore, within existing concurrent training literature, several studies have conducted training in the fasted state [13, 19, 20, 24, 93–95]. These practices are often unrepresentative of athlete practices, whereby carbohydrates and/or protein are consumed before, during, and after training to facilitate exercise capacity, recovery, and adaptation [96].

Study Design and Statistical Considerations

Even though there are roughly as many women in the world as men, women are notably under-represented as participants in the sport-science training literature. Women represent less than 40% of the participants in published studies [97], and this is likely to be even less in concurrent training studies. In this context, it is important to remember that women are not little men [98], and one shouldn't rely on research performed in men to inform concurrent training guidelines for women. For example, some research suggests there are differences in strength and hormonal adaptations between men and women following concurrent training versus strength training only [99]. Other data suggests women and men do not have the same recovery of strength in the 4 days following resistance exercise [100]. On the other hand, no sex-based differences have been observed for the muscle protein synthesis response to resistance exercise in the fed state [101]. Given the limited research to date, it is clear more research with women is required to better inform concurrent training guidelines for women. Furthermore, when women are recruited, they are generally studied only at their most biologically “male-like” (when neither ovulating nor menstruating). However, women need to be studied at all stages of their menstrual cycle as this is representative of the female training experience.

When women are recruited, it is often when small numbers of men and women are studied together. Given the established physiological differences between sexes [98], this has the unintended consequence of increasing the intra-participant variability and decreasing the power of the study to detect small differences between conditions. This low power is also characteristic of most of the concurrent training literature (even when only one sex is recruited), and means that small (and possibly important) effects of concurrent training may not always be reported. One solution is obviously to increase the sample size of concurrent training studies. However,

some researchers are also moving beyond traditional significance testing to provide confidence intervals, magnitude of effects, and the likelihood that an effect is harmful/trivial/beneficial [73]. These approaches are not without difficulties, as making an inference about magnitudes requires justification of the smallest worthwhile effect (which has not been established for all concurrent training variables). Another important statistical consideration is that while most concurrent training studies have traditionally reported mean responses, it is clear there is considerable individual variability in the response to training and researchers should consider reporting individual values for all variables.

Summary

Concurrent training is a common practice, and it is therefore important to understand any potential interference effects in response to this type of training. However, there are a number of methodological considerations when planning, and interpreting the consequences of, concurrent training. These include training program design, nutritional practices, the participant group studied, and the statistical analyses used in the research. While more research is required, it appears the interference effect is more likely to be observed in those with a longer training history, when performing ≥ 3 sessions of endurance training per week, and when there is a high training volume. Intra-session order is also important, and scheduling priority should be assigned to whichever mode reflects the primary training goal so as to maximize the quality of the exercise session and consequently the stimulus for adaptation. Increasing the recovery duration between sessions should also allow for a greater quality of subsequent training and thus a better stimulus for adaptation. Further work is required to better define the role of endurance training intensity on modulating adaptation to concurrent training. More research is also required to better inform concurrent training guidelines for women. As some of the potential interference effects are likely to be small, there is also a need for researchers to consider how they can increase the power of concurrent training studies. Finally, there is a need to better understand the mechanisms mediating the interference effect in order to inform strategies for maximizing concurrent training outcomes.

References

1. Kraemer WJ, et al. Compatibility of high-intensity strength and endurance training on hormonal and skeletal muscle adaptations. *J Appl Physiol* (1985). 1995;78(3):976–89.
2. Hickson RC. Interference of strength development by simultaneously training for strength and endurance. *Eur J Appl Physiol Occup Physiol*. 1980;45(2–3):255–63.
3. Bell GJ, et al. Effect of concurrent strength and endurance training on skeletal muscle properties and hormone concentrations in humans. *Eur J Appl Physiol*. 2000;81(5):418–27.
4. Craig B, Lucas J, Pohlman R. Effects of running, weightlifting and a combination of both on growth hormone release. *J Appl Sport Sci Res*. 1991;5:198–203.
5. Hennessy L, Watson A. The interference effects of training for strength and endurance simultaneously. *J Strength Cond Res*. 1994;12:9–12.

6. Fyfe JJ, et al. Endurance training intensity does not mediate interference to maximal lower-body strength gain during short-term concurrent training. *Front Physiol.* 2016; 7:487.
7. Balabinis CP, et al. Early phase changes by concurrent endurance and strength training. *J Strength Cond Res.* 2003;17(2):393–401.
8. McCarthy JP, Pozniak MA, Agre JC. Neuromuscular adaptations to concurrent strength and endurance training. *Med Sci Sports Exerc.* 2002;34(3):511–9.
9. Häkkinen K, et al. Neuromuscular adaptations during concurrent strength and endurance training versus strength training. *Eur J Appl Physiol.* 2003;89(1):42–52.
10. Kazior Z, et al. Endurance exercise enhances the effect of strength training on muscle fiber size and protein expression of Akt and mTOR. *PLoS One.* 2016;11(2):e0149082.
11. Lundberg TR, et al. Aerobic exercise does not compromise muscle hypertrophy response to short-term resistance training. *J Appl Physiol (1985).* 2013;114(1):81–9.
12. Lundberg TR, Fernandez-Gonzalo R, Tesch PA. Exercise-induced AMPK activation does not interfere with muscle hypertrophy in response to resistance training in men. *J Appl Physiol (1985).* 2014;116(6):611–20.
13. Wang L, et al. Resistance exercise enhances the molecular signaling of mitochondrial biogenesis induced by endurance exercise in human skeletal muscle. *J Appl Physiol (1985).* 2011;111(5):1335–44.
14. Fernandez-Gonzalo R, Lundberg TR, Tesch PA. Acute molecular responses in untrained and trained muscle subjected to aerobic and resistance exercise training versus resistance training alone. *Acta Physiol (Oxf).* 2013;209(4):283–94.
15. Fyfe JJ, et al. Concurrent exercise incorporating high-intensity interval or continuous training modulates mTORC1 signalling and microRNA expression in human skeletal muscle. *Am J Physiol Regul Integr Comp Physiol.* 2016;310(11):R1297–311.
16. Fyfe JJ, Bishop DJ, Stepto NK. Interference between concurrent resistance and endurance exercise: molecular bases and the role of individual training variables. *Sports Med.* 2014;44(6):743–62.
17. Donges CE, et al. Concurrent resistance and aerobic exercise stimulates both myofibrillar and mitochondrial protein synthesis in sedentary middle-aged men. *J Appl Physiol (1985).* 2012;112(12):1992–2001.
18. Carrithers JA, et al. Concurrent exercise and muscle protein synthesis: implications for exercise countermeasures in space. *Aviat Space Environ Med.* 2007;78(5):457–62.
19. Coffey VG, et al. Consecutive bouts of diverse contractile activity alter acute responses in human skeletal muscle. *J Appl Physiol (1985).* 2009;106(4):1187–97.
20. Coffey VG, et al. Effect of consecutive repeated sprint and resistance exercise bouts on acute adaptive responses in human skeletal muscle. *Am J Physiol Regul Integr Comp Physiol.* 2009;297(5):R1441–51.
21. Lundberg TR, et al. Aerobic exercise alters skeletal muscle molecular responses to resistance exercise. *Med Sci Sports Exerc.* 2012;44(9):1680–8.
22. Coffey VG, et al. Interaction of contractile activity and training history on mRNA abundance in skeletal muscle from trained athletes. *Am J Physiol Endocrinol Metab.* 2006;290(5):E849–55.
23. Coffey VG, et al. Early signaling responses to divergent exercise stimuli in skeletal muscle from well-trained humans. *FASEB J.* 2006;20(1):190–2.
24. Vissing K, et al. Differentiated mTOR but not AMPK signaling after strength vs endurance exercise in training-accustomed individuals. *Scand J Med Sci Sports.* 2013;23(3):355–66.
25. Camera DM, et al. Early time course of Akt phosphorylation after endurance and resistance exercise. *Med Sci Sports Exerc.* 2010;42(10):1843–52.
26. Wilkinson SB, et al. Differential effects of resistance and endurance exercise in the fed state on signalling molecule phosphorylation and protein synthesis in human muscle. *J Physiol.* 2008;586(Pt 15):3701–17.
27. Coffey VG, Hawley JA. Concurrent exercise training: do opposites distract? *J Physiol.* 2017;595(9):2883–96.

28. Denadai BS, et al. Explosive training and heavy weight training are effective for improving running economy in endurance athletes: a systematic review and meta-analysis. *Sports Med.* 2017;47(3):545–54.
29. Wilson JM, et al. Concurrent training: a meta-analysis examining interference of aerobic and resistance exercises. *J Strength Cond Res.* 2012;26(8):2293–307.
30. Jones TW, et al. Performance and neuromuscular adaptations following differing ratios of concurrent strength and endurance training. *J Strength Cond Res.* 2013;27(12):3342–51.
31. Glowacki SP, et al. Effects of resistance, endurance, and concurrent exercise on training outcomes in men. *Med Sci Sports Exerc.* 2004;36(12):2119–27.
32. Weston KS, Wisloff U, Coombes JS. High-intensity interval training in patients with life-style-induced cardiometabolic disease: a systematic review and meta-analysis. *Br J Sports Med.* 2014;48(16):1227–34.
33. Milanovic Z, Sporis G, Weston M. Effectiveness of high-intensity interval training (HIT) and continuous endurance training for VO_{2max} improvements: a systematic review and meta-analysis of controlled trials. *Sports Med.* 2015;45(10):1469–81.
34. Buchheit M, Laursen PB. High-intensity interval training, solutions to the programming puzzle: part I: cardiopulmonary emphasis. *Sports Med.* 2013;43(5):313–38.
35. Bentley DJ, et al. Muscle activation of the knee extensors following high intensity endurance exercise in cyclists. *Eur J Appl Physiol.* 2000;81(4):297–302.
36. Bentley DJ, Zhou S, Davie AJ. The effect of endurance exercise on muscle force generating capacity of the lower limbs. *J Sci Med Sport.* 1998;1(3):179–88.
37. Leveritt M, MacLaughlin H, Abernethy PJ. Changes in leg strength 8 and 32 h after endurance exercise. *J Sports Sci.* 2000;18(11):865–71.
38. de Souza EO, et al. Acute effect of two aerobic exercise modes on maximum strength and strength endurance. *J Strength Cond Res.* 2007;21(4):1286–90.
39. Ratamess NA, et al. Acute resistance exercise performance is negatively impacted by prior aerobic endurance exercise. *J Strength Cond Res.* 2016;30(10):2667–81.
40. Lemos A, et al. The acute influence of two intensities of aerobic exercise on strength training performance in elderly women. *J Strength Cond Res.* 2009;23(4):1252–7.
41. Buchheit M, Laursen PB. High-intensity interval training, solutions to the programming puzzle: part II: anaerobic energy, neuromuscular load and practical applications. *Sports Med.* 2013;43(10):927–54.
42. Gergley JC. Comparison of two lower-body modes of endurance training on lower-body strength development while concurrently training. *J Strength Cond Res.* 2009;23(3):979–87.
43. Chtara M, et al. Effect of concurrent endurance and circuit resistance training sequence on muscular strength and power development. *J Strength Cond Res.* 2008;22(4):1037–45.
44. Cantrell GS, et al. Maximal strength, power, and aerobic endurance adaptations to concurrent strength and sprint interval training. *Eur J Appl Physiol.* 2014;114(4):763–71.
45. Sale DG, et al. Comparison of two regimens of concurrent strength and endurance training. *Med Sci Sports Exerc.* 1990;22(3):348–56.
46. Dudley GA, Djamil R. Incompatibility of endurance- and strength-training modes of exercise. *J Appl Physiol (1985).* 1985;59(5):1446–51.
47. Silva RF, et al. Concurrent training with different aerobic exercises. *Int J Sports Med.* 2012;33(8):627–34.
48. Edge J, Bishop D, Goodman C. The effects of training intensity on muscle buffer capacity in females. *Eur J Appl Physiol.* 2006;96(1):97–105.
49. Edge J, et al. Effects of high- and moderate-intensity training on metabolism and repeated sprints. *Med Sci Sports Exerc.* 2005;37(11):1975–82.
50. Leveritt M, et al. Concurrent strength and endurance training. A review. *Sports Med.* 1999;28(6):413–27.
51. Barnes KR, Kilding AE. Running economy: measurement, norms, and determining factors. *Sports Med Open.* 2015;1(1):8.
52. Sporer BC, Wenger HA. Effects of aerobic exercise on strength performance following various periods of recovery. *J Strength Cond Res.* 2003;17(4):638–44.

53. Bartolomei S, et al. Comparison of the recovery response from high-intensity and high-volume resistance exercise in trained men. *Eur J Appl Physiol*. 2017;117(7):1287–98.
54. Taylor JL, Gandevia SC. A comparison of central aspects of fatigue in submaximal and maximal voluntary contractions. *J Appl Physiol* (1985). 2008;104(2):542–50.
55. Jones TW, et al. Effects of strength and endurance exercise order on endocrine responses to concurrent training. *Eur J Sport Sci*. 2017;17(3):326–34.
56. Inoue DS, et al. Immunometabolic responses to concurrent training: the effects of exercise order in recreational weightlifters. *J Strength Cond Res*. 2016;30(7):1960–7.
57. Doma K, Deakin GB. The effects of strength training and endurance training order on running economy and performance. *Appl Physiol Nutr Metab*. 2013;38(6):651–6.
58. Cadore EL, et al. Strength prior to endurance intra-session exercise sequence optimizes neuromuscular and cardiovascular gains in elderly men. *Exp Gerontol*. 2012;47(2):164–9.
59. Cadore EL, et al. Neuromuscular adaptations to concurrent training in the elderly: effects of intrasession exercise sequence. *Age (Dordr)*. 2013;35(3):891–903.
60. Eklund D, et al. Acute endocrine and force responses and long-term adaptations to same-session combined strength and endurance training in women. *J Strength Cond Res*. 2016;30(1):164–75.
61. Collins MA, Snow TK. Are adaptations to combined endurance and strength training affected by the sequence of training? *J Sports Sci*. 1993;11(6):485–91.
62. Davitt PM, et al. The effects of a combined resistance training and endurance exercise program in inactive college female subjects: does order matter? *J Strength Cond Res*. 2014;28(7):1937–45.
63. Gravelle BL, Blessing DL. Physiological adaptation in women concurrently training for strength and endurance. *J Strength Cond Res*. 2000;14(1):5–13.
64. MacNeil LG, et al. The order of exercise during concurrent training for rehabilitation does not alter acute genetic expression, mitochondrial enzyme activity or improvements in muscle function. *PLoS One*. 2014;9(10):e109189.
65. Wilhelm EN, et al. Concurrent strength and endurance training exercise sequence does not affect neuromuscular adaptations in older men. *Exp Gerontol*. 2014;60:207–14.
66. Schumann M, et al. The order effect of combined endurance and strength loadings on force and hormone responses: effects of prolonged training. *Eur J Appl Physiol*. 2014;114(4):867–80.
67. Schumann M, et al. Fitness and lean mass increases during combined training independent of loading order. *Med Sci Sports Exerc*. 2014;46(9):1758–68.
68. Eklund D, et al. Neuromuscular adaptations to different modes of combined strength and endurance training. *Int J Sports Med*. 2015;36(2):120–9.
69. Makhlouf I, et al. Effect of sequencing strength and endurance training in young male soccer players. *J Strength Cond Res*. 2016;30(3):841–50.
70. McGawley K, Andersson PI. The order of concurrent training does not affect soccer-related performance adaptations. *Int J Sports Med*. 2013;34(11):983–90.
71. Abernethy PJ. Influence of acute endurance activity on isokinetic strength. *J Strength Cond Res*. 1993;7(3):141–6.
72. Leveritt M, Abernethy PJ. Acute effects of high-intensity endurance exercise on subsequent resistance activity. *J Strength Cond Res*. 1999;13(1):47–51.
73. Robineau J, et al. Specific training effects of concurrent aerobic and strength exercises depend on recovery duration. *J Strength Cond Res*. 2016;30(3):672–83.
74. Murach KA, Bagley JR. Skeletal muscle hypertrophy with concurrent exercise training: contrary evidence for an interference effect. *Sports Med*. 2016;46(8):1029–39.
75. Garcia-Pallares J, et al. Endurance and neuromuscular changes in world-class level kayakers during a periodized training cycle. *Eur J Appl Physiol*. 2009;106(4):629–38.
76. Garcia-Pallares J, et al. Performance changes in world-class kayakers following two different training periodization models. *Eur J Appl Physiol*. 2010;110(1):99–107.
77. Ronnestad BR, Hansen EA, Raastad T. High volume of endurance training impairs adaptations to 12 weeks of strength training in well-trained endurance athletes. *Eur J Appl Physiol*. 2012;112(4):1457–66.

78. Gamble P. Periodization of training for team sports athletes. *Strength Cond J.* 2006;28(5):56.
79. Varela-Sanz A, et al. Does concurrent training intensity distribution matter? *J Strength Cond Res.* 2017;31(1):181–95.
80. Bartlett JD, Hawley JA, Morton JP. Carbohydrate availability and exercise training adaptation: too much of a good thing? *Eur J Sport Sci.* 2015;15(1):3–12.
81. Bartlett JD, et al. Reduced carbohydrate availability enhances exercise-induced p53 signaling in human skeletal muscle: implications for mitochondrial biogenesis. *Am J Physiol Regul Integr Comp Physiol.* 2013;304(6):R450–8.
82. Psilander N, et al. Exercise with low glycogen increases PGC-1alpha gene expression in human skeletal muscle. *Eur J Appl Physiol.* 2013;113(4):951–63.
83. Chan MH, et al. Altering dietary nutrient intake that reduces glycogen content leads to phosphorylation of nuclear p38 MAP kinase in human skeletal muscle: association with IL-6 gene transcription during contraction. *FASEB J.* 2004;18(14):1785–7.
84. Hansen AK, et al. Skeletal muscle adaptation: training twice every second day vs. training once daily. *J Appl Physiol (1985).* 2005;98(1):93–9.
85. Yeo WK, et al. Skeletal muscle adaptation and performance responses to once a day versus twice every second day endurance training regimens. *J Appl Physiol (1985).* 2008;105(5):1462–70.
86. Yeo WK, et al. Acute signalling responses to intense endurance training commenced with low or normal muscle glycogen. *Exp Physiol.* 2010;95(2):351–8.
87. Apro W, Blomstrand E. Influence of supplementation with branched-chain amino acids in combination with resistance exercise on p70S6 kinase phosphorylation in resting and exercising human skeletal muscle. *Acta Physiol (Oxf).* 2010;200(3):237–48.
88. Tipton KD, Wolfe RR. Protein and amino acids for athletes. *J Sports Sci.* 2004;22(1):65–79.
89. Borgenvik M, Apro W, Blomstrand E. Intake of branched-chain amino acids influences the levels of MAFbx mRNA and MuRF-1 total protein in resting and exercising human muscle. *Am J Physiol Endocrinol Metab.* 2012;302(5):E510–21.
90. Smiles WJ, Hawley JA, Camera DM. Effects of skeletal muscle energy availability on protein turnover responses to exercise. *J Exp Biol.* 2016;219(Pt 2):214–25.
91. Areta JL, et al. Reduced resting skeletal muscle protein synthesis is rescued by resistance exercise and protein ingestion following short-term energy deficit. *Am J Physiol Endocrinol Metab.* 2014;306(8):E989–97.
92. Perez-Schindler J, et al. Nutritional strategies to support concurrent training. *Eur J Sport Sci.* 2015;15(1):41–52.
93. Apró W, et al. Resistance exercise induced mTORC1 signaling is not impaired by subsequent endurance exercise in human skeletal muscle. *Am J Physiol Endocrinol Metab.* 2013;305(1):E22–32.
94. Apro W, et al. Resistance exercise-induced S6K1 kinase activity is not inhibited in human skeletal muscle despite prior activation of AMPK by high-intensity interval cycling. *Am J Physiol Endocrinol Metab.* 2015;308(6):E470–81.
95. Camera DM, et al. Protein ingestion increases myofibrillar protein synthesis after concurrent exercise. *Med Sci Sports Exerc.* 2015;47(1):82–91.
96. Holway FE, Spriet LL. Sport-specific nutrition: practical strategies for team sports. *J Sports Sci.* 2011;29(Suppl 1):S115–25.
97. Costello JT, Bieuzen F, Bleakley CM. Where are all the female participants in Sports and Exercise Medicine research? *Eur J Sport Sci.* 2014;14(8):847–51.
98. Lewis DA, Kamon E, Hodgson JL. Physiological differences between genders implications for sports conditioning. *Sports Med.* 1986;3(5):357–69.
99. Bell G, et al. Effect of strength training and concurrent strength and endurance training on strength, testosterone, and cortisol. *J Strength Cond Res.* 1997;11(1):57–64.
100. Flores DF, et al. Dissociated time course of recovery between genders after resistance exercise. *J Strength Cond Res.* 2011;25(11):3039–44.
101. West DW, et al. Sex-based comparisons of myofibrillar protein synthesis after resistance exercise in the fed state. *J Appl Physiol.* 2012;112(11):1805–13.



Effects of the Concurrent Training Mode on Physiological Adaptations and Performance

14

Moritz Schumann

Introduction

The physiological challenges induced by aerobic and resistance training performed concurrently gained popularity since the initial study by Robert C Hickson [1]. However, while he clearly showed dramatically impaired maximal strength development after already a few weeks of training, it is often neglected that the training volume in this study consisted of 11 weekly training sessions—much more than is typically performed in recreational athletes. Moreover, the large number of training sessions performed ultimately led to the recovery between subsequent training sessions being very short but residual fatigue was not considered as a possible cause for the compromised changes in muscle strength.

Almost 40 years later, convincing evidence has emerged that the training mode indeed is considered a crucial component in explaining the “interference” phenomenon. Especially the recovery between subsequent training sessions appears to determine the magnitude of adaptations induced by concurrent training [2, 3] but some evidence also exists for adaptations being specific to the intra-session sequence, at least in certain subject populations [4, 5]. In this context, a clear distinction of terminology needs to be made when interpreting the literature of concurrent training. While the “interference effect” generally refers to the magnitude of adaptations obtained by concurrent training as compared to aerobic or strength training only [1], the “order effect” commonly describes the interaction of aerobic and strength training performed in close proximity with different exercise sequences (i.e., commencing with aerobic or resistance training, respectively) [6, 7].

M. Schumann

Department of Molecular and Cellular Sports Medicine, German Sport University,
Cologne, Germany

e-mail: m.schumann@dshs-koeln.de

On a further note, numerous cross-sectional studies were carried out especially during the past decade, aiming at elucidating the acute neuromuscular, hormonal or cardiorespiratory effects of concurrent aerobic and strength training sessions. While in these studies often rather strong claims towards possible long-term adaptations are made, very often these findings do not actually translate into performance adaptations observed after multiple weeks or months of training. Thus, this chapter aims at critically discussing the acute and chronic effects of different modes of concurrent aerobic and strength training by combining findings of cross-sectional and longitudinal study designs. Special reference will be given to effects of the exercise sequence within one training session and the importance of recovery between subsequent training sessions. Moreover, as the molecular signaling pathways of aerobic and strength exercise have been discussed elsewhere in this book, this chapter will focus on neuromuscular, cardiorespiratory and hormonal aspects, as well as the specific exercise performance.

The “Acute Hypothesis”

The initially observed impaired strength development during high volume concurrent aerobic and strength training (i.e., “interference”) may be explained both by a chronic and an acute hypothesis. Hickson [1] suggested that compromised strength development may occur due to the inability of muscles to adapt to both forms of exercise simultaneously. Craig et al. [8], on the other hand, proposed that during training programs in which aerobic and strength training are performed in close proximity, residual fatigue from the first exercise will detrimentally affect the quality of the subsequent loading, possibly compromising long-term adaptations.

The “acute hypothesis” is supported by studies reporting that the recovery from strenuous exercise may depend on the exercise intensity and/or volume and may take up to multiple days [9–11]. Thereby the magnitude of neuromuscular fatigue may be much larger following strenuous types of strength loadings [9] compared to prolonged aerobic exercise [11]. This is interesting because concerns are typically raised especially with regard to the detrimental effects of residual fatigue induced by aerobic exercise on subsequent strength performance rather than possible acute effects of strength loading on aerobic performance (e.g., [12]). The effects of an initial bout of exercise on subsequent aerobic or strength performance have been discussed elsewhere in this book.

Acute Effects of the Intra-session Sequence on Force Responses

Even though the interest in concurrent training methods has increased tremendously over the past decade, the literature concerning the acute responses to concurrent aerobic and strength loadings (i.e., either performing endurance exercise followed by strength loading or vice versa) is sparse. Obviously the most important indices

for possible exercise sequence-dependent responses would be differences in neuromuscular fatigue. However, surprisingly only very few studies have compared the overall force responses to concurrent exercise loadings. In these investigations, similar declines in maximal and rapid force production were observed in both recreational endurance athletes [13] and previously untrained men [6, 14] and women [15], following strenuous strength loadings combined with moderate intensity endurance running or cycling. Moreover, force levels returned to baseline already after 24 h in all of these studies.

In our own studies, [6, 14, 15] the loading consisted of mixed hypertrophic, maximal and explosive exercise bouts combined with continuous endurance cycling at anaerobic threshold intensity. While the overall magnitude of muscular fatigue was similar following both exercise sequences, the contribution of force loss by strength or endurance exercise was specific to the exercise order performed [6, 14]. Endurance cycling performed before the strength loading led to a reduction in maximal force of ~10% while in the opposite order aerobic exercise did not further reduce force production. Hence, while strength loadings may produce neuromuscular fatigue when performed both before and after endurance exercise, endurance cycling does not seem add to the overall magnitude of fatigue, considering a certain level of pre-fatigue is achieved. Similar findings are actually also shown in studies investigating the acute neuromuscular responses to prolonged strength loadings only [9, 16] but the underlying causes may be manifold. For example, during endurance cycling of moderate intensity both type I and type IIa fibers are typically active [17] and it is likely that strength loading activates high threshold motor units characterized by high fatigability, while subsequent endurance cycling may only recruit fatigue-resistant slow twitch fibers [18], apparently not increasing the magnitude of overall fatigue.

Acute Effects of the Intra-session Sequence on Hormonal Responses

Acute exercise-induced reductions in force production are typically accompanied by temporary alterations in hormonal concentrations. While the association between acutely increased hormone concentrations and muscle growth were questioned in a recent review paper [19], several studies have shown statistically significant correlations between basal and/or loading-induced concentrations of e.g., circulating testosterone and the chronic development of muscle mass and strength during strength training [20–24]. These findings provide at least some evidence for a supporting role of acute endocrine alterations in long-term physiological adaptations and may also help explaining distinct adaptations to concurrent aerobic and strength training.

When comparing existing studies concerning the acute hormonal responses to concurrent loadings (i.e., aerobic and strength exercise performed within the same training session), it should be noted that the magnitude of hormonal responses is typically associated with the characteristics of the exercise session (i.e., exercise

intensity and volume) and, thus, findings may be specific to the concurrent training session performed. Comparing findings of previous studies, it appears that the acute growth hormone responses (22-kDa) may consistently be larger when concurrent loadings are commenced with strength exercise in previously untrained men [6] and women [15], using a similar mixed-strength training protocol combined with stationary cycling exercise. One theory explaining these findings may lay in an accumulation of fatty acids induced by the aerobic exercise, which might suppress the endocrine release of growth hormone [25]. Consequently, one may hypothesize that strength exercise performed prior to aerobic training optimizes the anabolic milieu, required for neuromuscular adaptations to take place. Although such assumptions are not supported by acute testosterone accumulation in these studies, in previously untrained men we have shown that testosterone concentrations may be dramatically reduced for up to 48 h when strength exercise is preceded by endurance cycling [6]. Furthermore, no acute increases in cortisol concentrations were observed in either of the concurrent loadings, while significant reductions were observed for up to 48 h in both groups.

Reduced hormone concentrations during recovery have generally been linked with an upregulation of androgen receptors accompanied by increased target tissue uptake or an inhibited production of these hormones in the releasing gland or at the hypothalamus level [16, 26]. Unfortunately, we were not able to study the target receptor kinetics and, thus, the meaning of these findings remains speculative [26]. Along with attenuated growth hormone responses, however, it is likely that aerobic training performed prior to strength exercise may prolong the needs for recovery as opposed to the opposite exercise order due to the observed reduced testosterone concentrations.

Importantly, our findings were quite different compared to those observed in other studies in recreationally strength-trained [27] and concurrent endurance and strength athletes [28], performing hypertrophic resistance loadings combined with endurance cycling [27] and running [28]. Both of these studies showed acute increases in testosterone concentrations following the exercise sequence commencing with aerobic training. Furthermore, Cadore et al. [27] showed that the cortisol concentrations were elevated after the first exercise modality (endurance and strength, respectively) in both loading sequences but returned to baseline during the second exercise (strength and endurance, respectively), while Rosa et al. [28] observed increased cortisol and growth hormone concentrations following both loading conditions. While the authors of these studies concluded that the anabolic environment was optimized when endurance exercise preceded bouts of strength training, it appears that the hormonal responses to combined exercise sessions seem to differ between trained and untrained populations. This hypothesis is indeed supported by our data showing that after 24 weeks of exercise sequence-specific concurrent training, the initial reductions in recovery testosterone concentrations in the group which performed aerobic prior to strength training were diminished [14]. Furthermore, as opposed to previously untrained subjects, in trained individuals performing endurance exercise prior to strength training may in fact provide a cumulative anabolic stimulus (although the opposite exercise order was not

performed in this study) [29]. This was e.g., shown by the activation of molecular signaling pathways required for muscle growth and would aid explaining the increased testosterone concentrations following this exercise sequence in the studies by Cadore et al. and Rosa et al.

Acute Effects of the Intra-session Sequence on Cardiorespiratory Responses

Currently very little is known on the cardiorespiratory responses to concurrent loading sessions and typically the data are limited to excess post-exercise oxygen consumption (EPOC). These findings, however, remain equivocal and at least from a physiological point of view it remains uncertain why the exercise sequence would affect overall EPOC responses. Di Blasio et al. [30] found the magnitude of EPOC to be similar in previously untrained women performing aerobic followed by strength training and vice versa. However, in physically active men both no differences [31, 32] and a greater EPOC response following the exercise order commencing with aerobic exercise [33] were observed. The latter finding may at least in part be explained with a rather low endurance exercise intensity and volume (25 min at 70% of $\text{VO}_{2\text{max}}$) in this study, in fact being comparable to an active recovery strategy and, thus, enhancing lactate removal [34]. Interestingly, the EPOC response following alternating endurance and resistance exercise (i.e., 3 × 10 min of treadmill running, each followed by 1 set of 8 exercises of circuit training) has been shown to be larger than that observed when endurance and strength exercise were performed subsequently [30] but the reasons for this phenomenon remain to be investigated.

Chronic Adaptations to Same-Session Combined Training

The findings stemming from cross-sectional study designs provide at least some indications for possible exercise sequence-specific adaptations, when long-term concurrent aerobic and strength training is performed. However, it appears that these findings translate only in very few cases into the findings of chronic training studies. This is likely attributed to factors which may be controlled well in laboratory conditions but will affect training over multiple weeks or months (i.e., sleeping habits, nutrition, psychological stress, daily activities). Table 14.1 provides a summary of studies dealing with the exercise sequence of concurrent training in healthy subjects performing regular aerobic and strength training.

Recently two meta-analyses were published on this topic [47, 48] and both of these investigations provided quite similar conclusions, indicating that dynamic strength development may be optimized when strength training is performed prior to aerobic training, while the exercise sequence may not matter seem to for morphological [47] or cardiorespiratory adaptations [47, 48]. Referring to Table 14.1, however, it appears that in fact only very few studies have provided statistical evidence for this claim. Moreover, it can be noted that the currently available studies differ

Table 14.1 Literature review on current studies investigating the “order effect” of prolonged concurrent aerobic and strength training in healthy subjects

Study	Subjects	Training duration	Training mode	Cardiorespiratory function ($p < 0.05$)	Neuromuscular function ($p < 0.05$)	Between-group difference ($p < 0.05$)
Collins and Snow [35]	Untrained men and women ES ($n = 15$) SE ($n = 15$)	7 weeks	3 day week $^{-1}$ E: 20–25 min running at 60–90% of heart rate reserve S: Whole body, 2 × 3–12 repetitions at 50–90% of 1 RM	ES ↑ SE ↑	ES ↑ SE ↑	C: No N: No
Gravelle and Blessing [36]	Active women ES ($n = 6$) SE ($n = 7$)	11 weeks	3 day week $^{-1}$ E: 45 min at 70% of $\dot{V}O_{2\max}$ S: Lower body 2–4 × 6–10 RM	ES ↑ SE →	ES ↑ SE ↑	C: Yes N: No
Chitara et al. [37]	Male sport students ES ($n = 10$) SE ($n = 10$)	12 weeks	2 day week $^{-1}$ E: Interval running on an indoor track at 100% $\dot{V}O_{2\max}$ with recovery of 60% $\dot{V}O_{2\max}$ (duration 50% of time to exhaustion) S: Whole body circuit including strength-endurance and explosive protocols	ES ↑ SE ↑	N/A	Yes
Chitara et al. [38]	Male sport students ES ($n = 10$) SE ($n = 10$)	12 weeks	2 day week $^{-1}$ E: Interval running on an indoor track at 100% $\dot{V}O_{2\max}$ with recovery of 60% $\dot{V}O_{2\max}$ (duration 50% of time to exhaustion) S: Whole body circuit training, including strength-endurance and explosive protocols	N/A	ES ↑ SE ↑	No

Cadore et al. [4]	Untrained older men ES (<i>n</i> = 13) SE (<i>n</i> = 13)	12 weeks	3 day week ⁻¹ E: Cycling, 20–30 min continuous at 80–90% of heart rate at second ventilatory threshold, interval cycling 6 × 4 min at second ventilatory threshold S: Whole body, 2–3 × 6–20 RM	ES ↑ SE ↑↑	ES ↑ SE ↑↑	C: No N: Yes
Cadore et al. [39]	Untrained older men ES (<i>n</i> = 13) SE (<i>n</i> = 13)	12 weeks	3 day week ⁻¹ E: Cycling, 20–30 min continuous at 80–90% of heart rate at second ventilatory threshold, interval cycling 6 × 4 min at second ventilatory threshold S: Whole body, 2–3 × 6–20 RM	N/A	ES ↑ SE ↑↑	Yes
McGawley and Andersson [40]	Semi- and fully professional soccer player ES (<i>n</i> = 9) SE (<i>n</i> = 9)	5 weeks	3 day week ⁻¹ E: ST 5–60 s at 90–95% HRmax, HIIT 4–5 min, (rest not defined) S: 2–3 × 5–10 repetitions at 75–90% 1 RM and 3 × 3–20 repetitions jumps with bodyweight	ES ↑ SE ↑	ES ↑ SE ↑	C: No N: No
Davitt et al. [41]	Inactive young women ES (<i>n</i> = 13) SE (<i>n</i> = 10)		4 day week ⁻¹ E: 30 min at 70–80% of HR reserve (not specified if performed as running or cycling) S: Whole body, 3 × 8–12 repetitions at 90–100% of 1 RM	ES ↑ SE ↑	ES ↑ SE ↑	C: No N: No

(continued)

Table 14.1 (continued)

Study	Subjects	Training duration	Training mode	Cardiorespiratory function ($p < 0.05$)	Neuromuscular function ($p < 0.05$)	Between-group difference ($p < 0.05$)
Wilhelm et al. [42]	Untrained older men ES ($n = 11$) SE ($n = 12$)	12 weeks	2 day week ⁻¹ E: 20 min cycling at 85–95% of HR at the second ventilator threshold S: Whole body, explosive strength with 2–3 × 8–18 RM	ES ↑ SE ↑	ES ↑ SE ↑	C: No N: No
Schumann et al. [43]	Untrained men ES ($n = 16$) SE ($n = 18$)	24 weeks	2–3 day week ⁻¹ E: 30–50 min, continuous and HIIT cycling, progressively increasing from aerobic threshold intensity to anaerobic intensity S: Whole body, 2–4 × 15–20 repetitions at 40–60% of 1 RM, 2–5 × 8–10 repetitions at 80–85% of 1 RM, 2–5 × 3–5 repetitions at 85–95% of 1 RM	ES ↑ SE ↑	ES ↑ SE ↑	C: No N: No
Makhlof et al. [44]	Male elite soccer players ES ($n = 14$) SE ($n = 15$)	12 weeks	2 day week ⁻¹ E: 2 × 12–16 × 15 s at 110–120% of maximal speed S: Whole body 3 × 5–10 RM	ES ↑ SE ↑	ES ↑ SE ↑	C: No N: No
Eklund et al. [15]	Untrained women ES ($n = 15$) SE ($n = 14$)	24 weeks	2–3 day week ⁻¹ E: 30–50 min, continuous and HIIT cycling, progressively increasing from aerobic threshold intensity to anaerobic intensity S: Whole body, 2–4 × 15–20 repetitions at 40–60% of 1 RM, 2–5 × 8–10 repetitions at 80–85% of 1 RM, 2–5 × 3–5 repetitions at 85–95% of 1 RM	ES ↑ SE ↑	ES ↑ SE ↑	C: No N: No

Küttismaa et al. [45]	Untrained men ES ($n = 21$) SE ($n = 21$)	24 weeks	2–3 day week $^{-1}$ E: 30–50 min, progressive continuous (65–80% HRmax) and HIIT (85–100% HRmax) cycling S: 2–3 × 10–20 repetitions at 40–70% of 1 RM, 3–4 × 10–15 repetitions at 70–85% of 1 RM, 3–5 × 3–8 repetitions at 85–95%	ES ↑ SE ↑	ES ↑ SE ↑	C: Yes N: No
Cadore et al. [46]	Untrained elderly men ES ($n = 12$) SE ($n = 13$)	12 weeks	3 day week $^{-1}$ E: Cycling, 20–30 min continuous at 80–90% of heart rate at second ventilatory threshold, interval cycling 6 × 4 min at second ventilatory threshold S: Whole body, 2–3 × 6–20 RM	ES ↑ SE ↑	N/A	No

E: endurance exercise, *S*: strength exercise, *C*: indices of cardiorespiratory function, *N*: indices of neuromuscular function, *RM*: repetition maximum, *HR*: heart rate,
 ↑: significant increase in either of the outcome variables being classified as “neuromuscular” or “cardiorespiratory” ($p < 0.05$), Note: Larger increases in one group denoted by “↑↑” may not necessarily lead to a statistical between-group difference ($p < 0.05$)

quite drastically in the study design and population studied, providing a rather heterogeneous sample for a meta-analysis.

Based on our study showing exercise order-specific differences in hormonal responses, one may expect commencing training with strength exercise to induce superior neuromuscular adaptations as compared to the opposite exercise order, due to maintained recovery testosterone concentrations in this group [6]. However, when subjects systematically continued training with a periodized endurance and strength training program for 24 weeks, adaptations in muscle hypertrophy and dynamic strength were similar in the two groups [14, 43]. Moreover, no statistical associations between the acute changes in growth hormone or testosterone concentrations and the magnitude of maximal strength gains or hypertrophy were observed.

These findings are in line with several previous studies in young men and women with various training backgrounds (Table 14.1) [15, 35, 36, 38, 40, 41, 43–45]. Unfortunately, while the initial reduction in testosterone concentrations in our study [6] was no longer observed after 24 weeks of training [14], the exact time line for these adaptations cannot be ruled out by the study design. Furthermore, it needs to be acknowledged that the training frequency in our (as well as in most other previous studies) was rather low (i.e., 2–3 weekly combined training sessions), allowing for at least 2 full days of rest between consecutive training sessions, while the initial reductions in testosterone were observed for 48 h only [6, 14]. It remains, thus, unknown whether performing concurrent training sessions more frequently will actually lead to sequence-specific training adaptations.

While maximal exercise performance did not seem to be affected by the order of exercise, we actually did observe at least small differences in neural adaptations between the groups [5]. During isometric knee extension, the EMG of vastus lateralis statistically increased only in the group commencing training with strength, while the magnitude of improvement was much smaller in the opposite exercise sequence. Supporting these findings, a statistically significant correlation between changes in voluntary activation (assessed by the superimposed twitch technique) and strength performance was observed in the group commencing with endurance training during the latter 12 weeks of the training program, where about half of the subjects actually decreased both isometric strength and voluntary activation. In line with this, in the same group no statistically significant increases in rapid force production were observed [43], indicating indeed at least to some extent neural inhibition when aerobic exercise continuously precedes strength training, despite no differences in maximal strength performance. This finding is in line with studies in older men, in which it was shown that the force per unit of muscle mass of knee extensors increased to a larger extent when strength training was performed before endurance training [4]. Similarly, lower body strength gains and improved neuromuscular economy (normalized EMG at 50% of peak torque) were found when strength training preceded endurance training compared to the opposite exercise sequence, while no differences in muscle thickness were observed [39].

With regard to cardiorespiratory adaptations, studies have found limited increases in $\text{VO}_{2\text{max}}$ following the order commencing with strength training in young women [36] and men [37, 45], while others have found no statistical between-group differences in young subjects [15, 35, 40, 41, 43, 44]. Interestingly, while in old men no

differences in $\text{VO}_{2\text{max}}$ and absolute as well as relative cycling economy were observed [4, 46], the load at the first ventilatory threshold was statistically increased only in the group commencing the training with strength exercise [4]. This finding was opposed to our own study in which we showed improved cycling economy when training was commenced with aerobic exercise in previously untrained women but not men [3]. As in the study by Cadore et al. [4] also neuromuscular performance was optimized following the exercise order commencing with strength training, the authors concluded that improved muscular strength beneficially affected cycling economy at least in some intensities. This was somewhat confirmed by the finding of larger individual responses when commencing training with aerobic exercise [46] and may indicate that the training sequence may be important to optimize training adaptations both in women and in elderly men, as has been described in depth elsewhere in this book.

Chronic Adaptations to Same-Session Combined Training Versus Concurrent Training Performed on Separate Days

While so far the adaptions in respect to the exercise sequence were discussed, findings from these studies do not allow drawing conclusions on whether performing aerobic and strength training in close proximity may actually induce distinct adaptations when compared to combined training performed on separate days. From a practical point of view, splitting aerobic and strength exercise onto alternating days may reduce residual fatigue between aerobic and strength training sessions but at the same time may reduce overall recovery time due to a higher training frequency when total training volume is matched. Indeed, the evidence underlying this concern is still rather sparse but especially during the past 5 years studies concerning this question were carried out.

Already an early study by Sale et al. [49] reported that previously untrained subjects training on different days improved strength performance over 20 weeks to a larger extent than those subjects performing both modes within the same session, even though both training groups improved both fast and slow twitch fiber area and muscle size to a similar extent. More recently, the benefits of a longer recovery time between the two distinct exercise modes were nicely demonstrated by a study of Robineau et al. [2] and have been described in detail elsewhere in this book. Briefly, it was shown that a recovery of at least 6 h between strength and aerobic training sessions may optimize overall strength gains, while for aerobic performance even 24 h might be required.

The findings of these previous studies were at least somewhat well in line with results obtained by our group. In previously untrained subjects, we showed that performing a periodized aerobic and strength training program on separate days nearly doubled the magnitude of cardiorespiratory adaptations as compared to volume-matched combined training performed within the same training session, while no difference in dynamic strength or muscle mass was observed [3, 50]. It should, however, be noted that the initial values of maximal oxygen consumption were significantly lower in the group performing concurrent training on separate days. While this was accounted for in the statistical analysis, initial lower cardiorespiratory

fitness provides a much larger window/potential for physiological adaptations induced by training and may, thus, have at least in part be contributed to the much larger changes in $\text{VO}_{2\text{max}}$ in this group.

The distinct changes in cardiorespiratory adaptations in our study were accompanied by significant reductions in total fat mass, exclusively observed in the group performing concurrent training on separate days [50]. While the effects of such training regimen on body composition and health were beyond the scope of this chapter, it is likely that these adaptations were at least in part explained by the frequency of acute peaks in fat oxidation, despite a similar total training volume. In line with this, it was previously shown that the accumulated EPOC response following split sessions (i.e., a 2 h training session split into 2×1 h of aerobic exercise) was much larger than that observed following a volume and time-matched single training session [51], indicating training frequency to be an important variable to consider when planning concurrent training programs.

When comparing concurrent training performed on alternating days or within the same training session, possible differences may also be observed between alternating days and either of the two exercise sequences only (i.e., aerobic exercise performed prior to or after strength exercise). Makhlof et al. [44] found that adolescent soccer players' adaptations in countermovement jumping height were significant only when concurrent training was performed on separate days or within the same session, commencing with strength training but not vice versa. This observation is not surprising as in both scenarios strength training was performed in a "recovered" state or at least not immediately preceded by aerobic exercise. While not reflected in overall strength performance, these findings are somewhat in line with a study of our group in which we showed that the neural adaptations are optimized when strength training is performed on separate days or at least prior to aerobic training [5].

Summary

This chapter aimed at providing a summary on the acute physiological and performance responses and adaptations to concurrent aerobic and strength training, with special reference to the training mode. Current literature provides evidence for distinct acute physiological responses, appearing to be specific to the sequence of concurrent training sessions. However, these different responses may not necessarily be reflected in force responses, requiring more advanced tools for monitoring. This is for example shown by reduced hormone concentrations for up to 48 h, which are especially pronounced when strength training is preceded by aerobic exercise. However, even though some indices of neural inhibition may be observed when aerobic training is consistently performed prior to strength exercise the acute sequence-specific differences may not translate into performance gains after prolonged training. Thus, considering that aerobic and strength exercise are to be performed in the same training session the exercise order may not be crucial for physiological adaptations when sufficient recovery (i.e., >48 h) is provided between subsequent training sessions. However, in order to optimize gains in physical fitness both in men and women, aerobic and strength exercises should be separated by 6–24 h.

References

1. Hickson RC. Interference of strength development by simultaneously training for strength and endurance. *Eur J Appl Physiol Occup Physiol*. 1980;45(2–3):255–63.
2. Robineau J, Babault N, Piscione J, Lacome M, Bigard AX. Specific training effects of concurrent aerobic and strength exercises depend on recovery duration. *J Strength Cond Res*. 2016;30(3):672–83. <https://doi.org/10.1519/JSC.0000000000000798>.
3. Schumann M, Yli-Peltola K, Abbiss CR, Häkkinen K. Cardiorespiratory adaptations during concurrent aerobic and strength training in men and women. *PLoS One*. 2015;10(9):e0139279. <https://doi.org/10.1371/journal.pone.0139279>.
4. Cadore EL, Izquierdo M, Alberton CL, Pinto RS, Conceição M, Cunha G, et al. Strength prior to endurance intra-session exercise sequence optimizes neuromuscular and cardiovascular gains in elderly men. *Exp Gerontol*. 2012a;47(2):164–9. <https://doi.org/10.1016/j.exger.2011.11.013>.
5. Eklund D, Pulverenti T, Bankers S, Avela J, Newton R, Schumann M, Häkkinen K. Neuromuscular adaptations to different modes of combined strength and endurance training. *Int J Sports Med*. 2015;36(2):120–9. <https://doi.org/10.1055/s-0034-1385883>.
6. Schumann M, Eklund D, Taipale RS, Nyman K, Kraemer WJ, Häkkinen A, et al. Acute neuromuscular and endocrine responses and recovery to single-session combined endurance and strength loadings. “Order effect” in untrained young men. *J Strength Cond Res*. 2013;27(2):421–33. <https://doi.org/10.1519/JSC.0b013e31827f4a10>.
7. Taipale RS, Häkkinen K. Acute hormonal and force responses to combined strength and endurance loadings in men and women. The “order effect”. *PLoS One*. 2013;8(2):e55051. <https://doi.org/10.1371/journal.pone.0055051>.
8. Craig BW, Lucas J, Pohlman R, Stelling H. The effects of running, weightlifting and a combination of both on growth hormone release. *J Strength Cond Res*. 1991;5(4):198–203.
9. Ahtiainen JP, Pakarinen A, Kraemer WJ, Häkkinen K. Acute hormonal and neuromuscular responses and recovery to forced vs maximum repetitions multiple resistance exercises. *Int J Sports Med*. 2003a;24(6):410–8. <https://doi.org/10.1055/s-2003-41171>.
10. McCaulley GO, McBride JM, Cormie P, Hudson MB, Nuzzo JL, Quindry JC, Travis Triplett N. Acute hormonal and neuromuscular responses to hypertrophy, strength and power type resistance exercise. *Eur J Appl Physiol*. 2009;105(5):695–704. <https://doi.org/10.1007/s00421-008-0951-z>.
11. Millet GY, Lepers R. Alterations of neuromuscular function after prolonged running, cycling and skiing exercises. *Sports Med (Auckland, NZ)*. 2004;34(2):105–16.
12. Fyfe JJ, Bishop DJ, Stepto NK. Interference between concurrent resistance and endurance exercise. Molecular bases and the role of individual training variables. *Sports Med (Auckland, NZ)*. 2014;44(6):743–62. <https://doi.org/10.1007/s40279-014-0162-1>.
13. Taipale RS, Schumann M, Mikkola J, Nyman K, Kyröläinen H, Nummela A, Häkkinen K. Acute neuromuscular and metabolic responses to combined strength and endurance loadings. The “order effect” in recreationally endurance trained runners. *J Sports Sci*. 2014;32(12):1155–64. <https://doi.org/10.1080/02640414.2014.889842>.
14. Schumann M, Walker S, Izquierdo M, Newton RU, Kraemer WJ, Häkkinen K. The order effect of combined endurance and strength loadings on force and hormone responses. Effects of prolonged training. *Eur J Appl Physiol*. 2014b;114(4):867–80. <https://doi.org/10.1007/s00421-013-2813-6>.
15. Eklund D, Schumann M, Kraemer WJ, Izquierdo M, Taipale RS, Häkkinen K. Acute endocrine and force responses and long-term adaptations to same-session combined strength and endurance training in women. *J Strength Cond Res*. 2016b;30(1):164–75. <https://doi.org/10.1519/JSC.00000000000001022>.
16. Häkkinen K, Pakarinen A. Acute hormonal responses to two different fatiguing heavy-resistance protocols in male athletes. *J Appl Physiol (Bethesda, MD 1985)*. 1993;74(2):882–7. <https://doi.org/10.1152/jappl.1993.74.2.882>.
17. Vøllestad NK, Vaage O, Hermansen L. Muscle glycogen depletion patterns in type I and subgroups of type II fibres during prolonged severe exercise in man. *Acta Physiol Scand*. 1984;122(4):433–41. <https://doi.org/10.1111/j.1748-1716.1984.tb07531.x>.

18. Henneman E, Somjen G, Carpenter DO. Excitability and inhibitability of motoneurons of different sizes. *J Neurophysiol.* 1965;28(3):599–620. <https://doi.org/10.1152/jn.1965.28.3.599>.
19. Fink J, Schoenfeld BJ, Nakazato K. The role of hormones in muscle hypertrophy. *Phys Sportsmed.* 2018;46(1):129–34. <https://doi.org/10.1080/00913847.2018.1406778>.
20. Ahtiainen JP, Pakarinen A, Alen M, Kraemer WJ, Häkkinen K. Muscle hypertrophy, hormonal adaptations and strength development during strength training in strength-trained and untrained men. *Eur J Appl Physiol.* 2003b;89(6):555–63. <https://doi.org/10.1007/s00421-003-0833-3>.
21. Häkkinen K, Pakarinen A, Kraemer WJ, Newton RU, Alen M. Basal concentrations and acute responses of serum hormones and strength development during heavy resistance training in middle-aged and elderly men and women. *J Gerontol A Biol Sci Med Sci.* 2000;55(2):B95–105.
22. Kvorning T, Andersen M, Brixen K, Madsen K. Suppression of endogenous testosterone production attenuates the response to strength training. A randomized, placebo-controlled, and blinded intervention study. *Am J Phys Endocrinol Metab.* 2006;291(6):E1325–32. <https://doi.org/10.1152/ajpendo.00143.2006>.
23. McCall GE, Byrnes WC, Fleck SJ, Dickinson A, Kraemer WJ. Acute and chronic hormonal responses to resistance training designed to promote muscle hypertrophy. *Can J Appl Physiol.* 1999;24(1):96–107.
24. Rønnestad BR, Nygaard H, Raastad T. Physiological elevation of endogenous hormones results in superior strength training adaptation. *Eur J Appl Physiol.* 2011;111(9):2249–59. <https://doi.org/10.1007/s00421-011-1860-0>.
25. Goto K, Higashiyama M, Ishii N, Takamatsu K. Prior endurance exercise attenuates growth hormone response to subsequent resistance exercise. *Eur J Appl Physiol.* 2005;94(3):333–8. <https://doi.org/10.1007/s00421-004-1296-x>.
26. Vingren JL, Kraemer WJ, Ratamess NA, Anderson JM, Volek JS, Maresh CM. Testosterone physiology in resistance exercise and training. The up-stream regulatory elements. *Sports Med (Auckland, NZ).* 2010;40(12):1037–53. <https://doi.org/10.2165/11536910-000000000-00000>.
27. Cadore EL, Izquierdo M, Santos d, Gonçalves M, Martins JB, Lhullier R, Francisco L, Pinto RS, et al. Hormonal responses to concurrent strength and endurance training with different exercise orders. *J Strength Cond Res.* 2012b;26(12):3281–8. <https://doi.org/10.1519/JSC.0b013e318248ab26>.
28. Rosa C, Vilaça-Alves J, Fernandes HM, Saavedra FJ, Pinto RS, dos Reis VM. Order effects of combined strength and endurance training on testosterone, cortisol, growth hormone, and IGF-1 binding protein 3 in concurrently trained men. *J Strength Cond Res.* 2015;29(1):74–9. <https://doi.org/10.1519/JSC.0000000000000610>.
29. Apró W, Moberg M, Hamilton DL, Ekblom B, van Hall G, Holmberg H-C, Blomstrand E. Resistance exercise-induced S6K1 kinase activity is not inhibited in human skeletal muscle despite prior activation of AMPK by high-intensity interval cycling. *Am J Physiol Endocrinol Metab.* 2015;308(6):E470–81. <https://doi.org/10.1152/ajpendo.00486.2014>.
30. Di Blasio A, Gemello E, Di Iorio A, Di Giacinto G, Celso T, Di Renzo D, et al. Order effects of concurrent endurance and resistance training on post-exercise response of non-trained women. *J Sports Sci Med.* 2012;11(3):393–9.
31. Oliveira NL, Oliveira J. Excess postexercise oxygen consumption is unaffected by the resistance and aerobic exercise order in an exercise session. *J Strength Cond Res.* 2011;25(10):2843–50. <https://doi.org/10.1519/JSC.0b013e318207ef4b>.
32. Vilacxa Alves J, Saavedra F, Simão R, Novaes J, Rhea MR, Green D, Machado Reis V. Does aerobic and strength exercise sequence in the same session affect the oxygen uptake during and postexercise? *J Strength Cond Res.* 2012;26(7):1872–8. <https://doi.org/10.1519/JSC.0b013e318238e852>.
33. Drummond MJ, Vehrs PR, Schaalje GB, Parcell AC. Aerobic and resistance exercise sequence affects excess postexercise oxygen consumption. *J Strength Cond Res.* 2005;19(2):332–7. <https://doi.org/10.1519/R-14353.1>.
34. Bond V, Adams RG, Tearney RJ, Gresham K, Ruff W. Effects of active and passive recovery on lactate removal and subsequent isokinetic muscle function. *J Sports Med Phys Fitness.* 1991;31(3):357–61.

35. Collins MA, Snow TK. Are adaptations to combined endurance and strength training affected by the sequence of training? *J Sports Sci.* 1993;11(6):485–91. <https://doi.org/10.1080/02640419308730017>.
36. Gravelle BL, Blessing DL. Physiological adaptation in women concurrently training for strength and endurance. *J Strength Cond Res.* 2000;14(1):5–13.
37. Chtara M, Chamari K, Chaouachi M, Chaouachi A, Koubaa D, Feki Y, et al. Effects of intra-session concurrent endurance and strength training sequence on aerobic performance and capacity. *Br J Sports Med.* 2005;39(8):555–60. <https://doi.org/10.1136/bjsm.2004.015248>.
38. Chtara M, Chaouachi A, Levin GT, Chaouachi M, Chamari K, Amri M, Laursen PB. Effect of concurrent endurance and circuit resistance training sequence on muscular strength and power development. *J Strength Cond Res.* 2008;22(4):1037–45. <https://doi.org/10.1519/JSC.0b013e31816a4419>.
39. Cadore EL, Izquierdo M, Pinto SS, Alberton CL, Pinto RS, Baroni BM, et al. Neuromuscular adaptations to concurrent training in the elderly. Effects of intrasession exercise sequence. *Age (Dordr).* 2013;35(3):891–903. <https://doi.org/10.1007/s11137-012-9405-y>.
40. McGawley K, Andersson P-I. The order of concurrent training does not affect soccer-related performance adaptations. *Int J Sports Med.* 2013;34(11):983–90. <https://doi.org/10.1055/s-0033-1334969>.
41. Davitt PM, Pellegrino JK, Schanzer JR, Tjionas H, Arent SM. The effects of a combined resistance training and endurance exercise program in inactive college female subjects. Does order matter? *J Strength Cond Res.* 2014;28(7):1937–45. <https://doi.org/10.1519/JSC.00000000000000355>.
42. Wilhelm EN, Rech A, Minozzo F, Botton CE, Radaelli R, Teixeira BC, et al. Concurrent strength and endurance training exercise sequence does not affect neuromuscular adaptations in older men. *Exp Gerontol.* 2014;60:207–14. <https://doi.org/10.1016/j.exger.2014.11.007>.
43. Schumann M, Küüsmaa M, Newton RU, Sirparanta A-I, Syväoja H, Häkkinen A, Häkkinen K. Fitness and lean mass increases during combined training independent of loading order. *Med Sci Sports Exerc.* 2014a;46(9):1758–68. <https://doi.org/10.1249/MSS.0000000000000303>.
44. Makhlof I, Castagna C, Manzi V, Laurencelle L, Behm DG, Chaouachi A. Effect of sequencing strength and endurance training in young male soccer players. *J Strength Cond Res.* 2016;30(3):841–50. <https://doi.org/10.1519/JSC.00000000000001164>.
45. Küüsmaa M, Schumann M, Sedliak M, Kraemer WJ, Newton RU, Malinen J-P, et al. Effects of morning versus evening combined strength and endurance training on physical performance, muscle hypertrophy, and serum hormone concentrations. *Appl Physiol Nutr Metab.* 2016;41(12):1285–94. <https://doi.org/10.1139/apnm-2016-0271>.
46. Cadore EL, Pinto RS, Teodoro JL, da Silva LZN, Menger E, Alberton CL, et al. Cardiorespiratory adaptations in elderly men following different concurrent training regimes. *J Nutr Health Aging.* 2018;22(4):483–90. <https://doi.org/10.1007/s12603-017-0958-4>.
47. Eddens L, van Someren K, Howatson G. The role of intra-session exercise sequence in the interference effect. A systematic review with meta-analysis. *Sports Med (Auckland, NZ).* 2018;48(1):177–88. <https://doi.org/10.1007/s40279-017-0784-1>.
48. Murlasits Z, Kneffel Z, Thalib L. The physiological effects of concurrent strength and endurance training sequence. A systematic review and meta-analysis. *J Sports Sci.* 2018;36(11):1212–9. <https://doi.org/10.1080/02640414.2017.1364405>.
49. Sale DG, Jacobs I, MacDougall JD, Garner S. Comparison of two regimens of concurrent strength and endurance training. *Med Sci Sports Exerc.* 1990;22(3):348–56.
50. Eklund D, Häkkinen A, Laukkanen JA, Balandzic M, Nyman K, Häkkinen K. Fitness, body composition and blood lipids following 3 concurrent strength and endurance training modes. *Appl Physiol Nutr Metab.* 2016a;41(7):767–74. <https://doi.org/10.1139/apnm-2015-0621>.
51. Almuzaini KS, Potteiger JA, Green SB. Effects of split exercise sessions on excess postexercise oxygen consumption and resting metabolic rate. *Can J Appl Physiol.* 1998;23(5):433–43.



Recovery Strategies to Optimise Adaptations to Concurrent Aerobic and Strength Training

15

Nicholas G. Allen, Samuel M. Higham, and Rob Duffield

Introduction

Concurrent training represents a broad framework whereby divergent exercise modalities (e.g. endurance and strength training) are undertaken concomitantly within a single session or across a larger training cycle [1]. Specifically, it involves the mixed use of continuous submaximal/intermittent exercise, alongside higher-load resistance exercise to stimulate metabolic and morphological adaptations associated with the differing training modalities [1, 2]. The rationale for this training method is discussed in detail elsewhere in this book, though it is used by numerous athletic events requiring both endurance and strength/power training for successful performance outcomes [2]. For example, simultaneous endurance and resistance training is common for those in sports such as cycling, running and team sports [3], as well as the general population seeking to achieve a broad range of exercise-related outcomes simultaneously [4]. However, by engaging in concurrent training, both the load (volume and intensity) and potential interference to adaptive responses will increase [5]. Consequently, there is an additional requirement for appropriate recovery strategies to promote adaptation or prevent interference and non-functional overreaching [5]. Exploration of appropriate recovery methods may also be of use to limit the potential negative outcomes of concurrent training.

Recovery is a multifaceted concept that describes the return of physiological and psychological systems to (near) pre-exercise levels [6]. Recovery is also specific to the imposed physiological disturbance, and thus selected recovery interventions should be similarly specific to imposed loads [6]. Accordingly, key issues related to the training loads and stimuli of concurrent training necessitate awareness of appropriate recovery strategies. Firstly, the cumulative effects of

N. G. Allen (✉) · S. M. Higham · R. Duffield
Sport and Exercise Discipline Group, Faculty of Health, University of Technology Sydney (UTS), Ultimo, NSW, Australia
e-mail: Nicholas.Allen@uts.edu.au

training-induced fatigue resulting from concurrent training sessions can negatively impact subsequent training bouts [7]. With this loading issue in mind, appropriate recovery methods may be deemed advantageous to improve the ability to perform and tolerate successive training bouts. Secondly, evidence suggests that acute adaptive molecular signalling processes related to endurance and resistance exercise may interact in some way, resulting in possibly antagonistic responses [8]. Thus, the optimal periodisation of these respective training stimuli may help to reduce molecular ‘crosstalk’ that can suppress phenotypic adaptations [8]. Finally, the nutritional requirements to aid recovery and promote myofibrillar and mitochondrial adaptation within concurrent training warrant consideration, particularly, training-induced glycogen depletion, timing and quantity of protein consumption, and dietary supplementation strategies [7].

Concurrent Training and the Need for Recovery

Further exploring the aforementioned potential issues, the completion of multiple training sessions in close temporal proximity, as well as accumulated fatigue from greater overall training volumes, can impact upon strength and hypertrophic adaptations [4]. Specifically, evidence suggests that localised fatigue can persist for several hours following aerobic exercise, possibly impacting on the volume of work performed during subsequent resistance exercise bouts [9]. Accordingly, it is recommended that athletes separate same-day training sessions by several hours to minimise any potential interference, and perhaps more importantly, reduce the effects of fatigue as discussed in previous chapters [7]. Ultimately, recovery interventions that promote higher-quality training of either modality are important when undertaking concurrent training within or between days [7].

A separate concern of concurrent training is the ‘crosstalk’ in molecular signalling driving adaptations from the varied training stimuli [2]. For example, it is suggested that aerobic exercise may inhibit load-induced anabolic signalling via the downregulation of hypertrophic mechanisms related to energy-sensitive signals [4]. However, despite potential for acute molecular ‘crosstalk’, it is unclear whether these responses are predictive of long-term adaptations [4], and the current data do not ultimately seem to support a chronic interference effect [10]. Nonetheless, promoting an optimal recovery state, particularly from peri-training nutritional intake, may be beneficial to optimise concurrent training adaptations and minimise potential interference [1]. Hypertrophic signalling may be affected by a number of antagonistic processes related to substrate availability, and thus the overall energy status and individual nutrient intake following exercise should be considered to aid nutrition-driven recovery [7]. For example, the importance of protein or carbohydrate availability to enhance muscle recovery warrants careful consideration [11]. In addition, many dietary supplements, including those that reduce muscle damage, optimise perceived recovery, or enhance subsequent training bouts, may be of use in the context of concurrent training. Considering the abovementioned issues, the following sections will examine specific and practical strategies to enhance post-exercise recovery.

Nutritional Considerations for Recovery

Carbohydrate

Given that both resistance and endurance exercise can decrease intramuscular and hepatic glycogen stores, carbohydrate (CHO) feeding may occupy a central role in training recovery [1, 12]. Specifically, low muscle glycogen is related to increased fatigue and may inhibit performance [13, 14] and protein synthesis signalling [4]. Thus, it is recommended to consume CHO following fatiguing training sessions to minimise blunted recovery induced by low glycogen status [15], alongside ensuring adequate substrate availability for subsequent sessions. In particular, when the between-session recovery period is <8 h, CHO should be consumed as soon as possible following training, with the required quantities varying from 3–5 g kg day⁻¹ (low-load activity) to 8–12 g kg day⁻¹ (>4 h training per day) [16]. Separately, the synergistic interaction of CHO and protein as part of a post-exercise nutritional plan suggests some potential for aiding recovery within the context of concurrent resistance and aerobic training loads [16]. However, resistance training adaptations may occur irrespective of glycogen availability [17, 18], and thus there is an increased emphasis on the role of protein during recovery for concurrent athletes.

Protein

Dietary protein is a key consideration during concurrent training given its essential role in the remodelling and recovery of skeletal muscle [1]. Furthermore, if endurance and resistance exercise are performed on the same day, a rapidly absorbed protein source may be appropriate for between-session recovery [7]. A leucine-rich protein (e.g. whey) is recommended for consumption post-resistance exercise, and approximately 0.25 g kg⁻¹ of high-quality protein is suggested to optimise post-session protein turnover and stimulate myofibrillar hypertrophy—a mechanism which can be compromised during concurrent training [1]. Also, the timing of protein intake may be of importance during concurrent training. For example, repeated doses of ~20 g high-quality protein every 3 h was more effective to induce a positive protein balance than more frequent (10 g every 90 min) or less frequent (40 g every 6 h) consumption patterns and thus bears relevance to multiple training sessions per day [19]. Furthermore, a larger dose of protein (~0.5 g kg⁻¹) may be appropriate prior to sleep to offset the catabolic effects of the overnight fast and further enhance post-exercise recovery [20].

Dietary Supplementation to Enhance Recovery

Creatine

Creatine supplementation represents a potential strategy to optimise concurrent training adaptations, particularly given the issues related to fatigue accumulation from high-volume training. Exogenous creatine improves work capacity via

accelerated resynthesis of phosphocreatine and subsequent adenosine diphosphate buffering, increasing fatigue resistance and providing a potential buffer to metabolic acidosis [21]. Nutritional supplementation using creatine monohydrate (~5 g/day) may facilitate greater adaptations to concurrent training via an increased capacity to train [1]. Specifically, creatine monohydrate supplementation attenuated strength loss during concurrent training in recreationally strength-trained individuals [22]. Conversely, no advantage from creatine supplementation was reported in rowers during a 10-week combined strength and aerobic interval training programme [23]. Evidently, a paucity of data exists from which to draw conclusions for concurrent athletes; however, given the established ergogenic effects of creatine supplementation on resistance training and the role it plays in fatigue resistance, it is a promising strategy to minimise the fatiguing effect of consecutive exercise sessions [21]. Thus, it may serve to minimise interference between training sessions and optimise the recovery process during concurrent training.

Nitrate

Present in many leafy green vegetables, dietary nitrate represents a potential ergogenic strategy to assist recovery for concurrent athletes. Under conditions of hypoxia and low pH, nitrate is reduced to nitric oxide (NO), which may subsequently confer performance-enhancing effects through regulation of peripheral blood flow, mitochondrial respiration and excitation-contraction coupling [24]. Acute administration of beetroot juice supplementation ($\approx 0.1 \text{ mmol kg}^{-1}$ body mass NO) is proposed to lower the oxygen cost of exercise and improve exercise tolerance, particularly under hypoxic conditions [25]. The ergogenic effects of exogenous nitrate supplementation may be useful to offset fatigue-related decrements in performance that can be evident when training in a pre-fatigued state, as is often the case for athletes undertaking multiple sessions involved in concurrent training [1]. However, current evidence relates primarily to endurance events, and as such it is difficult to make recommendations for concurrent training. That said, and noting that fatigue-management strategies are a primary consideration in this scenario, a potential application exists for supplementation with nitrate in concurrent training. Questions still remain regarding its efficacy in highly trained athletes [25] and the potential negative effects of chronic use [26], though nitrate supplementation still represents a potential tool to enhance recovery. As with any nutritional supplement, it must be applied with careful consideration of dosage, timing, exercise modalities and the training status of the user.

Caffeine

Caffeine is an extensively studied and commonly used dietary supplement which is supported as having a potent performance-enhancing effect [27]. It is a rapidly absorbed compound that is readily able to cross the blood–brain barrier [28] and

works to reduce perceptions of fatigue [27]. Caffeine may exert an analgesic effect through enhanced secretion of β -endorphins [29] and increase substrate mobilisation via adrenal cortisol release [29]. Further, it is suggested to act upon the central nervous system to enhance neuromuscular function and contractile force, alongside improved alertness and reaction time [27]. In the context of concurrent training, the need to tolerate increased training volumes and manage fatiguing stimuli suggests a potential role for caffeine. Additionally, co-ingestion with CHO has shown some effectiveness to increase glycogen resynthesis after exhaustive exercise compared to CHO alone [30]. Although caffeine is highly effective in improving exercise tolerance, prescription for concurrent athletes remains circumstantial, and there is insufficient evidence of a positive effect on recovery within or between concurrent training sessions. Moreover, clearance of caffeine from the circulation occurs after 3–6 h, and thus some concerns have been raised regarding the timing of consumption and the potential effect on sleep [27]. This is of particular relevance for athletes undertaking multiple sessions in 1 day, with sleep between sessions likely to be negatively affected. Despite extensive evidence of the ergogenic effects of caffeine for different modes of exercise, evidence for improved concurrent training is lacking. However, given the concerns of increased load from concurrent training, caffeine may provide some benefits to aid preparation for ensuing sessions.

Antioxidants

An acute bout of exercise represents a disruption to redox balance via a short-term elevation of reactive oxygen species (ROS) in the cells [31], whilst frequent training elicits adaptive responses by which the resistance to oxidative stress becomes greater over time [31]. Thus, despite detrimental cellular effects of ROS, regular pro-oxidative states may strengthen antioxidant mechanisms and allow adaptation to subsequent oxidative challenges [31]. Conversely, excessive ROS production (e.g. through intense/prolonged exercise) can cause muscle damage [32], soreness [31] and a localised decrement in force production [33]. In concurrent training where resistance loading may result in damage and aerobic exercise in metabolic challenges, the role of antioxidants may have merit. Thus, strategies to attenuate these changes via modulation of redox mechanisms have attracted some interest in the recovery literature. For example, antioxidant supplementation (vitamin E) is suggested to defend sarcolemmal membranes against ROS-induced destabilisation and creatine kinase release [34]. Further, there is some evidence to suggest that antioxidant treatments can reduce fatigue-induced decrements in muscle contractile force [35]. However, current evidence for an effect of antioxidants to improve recovery, soreness or delayed onset muscle soreness (DOMS) is equivocal [31] and justification for use during concurrent training remains conceptual only [36]. Moreover, it has been observed that supplementary antioxidants (vitamin C) may blunt the exercise-induced spike in the expression of cytoprotective proteins, i.e. interfere with positive cellular adaptations [37]. In summary, although antioxidant supplementation may reduce the acute oxidative impact of strenuous exercise, it is

likely inappropriate as a long-term recovery strategy. Although a number of commercially available supplements have yet to be formally investigated, a lack of evidence specific to concurrent training renders their use unsubstantiated, and for concurrent athletes, a sufficient dietary intake of adequate fruits and vegetables remains the primary focus [31].

Anti-inflammatories

The period following a concurrent exercise bout is characterised by a localised elevation in leukocytes and inflammatory cytokines via an integrated tissue remodelling response [38, 39]. Specifically, it is suggested that macrophage-based prostaglandin synthesis, as well as localised oedema, stimulates pain receptors and contribute to feelings of DOMS [40]. Accordingly, for concurrent athletes seeking to undertake consecutive exercise bouts with abbreviated recovery periods, inflammatory processes have become a target for post-training interventions [41]. Purportedly, pharmacological and nutraceutical strategies may reduce training-induced performance decrements by manipulating inflammatory pathways and the associated neuromuscular mechanisms [42, 43]. However, some concerns are present with this strategy, as inhibition of inflammatory processes may interfere with important adaptation and repair mechanisms in skeletal muscle [44]. Thus, these interventions are dependent on contextual factors and should be interpreted with an understanding of the appropriateness of their application.

A number of foods and medicines are recognised to have anti-inflammatory properties, and thus there has been some investigation into supplementation as a means of blunting the inflammatory response to exercise. For example, curcumin (a flavonoid present in turmeric) may exert an anti-inflammatory effect via multiple mechanisms including reduced NF- κ B activity and cytokine release [45] and improved scavenging of free radicals [46]. Despite numerous data showing an anti-inflammatory effect with curcumin, there is a lack of research specific to concurrent training recovery. A study in mice showed that oral administration of curcumin prior to eccentric running attenuated the localised inflammation and muscle damage present with a placebo group, and also reversed training-induced performance decrements for 3 days [46]. Further, a pre- and post-exercise curcumin supplement caused a reduction in DOMS, inflammatory biomarkers, and improved jumping performance 24 h after eccentric resistance exercise in healthy men [47]. Indeed, there is preliminary support for the use of curcumin to augment recovery from exercise-induced muscle damage [48]. However, many supporting studies utilise eccentric-based exercise to induce DOMS and inflammatory responses, making findings difficult to apply to concurrent resistance and endurance training [48]. Alternatively, pharmacological anti-inflammatory treatments are commonly used amongst athletes due to their proposed anti-inflammatory and analgesic effects [49], which may aid the recovery process.

Non-steroidal anti-inflammatory drugs (NSAIDs), such as ibuprofen and aspirin, have been suggested as a potential recovery tool. These drugs work to reduce

inflammation via inhibition of cyclooxygenase-2 (COX-2) activity and subsequent prostaglandin synthesis [46]. If inflammation is considered a primary driver of DOMS and reduced muscle function, NSAIDs could conceivably play a role in minimising these effects. Previous investigations of this strategy have provided underwhelming results. In an acute setting, an ibuprofen tablet every 8 h post-eccentric resistance exercise caused reduced muscle damage markers, and a non-significant decrease in 48 h muscle soreness, but did not affect the acute recovery of strength/power performance in healthy participants [42]. Separately, untrained subjects showed no improvement in DOMS or strength performance after an eccentric exercise bout with NSAID treatment, and this outcome did not change for 3 days post-exercise [50]. There is some evidence to suggest that prophylactic NSAID administration (i.e. before exercise) may be more effective to improve recovery versus a post-exercise dose [51]; however, evidence in concurrent training models is lacking. Whilst promising evidence for the use of some anti-inflammatory compounds exists to reduce acute inflammation and possibly aid recovery, however, due to a lack of long-term studies relevant to concurrent training, it is difficult to make specific recommendations for such athletes.

Sleep and Timing of Recovery Periods

Sleep is an altered state of consciousness, without loss of neurophysiological control, and given the large periods in which sleep is undertaken, it represents a concentrated recovery period where metabolic and neural adaptations occur [52]. Given the large daily and microcycle volumes required for concurrent training, alongside potential molecular crosstalk adaptations and perceived fatigue, sleep and recovery periods are important to promote ensuing recovery [53, 54]. Of concern is when athletes do not gain sufficient sleep, either due to sleep deprivation or sleep restriction [55]. Sleep deprivation refers to severe sleep loss (i.e. entire nights) [56], and negatively impacts recovery—although its occurrence in athletes seems minimal [56, 57]. Alternatively, sleep restriction involves the disturbance of normal sleeping patterns, and smaller disturbances of sleep (i.e. 50% normal duration) [58]. Previous research has shown greater negative effects of sleep deprivation than restriction on recovery, though neither are ideal for concurrent athletes [56]. For example, sleep restriction (50% normal sleep) after high-intensity interval training increased feelings of sleepiness, and decreased peak power output and exercise motivation compared to normal sleep [58]. Given that high-intensity aerobic training is a common component of concurrent training [59], the decrease in mental and physical recovery may hinder an athlete's capacity to perform subsequent resistance training [60], in turn reducing training quality and potential adaptations. Additional research showed that total sleep deprivation decreased sprint times, perceived liveliness, muscle glycogen content, and peak voluntary force and voluntary activation of the quadriceps compared to normal sleep [57]. From the standpoint of a concurrent athlete, such alterations following training highlight the negative impact that sleep deprivation may have on ensuing training. Overall, maintaining normal sleep

patterns (7–9 h/night) appears vital to prevent the negative effect of sleep restriction or deprivation on strength and power outcomes, and psychological recovery [56] and as such, may support next-day training sessions, and concomitant physiological responses. As a recommendation, athletes should consider appropriate sleep hygiene practices to aid sleep, including avoiding electronic equipment and bright light prior to bed time, and avoiding use of caffeine and alcohol after 3:00 pm [61]. Shorter duration afternoon naps (10–30 min) between training sessions may also be utilised to attenuate the negative effects of sleep loss on recovery, if not ensure improved readiness to train regardless of prior sleep debt [61]. However, further research into the effect of chronic sleep loss on adaptations to concurrent training is required so that more specific recommendations for recovery can be made [56].

Given concurrent training increases the number and volume of training sessions, appropriate recovery time becomes an important consideration. Between-session recovery periods, as well as the timing of sessions on a given day, can influence the cumulative fatigue that is evident with concurrent training and, in turn, affect training performance [62]. As evidence, Robineau et al. [62] investigated the effects of different recovery periods on strength and endurance measures over a 7-week concurrent training programme in rugby players. The authors reported that strength and endurance measures increased to a greater extent when 24 h recovery was provided between endurance and strength training sessions, as compared to 0 h and 6 h between sessions [62]. Additionally, Sale et al. [63] studied the effect of 20 weeks' endurance and resistance training performed on the same day, compared to separate days, in untrained men. Separate-day training increased maximal leg press strength compared to same-day training. However, measures of muscle size and endurance capacity were similar between the respective methods [63]. Seemingly, sufficient recovery periods between endurance and strength sessions are important to facilitate adaptations from concurrent training; however, the abovementioned studies did not involve highly trained athletes, who may have greater training demands, and limitations on between-session recovery [64].

Many elite athletes undertake separate sessions of resistance and aerobic exercise in the same day (e.g. morning and evening). In this context, the recovery time between sessions, as well as the session order (i.e. endurance then resistance or vice versa) are worthy of consideration. Current evidence indicates that prior endurance exercise can negatively affect subsequent resistance training via inhibited force production [65] and a downregulated protein signalling response [4]. Further, it is suggested that this suppression of hypertrophic adaptations persists for at least 6 h [66], and possibly as long as 8 h [9], following an endurance-based training session. Thus it is suggested that endurance exercise be performed earlier in the day, with ≥ 6 h recovery before the later resistance training session [4]. As further evidence, the metabolic signalling response to aerobic exercise is reported to persist for 3 h post-session [67], and thus delaying resistance training until later in the day may permit sufficient recovery to allow the hypertrophic signalling cascade to proceed without interference [7]. An additional rationale for this strategy pertains to 'nutritional recovery', in that sufficient recovery time between same-day sessions also allows the athlete time to replenish protein and CHO [7]. The combined benefit of longer

durations between sessions and adequate nutritional intake ensures resistance training is performed in an energy-rich state, maximising protein signalling responses to the session and reducing the blunting effect of glycogen depletion on protein synthetic signalling [15]. Notwithstanding specific recovery methods, it is apparent that exercise-induced fatigue precipitates a split-session approach whereby training is organised such that recovery periods are sufficient to minimise fatigue-induced performance decrements [68].

Other Recovery Strategies

Whilst training load periodisation and nutritional intake represent the biggest drivers of recovery for concurrent athletes, implementation of specific recovery methods to improve between-session recovery and subsequent performance are likely to be of importance. Cold-water immersion (CWI) is one such method that may be used to improve symptoms of DOMS [69], and reduce performance decrements following exercise [70]. This strategy is suggested to ameliorate the central fatigue associated with prolonged or intense exercise and reduce post-session decrements in muscle function [71]. Specifically, CWI has been shown to improve subjective ratings of muscle soreness following intermittent running [72], team sport [73] and eccentric resistance training [74]; and may help to reverse decrements in muscle function after high-intensity exercise [72, 75]. When concurrent athletes are required to perform an increased number of sessions per day or within a microcycle, alleviation of DOMS may be important to ensure readiness to train and the quality of work performed.

Despite potential as an acute recovery strategy, the efficacy of CWI as a long-term recovery method has been questioned [76]. Recently, studies have suggested that the use of CWI after resistance training may inhibit strength and hypertrophic gains, with recent data showing blunted resistance training adaptations with post-exercise CWI [76, 77]. Acute studies support this notion, showing that post-resistance exercise CWI may attenuate muscle protein synthesis signalling (p70S6k), supposedly via reduced blood flow to skeletal muscle [77]. Further, the specific cooling protocol used seems to influence the response, with prolonged CWI inhibiting glycogen resynthesis, although current research is inconclusive on this matter [78]. In brief, despite showing promise as a tool to restore acute performance decrements, CWI may interfere with training adaptations (especially resistance training) when applied regularly. As such, care should be taken to consider the appropriateness of this intervention to the concurrent athlete.

The use of compression garments (CGs) may also facilitate recovery from concurrent training via reduced muscle damage and post-exercise ratings of soreness [79]. One suggested mechanism for this effect is compression of diluted blood vessels, leading to reduced levels of oedema and cell trauma [80]. Minimising residual fatigue from training is vital to maximise an individual's capacity to complete and adapt to concurrent training; hence, compression garments applied to fatigued muscle groups may be effective to restore the performance decrements associated with

successive sessions. As evidence, an accelerated recovery of strength performance compared to a non-CG control has been reported [81], though the explanatory mechanisms were unclear as muscle damage markers (myoglobin, creatine kinase) were similar across the two groups. Conversely, the effect on recovery from endurance exercise is less clear. A recent meta-analysis showed no benefit to post-running CGs, and the authors surmised that this was due to the multi-factorial nature of exercise-induced fatigue, whereby interventions to reduce muscle damage may have a minimal effect on overall recovery of performance [79]. During concurrent training, however, resistance training seems to have no detrimental effects on endurance training outcomes [5] and as such the necessity of CGs is questionable in this scenario. Moreover, a key concurrent recovery consideration is endurance exercise-induced fatigue, and presently, there are insufficient data to recommend CGs as a recovery strategy for the concurrent athlete. However, the use of CGs is regularly reported to improve perceived recovery, often via a placebo effect, and such perceptual assistance may still be of use for concurrent training to facilitate perceived readiness to train.

Summary

During concurrent training, appropriate recovery strategies are critical to maximise the individual's capacity to complete sessions, avoid injury and optimise adaptations. Generally, concurrent training presents a range of methodological obstacles relating to session schedules, rest periods and nutritional intake. Accordingly, an individualised approach targeting load distribution, nutrient timing and potential novel recovery interventions seems to be most appropriate for the concurrent athlete. Given the range and diversity of potential recovery interventions, Table 15.1 highlights a selection of these interventions and associated ranking of evidence to support their use. Future research should further examine the role of specific recovery methods within the context of concurrent training.

Practical Applications

- Fundamental recovery strategies (load scheduling, sleep and protein/carbohydrate consumption) should be the primary methods used by athletes undertaking concurrent training.
- Increased fatigue induced by large concurrent training volumes may be partially alleviated with the use of ergogenic aids such as creatine, nitrate and caffeine; though further mode-specific evidence is required.
- Nutraceutical and pharmacological recovery aids such as antioxidants and anti-inflammatories show promise to reduce acute fatigue. However, their long-term applicability and possible interference effects raise questions relating to potential applications for concurrent athletes.

- Compression garments and water immersion techniques are effective to enhance perceived recovery from muscle-damaging interventions (e.g. resistance training), although the effect on endurance performance recovery is less clear.
- Ensuring adequate rest must be a primary consideration for concurrent athletes—allowing at least 6 h recovery time between training sessions allows individuals to minimise fatigue-induced performance decrements, and provides time to implement nutrition-based recovery strategies. Athletes should aim for 7–9 h sleep per night, and follow appropriate sleep hygiene practices to minimise disturbances.

Table 15.1 Levels of evidence for a variety of potential recovery interventions for athletes undertaking concurrent training

Level of evidence	Intervention	Dosage	Proposed effect
A Body of evidence can be trusted to guide practice	Protein	1.7–2.2 g kg day ⁻¹	Aid muscle remodelling and promote strength adaptations
	Carbohydrate	3–12 g kg day (depending on activity)	Restore hepatic and intramuscular glycogen; support immune function
	Creatine	~5 g day in 3–5 day cycle	Improve PCr synthesis and buffer against acidosis
B Body of evidence can be trusted to guide practice in most situations	Caffeine	3–10 mg kg ⁻¹ (depending on individual response to dose)	Reduce perceptions of fatigue
C Body of evidence provides some support for recommendation(s) but care should be taken in its application	Cold-water immersion	10–15 min, 10–15 °C	Reduce soreness and restore muscle function via reduced central fatigue
	Curcumin	~25 g day ⁻¹	Reduce DOMS and muscle damage via anti-inflammatory effects
	Nitrate	400–600 mg day ⁻¹	Improve blood flow, mitochondrial respiration and muscle contractility
D Body of evidence is weak and recommendation must be applied with caution	Antioxidants		Protect against oxidative stress and reduce acute fatigue
	Compression garments		Reduce oedema and DOMS
	NSAIDs	~1200 mg day ⁻¹ (400 mg initial dose)	Reduce DOMS and muscle damage via anti-inflammatory effects

NHMRC levels of evidence and grades for recommendations for developers [82]

References

1. Perez-Schindler J, et al. Nutritional strategies to support concurrent training. *Eur J Sport Sci.* 2015;15(1):41–52.
2. Coffey VG, Hawley JA. Concurrent exercise training: do opposites distract? *J Physiol.* 2017;595(9):2883–96.
3. Jones TW, et al. Strength and conditioning and concurrent training practices in elite rugby union. *J Strength Cond Res.* 2016;30(12):3354–66.
4. Fyfe JJ, Bishop DJ, Stepto NK. Interference between concurrent resistance and endurance exercise: molecular bases and the role of individual training variables. *Sports Med.* 2014;44(6):743–62.
5. Wilson JM, et al. Concurrent training: a meta-analysis examining interference of aerobic and resistance exercises. *J Strength Cond Res.* 2012;26(8):2293–307.
6. Beelen M, et al. Nutritional strategies to promote postexercise recovery. *Int J Sport Nutr Exerc Metab.* 2010;20(6):515–32.
7. Baar K. Using molecular biology to maximize concurrent training. *Sports Med.* 2014;44(2):117–25.
8. Inoki K, Zhu T, Guan K-L. TSC2 mediates cellular energy response to control cell growth and survival. *Cell.* 2003;115(5):577–90.
9. Sporer BC, Wenger HA. Effects of aerobic exercise on strength performance following various periods of recovery. *J Strength Cond Res.* 2003;17(4):638–44.
10. Murach KA, Bagley JR. Skeletal muscle hypertrophy with concurrent exercise training: contrary evidence for an interference effect. *Sports Med.* 2016;46(8):1029–39.
11. Long X, et al. Rheb binding to mammalian target of rapamycin (mTOR) is regulated by amino acid sufficiency. *J Biol Chem.* 2005;280(25):23433–6.
12. Knuiman P, Hopman MT, Mensink M. Glycogen availability and skeletal muscle adaptations with endurance and resistance exercise. *Nutr Metab.* 2015;12(1):59.
13. Burnley M, Jones AM. Power-duration relationship: physiology, fatigue, and the limits of human performance. *Eur J Sport Sci.* 2016;18(1):1–12.
14. Ørtenblad N, Westerblad H, Nielsen J. Muscle glycogen stores and fatigue. *J Physiol.* 2013;591(18):4405–13.
15. McBride A, et al. The glycogen-binding domain on the AMPK β subunit allows the kinase to act as a glycogen sensor. *Cell Metab.* 2009;9(1):23–34.
16. Burke LM, et al. Carbohydrates for training and competition. *J Sports Sci.* 2011;29(sup1):S17–27.
17. Camera DM, et al. Low muscle glycogen concentration does not suppress the anabolic response to resistance exercise. *J Appl Physiol.* 2012;113(2):206–14.
18. Sawyer JC, et al. Effects of a short-term carbohydrate-restricted diet on strength and power performance. *J Strength Cond Res.* 2013;27(8):2255–62.
19. Moore DR, et al. Daytime pattern of post-exercise protein intake affects whole-body protein turnover in resistance-trained males. *Nutr Metab.* 2012;9(1):91.
20. Res PT, et al. Protein ingestion before sleep improves postexercise overnight recovery. *Med Sci Sports Exerc.* 2012;44(8):1560–9.
21. Bemben MG, Lamont HS. Creatine supplementation and exercise performance. *Sports Med.* 2005;35(2):107–25.
22. de Salles Painelli V, et al. Creatine supplementation prevents acute strength loss induced by concurrent exercise. *Eur J Appl Physiol.* 2014;114(8):1749–55.
23. Syrotuik DG, et al. Effects of creatine monohydrate supplementation during combined strength and high intensity rowing training on performance. *Can J Appl Physiol.* 2001;26(6):527–42.
24. Stamler JS, Meissner G. Physiology of nitric oxide in skeletal muscle. *Physiol Rev.* 2001;81(1):209–37.
25. Jones AM. Influence of dietary nitrate on the physiological determinants of exercise performance: a critical review. *Appl Physiol Nutr Metab.* 2014;39(9):1019–28.

26. Carlström M, et al. Cross-talk between nitrate-nitrite-NO and NO synthase pathways in control of vascular NO homeostasis. *Antioxid Redox Signal*. 2015;23(4):295–306.
27. Goldstein ER, et al. International society of sports nutrition position stand: caffeine and performance. *J Int Soc Sports Nutr*. 2010;7(1):5.
28. Fredholm BB, et al. Actions of caffeine in the brain with special reference to factors that contribute to its widespread use. *Pharmacol Rev*. 1999;51(1):83–133.
29. Laurent D, et al. Effects of caffeine on muscle glycogen utilization and the neuroendocrine axis during exercise. *J Clin Endocrinol Metab*. 2000;85(6):2170–5.
30. Pedersen DJ, et al. High rates of muscle glycogen resynthesis after exhaustive exercise when carbohydrate is coingested with caffeine. *J Appl Physiol*. 2008;105(1):7–13.
31. Peternelj T-T, Coombes JS. Antioxidant supplementation during exercise training. *Sports Med*. 2011;41(12):1043–69.
32. Van Der Meulen JH, et al. Contraction-induced injury to the extensor digitorum longus muscles of rats: the role of vitamin E. *J Appl Physiol*. 1997;83(3):817–23.
33. Reid MB, Moody MR. Dimethyl sulfoxide depresses skeletal muscle contractility. *J Appl Physiol*. 1994;76(5):2186–90.
34. Beaton LJ, et al. Contraction-induced muscle damage is unaffected by vitamin E supplementation. *Med Sci Sports Exerc*. 2002;34(5):798–805.
35. Reid MB, et al. N-acetylcysteine inhibits muscle fatigue in humans. *J Clin Investig*. 1994;94(6):2468.
36. Close GL, et al. Ascorbic acid supplementation does not attenuate post-exercise muscle soreness following muscle-damaging exercise but may delay the recovery process. *Br J Nutr*. 2006;95(5):976–81.
37. Khassaf M, et al. Effect of vitamin C supplements on antioxidant defence and stress proteins in human lymphocytes and skeletal muscle. *J Physiol*. 2003;549(2):645–52.
38. Peake J, Nosaka K, Suzuki K. Characterization of inflammatory responses to eccentric exercise in humans. *Exerc Immunol Rev*. 2005;11:64–85.
39. Monteiro PA, et al. Modulation of inflammatory response arising from high-intensity intermittent and concurrent strength training in physically active males. *Cytokine*. 2017;91:104–9.
40. Smith LL. Acute inflammation: the underlying mechanism in delayed onset muscle soreness? *Med Sci Sports Exerc*. 1991;23(5):542–51.
41. Toumi H, Best TM. The inflammatory response: friend or enemy for muscle injury? *Br J Sports Med*. 2003;37(4):284–6.
42. Tokmakidis SP, et al. The effects of ibuprofen on delayed muscle soreness and muscular performance after eccentric exercise. *J Strength Cond Res*. 2003;17(1):53–9.
43. Lima F, et al. Ibuprofen intake increases exercise time to exhaustion: a possible role for preventing exercise-induced fatigue. *Scand J Med Sci Sports*. 2016;26(10):1160–70.
44. Barnett A. Using recovery modalities between training sessions in elite athletes. *Sports Med*. 2006;36(9):781–96.
45. Biswas SK, et al. Curcumin induces glutathione biosynthesis and inhibits NF-κB activation and interleukin-8 release in alveolar epithelial cells: mechanism of free radical scavenging activity. *Antioxid Redox Signal*. 2005;7(1–2):32–41.
46. Davis JM, et al. Curcumin effects on inflammation and performance recovery following eccentric exercise-induced muscle damage. *Am J Physiol Regul Integr Comp Physiol*. 2007;292(6):R2168–73.
47. Nicol LM, et al. Curcumin supplementation likely attenuates delayed onset muscle soreness (DOMS). *Eur J Appl Physiol*. 2015;115(8):1769–77.
48. Heaton LE, et al. Selected in-season nutritional strategies to enhance recovery for team sport athletes: a practical overview. *Sports Med*. 2017;47(11):2201–18.
49. Warden SJ. Prophylactic use of NSAIDs by athletes: a risk/benefit assessment. *Phys Sportsmed*. 2010;38(1):132–8.
50. Stone MB, et al. Preliminary comparison of bromelain and ibuprofen for delayed onset muscle soreness management. *Clin J Sport Med*. 2002;12(6):373–8.

51. Hasson SM, et al. Effect of ibuprofen use on muscle soreness, damage, and performance: a preliminary investigation. *Med Sci Sports Exerc.* 1993;25(1):9–17.
52. Van Cauter E, et al. Metabolic consequences of sleep and sleep loss. *Sleep Med.* 2008;9:S23–8.
53. Thornton HR, et al. Effects of pre-season training on the sleep characteristics of professional rugby league players. *Int J Sports Physiol Perform.* 2017;13(2):176–82.
54. Schwellnus M, et al. How much is too much? (Part 2) International Olympic Committee consensus statement on load in sport and risk of illness. *Br J Sports Med.* 2016;50(17):1043–52.
55. Fullagar HH, et al. Sleep and recovery in team sport: current sleep-related issues facing professional team-sport athletes. *Int J Sports Physiol Perform.* 2015;10(8):950–7.
56. Fullagar HH, et al. Sleep and athletic performance: the effects of sleep loss on exercise performance, and physiological and cognitive responses to exercise. *Sports Med.* 2015;45(2):161–86.
57. Skein M, et al. Intermittent-sprint performance and muscle glycogen after 30 h of sleep deprivation. *Med Sci Sports Exerc.* 2011;43(7):1301–11.
58. Rae DE, et al. One night of partial sleep deprivation impairs recovery from a single exercise training session. *Eur J Appl Physiol.* 2017;117(4):699–712.
59. Robineau J, et al. Concurrent training in rugby sevens: effects of high-intensity interval exercises. *Int J Sports Physiol Perform.* 2017;12(3):336–44.
60. Marcora SM, Staiano W, Manning V. Mental fatigue impairs physical performance in humans. *J Appl Physiol.* 2009;106(3):857–64.
61. Nédélec M, et al. Sleep hygiene and recovery strategies in elite soccer players. *Sports Med.* 2015;45(11):1547–59.
62. Robineau J, et al. Specific training effects of concurrent aerobic and strength exercises depend on recovery duration. *J Strength Cond Res.* 2016;30(3):672–83.
63. Sale D, et al. Comparison of two regimens of concurrent strength and endurance training. *Med Sci Sports Exerc.* 1990;22(3):348–56.
64. Issurin VB. New horizons for the methodology and physiology of training periodization. *Sports Med.* 2010;40(3):189–206.
65. Leveritt M, Abernethy PJ. Acute effects of high-intensity endurance exercise on subsequent resistance activity. *J Strength Cond Res.* 1999;13(1):47–51.
66. Bentley DJ, Zhou S, Davie AJ. The effect of endurance exercise on muscle force generating capacity of the lower limbs. *J Sci Med Sport.* 1998;1(3):179–88.
67. Wojtaszewski JF, et al. Isoform-specific and exercise intensity-dependent activation of 5'-AMP-activated protein kinase in human skeletal muscle. *J Physiol.* 2000;528(1):221–6.
68. Baar K. Using nutrition and molecular biology to maximize concurrent training. *Sports Sci Exch.* 2014;136:1–5.
69. Hohenauer E, et al. The effect of post-exercise cryotherapy on recovery characteristics: a systematic review and meta-analysis. *PLoS One.* 2015;10(9):e0139028.
70. Versey NG, Halson SL, Dawson BT. Water immersion recovery for athletes: effect on exercise performance and practical recommendations. *Sports Med.* 2013;43(11):1101–30.
71. De Pauw K, et al. Brain mapping after prolonged cycling and during recovery in the heat. *J Appl Physiol.* 2013;115(9):1324–31.
72. Bailey D, et al. Influence of cold-water immersion on indices of muscle damage following prolonged intermittent shuttle running. *J Sports Sci.* 2007;25(11):1163–70.
73. Montgomery PG, et al. The effect of recovery strategies on physical performance and cumulative fatigue in competitive basketball. *J Sports Sci.* 2008;26(11):1135–45.
74. Kuligowski LA, et al. Effect of whirlpool therapy on the signs and symptoms of delayed-onset muscle soreness. *J Athl Train.* 1998;33(3):222.
75. Ingram J, et al. Effect of water immersion methods on post-exercise recovery from simulated team sport exercise. *J Sci Med Sport.* 2009;12(3):417–21.
76. Fröhlich M, et al. Strength training adaptations after cold-water immersion. *J Strength Cond Res.* 2014;28(9):2628–33.
77. Roberts LA, et al. Post-exercise cold water immersion attenuates acute anabolic signalling and long-term adaptations in muscle to strength training. *J Physiol.* 2015;593(18):4285–301.

78. Ihsan M, Watson G, Abbiss CR. What are the physiological mechanisms for post-exercise cold water immersion in the recovery from prolonged endurance and intermittent exercise? *Sports Med.* 2016;46(8):1095–109.
79. Brown F, et al. Compression garments and recovery from exercise: a meta-analysis. *Sports Med.* 2017;47(11):2245–67.
80. Liu R, et al. Effects of graduated compression stockings with different pressure profiles on lower-limb venous structures and haemodynamics. *Adv Ther.* 2008;25(5):465–78.
81. Goto K, Morishima T. Compression garment promotes muscular strength recovery after resistance exercise. *Med Sci Sports Exerc.* 2014;46(12):2265–70.
82. Merlin T, et al. NHMRC levels of evidence and grades for recommendations for developers of guidelines. Canberra, ACT: National Health and Medical Research Council (NHMRC), Australian Government; 2009.



Nutritional Considerations for Concurrent Training

16

Timothy Etheridge and Philip J. Atherton

Introduction

Although not a new training paradigm [1], the concept of concurrent resistance and endurance training has recently gained increasing attention amongst athletes, coaches and exercise scientists alike [2]. The goals of concurrent training are straightforward: increase muscle mass and strength whilst simultaneously increasing aerobic capacity. The key limitation of concurrent training however (discussed in detail elsewhere in this book), is the reported ‘interference effect’ whereby performing endurance exercise (EE) concomitantly with resistance exercise (RE) may inhibit chronic strength and possibly mass gains versus resistance training alone, despite comparable aerobic adaptation to isolated endurance training [1]. Thus, nutritional strategies for the concurrent athlete should aim to:

1. Optimise the post-exercise anabolic environment in an attempt to rejuvenate chronic muscle strength and hypertrophic adaptation whilst;
2. Continuing to promote aerobic adaptation in response to the metabolic stress associated with endurance training.

Detailed examination of the nutritional requirements posed by the unique demands of concurrent training is lacking. Nonetheless, considerable theoretical evidence may be derived from acute and chronic intervention studies investigating the ergogenic influence of nutrient intake upon isolated resistance or endurance exercise/training—which when combined, can be assimilated to concurrent training. Within this

T. Etheridge
University of Exeter, Exeter, UK

P. J. Atherton (✉)
University of Nottingham, Nottingham, UK
e-mail: Philip.Atherton@nottingham.ac.uk

context, this chapter will evaluate the role of established and emerging nutrients in augmenting muscle strength and aerobic adaptations to training. This knowledge will be consolidated to extrapolate practical recommendations that might benefit the concurrent athlete, namely minimising the ‘interference’ effect.

Macronutrients for Supporting Concurrent Exercise Adaptation

Protein Supplementation and Resistance Exercise

Adequate dietary protein intake is an essential component of the exercise x nutrient interaction. RE alone in the fasted state causes a transient (2–3 h post-exercise) rise in both the breakdown and synthesis (i.e. ‘turnover’) of muscle proteins [3]. However, in the absence of protein nutrition the post-RE rise in muscle protein breakdown (MPB) exceeds that of muscle protein synthesis (MPS) [4, 5]; the ensuing negative net muscle protein balance, if continued throughout training, would lead to maladaptation due to failed muscle growth and remodelling responses. Dietary protein intake reverses this by amplifying and prolonging the protein synthetic response to RE to achieve a positive net protein balance [5]. Indeed, when ingested in close proximity to acute RE, a single protein bolus stimulates MPS (regarded as the primary driver of post-RE anabolism) for ~48 h [5]. This is due to enhanced sensitivity of active muscle to the anabolic properties of dietary protein for at least 24 h post-RE [6]. In turn, cumulative periods of extended muscle protein accretion with repeated bouts of RE plus protein feeding ultimately drives training-induced muscle remodelling and hypertrophy [7]. In the context of concurrent RE followed by EE, MPS of contractile myofibrillar proteins is increased in the presence of post-exercise protein administration [8, 9]. Since this ‘normal’ acute anabolic response to concurrent exercise and feeding should translate to comparable adaptive hypertrophy to fed-state RE alone, this finding is somewhat contradictory to the interference effect, the cause(s) of which remain to be defined. Regardless, it is prudent to incorporate protein into the concurrent athlete’s dietary plan. Though what type of protein should be ingested, how much, and how often in relation to concurrent training bouts?

First we have to look at general relationships between dietary protein and muscle protein metabolism. It is well established that of the 20 protein encoding amino acids that comprise whole protein feeding, the 9 essential amino acids (EAA, i.e. those that cannot be synthesised de novo and must therefore be obtained through the diet) are responsible for stimulating MPS [10] and indirectly inhibiting MPB by serving as an insulin secretagogue [11]. Of the EAA, the branched-chain amino acids (BCAA), and in particular leucine, provides the most potent anabolic stimulus [12, 13]. The protein synthetic response to whole protein and EAA are also dose-dependent: maximal stimulation of MPS occurs with ~10 g of EAA, equivalent to ~20 g of high-quality (e.g. whey) protein, or ~0.25 g kg⁻¹ body mass [14, 15]. Thus, in the non-training healthy adult ~0.8 g protein kg⁻¹ day⁻¹ is sufficient to maintain

protein balance and muscle mass. Importantly for the athlete, this dose-dependency remains at a saturable 20 g when protein feeding is performed in conjunction with RE [14] above which amino acid oxidation is increased and excess protein catabolised. Thus, simply increasing the protein or EAA load of individual meals will not increase net muscle growth, even in resistance-trained athletes.

Optimising timings of protein intake (i.e. prior to, during or after RE) has received considerable attention for maximising post-RE anabolism and ensuing adaptation. Little evidence exists to support the use of protein supplementation prior to [16] or during RE [17]. Pre-exercise feeding strategies do increase MPS after RE [16], presumably due to blood EAA levels remaining elevated for ~3 h post-feeding. However, MPS is inhibited during exercise because the energy-expensive process of protein synthesis (e.g. via ATP-dependent peptide bonding) is subdued in favour of diverting towards energy producing pathways to fuel muscle contraction [17]. There is therefore likely no adaptive advantage to be gained by proximity-dependent feeding patterns, at least for RE lasting ≤ 1 h. Conversely, the 0–4 h post-RE window represents an indisputable time frame for protein-stimulated muscle growth. Because a single bout of RE sensitises muscle to feeding for at least 24 h, the precise timing of protein intake is likely to be irrelevant to the concurrent athlete, providing protein requirements per se are met. Indeed, despite reports that the ‘anabolic window’ may be truncated to ≤ 4 h in resistance-trained individuals [18], muscle strength and mass gains are similar irrespective of the timing of protein intake [19, 20].

Perhaps more relevant to maximising RE-mediated muscle adaptation is the refractory period in MPS that accompanies individual meals. In response to a single protein bolus, MPS increases for ~1.5 h before returning to baseline by 2 h [21], despite continued availability of EAA in the muscle and circulation. Thus, muscle exhibits a post-feeding period whereby muscle is ‘full’ of AAs, and provision of additional protein will fail to re-stimulate MPS. The same is also true for exercise, where 20 g of high-quality protein acutely maximises post-RE MPS [14]. Sufficient time must therefore elapse between feeding doses in order to avoid ‘wasted’ protein intake during the refractory period. Although the precise duration of this latent period remains to be defined, it is probable that protein feeding every 3–4 h (approximately double the acute period of MPS stimulation) is near optimal. Advocating this strategy is the finding that feeding 20 g protein every 3 h over 12 h led to greater daily muscle protein accretion versus 10 g administered every 1.5 h or 40 g every 6 h [22]. Finally, pre-sleep protein intake should be considered since overnight is the longest fasting and, therefore, catabolic period of the diurnal cycle. Therefore, to offset nighttime catabolic losses of muscle protein and maximise RE-induced remodelling, a protein bolus close to sleeping should be consumed [23].

Protein Supplementation and Endurance Exercise

Examination of the relationship between exercise and protein has historically focussed on RE and augmenting hypertrophic adaptation, primarily via the stimulation of myofibrillar (i.e. contractile proteins) MPS. Nonetheless, acute EE in

isolation also stimulates *mixed* MPS, i.e. representing all muscle proteins, including myofibrillar, mitochondrial and sarcoplasmic fractions [24]. Subsequent studies demonstrated the impressive adaptive specificity of muscle, whereby EE selectively increases mitochondrial but not myofibrillar MPS, whilst the reverse is true following RE [25]. Although a more generic MPS response may occur in untrained individuals [25, 26], the training-related selective activation of mitochondrial biogenesis by EE would confer a phenotypic advantage since mitochondrial expansion drives aerobic adaptation to endurance training (whilst also explaining why EE alone fails to increase muscle size). So how can supplemental protein affect these unique responses to EE? Recent evidence indicates that, similarly to post-RE, it is the contractile myofibrillar proteins that are responsive to amino acids after both endurance [27] and concurrent [8] exercise bouts, with no potentiation of mitochondrial protein synthesis [8, 28]. Thus, protein ingestion does not stand to benefit aerobic adaptation e.g. augmenting maximal aerobic capacity ($\text{VO}_{2\text{max}}$) or rightward-shifting the exercise intensity at ‘lactate threshold’. Nonetheless, optimal protein doses during [29] or post-EE [30] might still be advantageous for concurrent training by augmenting daily net muscle myofibrillar remodelling/accrual, which could theoretically minimise the interference effect of endurance training on strength training adaptations.

Summary of Protein Requirements for the Concurrent Athlete

For the essential role of exogenous protein in supporting muscle remodelling after both RE and EE and, indeed, concurrent exercise [8], increased dietary protein or EAA-enriched diets are recommended. Based on the considerations outlined above, per feed the concurrent athlete should aim to consume ~20 g high-quality protein. To achieve the maximum number of anabolic phases within a diurnal cycle, but within the limitation of post-feeding refractory periods, protein boluses should be consumed every 3–4 h irrespective of proximity to training sessions. Additional pre-bedtime protein feeding will also help offset nighttime catabolic losses. Taken together, this equates to an increased (versus recommendations for sedentary individuals) daily protein requirement of ~1.2–1.7 g kg⁻¹ day⁻¹, which is in line with previous recommendations for general athletic populations [31, 32]. Importantly, such nutritional strategies appear to hold functional efficacy: a recent meta-analysis supports a potentiating effect of high-protein feeding upon muscle mass and strength gains afforded by RE programmes [33, 34]. Whilst it is possible to obtain this level and frequency of protein intake through the diet, supplemental protein in various forms including 10 g EAA or 4–5 g leucine [13, 35, 36] are practical methods for ensuring adequate protein ingestion for the concurrent athlete.

CHO Considerations for Both Aerobic and Hypertrophic Conditioning

One of the earliest nutrients to be studied as an ergogenic aid was CHO, the primary performance limiting fuel for endurance-trained individuals exercising at

moderate-high intensities (~40–75% $\text{VO}_{2\text{max}}$) lasting 2–3 h [37]. CHO nutritional interventions ultimately aim to manipulate the content of stored CHO in muscle, in the form of glycogen as a metabolic source for glycolysis to drive prolonged muscle contraction. High CHO feeding patterns robustly increase muscle glycogen concentrations [38]. As a result, ‘CHO loading’ (5–7 g kg⁻¹ day⁻¹) has been repeatedly shown to enhance performance in endurance exercise lasting >2 h [39]. Whilst it may be rationalised that CHO loading will maximise the duration/output of individual training sessions, leading to optimal training-induced aerobic adaptation, it is unlikely each (particularly concurrent) training bout will be of a duration (i.e. >2 h) and intensity sufficient to warrant CHO loading. The focus herein will therefore be on how altering dietary CHO and muscle glycogen levels can influence post-exercise adaptation associated with improved aerobic and strength performance following endurance and resistance training, respectively.

Traditionally, endurance training combined with post-exercise CHO ingestion has been promoted for facilitating exercise recovery via expedited glycogen re-synthesis [40] to improve performance during subsequent training bouts. With regard to aerobic conditioning however, high CHO consumption might inhibit several pro-aerobic adaptive signals [41]. Conversely, mounting evidence indicates that limiting muscle CHO availability can enhance endurance training responses. Reflective of higher activation of molecules regulating key aerobic muscle phenotypes, such as mitochondrial biogenesis [42], performing endurance training in the glycogen-depleted state increases oxidative capacity and performance (time to exhaustion) versus a glycogen repleted state [43]. However, despite reporting improved mitochondrial enzyme content/activity and glycogen sparing, subsequent studies have failed to demonstrate performance gains resulting from training under low-glycogen conditions [44–46] or with low-CHO diets [47, 48]. Similarly, despite altering patterns of substrate utilisation, the efficacy of low-CHO, high-fat dieting fails to provide robust improvements in endurance performance or adaptation [reviewed in 37, 49, 50]. Manipulation of fat macronutrient intake is therefore unlikely to yield benefits for concurrent training.

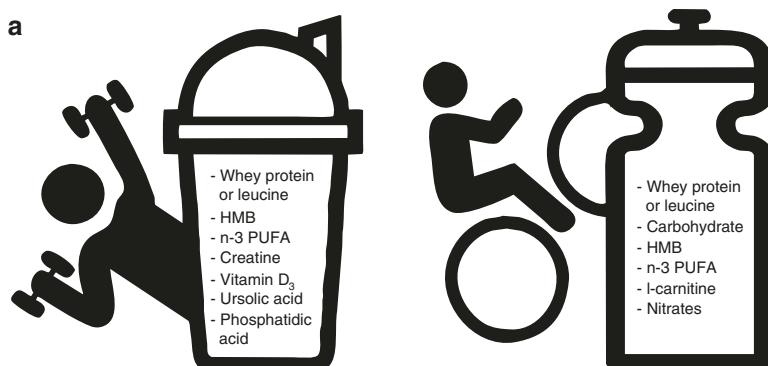
Regardless, an important caveat to integrating glycogen depletion into concurrent training programmes is the impact of low CHO availability upon post-EE protein turnover. Early studies suggested that CHO restriction negatively impacts net protein balance after endurance exercise—primarily via accelerating rates of MPB [51–53]. Future studies directly assessing metabolism using stable isotope tracers extended these findings by highlighting that reduced MPS, as well as the prevailing increases in MPB, contributes to attenuated net protein balance after prolonged exercise when CHO was depleted [54]. Furthermore, although protein and CHO co-ingestion stimulates post-endurance exercise MPS and associated molecular signalling pathways [27], this response is ablated when leucine-enriched feeds are administered in the CHO restricted state [45]. Thus, although EE will increase muscle mass only marginally, if one presumes an appropriate goal for the concurrent athlete is to maximise 24 h net protein accrual to minimise the magnitude of the interference effect, ensuring post-EE CHO re-synthesis can be recommended. For example, in the 0–4 h post-EE period, ~1 g kg body mass⁻¹ CHO will suffice, since

glycogen depletion provides a strong drive for its own replenishment. Between 4–24 h post-EE, CHO intake should match the energetic needs of the exercise, at which point total CHO intake is more important than timing or form of CHO [40]. Moderate daily CHO intake (3–7 g kg⁻¹ day⁻¹) should suffice for offsetting post-EE decrements in protein balance [55, 56]. This may, however, be at the expense of optimal endurance adaptation.

One further consideration specific to concurrent training is the potential influence of prior exhaustive EE and/or low dietary CHO, and associated muscle glycogen depletion, on the anabolic response to subsequent RE. Reduced glycogen concentrations perturb energy homeostasis to mediate activation of cellular energy-sensing molecules, such as adenosine monophosphate-activated protein kinase (AMPK). Because AMPK is well established to inhibit key regulatory molecules of MPS (e.g. mechanistic target of rapamycin, mTOR) in lower organisms [57, 58], glycogen depletion has been proposed to interfere with the protein synthetic responses to RE [45, 59]. However, this theory has not been substantiated to date. Several studies of pre-RE glycogen depletion or CHO energy restriction consistently highlight that muscle glycogen content has negligible consequences for RE-induced anabolic molecular signalling or MPS [55]. Similarly, supplementing post-RE protein with CHO does not augment the anabolic response to RE [60, 61]. Therefore, despite RE reducing muscle glycogen content by 25–40% [62], EAA present as the principal (and perhaps only) macronutrients required for optimising anabolic responses to exercise [63]. As such, the above observations suggest the high mechanical stimulus associated with RE is sufficient to overcome any putative inhibitory effects of metabolic stress upon muscle growth. Presuming post-RE protein intake and restored energy balance (via standard mixed meal consumption) within ~3 h, manipulation of CHO intake for the RE component of concurrent training is likely to be of low importance. Future research in this area, on the nature of the glycogen-concurrent training relationship will shed important new light on how CHO should be integrated into the diet for facilitating concurrent training.

'Nutraceuticals' for Promoting Adaptation to Concurrent Training

The term 'nutraceuticals' has recently been proposed to define a nutritional compound that '...alone or in tandem with exercise, impacts major physiological endpoint(s)' (e.g. see [64]). In the context of concurrent training, this relates to nutraceuticals that influence metabolism, aerobic capacity and/or muscle size and strength adaptations to EE and RE. However, studies examining specific concurrent training responses to nutraceuticals are even scarcer than for the macronutrients. Knowledge must therefore be sourced again from isolated EE- or RE-induced changes to nutraceutical administration and, additionally, from studies utilising *in vitro* and lower organism (i.e. rodent) models. The following sections will firstly focus on nutraceuticals with potential efficacy for optimising adaptation to both resistance and endurance exercise, under the continued theme of minimising the interference effect. This will be followed by discussion of nutraceuticals with a

**b**

	Daily doses	Dosing regimen	Supplement period	Practical considerations
Anabolic and aerobic adaptation:				
Whey protein	1.2 – 1.7 g·kg ⁻¹ ·day ⁻¹	20 g doses, every 3 – 4 h	Throughout training	Precise timing irrelevant if total daily intake is sufficient
Carbohydrate	3 – 7 g·kg ⁻¹ ·day ⁻¹	8 × 0.75 g·kg ⁻¹	Throughout training	Alternatively ingest low dose <1 h post-EE, larger dose > 4 h post-EE
HMB	3 g·day ⁻¹	3 × 1 g	4 weeks	Consume 30 min pre-, and 1 h post-RE
n-3 PUFA	4 – 6 g·day ⁻¹	4 × ~1000 mg, or 5 × ~600 mg	1 – 8 weeks	Use 2:1 ratio of EPA to DHA
Anabolic adaptation:				
Creatine	Load phase: 20 – 30 g·day ⁻¹ Maintain phase: 5 g·day ⁻¹	Load phase: 5 × ~5 g Maintain phase: 1 × 5 g	Load phase: 2 – 5 day Maintain phase: 3 – 12 weeks	Ingest maintenance phase dose every 2 – 3 h
Vitamin D	~2000 – 5000 IU·day ⁻¹ (~50–125 µg·day ⁻¹)	1 × 50 – 125 µg, or 2 × 25 – 75 µg	4 – 12 weeks	Co-ingest with ~800 calcium intake
Ursolic acid	450 mg·day ⁻¹	3 × 150 mg	8 weeks	Ingest in close proximity to RE
Phosphatidic acid	750 mg·day ⁻¹	5 × 150 mg	8 weeks	Ingest 450 mg 30 min pre-RE and 300 mg post-RE
Aerobic adaptation:				
Carnitine	2 – 4 g·day ⁻¹	2 × ~2 g	2 – 4 weeks	Co-ingest with ~80 g carbohydrate and avoid protein
Nitrates	500 mL·day ⁻¹	2 × 250 mL	1 – 15 days	Ingest pre-EE for acute aerobic performance benefits

Fig. 16.1 (a) Overview of nutraceuticals that can be considered by concurrent athletes to support resistance (right) and endurance (left) training adaptation. (b) Recommended dosing amounts, protocols and practical considerations for individual nutraceuticals. *HMB* β-hydroxy-β-methylbutyrate, *n-3 PUFA* n-3 polyunsaturated fatty acids, *EPA* eicosapentaenoic acid, *DHA* docosahexaenoic acid, *RE* resistance exercise, *EE* endurance exercise

potential role in augmenting anabolic responses to RE alone, and subsequently aerobic responses to EE (summarised in Fig. 16.1).

Nutraceuticals for Augmenting Anabolic and Aerobic Adaptation to Concurrent Exercise

β-Hydroxy-β-Methylbutyrate (HMB)

The concept that distal metabolites of leucine, the most potent nutrient for stimulating anabolism, was first proposed two decades ago [65]. Leucine can be

metabolised intramuscularly by branched-chain amino acid transaminase to reversibly form α -ketoisocaproate (α -KIC). Downstream metabolism of α -KIC can reach two fates, one of which is to form HMB by α -KIC dioxygenase [66]. Recent work has elucidated the anabolic potential of HMB administered in isolation. In the rested post-absorptive state, 3 g orally ingested HMB stimulated MPS, and inhibited MPB comparably to 3 g leucine [13]. Intriguingly, in contrast to the insulin-mediated inhibition of MPB by leucine, HMB suppressed MPB through insulin independent mechanisms, rendering the attractive possibility that combined leucine-HMB supplementation might maximise fed-state net protein balance by synergistically suppressing MPB.

The acute pro-anabolic feeding effects also appear to potentiate the muscle mass and strength adaptations afforded by RE training. A seminal study [66] reported that 3 g HMB day $^{-1}$ (vs. 1.5 g HMB day $^{-1}$ and controls) led to higher gains in muscle strength and lean tissue mass during 3 weeks resistance training. Interestingly, in this study HMB and control groups ingested approximately double the recommended daily intake of protein. This finding is suggestive of additive and/or independent anabolic effects of HMB upon high-protein diets when combined with RE programmes, and is in agreement with recent studies of the acute effects of HMB on rates of MPB [13]. Later works corroborated the efficacy of HMB for facilitating RE-induced muscle strength and mass increases [67, 68]. Because these studies employed untrained [66, 67] and trained [68] volunteers, HMB appears efficacious irrespective of training status. Finally, whilst negligible effects of HMB on responses to resistance training have been reported [69, 70], HMB has been administered in its calcium form (CaHMB). However, since CaHMB has lower bioavailability compared to its free acid form (FA-HMB), CaHMB may result in poorer anabolic potential [71] and FA-HMB may be favoured for sports nutrition.

Importantly, HMB supplementation may also enhance adaptation to EE. For example, 2 weeks of 3 g HMB day $^{-1}$ in endurance-trained cyclists increased the time to reach VO $_{2\max}$ and delayed the onset of blood lactate accumulation, responses indicative of positive aerobic adaptation [72]. Chronic improvements in VO $_{2\max}$ [73], aerobic power [74] and physical capacity at the onset of fatigue [75] after 4–5 weeks high-intensity interval training (HIIT) are also potentiated with 3 g HMB day $^{-1}$ vs. placebo. Additionally, 6 weeks of HMB supplementation attenuated rises in plasma creatine phosphokinase and lactate dehydrogenase after a 20 km time trial run [76], suggesting HMB can attenuate exercise-induced muscle damage (EIMD). Clearly, if such effects persist following RE bouts then HMB might serve as a general nutraceutical for diminishing symptoms of EIMD (e.g. strength decline and sensations of soreness), though this remains to be tested. Whilst the mechanisms of these multiple ergogenic properties are unstudied, HMB is precursor of de novo cholesterol synthesis [65], which is essential for cell membrane maintenance. As such, HMB might preserve membrane integrity during prolonged/muscle damaging exercise.

Collectively, despite a lack of studies directly examining HMB during concurrent training regimes, HMB possesses efficacy for optimising multiple desirable muscular adaptations across exercise modalities, and irrespective of training status. Supplementing 3 g HMB day $^{-1}$ (ideally in the FA-HMB form) therefore represents

a highly attractive nutraceutical candidate for inclusion into the concurrent athlete's dietary regimen. As a practical consideration, only small amounts of HMB (~5%) are generated from normal leucine metabolism [77], meaning that 60 g leucine would be required to generate the effective HMB dose of 3 g [78]. It is therefore unlikely that HMB is the primary 'active' component of leucine and might act independently and/or synergistically to the anabolic effects of leucine [66]. Thus, HMB supplementation can be considered in addition to standard protein recommendations for the concurrent training un/trained athlete.

n-3 Polyunsaturated Fatty Acids (n-3 PUFAs)

There are three types of n-3 PUFA: (1) alpha-linoleic acid (ALA), (2) eicosapentaenoic acid (EPA) and (3) docosahexaenoic acid (DHA), which can be obtained in the diet with walnuts and oily fish. In untrained individuals, 5 g day⁻¹ fish oil led to continual rises in intramuscular n-3 PUFA concentration throughout the 4 week supplementation period [79]. Parallel increased content of molecular regulators of MPS (e.g. mTOR and focal adhesion kinase) suggests that raised n-3 PUFA positively influences muscle anabolic potential [79]. Indeed, in the fed state (hyperaminoacidaemia-hyperinsulinemia) MPS and associated anabolic signals are potentiated in young healthy individuals following n-3 PUFA (1.86 g day⁻¹ EPA plus 1.5 g day⁻¹ DHA) supplementation for 8 weeks [80]. Individual n-3 PUFAs may also exert distinct anabolic properties. For example, in vitro studies demonstrated upregulation of MPS after EPA treatment, which was absent following DHA [81]; whether this unique efficacy of EPA translates to human is currently unknown.

The efficacy of n-3 PUFA supplementation on the muscular response to RE is less clear. Chronic n-3 PUFA supplementation increases anabolic responses to acute RE [82] and promotes strength gains after 12 weeks resistance training in older individuals [83]. Contrastingly, a single study in younger people found no benefits of 8 weeks fish oil supplementation on the MPS response to an acute bout of RE [84]. However, a lack of pre-supplement measurements renders interpretation of efficacy difficult in this instance. The potential benefits of n-3 PUFA when administered alongside chronic resistance training are also unknown and should be examined in future studies. However, the ergogenic potential of n-3 PUFAs may extend beyond anabolic stimulation. n-3 PUFAs serve as precursors to the prostaglandin family of anti-inflammatory hormones [85], and reduce production of the inflammatory inducer, leukotriene B4 [86]. The role of n-3 PUFAs in aiding post-exercise recovery by attenuating exercise-induced increases in inflammation and perceived muscle soreness has therefore been investigated. Supplementation of 3–6 g day⁻¹ of n-3 PUFA (e.g. 3 g day⁻¹ EPA plus 0.6 g day⁻¹ DHA) for 1–6 weeks prior to an acute bout of strenuous exercise inhibited the appearance of plasma markers of muscle damage, range of motion [87] and muscle soreness at 48 h post-exercise [88, 89]. As such, assuming the normal inflammatory response is not required for appropriate muscle remodelling [90], n-3 PUFA might facilitate training adaptation by expediting the recovery process.

Supplementing n-3 PUFA s can also mediate changes in fuel utilisation during EE. During single bouts of 60–90 min cycling at 60% $\text{VO}_{2\text{max}}$, 3 weeks of prior fish oil intake (6 g day^{-1}) causes higher rates of fat oxidation [91, 92] as a possible compensatory mechanism for lower CHO oxidation. Nonetheless, aerobic adaptive benefits are yet to be determined, and improved fat oxidation rates may have limited efficacy for endurance performance [37]. However, in rodents n-3 PUFA intake upregulates central genes involved in mitochondrial biogenesis, such as peroxisome proliferator-activated receptor-alpha (PPAR α) [93], and mice fed a low fat, DHA enriched diet displayed higher mitochondrial oxygen consumption vs. placebo—indicative of enhanced mitochondrial function [94]. Overall, therefore, whilst greater clarity of the functional consequences of n-3 PUFA s when combined with RE and/or EE is required, doses of $3\text{--}6 \text{ g day}^{-1}$ for periods of 1–6 weeks may contribute to gains in muscle mass and strength after RE, and for augmenting EE-induced aerobic adaptations.

Nutraceuticals for Augmenting Anabolic Adaptation to Resistance Exercise

Creatine

Found almost exclusively in muscle, creatine (Cr) is endogenously synthesised from arginine, glycine and methionine [95]. Creatine can be reversibly phosphorylated by creatine kinase to form phosphocreatine (PCr), whose ‘high-energy’ phosphate can be liberated to rapidly generate ATP from cytosolic ADP. Dietary meat and fish serve as rich sources of exogenous Cr, and are capable of increasing the muscle Cr pool [96]. Alternatively, Cr supplementation of $20\text{--}30 \text{ g day}^{-1}$ for ≥ 2 days increases muscle Cr content by $>20\%$, of which $\sim 20\text{--}30\%$ is in PCr form [97]. Basal Cr content also determines the efficacy of Cr supplementation, since the greatest gains are observed when Cr levels are low, such as in vegetarians [96].

Whilst Cr supplementation has no negative, nor beneficial effects on EE performance, extensive research has established Cr loading as efficacious for augmenting performance during acute high intensity efforts lasting $\sim 10\text{--}30 \text{ s}$ [98], and sustaining torque/power output over repeated bouts of sprint exercise [99–101]. These ergogenic benefits are mediated by the Cr-induced rise in muscle PCr, and associated capacity for PCr-based anaerobic ATP re-synthesis both during and after individual sprints, and act predominantly in fatigue-susceptible type II ‘fast-twitch’ muscle fibres [98]. Indeed, studies where muscle Cr levels remained low ($\sim 12 \text{ mm kg}^{-1}$ dry weight) found no ergogenic effects of Cr loading on sprint performance [102]. For the concurrent athlete, Cr intake can also influence hypertrophic and functional gains afforded by resistance training. Cr nutrition protocols consisting of a ‘loading phase’ ($20\text{--}30 \text{ g}$ for ~ 5 days) and subsequent ‘maintenance phase’ (5 g day^{-1}) administered during 12–14 week resistance training programmes leads to greater gains in muscle mass, fibre cross-sectional area and maximal strength capacity vs. placebo [103, 104]. Strikingly, a recent meta-analysis revealed

that Cr was more effective than whey protein when combined with RE training for increasing fat-free mass (1.33 vs. 0.69 kg weight mean difference, respectively) [105]. However, the mechanism(s) by which Cr augments hypertrophic responses to RE remain elusive. Elevated muscle Cr content does not promote MPS either when rested [106] or post-RE [107], but can inhibit resting rates of MPB [108]. Though under debate [109], Cr may act by increasing RE-induced satellite cell activation [110], therein providing the nuclear expansion thought to be required for maintaining DNA content and transcriptional capacity of regenerating/growing muscle fibres. It is also well established that the osmotic shift associated with Cr loading leads to intramuscular water retention and subsequent cell swelling [111]. It is plausible that this cell swelling causes stretch activation of cell membrane-located mediators of muscle anabolism, such as focal adhesion kinase [112]. Finally, enhanced work capacity resulting from Cr loading might increase the stimuli for exercise-induced muscle gene expression changes, thereby augmenting the transcriptional signal for chronic muscle remodelling [112–114]. Regardless of the cellular effectors, supplemental Cr loading protocols would appear to be a stimulus for supporting muscular gains following chronic RE and, although presently unknown, perhaps for maximising muscle hypertrophic gains during concurrent training.

Vitamin D

Vitamin D (VitD) is a steroid hormone obtained primarily through sun exposure, though VitD can be obtained through supplementation or dietary sources (e.g. oily fish, cheese, egg yolks). Following sequential hydroxylation steps at the liver and kidney, circulating VitD is converted to its biologically active form, 25-hydroxyvitamin D, also termed cholecalciferol or VitD₃ [115]. Interest in the effects of VitD on muscle metabolism increased since expression of the VitD receptor (VDR) was observed in skeletal muscle [116], amid conflicting reports of VDR presence in muscle [117, 118] that are likely attributable to discrepant methodologies employed for detecting the receptor [116]. Early in vitro studies provided the pre-clinical efficacy of VitD interventions for increasing myotube size (muscle cells in culture) [119] and increasing the MPS responses to leucine and insulin provision [120]. Although not fully understood, the anabolic action of VitD is thought to occur through two distinct mechanisms. Firstly, elevated intramuscular VitD levels increase VitD binding to the VDR and, consequentially, promote gene transcription via interaction with VitD response elements on the DNA [115, 121]. Secondly, VitD may exert non-genomic effects on secondary messenger signalling pathways. For example, 25-hydroxyvitamin D may bind to the VDR at the cell surface following VDR translocation from the nucleus [122], with subsequent upregulation of Akt, mitogen-activated protein kinases [123] and mTOR complex 1 (mTORC1) [120].

Studies in humans have attempted to forward translate these findings for augmenting muscle mass and function. In doing so it has been shown that VitD supplementation of ~2000–4000 IU day⁻¹ for 4–12 weeks was effective at raising circulating VitD₃ concentrations [124, 125]. The efficacy of such VitD schedules alone on

improving muscle health appears to be confined primarily to elderly individuals [126, 127] where habitual VitD₃ levels are frequently depressed [128]. However, meta-analyses of 30 randomised control trials revealed a small positive impact of VitD supplementation on muscle strength in healthy young adults (in the absence of adjunct exercise), although studies employing all forms of VitD were included in the analyses, without focussing on those that administered VitD₃ alone [128]. It should further be noted that combining VitD₃ with ~800 mg calcium ingestion appears necessary for the strength improving effects of VitD₃ to be observed [124].

A few studies have examined the combined effects of VitD intake and resistance training. A recent systematic review analysed 6 controlled trials that administered VitD (600–5000 IU day⁻¹ for ≥4 weeks) to various athletic populations alongside normal training regimens, which included intermittent team sports (i.e. relevant to concurrent training programmes) [129]. Four studies that employed VitD₃ reported strength improvements that ranged from 1.4 to 18.8%, with 2 studies reporting significant strength improvements ($P < 0.05$). Conversely, 2 studies that supplemented with VitD₂ (a less biologically active form of VitD) had no effect on muscle strength [129]. Furthermore, untrained young men that underwent 4 weeks VitD₃ supplementation (1920 IU day⁻¹) followed by 12 weeks VitD₃ plus resistance training exhibited lower myostatin expression, a negative regulator of muscle mass, and increased the percentage of type IIa muscle fibres [124]. Whilst muscle mass and strength were unaffected by VitD₃ in this study, these morphological changes indicate VitD₃ improves muscle ‘quality’. Supplementing VitD₃ (~2000–5000 IU day⁻¹ for ≥4 weeks) can therefore likely be recommended as part of the concurrent athletes’ nutritional plan.

Phosphatidic Acid

Phosphatidic acid (PA) is a diacyl-glycerophospholipid, which can be sourced in the diet, e.g. from raw cabbage [130]. PA is also present in low amounts endogenously in cell membranes, which can be increased by mitogenic stimulation [131] and RE [132], suggesting a role of PA in muscular responses to growth stimuli. As a lipid second messenger, PA regulates a growing number of cell signalling events [133]. For example, PA treatment of cultured skeletal muscle cells [131] and rodents [134] activates the extracellular signal-related kinase/mTOR anabolic pathway comparably to whey protein. PA interventions also tend to increase rates of MPS, but also blunted the MPS response when combined with whey protein [134]. Administering PA may also benefit net protein balance by inhibiting signals regulating MPB under atrophic conditions [135], although this is far from conclusive.

In humans PA is readily bioavailable, with 1.5 g oral PA sufficient to increase levels of circulating PA (and its extracellular conversion to the predicted bioactive form lysophosphatidic acid) within 30 min and remain elevated for 7 h post-ingestion [136]. When applied to a RE context, 750 mg day⁻¹ PA consumed during 8 weeks supervised resistance training significantly increased lean body mass and quadriceps cross-sectional area vs. placebo, though strength gains were comparable between groups [137]. Similarly, Escalante et al. [138] found augmented muscle

mass and maximal strength gains after 8 weeks RE with daily PA-containing multi-ingredient supplement. However, attributing these positive effects to PA alone is impossible, since the supplement included both HMB and VitD₃. Two further studies employed magnitude-based inference to detect likely to very-likely benefits of PA intake on 8 weeks resistance training-induced lean body mass and strength increases; however, these studies are confounded by a lack of supervised training [139] and lower PA dosages of 250 and 375 mg day⁻¹ [140]. Most recently, Gonzalez et al. [141] employed 750 mg day⁻¹ PA during training protocols consistent with previous studies and found no supplement effect for improving muscle thickness or maximal strength, though body composition was not assessed. Reports on the efficacy of PA for supporting RE adaptation are therefore equivocal and might be explained by methodological discrepancies including: training supervision and design, habitual dietary control or lack thereof, approaches to assessing body composition and performance gains and dosing/timing of PA ingestion [141, 142]. It is also notable that all above studies recruited resistance-trained individuals, thus the effects of PA during the early stages of training where the majority of muscular adaptation occurs [7] are unknown. Nevertheless, the weight of existing evidence supports at least modest gains in muscle size and performance following RE programmes which may facilitate offsetting the interference effect in concurrent programmes. Clearly, further work is needed to define direct ergogenic impacts of RE nutraceuticals in respect to concurrent training.

Nutraceuticals for Augmenting Aerobic Adaptation to Endurance Exercise

Carnitine

Carnitine is endogenously synthesised from AA precursors and exists as D & L isomers; however, only L-carnitine is bioactive [143]. Dietary sources of carnitine include red meat and dairy products. The majority (~95%) of L-carnitine is stored in muscle, the most well established function of which is the translocation of long-chain fatty acids from the cytosol into the mitochondrial matrix for subsequent β-oxidation [144, 145]. This process requires fatty acid conversion to acyl-CoA prior to esterification with carnitine to form acylcarnitine by the mitochondrial membrane enzyme carnitine palmitoyltransferase 1 (CPT1). Acylcarnitine is then transported into the mitochondrial matrix and acts as a substrate for carnitine palmitoyltransferase 1, which converts acylcarnitine to the respective acyl-CoAs for entry into the β-oxidation pathway [146, 147]. As such, without carnitine most dietary lipids cannot be used as energy sources.

L-carnitine has therefore been studied for its ability to enhance fat metabolism and spare glycogen, therein delaying fatigue during prolonged, moderate-high intensity exercise. Acutely elevated muscle carnitine content inhibited CHO oxidation despite high CHO availability, and increased overnight glycogen storage [148]. Similarly, chronic L-carnitine supplementation (1.36–2 g day⁻¹ taken twice daily for 12–24 weeks) reduced glycogen utilisation by ~55% [149] and increased energy expenditure and

CPT1 enzymatic activity [150] during 30 min of low-moderate (50% $\text{VO}_{2\text{max}}$) intensity exercise. Importantly, several studies have demonstrated that L-carnitine loading results in improved endurance performance. Acute intake of 3–15 g L-carnitine ingested 1–2 h pre-exercise improved $\text{VO}_{2\text{max}}$ [151], increased running speed [152] and cycling time to exhaustion [153] in endurance-trained athletes. These findings were accompanied by a stimulation of fat oxidation [153] and decreased lactate appearance [152], suggesting altered fuel metabolism accounted for the performance benefits. Longer-term L-carnitine supplementation in athletes (2–4 g day⁻¹ for 2–6 weeks) increased fat oxidation (i.e. lowered respiratory quotient) during prolonged exercise [154], increased $\text{VO}_{2\text{max}}$ by 6% [155] and raised 30 min moderate endurance work output 11% [149]. However, conflicting studies have failed to observe beneficial effects of L-carnitine on fat oxidation [156] and endurance performance [156, 157].

The discrepant findings between studies might be explained by higher exercise intensities employed leading to greater CHO oxidation as a fuel source [149, 158] and failure to include CHO in the L-carnitine dosing regime. The incorporation of CHO into L-carnitine supplementation is pertinent since oral carnitine alone does not increase muscle carnitine stores [159, 160]. Subsequent work discovered that combined carnitine and hyperinsulinaemia increased muscle carnitine accretion ~15% [161]. Practical strategies for overcoming the poor bioavailability of carnitine include co-ingestion with ~80 g CHO [162], owing to the insulinotropic actions of CHO. Conversely, carnitine plus oral protein blunts muscle carnitine uptake [162], though the mechanisms of this phenomenon remain unclear. Overall, 2–4 g day⁻¹ of L-carnitine administered acutely or over 2–4 weeks (and ideally in combination with ~80 g CHO) may lead to a shift in metabolism away from CHO and towards fat as a fuel source for low-moderate intensity exercise sessions. The associated improvements in endurance performance capacity may, therefore, maximise the adaptive responses to concurrent training.

Nitrates

Oral ingestion of foods rich in dietary nitrates (NO_3^- , e.g. beetroot and lettuce) results in NO_3^- reduction to nitrite (NO_2^-) by salivary nitrate reductases [163]. The acidic stomach environment subsequently converts NO_2^- to nitric oxide (NO), thus NO_3^- represents an important alternative source of NO to the classical L-arginine-NO synthase pathway [164]. In turn, NO regulates several important functions such as vasodilation, blood flow, glucose/fatty acid oxidation and mitochondrial biogenesis [165]. Supplementing 500 mL day⁻¹ of NO_3^- -rich beetroot juice for 6 days [166] or 0.1 mmol day⁻¹ of NaNO_3^- for 3 days [167] lowers the O_2 cost of submaximal cycling, indicating improved exercise metabolic efficiency, and increases basal mitochondrial function [168]. Similar reductions in the oxygen cost of exercise have also been reported with longer, 15 days (500 mL day⁻¹ beetroot juice) supplementation [169]. Acute consumption of 500 mL NO_3^- between 2.5 and 30 h before exercise also improves 4 and 16 km cycling time trial performance [170] and team sport-specific intermittent performance [171]. However, several authors have failed to observe any ergogenic effect of NO_3^- intake [172–174]. It is likely that the

positive effects of NO_3^- on endurance performance are limited to recreational athletes, since negligible effects of NO_3^- are reported in athletic populations [175, 176]. Higher basal levels of plasma NO_3^- and NO_2^- might partially explain this phenomenon [177]. Supplemental NO_3^- (~500 mL day $^{-1}$ beetroot juice for 1–15 days) may therefore be recommended to promote endurance performance adaptation in untrained individuals during the initial phases of a concurrent training programme [178], though NO_3^- may become less important once (an as yet unknown) period of muscular adaptation has taken place.

Summary

In the search for the ‘optimal’ exercise nutrition strategy an enormous range of scientific studies has been conducted on the efficacy of a long list of nutritional compounds, often with conflicting or ambiguous results. In the context of minimising the detrimental effects of the interference effect on muscle mass and strength gains, a central component of the concurrent athletes diet should be protein supplementation, ideally administered soon after endurance and resistance exercise bouts, as well as regular high-quality protein-containing meals. At the possible expense of optimal aerobic adaptation, CHO should be ingested post-EE to facilitate glycogen re-synthesis but, importantly, to avoid the catabolic environment associated with low-glycogen levels. Intake of various nutraceuticals may be employed, with precise timings likely being less important than ensuring adequate daily intakes of each respective compound. A practical consideration of note includes ensuring combined carnitine-CHO intake, but avoiding carnitine co-ingestion with protein, to maximise carnitine uptake into muscle. Overall, whilst the efficacy of certain nutraceuticals is contentious, at the very least there is no evidence of nutraceutical supplementation causing detrimental effects to performance, and all nutraceuticals summarised in Fig. 16.1 should be the focus of the concurrent athlete. Finally, future work should aim to provide highly controlled, large cohort and longitudinal studies of the effects specific nutrients have on concurrent training adaptation. Additionally, as concurrent training programmes evolve (e.g. combined HIIT and RE) new nutritional considerations will emerge with a need for new empirical evidence of efficacy.

References

1. Hickson RC. Interference of strength development by simultaneously training for strength and endurance. *Eur J Appl Physiol*. 1980;45:255–63.
2. Coffey VG, Hawley JA. Concurrent exercise training: do opposites distract? *J Physiol*. 2017;595(9):2883–96.
3. Kumar V, Selby A, Rankin D, Patel R, Atherton P, Hildebrandt W, Williams J, Smith K, Seynnes O, Hiscock N, Rennie MJ. Age-related differences in the dose-response of muscle protein synthesis to resistance exercise in young and old men. *J Physiol*. 2009;587:211–7.
4. Biolo G, Maggi SP, Williams BD, Tipton KD, Wolfe RR. Increased rates of muscle protein turnover and amino acid transport after resistance exercise in humans. *Am J Phys*. 1995;268(3 Pt 1):E514–20.

5. Phillips S, Tipton K, Aarsland A, Wolf SE, Wolfe R. Mixed muscle protein synthesis and breakdown after resistance exercise in humans. *Am J Phys.* 1997;273:E99–107.
6. Burd NA, West DWD, Moore DR, Atherton PJ, Staples AW, Prior T, Tang JE, Rennie MJ, Baker SK, Phillips SM. Enhanced amino acid sensitivity of myofibrillar protein synthesis persists for up to 24 h after resistance exercise in young men. *J Nutr.* 2011;141(4):568–73.
7. Brook MS, Wilkinson DJ, Mitchell WK, Lund JN, Szewczyk NJ, Greenhaff PL, Smith K, Atherton PJ. Skeletal muscle hypertrophy adaptations predominate in the early stages of resistance exercise training, matching deuterium oxide-derived measures of muscle protein synthesis and mechanistic target of rapamycin complex 1 signaling. *FASEB J.* 2015;29(11):4485–96.
8. Camera DM, West DW, Phillips SM, Rerecich T, Stellingwerff T, Hawley JA, et al. Protein ingestion increases myofibrillar protein synthesis after concurrent exercise. *Med Sci Sports Exerc.* 2015;47(1):82–91.
9. Donges CE, Burd NA, Duffield R, Smith GC, West DW, Short MJ, et al. Concurrent resistance and aerobic exercise stimulates both myofibrillar and mitochondrial protein synthesis in sedentary middle-aged men. *J Appl Physiol.* 2012;112:1992–2001.
10. Smith K, Reynolds N, Downie S, Patel A, Rennie MJ. Effects of flooding amino acids on incorporation of labeled amino acids into human muscle protein. *Am J Phys.* 1998;275:E73–8.
11. Greenhaff PL, Karagounis LG, Peirce N, Simpson EJ, Hazell M, Layfield R, et al. Dissociation between the effects of amino acids and insulin on signaling, ubiquitin ligases, and protein turnover in human muscle. *Am J Physiol Endocrinol Metab.* 2008;295:E595–604.
12. Atherton PJ, Smith K, Etheridge T, Rankin D, Rennie MJ. Distinct anabolic signalling responses to amino acids in C2C12 skeletal muscle cells. *Amino Acids.* 2010a;38:1533–9.
13. Wilkinson DJ, Hossain T, Hill DS, Phillips BE, Crossland H, Williams J, et al. Effects of leucine and its metabolite β -hydroxy- β -methylbutyrate on human skeletal muscle protein metabolism. *J Physiol.* 2013;591:2911–23.
14. Moore DR, Robinson MJ, Fry JL, Tang JE, Glover EI, Wilkinson SB, et al. Ingested protein dose response of muscle and albumin protein synthesis after resistance exercise in young men. *Am J Clin Nutr.* 2009;89:161–8.
15. Witard OC, Jackman SR, Breen L, Smith K, Selby A, Tipton KD. Myofibrillar muscle protein synthesis rates subsequent to a meal in response to increasing doses of whey protein at rest and after resistance exercise. *Am J Clin Nutr.* 2014;99(1):86–95.
16. Tipton KD, Elliott TA, Cree MG, Aarsland AA, Sanford AP, Wolfe RR. Stimulation of net muscle protein synthesis by whey protein ingestion before and after exercise. *Am J Physiol Endocrinol Metab.* 2007;292(1):E71–6.
17. Atherton PJ, Rennie MJ. Protein synthesis a low priority for exercising muscle. *J Physiol.* 2006;573(Pt 2):288–9.
18. Tang JE, Perco JG, Moore DR, Wilkinson SB, Phillips SM. Resistance training alters the response of fed state mixed muscle protein synthesis in young men. *Am J Physiol Regul Integr Comp Physiol.* 2008;294(R172–8).
19. Hoffman JR, Ratamess NA, Tranchina CP, Rashti SL, Kang J, Faigenbaum AD. Effect of protein-supplement timing on strength, power, and body-composition changes in resistance-trained men. *Int J Sport Nutr Exerc Metab.* 2009;19(2):172–85.
20. Schoenfeld BJ, Aragon AA, Krieger JW. The effect of protein timing on muscle strength and hypertrophy: a meta-analysis. *J Int Soc Sports Nutr.* 2013;10(1):53.
21. Atherton PJ, Etheridge T, Watt PW, Wilkinson D, Selby A, Rankin D, et al. Muscle full effect after oral protein: time-dependent concordance and discordance between human muscle protein synthesis and mTORC1 signaling. *Am J Clin Nutr.* 2010b;92:1080–8.
22. Areta JL, Burke LM, Ross ML, Camera DM, West DW, Broad EM, et al. Timing and distribution of protein ingestion during prolonged recovery from resistance exercise alters myofibrillar protein synthesis. *J Physiol.* 2013;591(Pt 9):2319–31.
23. Res PT, Groen B, Pennings B, Beelen M, Wallis GA, Gijsen AP, et al. Protein ingestion before sleep improves postexercise overnight recovery. *Med Sci Sports Exerc.* 2012;44:1560–9.
24. Harber MP, Konopka AR, Jemiolo B, Trappe SW, Trappe TA, Reidy PT. Muscle protein synthesis and gene expression during recovery from aerobic exercise in the fasted and fed states. *Am J Physiol Regul Integr Comp Physiol.* 2010;299(5):R1254–62.

25. Wilkinson SB, Phillips SM, Atherton PJ, Patel R, Yarasheski KE, Tarnopolsky MA, et al. Differential effects of resistance and endurance exercise in the fed state on signalling molecule phosphorylation and protein synthesis in human muscle. *J Physiol.* 2008;586(15):3701–17.
26. Coffey VG, Zhong Z, Shield A, Canny BJ, Chibalin AV, Zierath JR, et al. Early signaling responses to divergent exercise stimuli in skeletal muscle from well-trained humans. *FASEB J.* 2006;20(1):190–2.
27. Breen L, Philp A, Witard OC, Jackman SR, Selby A, Smith K, et al. The influence of carbohydrate-protein co-ingestion following endurance exercise on myofibrillar and mitochondrial protein synthesis. *J Physiol.* 2011;589(Pt 16):4011–25.
28. Moore DR, Camera DM, Areta JL, Hawley JA. Beyond muscle hypertrophy: why dietary protein is important for endurance athletes. *Appl Physiol Nutr Metab.* 2014;7:1–11.
29. Pasiakos SM, McClung HL, McClung JP, Margolis LM, Andersen NE, Cloutier GJ, et al. Leucine-enriched essential amino acid supplementation during moderate steady state exercise enhances postexercise muscle protein synthesis. *Am J Clin Nutr.* 2011;94:809–18.
30. Lunn WR, Pasiakos SM, Colletto MR, Karfonta KE, Carbone JW, Anderson JM, et al. Chocolate milk and endurance exercise recovery: protein balance, glycogen, and performance. *Med Sci Sports Exerc.* 2012;44(4):682–91.
31. Phillips SM. Dietary protein requirements and adaptive advantages in athletes. *Br J Nutr.* 2012;108(Suppl. 2):S158–67.
32. Tarnopolsky M. Protein requirements for endurance athletes. *Nutrition.* 2004;20:662–8.
33. Cermak NM, Res PT, de Groot LC, Saris WH, van Loon LJ. Protein supplementation augments the adaptive response of skeletal muscle to resistance-type exercise training: a meta-analysis. *Am J Clin Nutr.* 2012a;96(6):1454–64.
34. Naclerio F, Larumbe-Zabala E. Effects of whey protein alone or as part of a multi-ingredient formulation on strength, fat-free mass, or lean body mass in resistance-trained individuals: a meta-analysis. *Sports Med.* 2016;46(1):125–37.
35. Atherton PJ, Kumar V, Selby AL, Rankin D, Hildebrandt W, Phillips BE, et al. Enriching a protein drink with leucine augments muscle protein synthesis after resistance exercise in young and older men. *Clin Nutr.* 2017;36(3):888–95.
36. Churchward-Venne TA, Breen L, Di Donato DM, Hector AJ, Mitchell CJ, Moore DR, et al. Leucine supplementation of a low-protein mixed macronutrient beverage enhances myofibrillar protein synthesis in young men: a double-blind, randomized trial. *Am J Clin Nutr.* 2014;99(2):276–86.
37. Hawley JA, Leckey JJ. Carbohydrate dependence during prolonged, intense endurance exercise. *Sports Med.* 2015;45(Suppl 1):S5–12.
38. Hultman E, Bergstrom J. Muscle glycogen synthesis in relation to diet studied in normal subjects. *Acta Med Scand.* 1967;182:109–17.
39. Burke LM, Millet G, Tarnopolsky MA, International Association of Athletics Federations. Nutrition for distance events. *J Sports Sci.* 2007;25(Suppl 1):S29–38.
40. Burke LM, van Loon LJC, Hawley JA. Postexercise muscle glycogen resynthesis in humans. *J Appl Physiol.* 2017;122(5):1055–67.
41. Philp A, Hargreaves M, Baar K. More than a store: regulatory roles for glycogen in skeletal muscle adaptation to exercise. *Am J Physiol Endocrinol Metab.* 2012;302:E1343–51.
42. Philp A, Burke LM, Baar K. Altering endogenous carbohydrate availability to support training adaptations. *Nestle Nutr Inst Workshop Ser.* 2011;69:19–31.
43. Hansen AK, Fischer CP, Plomgaard P, Andersen JL, Saltin B, Pedersen BK. Skeletal muscle adaptation: training twice every second day vs. training once daily. *J Appl Physiol.* 2005;98:93–9.
44. Hulston CJ, Venables MC, Mann CH, Martin C, Philp A, Baar K, et al. Training with low muscle glycogen enhances fat metabolism in well-trained cyclists. *Med Sci Sports Exerc.* 2010;42:2046–55.
45. Impey SG, Hammond KM, Shepherd SO, Sharples AP, Stewart C, Limb M, et al. Fuel for the work required: a practical approach to amalgamating train-low paradigms for endurance athletes. *Physiol Rep.* 2016;4(10):e12803.
46. Yeo WK, Paton CD, Garnham AP, Burke LM, Carey AL, Hawley JA. Skeletal muscle adaptation and performance responses to once a day versus twice every second day endurance training regimens. *J Appl Physiol.* 2008;105:1462–70.

47. Vogt M, Puntschart A, Howald H, Mueller B, Mannhart C, Gfeller-Tuescher L, et al. Effects of dietary fat on muscle substrates, metabolism, and performance in athletes. *Med Sci Sports Exerc.* 2003;35:952–60.
48. Zajac A, Poprzecki S, Maszczyk A, Czuba M, Michalczyk M, Zydek G. The effects of a ketogenic diet on exercise metabolism and physical performance in off-road cyclists. *Nutrients.* 2014;6:2493–508.
49. Burke LM. Re-examining high-fat diets for sports performance: did we call the ‘nail in the coffin’ too soon? *Sports Med.* 2015;45(Suppl 1):S33–49.
50. Knuiman P, Hopman MTE, Mensink M. Glycogen availability and skeletal muscle adaptations with endurance and resistance exercise. *Nutr Metab (Lond).* 2015;12:59.
51. Blomstrand E, Saltin B. Effect of muscle glycogen on glucose, lactate and amino acid metabolism during exercise and recovery in human subjects. *J Physiol.* 1999;514(Pt 1):293–302.
52. Lemon PW, Mullin JP. Effect of initial muscle glycogen levels on protein catabolism during exercise. *J Appl Physiol Respir Environ Exerc Physiol.* 1980;48:624–9.
53. Van Hall G, Saltin B, Wagenmakers AJ. Muscle protein degradation and amino acid metabolism during prolonged knee-extensor exercise in humans. *Clin Sci (Lond).* 1999;97:557–67.
54. Howarth KR, Moreau NA, Phillips SM, Gibala MJ. Coingestion of protein with carbohydrate during recovery from endurance exercise stimulates skeletal muscle protein synthesis in humans. *J Appl Physiol.* 2009;106:1394–402.
55. Escobar KA, Van Dusseldorp TA, Kerkhoff CM. Carbohydrate intake and resistance-based exercise: are current recommendations reflective of actual need? *Br J Nutr.* 2017;116:2053–65.
56. Rosset R, Lecoultrre V, Egli L, Cros J, Dokumaci AS, Zwygart K, et al. Postexercise repletion of muscle energy stores with fructose or glucose in mixed meals. *Am J Clin Nutr.* 2017;105(3):609–17.
57. Bolster DR, Crozier SJ, Kimball SR, Jefferson LS. AMP-activated protein kinase suppresses protein synthesis in rat skeletal muscle through down-regulated mammalian target of rapamycin (mTOR) signaling. *J Biol Chem.* 2002;277(27):23977–80.
58. Xu J, Ji J, Yan XH. Cross-talk between AMPK and mTOR in regulating energy balance. *Crit Rev Food Sci Nutr.* 2012;52(5):373–81.
59. Pasikatos SM, Vislocky LM, Carbone JW, Altieri N, Konopelski K, Freake HC, et al. Acute energy deprivation affects skeletal muscle protein synthesis and associated intracellular signaling proteins in physically active adults. *J Nutr.* 2010;140:745–51.
60. Hulmi JJ, Laakso M, Mero AA, Häkkinen K, Ahtiainen JP, Peltonen H. The effects of whey protein with or without carbohydrates on resistance training adaptations. *J Int Soc Sports Nutr.* 2015;12:48.
61. Rasmussen BB, Tipton KD, Miller SL, Wolfe RR. An oral essential amino acid-carbohydrate supplement enhances muscle protein anabolism after resistance exercise. *J Appl Physiol.* 2000;88(2):386–92.
62. Robergs RA, Pearson DR, Costill DL, Fink WJ, Pascoe DD, Benedict MA, et al. Muscle glycogenolysis during differing intensities of weightresistance exercise. *J Appl Physiol.* 1991;70:1700–6.
63. Staples AW, Burd NA, West DW, Currie KD, Atherton PJ, Moore DR, et al. Carbohydrate does not augment exercise-induced protein accretion versus protein alone. *Med Sci Sports Exerc.* 2011;43:1154–61.
64. Deane CS, Wilkinson DJ, Phillips BE, Smith K, Etheridge T, Atherton PJ. “Nutraceuticals” in relation to human skeletal muscle and exercise. *Am J Physiol Endocrinol Metab.* 2017;312:E282–99.
65. Nissen SL, Abumrad NN. Nutritional role of the leucine metabolite β -hydroxy β -methylbutyrate (HMB). *J Nutr Biochem.* 1997;8:300–11.
66. Nissen S, Sharp R, Ray M, Rathmacher JA, Rice D, Fuller JC, et al. Effect of leucine metabolite beta-hydroxy-beta-methylbutyrate on muscle metabolism during resistance-exercise training. *J Appl Physiol.* 1996;81:2095–104.
67. Panton LB, Rathmacher JA, Baier S, Nissen S. Nutritional supplementation of the leucine metabolite β -hydroxy- β -methylbutyrate (HMB) during resistance training. *Nutrition.* 2000;16:734–9.

68. Wilson JM, Lowery RP, Joy JM, Andersen JC, Wilson SMC, Stout JR, et al. The effects of 12 weeks of beta-hydroxy-beta-methylbutyrate free acid supplementation on muscle mass, strength, and power in resistance-trained individuals: a randomized, double-blind, placebo-controlled study. *Eur J Appl Physiol.* 2014;114:1217–27.
69. Kreider RB, Ferreira M, Wilson M, Almada AL. Effects of calcium β -hydroxy- β methylbutyrate (HMB) supplementation during resistance-training on markers of catabolism, body composition and strength. *Int J Sports Med.* 1999;20:503–9.
70. Slater G, Jenkins D, Logan P, Lee H, Vukovich M, Rathmacher J, et al. Beta hydroxy-beta-methylbutyrate (HMB) supplementation does not affect changes in strength or body composition during resistance training in trained men. *Int J Sport Nutr Exerc Metab.* 2001;11:384–96.
71. Fuller JC, Sharp RL, Angus HF, Khoo PY, Rathmacher JA. Comparison of availability and plasma clearance rates of β -hydroxy- β -methylbutyrate delivery in the free acid and calcium salt forms. *Br J Nutr.* 2015;114:1403–9.
72. Vukovich MD, Dreifort GD. Effect of beta-hydroxy beta-methylbutyrate on the onset of blood lactate accumulation and V(O)₂ peak in endurance-trained cyclists. *J Strength Cond Res.* 2001;15:491–7.
73. Lamboley CRH, Royer D, Dionne IJ. Effects of beta-hydroxy-beta-methylbutyrate on aerobic-performance components and body composition in college students. *Int J Sport Nutr Exerc Metab.* 2007;17:56–69.
74. Robinson EH, Stout JR, Miramonti AA, Fukuda DH, Wang R, Townsend JR, et al. High-intensity interval training and β -hydroxy- β -methylbutyric free acid improves aerobic power and metabolic thresholds. *J Int Soc Sports Nutr.* 2014;11:16.
75. Miramonti AA, Stout JR, Fukuda DH, Robinson EH, Wang R, La Monica MB, et al. The effects of four weeks of high intensity interval training and β -hydroxy- β -methylbutyric free acid supplementation on the onset of neuromuscular fatigue. *J Strength Cond Res.* 2016;30:626–34.
76. Knitter AE, Panton L, Rathmacher JA, Petersen A, Sharp R. Effects of beta-hydroxy-beta-methylbutyrate on muscle damage after a prolonged run. *J Appl Physiol.* 2000;89:1340–4.
77. Van Koevering M, Nissen S. Oxidation of leucine and a-ketoisocaproate to b-hydroxy-b-methylbutyrate in vivo. *Am J Phys.* 1992;262(1 Pt 1):E27–31.
78. Wilson GJ, Wilson JM, Manninen AH. Effects of beta-hydroxy-beta-methylbutyrate (HMB) on exercise performance and body composition across varying levels of age, sex, and training experience: a review. *Nutr Metab (Lond).* 2008;5(1):17.
79. McGlory C, Galloway SDR, Hamilton DL, McClintock C, Breen L, Dick JR, et al. Temporal changes in human skeletal muscle and blood lipid composition with fish oil supplementation. *Prostaglandins Leukot Essent Fatty Acids.* 2014;90:199–206.
80. Smith GI, Atherton PJ, Reeds DN, Mohammed BS, Rankin D, Rennie MJ, et al. Omega-3 polyunsaturated fatty acids augment the muscle protein anabolic response to hyperamino-acidemia/hyperinsulinemia in healthy young and middle aged men and women. *Clin Sci.* 2011;121:267–78.
81. Kamolrat T, Gray SR. The effect of eicosapentaenoic and docosahexaenoic acid on protein synthesis and breakdown in murine C2C12 myotubes. *Biochem Biophys Res Commun.* 2013;432:593–8.
82. Lalia AZ, Dasari S, Robinson MM, Abid H, Morse DM, Klaus KA, et al. Influence of omega-3 fatty acids on skeletal muscle protein metabolism and mitochondrial bioenergetics in older adults. *Aging.* 2017;9(4):1096–129.
83. Rodacki LF, Pereira G, Naliwaiko K, Coelho I, Pequito D. Fish-oil supplementation enhances the effects of strength training in elderly women. *J Clin Nutr.* 2012;95(2):428–36.
84. McGlory C, Wardle SL, Macnaughton LS, Witard OC, Scott F, Dick J, et al. Fish oil supplementation suppresses resistance exercise and feeding-induced increases in anabolic signaling without affecting myofibrillar protein synthesis in young men. *Physiol Rep.* 2016;4:e12715.
85. Calder PC. n-3 polyunsaturated fatty acids, inflammation, and inflammatory diseases. *Am J Clin Nutr.* 2006;83(6 Suppl):1505S–19S.

86. Weber PC, Fischer D, von Schacky C, Lorenz R, Strasser T. Dietary Omega Polyunsaturated fatty acids and eicosanoid formation in man. In: *Health effects of polyunsaturated fatty acids in seafoods*. Orlando: Academic Press; 1986. p. 49–60.
87. Corder KE, Newsham KR, McDaniel JL, Ezekiel UR, Weiss EP. Effects of short-term docosahexaenoic acid supplementation on markers of inflammation after eccentric strength exercise in women. *J Sports Sci Med*. 2016;15(1):176–83.
88. Jouris KB, McDaniel JL, Weiss EP. The effect of omega-3 fatty acid supplementation on the inflammatory response to eccentric strength exercise. *J Sport Sci Med*. 2011;10:432–8.
89. Tinsley GM, Gann JJ, Huber SR, Andre TL, La Bounty PM, Bowden RG, et al. Effects of fish oil supplementation on postresistance exercise muscle soreness. *J Diet Suppl*. 2016;21:1–12.
90. Urso ML. Anti-inflammatory interventions and skeletal muscle injury: benefit or detriment? *J Appl Physiol*. 2013;115(6):920–8.
91. Delarue J, Labarthe F, Cohen R. Fish-oil supplementation reduces stimulation of plasma glucose fluxes during exercise in untrained males. *Br J Nutr*. 2003;90:777–86.
92. Huffman DM, Michaelson JL, Thomas TR, Derek M, Huffman JL, Michaelson TRT. Chronic supplementation with fish oil increases fat oxidation during exercise in young men. *J Exerc Physiol*. 2004;7:48–57.
93. Le Guen M, Chaté V, Hininger-Favier I, Laillet B, Morio B, Pieroni G, et al. A 9-week docosahexaenoic acid-enriched supplementation improves endurance exercise capacity and skeletal muscle mitochondrial function in adult rats. *Am J Physiol Endocrinol Metab*. 2016;310(3):E213–4.
94. Lanza IR, Blachnio-Zabielska A, Johnson ML, Schimke JM, Jakaitis DR, Lebrasseur NK, et al. Influence of fish oil on skeletal muscle mitochondrial energetics and lipid metabolites during high-fat diet. *Am J Physiol Endocrinol Metab*. 2013;304:E1391–403.
95. Bloch K, Schoenheimer R. Biological precursors of creatine. *J Biol Chem*. 1940;138:167–94.
96. Greenhaff PL, Bodin K, Soderlund K, Hultman E. Effect of oral creatine supplementation on skeletal muscle phosphocreatine resynthesis. *Am J Phys*. 1994;266:E725–30.
97. Harris RC, Soderlund K, Hultman E. Elevation of creatine in resting and exercised muscle of normal subjects by creatine supplementation. *Clin Sci (Lond)*. 1992;83:367–74.
98. Casey A, Greenhaff PL. Does dietary creatine supplementation play a role in skeletal muscle metabolism and performance? *Am J Clin Nutr*. 2000;72(2 Suppl):607S–17S.
99. Birch R, Noble D, Greenhaff PL. The influence of dietary creatine supplementation on performance during repeated bouts of maximal isokinetic cycling in man. *Eur J Appl Physiol Occup Physiol*. 1994;69:268–76.
100. Earnest CP, Snell PG, Rodriguez R, Almada AL, Mitchell TL. The effect of creatine monohydrate ingestion on anaerobic power indices, muscular strength and body composition. *Acta Physiol Scand*. 1995;153:207–9.
101. Greenhaff PL, Casey A, Short AH, Harris R, Soderlund K, Hultman E. Influence of oral creatine supplementation of muscle torque during repeated bouts of maximal voluntary exercise in man. *Clin Sci (Lond)*. 1993;84:565–71.
102. Snow RJ, McKenna MJ, Selig SE, Kemp J, Stathis CG, Zhao S. Effect of creatine supplementation on sprint exercise performance and muscle metabolism. *J Appl Physiol*. 1998;84:1667–73.
103. Branch JD. Effect of creatine supplementation on body composition and performance: a meta-analysis. *Int J Sport Nutr Exerc Metab*. 2003;13:198–226.
104. Volek JS, Duncan ND, Mazzetti SA, Staron RS, Putukian M, Gómez AL, et al. Performance and muscle fiber adaptations to creatine supplementation and heavy resistance training. *Med Sci Sports Exerc*. 1999;31:1147–56.
105. Cermak NM, Res PT, de Groot LCPGM, Saris WHM, van Loon LJC. Protein supplementation augments the adaptive response of skeletal muscle to resistance-type exercise training: a meta-analysis. *Am J Clin Nutr*. 2012b;96:1454–64.
106. Louis M, Poortmans JR, Francaux M, Hultman E, Berre J, Boisseau N, et al. Creatine supplementation has no effect on human muscle protein turnover at rest in the postabsorptive or fed states. *Am J Physiol Endocrinol Metab*. 2003a;284:E764–70.

107. Louis M, Poortmans JR, Francaux M, Berré J, Boisseau N, Brassine E, et al. No effect of creatine supplementation on human myofibrillar and sarcoplasmic protein synthesis after resistance exercise. *Am J Physiol Endocrinol Metab.* 2003b;285:E1089–94.
108. Parise G, Mihic S, MacLennan D, Yarasheski KE, Tarnopolsky MA. Effects of acute creatine monohydrate supplementation on leucine kinetics and mixed-muscle protein synthesis. *J Appl Physiol.* 2001;91:1041–7.
109. McCarthy JJ, Esser K. Counterpoint: satellite cell addition is not obligatory for skeletal muscle hypertrophy. *J Appl Physiol.* 2007;103:1100–2.
110. Brook MS, Wilkinson DJ, Phillips BE, Perez-Schindler J, Philp A, Smith K, et al. Skeletal muscle homeostasis and plasticity in youth and ageing: impact of nutrition and exercise. *Acta Physiol.* 2016;216(1):15–41.
111. Ziegenfuss T, Lowery LM, Lemon PW. Acute fluid volume changes in men during three days of creatine supplementation. *J Exerc Physiol.* 1998;1:1–9.
112. Safdar A, Yardley NJ, Snow R, Melov S, Tarnopolsky MA. Global and targeted gene expression and protein content in skeletal muscle of young men following short-term creatine monohydrate supplementation. *Physiol Genomics.* 2008;32:219–28.
113. Buford TW, Kreider RB, Stout JR, Greenwood M, Campbell B, Spano M, et al. International Society of Sports Nutrition position stand: creatine supplementation and exercise. *J Int Soc Sport Nutr.* 2007;4:1–8.
114. Willoughby DS, Rosene J. Effects of oral creatine and resistance training on myosin heavy chain expression. *Med Sci Sports Exerc.* 2001;33:1674–81.
115. Girgis CM, Clifton-Bligh RJ, Hamrick MW, Holick MF, Gunton JE. The roles of vitamin D in skeletal muscle: form, function, and metabolism. *Endocr Rev.* 2013;34:33–83.
116. Girgis CM, Mokbel N, Minn Cha K, Houweling PJ, Abboud M, Fraser DR, et al. The vitamin D receptor (VDR) is expressed in skeletal muscle of male mice and modulates 25-hydroxyvitamin D (25OHD) uptake in myofibers. *Endocrinology.* 2014a;155:3227–37.
117. Pike JW. Expression of the vitamin d receptor in skeletal muscle: are we there yet? *Endocrinology.* 2014;155:3214–8.
118. Wang Y, DeLuca HF. Is the vitamin D receptor found in muscle? *Endocrinology.* 2011;152:354–63.
119. Girgis CM, Clifton-Bligh RJ, Mokbel N, Cheng K, Gunton JE. Vitamin D signaling regulates proliferation, differentiation and myotube size in C2C12 skeletal muscle cells. *Endocrinology.* 2014b;155(2):347–57.
120. Salles J, Chanet A, Giraudet C, Patrac V, Pierre P, Jourdan M, et al. 1,25(OH)2-vitamin D3 enhances the stimulating effect of leucine and insulin on protein synthesis rate through Akt/ PKB and mTOR mediated pathways in murine C2C12 skeletal myotubes. *Mol Nutr Food Res.* 2013;57:1–10.
121. Ceglia L. Vitamin D and its role in skeletal muscle. *Curr Opin Clin Nutr Metab Care.* 2009;12:628–33.
122. Capiati D, Benassati S, Boland RL. 1,25(OH)2-vitamin D3 induces translocation of the vitamin D receptor (VDR) to the plasma membrane in skeletal muscle cells. *J Cell Biochem.* 2002;86:128–35.
123. Buitrago CG, Arango NS, Boland RL. 1 α ,25(OH)2D3-dependent modulation of Akt in proliferating and differentiating C2C12 skeletal muscle cells. *J Cell Biochem.* 2012;113:1170–81.
124. Agergaard J, Trøstrup J, Uth J, Iversen JV, Boesen A, Andersen JL, et al. Does vitamin-D intake during resistance training improve the skeletal muscle hypertrophic and strength response in young and elderly men?—a randomized controlled trial. *Nutr Metab (Lond).* 2015;12:32.
125. Barker T, Schneider ED, Dixon BM, Henriksen VT, Weaver LK. Supplemental vitamin D enhances the recovery in peak isometric force shortly after intense exercise. *Nutr Metab (Lond).* 2013;10:69.
126. Ceglia L, Niramitmahapanya S, da Silva Morais M, Rivas DA, Harris SS, Bischoff-Ferrari H, et al. A randomized study on the effect of vitamin d3 supplementation on skeletal muscle morphology and vitamin d receptor concentration in older women. *J Clin Endocrinol Metab.* 2013;98:E1927–35.

127. Ward KA, Das G, Roberts SA, Berry JL, Adams JE, Rawer R, et al. A randomized, controlled trial of vitamin D supplementation upon musculoskeletal health in postmenarchal females. *J Clin Endocrinol Metab.* 2010;95:4643–51.
128. Beaudart C, Buckinx F, Rabenda V, Gillain S, Cavalier E, Slomian J, et al. The effects of vitamin D on skeletal muscle strength, muscle mass and muscle power: a systematic review and meta-analysis of randomized controlled trials. *J Clin Endocrinol Metab.* 2014;99:4336–45.
129. Chiang CM, Ismaeel A, Griffis RB, Weems S. Effects of vitamin D supplementation on muscle strength in athletes: a systematic review. *J Strength Cond Res.* 2017;31(2):566–74.
130. Tanaka T, Kassai A, Ohmoto M, Morito K, Kashiwada Y, Takaishi Y, et al. Quantification of phosphatidic acid in foodstuffs using a thin-layer-chromatography-imaging technique. *J Agric Food Chem.* 2012;60:4156–61.
131. Fang Y, Vilella-Bach M, Bachmann R, Flanigan A, Chen J. Phosphatidic acid-mediated mitogenic activation of mTOR signaling. *Science.* 2001;294:1942–5.
132. Rasmussen BB. Phosphatidic acid: a novel mechanical mechanism for how resistance exercise activates mTORC1 signalling. *J Physiol.* 2009;587(Pt 14):3415–6.
133. English D, Cui Y, Siddiqui RA. Messenger functions of phosphatidic acid. *Chem Phys Lipids.* 1996;80:117–32.
134. Mobley CB, Hornberger TA, Fox CD, Healy JC, Ferguson BS, Lowery RP, et al. Effects of oral phosphatidic acid feeding with or without whey protein on muscle protein synthesis and anabolic signaling in rodent skeletal muscle. *J Int Soc Sports Nutr.* 2015;12:32.
135. Jaafar R, De Larichaudy J, Chanon S, Euthine V, Durand C, Naro F, et al. Phospholipase D regulates the size of skeletal muscle cells through the activation of mTOR signaling. *Cell Commun Signal.* 2013;11:55.
136. Purpura M, Jäger R, Joy JM, Lowery RP, Moore JD, Wilson JM. Effect of oral administration of soy-derived phosphatidic acid on concentrations of phosphatidic acid and lyso-phosphatidic acid molecular species in human plasma. *J Int Soc Sports Nutr.* 2013;10:P22.
137. Joy JM, Gundermann DM, Lowery RP, Jäger R, McCleary SA, Purpura M, et al. Phosphatidic acid enhances mTOR signaling and resistance exercise induced hypertrophy. *Nutr Metab.* 2014;11:1.
138. Escalante G, Alencar M, Haddock B, Harvey P. The effects of phosphatidic acid supplementation on strength, body composition, muscular endurance, power, agility, and vertical jump in resistance trained men. *J Int Soc Sports Nutr.* 2016;13(1):1.
139. Hoffman JR, Stout JR, Williams DR, Wells AJ, Fragala MS, Mangine GT, et al. Efficacy of phosphatidic acid ingestion on lean body mass, muscle thickness and strength gains in resistance-trained men. *J Int Soc Sports Nutr.* 2012;9(1):1.
140. Andre TL, Gann JJ, McKinley-Barnard SK, Song JJ, Willoughby DS. Eight weeks of phosphatidic acid supplementation in conjunction with resistance training does not differentially affect body composition and muscle strength in resistance-trained men. *J Sports Sci Med.* 2016;15:532–9.
141. Gonzalez AM, Sell KM, Ghigarelli JJ, Kelly CF, Shone EW, Accetta MR, et al. Effects of phosphatidic acid supplementation on muscle thickness and strength in resistance-trained men. *Appl Physiol Nutr Metab.* 2017;42(4):443–8.
142. Bond P. Phosphatidic acid: biosynthesis, pharmacokinetics, mechanisms of action and effect on strength and body composition in resistance-trained individuals. *Nutr Metab (Lond).* 2017;14:12.
143. Bremer J. Carnitine—metabolism and functions. *Physiol Rev.* 1983;63:1420–80.
144. Fritz IB, Marquis NR. The role of acylcarnitine esters and carnitine palmitoyltransferase in the transport of fatty acyl groups across mitochondrial membranes. *Proc Natl Acad Sci U S A.* 1965;54:1226–33.
145. Kerner J, Hoppel C. Fatty acid transport into mitochondria. *Biochem Biophys Acta.* 2000;1486:1–17.
146. Hoppel C. The role of carnitine in normal and altered fatty acid metabolism. *Am J Kidney Dis.* 2003;41:4–12.

147. Parvin R, Pande SV. Enhancement of mitochondrial carnitine and carnitine acylcarnitine translocase-mediated transport of fatty acids into liver mitochondria under ketogenic conditions. *J Biol Chem.* 1979;245:5423–9.
148. Stephens FB, Constantin-Teodosiu D, Laithwaite D, Simpson EJ, Greenhaff PL. Insulin stimulates L-carnitine accumulation in human skeletal muscle. *FASEB J.* 2006a;20:377–9.
149. Wall BT, Stephens FB, Constantin-Teodosiu D, Marimuthu K, Macdonald IA, Greenhaff PL. Chronic oral ingestion of L-carnitine and carbohydrate increases muscle carnitine content and alters muscle fuel metabolism during exercise in humans. *J Physiol.* 2011;589:963–73.
150. Stephens FB, Wall BT, Marimuthu K, Shannon CE, Constantin-Teodosiu D, Macdonald IA, et al. Skeletal muscle carnitine loading increases energy expenditure, modulates fuel metabolism gene networks and prevents body fat accumulation in humans. *J Physiol.* 2013;591(18):4655–66.
151. Vecchiet L, Di Lisa F, Pieralisi G, Ripari P, Menabò R, Giamberardino MA, et al. Influence of L-carnitine administration on maximal physical exercise. *Eur J Appl Physiol Occup Physiol.* 1990;61(5–6):486–90.
152. Rorer GE, Guzel NA. The effects of acute L-carnitine supplementation on endurance performance of athletes. *J Strength Cond Res.* 2014;28(2):514–9.
153. Cha YS, Choi SK, Suh H, Lee SN, Cho D, Li K. Effects of carnitine coingested caffeine on carnitine metabolism and endurance capacity in athletes. *J Nutr Sci Vitaminol (Tokyo).* 2001;47(6):378–84.
154. Gorostiaga EM, Maurer CA, Eclache JP. Decrease in respiratory quotient during exercise following L-carnitine supplementation. *Int J Sports Med.* 1989;10(3):169–74.
155. Marconi C, Sassi G, Carpinelli A, Cerretelli P. Effects of L-carnitine loading on the aerobic and anaerobic performance of endurance athletes. *Eur J Appl Physiol Occup Physiol.* 1985;54(2):131–5.
156. Broad EM, Maughan RJ, Galloway SD. Effects of four weeks L-carnitine L-tartrate ingestion on substrate utilization during prolonged exercise. *Int J Sport Nutr Exerc Metab.* 2005;15(6):665–79.
157. Lee JK, Lee JS, Park H, Cha YS, Yoon CS, Kim CK. Effect of L-carnitine supplementation and aerobic training on FABPc content and beta-HAD activity in human skeletal muscle. *Eur J Appl Physiol.* 2007;99(2):193–9.
158. Gonzalez JT, Stevenson EJ. New perspectives on nutritional interventions to augment lipid utilisation during exercise. *Br J Nutr.* 2012;107:339–49.
159. Soop M, Björkman O, Cederblad G, Hagenfeldt L, Wahren J. Influence of carnitine supplementation on muscle substrate and carnitine metabolism during exercise. *J Appl Physiol.* 1988;64:2394–9.
160. Wächter S, Vogt M, Kreis R, Boesch C, Bigler P, Hoppeler H, et al. Long-term administration of L-carnitine to humans: effect on skeletal muscle carnitine content and physical performance. *Clin Chim Acta.* 2002;318:51–61.
161. Stephens FB, Constantin-Teodosiu D, Laithwaite D, Simpson EJ, Greenhaff PL. An acute increase in skeletal muscle carnitine content alters fuel metabolism in resting human skeletal muscle. *J Clin Endocrinol Metab.* 2006b;91:5013–8.
162. Shannon CE, Nixon AV, Greenhaff PL, Stephens FB. Protein ingestion acutely inhibits insulin-stimulated muscle carnitine uptake in healthy young men. *Am J Clin Nutr.* 2016;103:276–82.
163. Duncan C, Dougall H, Johnston P, Green S, Brogan R, Leifert C, et al. Chemical generation of nitric oxide in the mouth from the enterosalivary circulation of dietary nitrate. *Nat Med.* 1995;1:546–51.
164. Lundberg JO, Weitzberg E, Gladwin MT. The nitrate-nitrite-nitric oxide pathway in physiology and therapeutics. *Nat Rev Drug Discov.* 2008;7(2):156–67.
165. Stamler JS, Meissner G. Physiology of nitric oxide in skeletal muscle. *Physiol Rev.* 2001;81(1):209–37.
166. Bailey SJ, Winyard P, Vanhatalo A, Blackwell JR, Dimenna FJ, Wilkerson DP, et al. Dietary nitrate supplementation reduces the O₂ cost of low-intensity exercise and enhances tolerance to high-intensity exercise in humans. *J Appl Physiol.* 2009;107:1144–55.

167. Larsen FJ, Weitzberg E, Lundberg JO, Ekblom B. Effects of dietary nitrate on oxygen cost during exercise. *Acta Physiol.* 2007;191:59–66.
168. Larsen FJ, Schiffer TA, Borniquel S, Sahlin K, Ekblom B, Lundberg JO, et al. Dietary inorganic nitrate improves mitochondrial efficiency in humans. *Cell Metab.* 2011;13:149–59.
169. Vanhatalo A, Bailey SJ, Blackwell JR, DiMenna FJ, Pavey TG, Wilkerson DP, et al. Acute and chronic effects of dietary nitrate supplementation on blood pressure and the physiological responses to moderate-intensity and incremental exercise. *Am J Physiol Regul Integr Comp Physiol.* 2010;299(4):R1121–31.
170. Lansley KE, Winyard PG, Bailey SJ, Vanhatalo A, Wilkerson DP, Blackwell JR, et al. Acute dietary nitrate supplementation improves cycling time trial performance. *Med Sci Sports Exerc.* 2011;43:1125–31.
171. Wyllie LJ, Mohr M, Krstrup P, Jackman SR, Ermidis G, Kelly J, et al. Dietary nitrate supplementation improves team sport-specific intense intermittent exercise performance. *Eur J Appl Physiol.* 2013;113:1673–84.
172. Arnold JT, Oliver SJ, Lewis-Jones TM, Wyllie LJ, Macdonald JH. Beetroot juice does not enhance altitude running performance in well-trained athletes. *Appl Physiol Nutr Metab.* 2015;40:590–5.
173. Cermak NM, Res P, Stinkens R, Lundberg JO, Gibala MJ, van Loon LJ. No improvement in endurance performance after a single dose of beetroot juice. *Int J Sport Nutr Exerc Metab.* 2012c;22:470–8.
174. Wilkerson DP, Hayward GM, Bailey SJ, Vanhatalo A, Blackwell JR, Jones AM. Influence of acute dietary nitrate supplementation on 50 mile time trial performance in well-trained cyclists. *Eur J Appl Physiol.* 2012;112:4127–34.
175. Jonvik KL, Nyakayiru J, van Loon LJ, Verdijk LB. Can elite athletes benefit from dietary nitrate supplementation? *J Appl Physiol.* 2015;119(6):759–61.
176. Poortmans JR, Gualano B, Carpentier A. Nitrate supplementation and human exercise performance: too much of a good thing? *Curr Opin Clin Nutr Metab Care.* 2015;18(6):599–604.
177. Poveda JJ, Riestra A, Salas E, Cagigas ML, López-Somoza C, Amado JA, et al. Contribution of nitric oxide to exercise-induced changes in healthy volunteers: effects of acute exercise and long-term physical training. *Eur J Clin Investig.* 1997;27:967–71.
178. Perez-Schindler J, Hamilton LD, Moore DR, Baar K, Philp A. Nutritional strategies to support concurrent training. *Eur J Sport Sci.* 2015;15(1):41–52.

Part IV

Concurrent Aerobic and Strength Training Throughout the Lifespan



Concurrent Training in Children and Adolescents

17

Martijn Gäßler and Urs Granacher

Introduction

The central theme of this chapter revolves around the additive but also interfering effects occurring in children and adolescents when combining aerobic and strength training (i.e., concurrent training). Because both training status and (biological) age can influence adaptations and training goals, distinctions are made between young athletes and non-athletic youth [1], and between children (boys aged 6–13 years; girls aged 6–11 years) and adolescents (boys aged 14–18 years; girls aged 12–18 years) [2]. Also, the relevance of certain physical fitness components is different depending on age and training goals. Caspersen [3] operationalized physical fitness as consisting of primarily health- and skill-related components (Table 17.1). It has to be noted that the training of health-related components (e.g., muscular strength, endurance) improves athletic performance [4] and that the training of skill-related components (e.g., balance, agility) also produces health benefits (e.g., injury prevention) [5]. As a matter of fact, most skill-related components of physical fitness (reaction time excluded) are considered as health-related fitness components [6]. The distinction made by Caspersen [3] is still useful to highlight the components that are relevant for sports performance.

M. Gäßler · U. Granacher (✉)

Division of Training and Movement Sciences, Faculty of Human Sciences,
University of Potsdam, Potsdam, Germany
e-mail: mgaebler@uni-potsdam.de; urs.granacher@uni-potsdam.de

Table 17.1 Components of physical fitness categorized as health- and skill-related according to Caspersen [3] and updated according to Bouchard et al. [6]

Health-related fitness components	Skill-related fitness components
Cardiorespiratory fitness (Heart/lung function, blood pressure)	Agility*
Morphological component (BMI, body composition, flexibility)	Balance*
Muscular fitness (Strength, power, endurance)	Coordination*
Motor component (Agility, balance, coordination, speed)	Speed*
Metabolic component (Glucose tolerance, inflammatory markers)	Power*
	Reaction time

Note: Components marked with * are also considered as health-related fitness components

The Importance of Aerobic and Strength Training in Children and Adolescents

It is undisputed that physical activity has positive effects on the health of children and adolescents. The World Health Organization (WHO) [7] recommends children and adolescents aged 5–17 years to accumulate daily at least 60 minutes of physical activity at moderate to vigorous intensity. Most of the daily physical activity should be aerobic in nature. Vigorous-intensity activities should be incorporated, including those that strengthen muscle and bone, at least three times per week. Physical activity includes both aerobic and strengthening activities that can either be accomplished through play and games, but also in organized exercise settings such as physical education classes and sport clubs. However, current guidelines [7] may undermine the development of muscular fitness (muscle strength, muscle power, and muscular endurance) that is a prerequisite for energetic and vigorous movement and play [8]. Moreover, an increasing percentage of youth do not meet the WHO physical activity recommendations [9, 10], which was identified as an exercise deficit disorder that can result in childhood obesity and pediatric dynapenia [9, 11–13]. In 2008, only 54% of children at pre-school age adhered to the recommended amount of physical activity [14]. A survey performed by the WHO in 2009/2010 suggested that this percentage shrinks with increasing age from 23% in 11-year-olds to 15% in 15-year-olds [15].

Besides non-athletic children and adolescents, concurrent training is of specific relevance for the sub-population of young athletes. Williams [1] defined a young athlete as “a child or adolescent who is still growing and maturing toward adulthood and who systematically trains (>once per week) and competes (>1-year competition history) in at least one specific sport.” Given that most types of sport require some combination of strength, endurance (and speed) [16], training in young athletes should at least involve a sufficient stimulus to help develop these components of

physical fitness. It is not surprising that adding strength exercises to an existing training program in young athletes aged 6–18 years resulted in improved skill-related components of physical fitness (e.g., speed and power) [4]. Thus, participation in concurrent training can help to meet the WHO requirements for physical activity, promote health, and improve movement skills and athletic performance.

Promoting Physical Development Throughout Childhood and Adolescence

The physical development of children and adolescents needs to be taken into account carefully when administering any form of physical training. Several models [17–20] have been proposed as a guide to systematically develop components of physical fitness, such as strength, endurance, speed, and movement skills throughout childhood and adolescence. The essence of these models is to optimize training for young athletes in order to achieve their optimal physical performance potential in adulthood, thus favoring long-term training goals over short-term success. Opposing the restricted focus on chronological age [21], these models acknowledge that the development of physical fitness components is not a linear process but is rather related to biological development. Therefore, training in youth should address those physical fitness components that show a high sensitivity to training stimuli. Furthermore, despite their focus on the physical development of young athletes, these models can best be viewed as “a pathway for all youth” [18, 20] that promote fun, confidence, and lifelong engagement in physical activity. As such, they are useful guides to individualize training programs for children and adolescents related to their biological age and prior training experience.

The first model to relate biological development to training and trainability of children and adolescents is the long-term athlete development (LTAD) model [17, 18]. This model uses the onset of peak height velocity (PHV) as a reference point. PHV is the age during adolescence at which an individual shows the largest change/growth in stature, and can be estimated from simple anthropometric measures (i.e., sitting and standing height), sex, and chronological age [22]. A free online PHV calculator can be found at the University of Saskatchewan website [23]. The inclusion of PHV assessment in fitness promotion in children and adolescents allows shaping training differently and individually for early, normal, and late maturing children. Thus, the LTAD model uses the onset of PHV as a reference to determine “windows of opportunity” as critical periods in physical development that are crucial for achieving one’s athletic potential [17, 18, 24]. However, a lack of empirical evidence in support of “windows of opportunity” led to the most important criticism on the LTAD model [19, 25].

Out of discontent with the LTAD model [17, 18], Lloyd et al. [19] proposed the youth physical development (YPD) model, which they later modified and titled the composite youth development (CYD) model [20]. The YPD model (later the CYD model) assumes that physical fitness components are trainable throughout childhood and adolescence, but the importance to train different components changes

with maturation. Similar to the LTAD, onset of PHV is used as a reference point to determine biological age. Furthermore, there are different CYD models for males and females and the model should be adapted according to the initial training status [19, 20]. The CYD model [20] further suggests that emphasis in training should be guided by the maturational status according to the years removed from PHV, growth rate, and the related developmental stages of the individual.

According to the CYD model, the importance of developing certain components of physical fitness changes over developmental stages. Early childhood is a period of rapid growth that starts roughly at the chronological age of 2–4 years. During this developmental stage, physical activity should be unstructured, playful, and fun. Developing fundamental movement skills (FMS) and muscle strength should be emphasized [19, 20, 26]. The remaining years pre-PHV involve the developmental stage of middle childhood and are associated with a steady increase in body height. This stage lasts usually longer for males (5–13 years) than for females (5–11 years) [27, 28]. During this period training and physical activities should be highly variable without specialization in a single sport [29]. Thus, emphasis should still be placed on developing muscle strength and FMS, and to a lesser extent on developing mobility, agility, speed, and power [19, 20]. The onset of adolescence is signified by an increase in growth rate that peaks at PHV and slowly declines thereafter until adulthood [27, 30]. Adolescence roughly lasts from the age of 14–20 years for boys and from the age of 12–18 years for girls. Training structure should be gradually increased towards adulthood and should specialize in a specific sport [19, 20, 29]. Emphasis should be placed on developing sport-specific skills, agility, speed, muscle power and strength and, after PHV, also muscle hypertrophy.

Training for endurance and metabolic conditioning become more important towards late adolescence but training goals may differ depending on the population and the practiced sport. Thus, there might be individual differences in the relative importance of certain components of physical fitness. Particularly young endurance athletes may want to expose themselves to larger volumes of aerobic training in order to develop a high aerobic capacity [31]. Taken together, the CYD model suggests that the development of muscle strength and movement competency should have a central position for both children and adolescents while the importance of aerobic training gradually increases over the developmental stages [20].

The central position of muscle strength in the CYD [20] seems contradictory to the views of the WHO [7], who emphasizes aerobic activity. This contradiction can probably best be understood through a distinction in training goals. The main concern of the WHO is to promote health by reducing physical inactivity, overweight, and obesity, while the CYD aims at promoting physical development, movement skill competency, and lifelong sports participation. Furthermore, when strength development is neglected and muscle strength levels are deficient, a negative cascade threatens to manifest itself that has been referred to as an exercise deficit disorder [11]. The cascade starts with reduced motor skill competence, leading to low movement confidence and increased sedentary behavior which ultimately results in adverse health outcomes later in life [28]. Closely related to this exercise deficit is the recent observation of pediatric dynapenia [8, 13]. Dynapenia is a deficiency in muscle strength that is usually found in old adults [32]. Recently, Faigenbaum [13]

described pediatric dynapenia as an acquired condition not caused by neurologic or muscular disease that is reversible with strength- and skill-based activities [8].

Consequently when recommendations are combined, it can be concluded that strength should be developed to promote physical development in youth [19, 20], while a minimum amount of aerobic activity (60 min/day) is recommended for positive health outcomes [7]. In a recently published narrative review paper, Pichardo et al. [33] summarized the available models on LTAD and integrated those into a new conceptualized approach.

Single-Mode Strength Training

Given the crucial effects muscle strength has on different physical fitness components [34], it is not surprising that national and international associations such as the WHO [7], the American Academy of Pediatrics [35], the International Olympic Committee [36], and the National Strength and Conditioning Associations of America [37] and the United Kingdom [21] recommend strength training throughout youth. Strength training can be started as soon as children are capable of understanding and following instructions [38], which usually comes down to a minimum calendar age of 6 years [39]. It should, however, be highlighted that learning the proper exercise technique and supervision by a strength and conditioning professional are necessities for safety purposes.

Effects

Meta-analyses generally show positive effects of strength training in youth on muscular fitness (i.e., muscular power, muscular strength, local muscular endurance [40]) and movement skills (see Table 17.2 for an overview). Payne et al. [41] found moderate effect sizes ($ES = 0.75$) of strength training on measures of muscular strength and muscular endurance in non-athletic youth (≤ 18 years). Isokinetic training programs seemed to be less effective than isometric or isotonic programs. Age and sex were not found to modify the effectiveness of strength training but it should be noted that the effect sizes in this study were not corrected for small sample sizes nor weighted. Behm et al. [42] analyzed the pre to post differences of 107 studies and revealed that strength training had small effects on sprinting ($ES = 0.48$), moderate effects on jumping ($ES = 0.53$), and large effects on lower body strength ($ES = 1.14$) in children and adolescents. Sub-analyses revealed that children and non-athletic youth responded to training with a larger magnitude in effect sizes.

Two more recent meta-analyses [43, 44] found that strength training in non-athletic youth (≤ 18 years) had large effects ($ES = 1.12$) on muscular strength [43], and moderate effects ($ES = 0.52$) on the motor skills running, jumping, and throwing [44]. Furthermore, age was negatively associated ($r = -0.25$) with training-induced improvements of movement skills [44], but adolescents showed larger gains than prepubertal children in muscular strength [43]. This finding was supported by an early meta-analysis [45] that indicated only moderate effects

Table 17.2 Effect sizes of strength training in youth on muscular fitness, movement skills, and sport-specific performance calculated in several meta-analyses

Study	Population	Measure of effect size	Muscular fitness ^a	Movement skills ^b	Sport-specific performance ^c
Payne et al., 1997 [41]	Non-athletic youth ≤ 18 years	Mean Cohen's d	0.75	–	–
Behringer et al., 2010 [43]	Non-athletic youth ≤ 18 years	Weighted mean Hedges' g	1.12	–	–
Behringer et al., 2011 [44]	Non-athletic youth ≤ 18 years	Weighted mean Hedges' g	–	0.52	–
Falk & Tenenbaum, 1996 [45]	Non-athletic youth Girls ≤ 12 years/ boys ≤ 13 years	Mean Cohen's d	0.57		
Harries et al., 2012 [46]	Adolescent athletes 13–18 years	Weighted mean difference (cm) ^d		3.08 ^d	
Lesinski et al., 2016 [4]	Young athletes 6–18 years	Weighted mean Hedges' g	1.09	0.58; 0.68; 0.80	0.75
Behm et al., 2017 [42]	All youth < 18 years	Within group standardized mean difference	1.14	0.48; 0.53	–

^aMuscular fitness includes measures of muscular strength, muscular power, and muscular endurance

^bMovement skills include sprinting, jumping, and tests of agility

^cSport-specific performances include measures such as throwing and kicking velocity

^dHarries et al., 2012 [46] reported no effect sizes, but absolute differences in jump height

(ES = 0.57) of strength training on measures of muscular strength in children (boys ≤ 13 years, girls ≤ 12 years). Two more meta-analyses have been published that specifically focused on young athletes [4, 46]. Harries et al. [46] found large effects of strength training on jump performance (mean difference = 3.1 cm) in adolescent athletes aged 13–18 years. They concluded that plyometric training resulted in the greatest improvements. Moreover, in a recent meta-analysis, Lesinski et al. [4] analyzed studies that included both child and adolescent athletes and found large effects of strength training on muscular strength (ES = 1.09) and vertical jump performance (ES = 0.80). Strength training had moderate positive effects on movement skills such as sprinting (ES = 0.58), agility (ES = 0.68), and sport-specific performance (ES = 0.75). The influence of age on training outcomes was reversed in athletes [4] compared to untrained peers [43, 44]. In athletes, it was found that children, compared to adolescents, showed greater benefits from strength training in terms of muscle strength, but not in terms of movement skills, especially for sport-specific performances. Faigenbaum et al. [28] suggested that dose-response relationships

may differ between trained and untrained children and adolescents (see next section). The greater training history adolescent athletes likely have over child athletes and untrained youth may explain the relative smaller training-induced gains in adolescent athletes. From these data it can be concluded that strength training can improve muscular strength, movement skills, and sports performance in children and adolescents and that age and training status have a moderating effect on these outcomes.

Dose–Response Relationships and Recommendations

Behringer et al. [44] found a positive linear relationship between intensity (% of the one-repetition maximum [1-RM]) and improvements in movement skills (throwing, jumping, and running) of untrained children and adolescents (≤ 18 years). Their data suggested that a minimum intensity of 50% of 1-RM was required to improve movement skills. Strength training parameters in young athletes aged 6–18 years can be derived from Lesinski et al.’s analysis of dose–response relationships between strength training parameters and improved muscular strength [4]. The largest gains in muscular strength were found when training with free-weights, at a frequency of two to three times per week, with five sets per exercise at an intensity corresponding to 80–89% of the 1-RM. However, future studies need to verify safety of training with such high loads in young athletes or untrained youth [28]. Expert opinion [2] on the progression of intensity deems it as a safe practice to learn the proper exercise technique with low loads before progressing to higher loads. Specific recommendations for youth starting with strength training can be found in the review articles of Behm et al. [47] and, more recently, Faigenbaum et al. [34]. According to these guidelines, strength training should be performed on 2 or 3 nonconsecutive days per week, performing 1 or 2 sets of 8–15 repetitions in 8–12 different exercises at an intensity of about 60% of the 1-RM. After establishing proper exercise technique, the child or adolescent can progress to 2–4 sets of 6–12 repetitions at an intensity of up to 80% of the 1-RM [21]. At this stage, more advanced movements could be introduced, [47] such as Olympic weight lifting (See Lloyd et al. [48] for guidelines on the progression towards advanced weight-lifting techniques). As training experience and exercise competence increase, intensity can be progressed even further (<6 repetitions at >85% of the 1-RM [4]). These recommendations are additionally summarized in Table 17.3.

Adaptations

Increased muscle strength can be accomplished both by neural [49–52] and muscular [51–55] adaptations. Training-induced neural adaptations include increased motor unit recruitment and firing rates, increased antagonist muscle inhibition, and improved inter- and intramuscular coordination. The major muscular adaptation leading to increased strength is muscle hypertrophy, but changes in muscle pennation

Table 17.3 Summary of evidence and expert-based recommendations for strength training, aerobic training, and physical activity according to skill level

Parameters	Low skill	Medium skill	High skill
<i>Strength training</i>			
Frequency (w^{-1})	2	2–3	2–4
Sets per exercise (N)	1–2	2–4	Multiple
Repetitions per set (N)	8–15	6–12	≤6
Intensity (% of 1-RM)	≤60%	≤80%	≥85%
<i>Aerobic training</i>			
Frequency	3–4 sessions per week		
Duration	40–60 min		
Intensity	85–90% of maximum heart rate		
<i>Physical activity</i>			
Frequency	7 days per week		
Duration	≥60 min		
Intensity	≥50% of maximum heart rate		

Note: Recommendations for physical activity should be viewed as integrated in either strength or aerobic training. E.g., 60 min of high-intensity running counts as both aerobic training and physical activity. Recommendations are based on Behm et al. [47], Faigenbaum et al. [34], Lesinski et al. [4] for strength training; Armstrong et al. [61] for aerobic training; and WHO [7] for physical activity

angle [55], in myosin isoforms [56, 57], as well as in tendon stiffness [58] can also contribute to increased strength. Recently, Legerlotz et al. [58] described the physiological adaptations of young athletes following strength training in their review. They concluded that training-induced improvements in motor skills in children are related to improved neuromuscular control and morphological adaptations of muscle and tendon, although muscle hypertrophy seemed limited. Because prepubertal children display only minimal training-induced muscle hypertrophy [59], it is generally believed that training-induced strength gains in this population reflect neural adaptations. Furthermore, children do not possess the levels of androgens required for muscle hypertrophy [19, 58]. It was indeed found [60] that children aged 10 years showed training-induced gains in elbow flexor strength that were accompanied by increased EMG, but not by increased upper arm circumference. In contrast to children, adolescents did demonstrate muscle hypertrophy following mechanical loading [58], which, together with neural adaptations, may have contributed to increased strength. It is likely to assume that this is related to the changes in hormonal levels (i.e., increased testosterone) with puberty, which may be crucial for muscle hypertrophy to occur [19, 24, 27]. These differences in adaptations again highlight the relevance of biological age in the planning of training and exercise prescription.

Single-Mode Aerobic Training

Unlike the clear benefits of strength training in youth, the trainability of measures of aerobic fitness appears rather limited [62]. A compound measure of aerobic fitness is the maximum rate of oxygen consumption ($VO_2 \text{ max}$) that depends on the

maximum cardiac output (stroke volume and heart rate) and the arterial-venous oxygen difference. However, due to the lack of a plateau in the VO_2 curve in many youth when exercising to exhaustion, the peak oxygen uptake (peak VO_2) is the preferred measure of aerobic fitness [63]. VO_2 is usually expressed in relation to body mass (in $\text{mL kg}^{-1} \text{min}^{-1}$). When normalized to body mass in non-athletes, peak VO_2 remains quite constant in males during growth and maturation, whereas females may even show a decline [31].

Payne and Morrow [64] found that aerobic training had small to large effects on VO_2 max in children but the magnitude depended on the study design (longitudinal: ES = 0.35, cross-sectional: ES = 0.94). Another systematic review [65] revealed that a 5–6% increase in peak VO_2 was observed following aerobic training in youth aged 5–16 years. Furthermore, some cross-sectional studies provide indirect evidence for the trainability of peak VO_2 in young individuals, because young athletes demonstrated higher peak VO_2 values than their untrained peers [31].

The observed differences in peak VO_2 values are generally attributed to differences in stroke volume, suggesting that any attempts at improving aerobic capacity in youth should aim at improving stroke volume. In addition, training intensity appears to be a crucial factor in improving peak VO_2 . Narrative and systematic reviews [31, 65, 66] demonstrated that only training at intensities close to the maximal heart rate (85–90%) but not at lower intensities (<80% of maximal heart rate) had an effect on peak VO_2 in youth. Based on these findings, Armstrong et al. [61] suggested that aerobic training in children and adolescents should be performed three to four times per week, with a duration of 40–60 min at an intensity corresponding to 85–90% of maximum heart rate (see also Table 17.3).

Concurrent Aerobic and Strength Training in Healthy Children and Adolescents

Single-mode aerobic and strength training programs may be used to improve components of physical fitness and have benefits for health and sports performance. However, the principle of training specificity [51] dictates that the range of adaptations following single-mode training is limited. Thus, concurrent aerobic and strength training may be preferred to improve a broader range of physical fitness components simultaneously. Interestingly, the result of combining both training modes in adults does not equal the sum of adaptations to single-mode strength and aerobic training. Especially adaptations to strength training (e.g., muscular fitness and muscle hypertrophy) can be compromised when aerobic exercise is performed concurrently compared to single-mode strength training [67]. The potential interfering effects of combining aerobic and strength training modes are discussed extensively in Part II of this book. Of relevance for this chapter is that a high volume of aerobic exercise may limit strength development by interfering with muscle hypertrophy, due to conflicting muscular adaptations [68]. However, there are also data [69] suggesting that interference may be more pronounced in maximum muscle strength and power (i.e., neuromuscular adaptations) rather than in muscle

hypertrophy. It should be noted that our current knowledge is almost exclusively drawn from studies in the adult population [67]. Because of scant literature, much less is known about concurrent training in children and adolescents. Importantly, due to growth and maturation, findings from studies in adults do not simply translate into youth populations [70, 71]. The adaptations to strength training described in a previous section of this chapter emphasize the importance of acknowledging biological age when designing exercise interventions. Because prepubescent children show little capacity for muscle hypertrophy, it could be speculated that there is only minimal interference of aerobic exercise on strength training adaptations. However, should interference occur in neural adaptations [69], it is relevant to take heed when planning training programs for children. Adolescents, on the other hand, show training-induced muscle hypertrophy next to neural adaptations and interference mechanisms may be at work when aerobic and strength training are combined.

Until recently, the only reviews that have been published on concurrent training in children and adolescents have been performed with studies in overweight individuals [72, 73] and will be discussed in a later section of this chapter. More recently, we have performed a systematic review and meta-analysis on the effects of concurrent training in healthy children and adolescents, with a special focus on young athletes [74]. Studies on concurrent training traditionally compare one group that performs both aerobic and strength training to a group that performs only single-mode training. Our meta-analysis [74] involved 15 studies, of which 11 were conducted in endurance athletes (runners, swimmers, rowers, and cross-country skiers) and 4 studies involved non-athletic children and adolescents. The studies involving athletes allowed comparisons between aerobic training and concurrent training, while the studies in untrained children and adolescents allowed only comparisons between strength training and concurrent training. The main results of the meta-analysis are presented in Fig. 17.1.

Additional Strength Training to Enhance Aerobic Performance

The addition of strength training to an aerobically dominant exercise protocol had small effects on time trial performance ($ES = 0.41$) in young athletes aged 10–18 years [73]. A sub-analysis revealed that effect sizes for adolescents were moderate ($ES = 0.52$) and only trivial for children ($ES = 0.17$). These findings suggest that aerobic training combined with strength training improves running, swimming, rowing, and cross-country skiing performance more than single-mode aerobic training in young athletes, especially in adolescents. Further data in the included studies indicated that concurrent training had trivial positive effects ($ES = 0.04$) on aerobic capacity ($VO_2 \text{ max}$ or peak VO_2), and exercise economy ($ES = 0.16$) (VO_2 at a given exercise intensity). These findings suggest that concurrent training can improve time trial performance in young athletes more than aerobic training alone. However, aerobic capacity and exercise economy appear unaffected by additional strength training. It should be noted that the majority of the included studies did not assess aerobic capacity and exercise economy. Further research is needed to elucidate the underlying mechanisms that contributed to improved athletic performance.

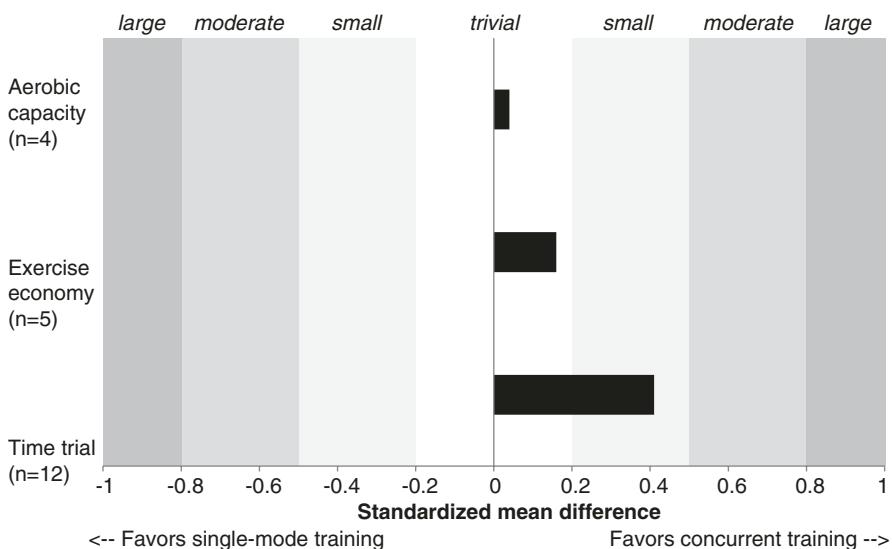


Fig. 17.1 Effects of concurrent training versus singular aerobic training on different outcome parameters in young athletes aged 10–18 years. Positive effect sizes are in favor of concurrent training. N represents the number of training groups (intervention arms) included in the meta-analysis [74]. Bars represent weighted standardized mean differences in aerobic capacity (peak VO_2 or $\text{VO}_2 \text{ max}$), exercise economy (VO_2 at a given exercise intensity), and athletic performance (time trial)

Probably the most sophisticated study on this topic was performed by Mikkola et al. [75] in a group of 25 young distance runners with a mean age of 17 years. Instead of adding extra training hours like most other studies do, they replaced 19% of the aerobic training volume by explosive type strength training, three times a week for 8 weeks. This procedure ensured that training volume was similar between both groups (aerobic training: 8.5 h/week; concurrent group: 8.8 h/week). Strength exercises performed included sprints (30–150 m), various jumps and weight-bearing exercises, in an attempt to strengthen the major muscle groups of the lower limb and core. The weight-bearing exercises were performed in 2–3 sets of 6–10 repetitions with low loads performed at high movement velocity. The aerobic training consisted mainly of running below the individually determined anaerobic threshold. The authors found that isometric leg-press strength (8% vs. 3%) was increased to larger magnitude in the concurrent compared to the aerobic training group and that these improvements were associated with increases in neural activity ($r = 0.7$) of the knee extensor muscles, while also thickness of the quadriceps femoris muscle increased (4% vs. 2%). What was more interesting for this specific population was that the training had an effect on running economy, without affecting $\text{VO}_2 \text{ max}$. The oxygen consumption at submaximal speeds was reduced following concurrent training (−3% at 14 km/h), but not following singular aerobic training (+3% at 14 km/h). These results suggested that explosive strength training reduced the energy cost of running in trained adolescent runners. To speculate on the underlying mechanisms, the

improved running economy might be the result of increased neuromuscular activity of type I motor units [76]. Possible training-induced adaptations in muscular and/or tendinous stiffness led to increased muscle and tendon contractility, which allowed for an increased storage of elastic energy in the elastic components of the musculotendinous system [76]. As a result, less energy is lost during each gait cycle, which means that less energy needs to be produced to maintain running speed.

No Interference of Additional Aerobic Training on Strength Development

To study the interference effect of aerobic training on strength, power, and muscle hypertrophy, a design where the effects of concurrent training are compared with single-mode strength training should be used. However, our systematic review identified only a few studies that adopted such a design in untrained children [77–79] and adolescents [80]. These identified studies were from the same research group and contained an experimental series with similar research methods. All studies were conducted at the same school cluster in Portugal and comprised one or more concurrent training groups, a single-mode strength training group and a passive control group. The strength training program was performed twice weekly for 8 weeks and consisted of medicine ball throws, jumping, and sprinting exercises. Additionally, also twice weekly, the concurrent training groups performed a submaximal 20-m shuttle run test as aerobic training. The aggregated data [74] of these studies showed that the addition of aerobic training to a strength training program had a small effect on leg power, as indicated by vertical jump height ($ES = 0.23$). The low heterogeneity in outcomes across training groups suggested that training adaptations in children and adolescents were similar. These findings imply that there was not an interfering, but an additive effect of aerobic training on power development (vertical jump height) in untrained children and adolescents. However, the methodological limitations of these four studies allow other interpretations as well. A potential confounding factor was the use of the 20-m shuttle run test both as a training and assessment tool. The repeated changes of direction in this test required constant accelerations and decelerations of the entire body. The shuttle run test may have been a sufficient stimulus to increase rapid force production in the lower limbs, which expressed itself in increased vertical jump height. Other reasons for the absence of an interference effect are the untrained status of the participants and the low training volume, which should be kept in mind when interpreting these data.

Sequencing

Under specific circumstances (e.g., high training volume in young athletes), aerobic and strength training have to be combined within one training day. The sequence in which the individual components of aerobic (A) and strength (S) training are performed may affect training adaptations (see Chaps. 10 and 11). So far, two studies are available that examined sequencing effects in youth [81, 82]. These studies

included young soccer players aged 14 (around PHV) and 17 years (post PHV). Here we calculated Hedges' g [83] from the mean differences (i.e., post – pre) and pooled standard deviations presented in the original data to determine which sequence (i.e., aerobic training before strength training [$A \rightarrow S$] or vice versa [$S \rightarrow A$]) produced the largest effects on muscle strength and power, muscle hypertrophy, and aerobic capacity. Figure 17.2 presents the Hedges' g and examples for each outcome. Two studies in adult soccer players [84] and non-athletes [85] were also included in Fig. 17.2 for comparative reasons. Although many effect sizes turned out to be trivial in magnitude, some interesting discrepancies between youth and adults were observed which will be discussed in the following.

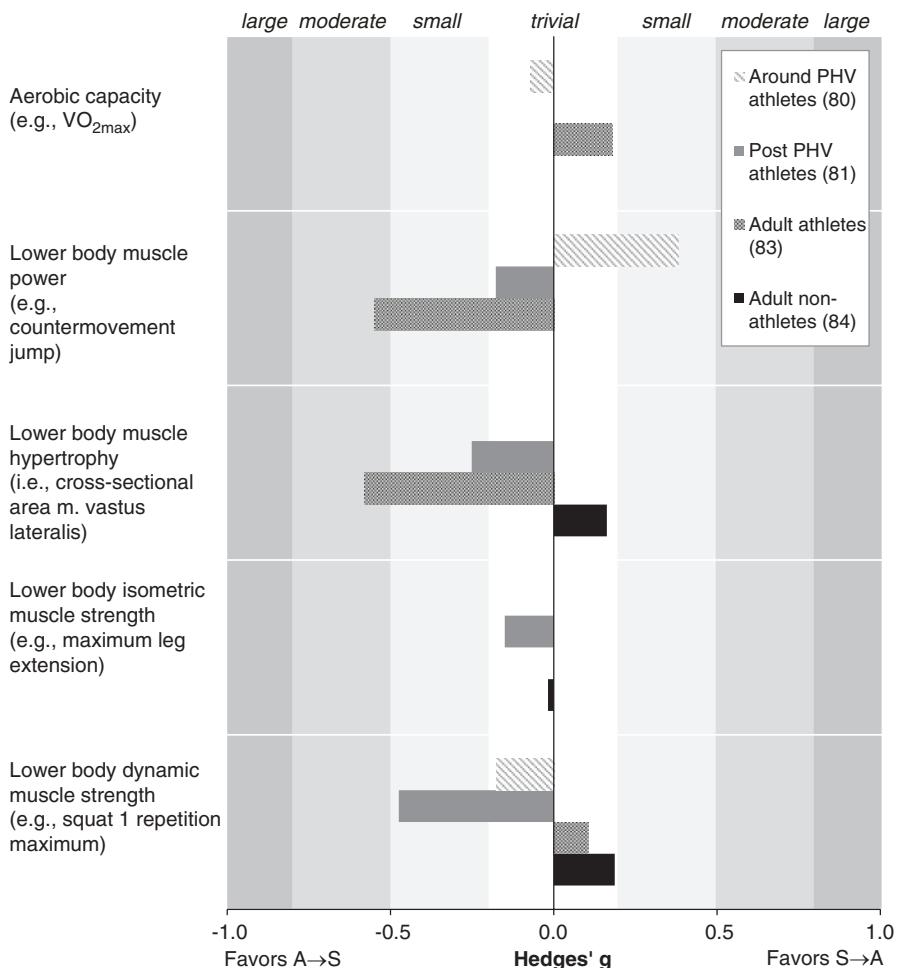


Fig. 17.2 Sequencing effects of aerobic and strength training on aerobic capacity, muscle strength and power, and muscle hypertrophy in different populations. Effect sizes were calculated from the mean differences of the respective groups ($A \rightarrow S$ and $S \rightarrow A$) and their pooled standard deviations [83]

In around PHV soccer players [81], small effects were found for proxies of muscle power in favor of S → A and trivial effects were observed for aerobic capacity and dynamic muscle strength in favor of A → S. Another experimental group in this study [81] performed A and S on alternating days, thereby allowing longer recovery time between training sessions. Makhlof et al. [81] reported that the performance of A and S on one day resulted in similar or greater improvements in aerobic capacity, muscle strength and power compared with the group that performed A and S on alternating days. Another study in post PHV soccer players [82] revealed small effects on measures of dynamic muscle strength and muscle hypertrophy and trivial effects on measures of static muscle strength and proxies of muscle power all in favor of A → S. The discrepancy in findings between around PHV and post PHV soccer players could be due to differences in maturational status of the examined cohorts. In post PHV youth, the hormonal status allows training-induced muscle hypertrophy [19]. In this context, Baar [86] suggested that S → A sequencing may compromise protein synthesis and thus muscle hypertrophy following strength training. This interference could specifically be attributed to post PHV youth.

In adult soccer players, moderate effects were found for proxies of muscle power and muscle hypertrophy in favor of A → S and trivial effects were observed for aerobic capacity and dynamic muscle strength in favor of S → A. For non-athletic adults, trivial effects were detected for muscle hypertrophy as well as measures of static and dynamic muscle strength. A consistent finding in adults appears that S → A is favored over A → S if the goal is to improve dynamic muscle strength [84, 85]. This was in fact confirmed by two recent meta-analyses [87, 88].

The abovementioned findings indicate a discrepancy between the adult and youth literature on sequencing effects of strength and aerobic training regarding improvements in dynamic muscle strength. While adults primarily benefit from S → A, youth benefit from A → S. Children and adolescents compared to adults generally demonstrate greater resistance to fatigue following high-intensity exercise [89]. Strength training quality may therefore be less affected by prior aerobic training when youth perform A → S compared to adults. Another important distinction is the difference in training status between the young and adult populations in the aforementioned studies. It was previously suggested that untrained individuals have a greater adaptive reserve regardless of the training mode (A or S) [90]. Taken together, preliminary data suggest that youth may be less susceptible than adults to interfering effects due to better resistance to fatigue. In around PHV soccer players, S → A may be favored over A → S to improve muscle power. Further, post PHV athletes may benefit most from A → S, because S → A could be more susceptible to interfere with muscle hypertrophy.

Concurrent Training for Health

Given the increasing number of obesity and rising levels of inactivity in young individuals, scientific interest has grown for exercise interventions to promote health already in young populations. To evaluate the effectivity of such interventions,

García-Hermoso et al. [73] have conducted a meta-analysis on data from 12 studies on the effects of concurrent training on body composition and metabolic outcomes in obese and overweight children aged 14–18 years. They specifically included the results of studies that compared a concurrent training group to an aerobic training group and found that additional strength training had small to intermediate effects on body composition (ES: 0.14–0.47), low-density lipoprotein cholesterol (ES: 0.35), and adiponectin concentrations (ES = 0.79), suggesting improved metabolism. These data suggested that concurrent training is more effective than single-mode aerobic training in controlling body weight, fat percentage, and reducing the risk of cardiac and metabolic diseases. However, the authors did not report whether strength training was performed additionally to, or as a replacement of aerobic training, which limits the interpretation of this review. In another meta-analysis, Marson et al. [72] looked specifically at studies that evaluated the effects of different training modes on factors associated with insulin resistance in obese and overweight children and adolescents aged 9–17 years. Increased insulin resistance is associated with obesity and metabolic symptoms later in life. Marson et al. [72] found that aerobic exercise was most successful in decreasing fasted state blood insulin levels, while strength and concurrent training showed only limited effects. Blood glucose levels were changed only minimally following any mode of exercise. The results suggested that aerobic exercise should be part of training in order to decrease resistance to insulin, which may reduce adverse outcomes later in life.

In two of the Portuguese studies mentioned in the previous section [79, 80], body fat was measured in healthy young populations aged 12–14 years. Body fat was reduced the most in concurrent training groups (2.6–2.8%), followed closely by the strength training groups (2.1–2.4%), and to a lesser extent in the passive control groups (0.0–0.9%). These results suggest that body fat can be reduced in young people by performing strength training as well as aerobic training. In studies assessing fat percentage in young athletes [75, 91, 92] both concurrent (−1.6% to +4.0%) and aerobic training (0.2–6.0%) seemed to increase, rather than decrease percentage body fat. Although a similar trend as in non-athletic populations was found, it is arguable that young athletes usually have normal or low levels of body fat and that further reductions are not desired. Taken together, concurrent training has greater and more diverse effects on body composition and other health-related factors than singular strength or singular aerobic training but it remains unclear to what extent this is the result of an increased training volume or of the higher diversity in exercise modes (i.e., aerobic and strength exercises).

Recommendations for Concurrent Training in Youth

The distinction between children and adolescents is important for the design of training programs. Age at PHV can be used as a valid measure to determine the developmental stage of an individual. Unlike in children, strength exercise in adolescents can promote muscle hypertrophy, but careful planning is required. Just as in adults, when training is planned poorly (e.g., aerobic exercise immediately

after strength exercise) and training volume is high, interfering effects of concurrent aerobic and strength training may be expected in adolescents.

Recent models on physical development dictate that training in prepubescent children should focus mainly on developing fundamental movement skills and (neuro-)muscular strength. At this age, strength training should focus on developing the correct exercise technique using loads corresponding to 60% of 1-RM. With increasing maturity, age, and (strength) training experience, loads can gradually progress up to 80% of the 1-RM and more advanced exercises can be introduced. The training of movement skills should become increasingly sport specific. Training with higher loads (>85% of 1-RM) should only be performed when exercise competence is high.

Aerobic activity should be part of any training program throughout all developmental stages due to its positive effects on health-related outcomes. When the goal is to increase aerobic capacity, intensity of training should be sufficiently high (85–90% of maximal heart rate).

The interference effect following concurrent training seems of little concern for untrained and recreationally trained children and adolescents due to overall low training volumes. When aerobic and strength training are performed within a single day or a single training session, aerobic training should not be performed shortly after strength training in young athletes that are post PHV when the goal is to improve muscle strength and hypertrophy. In younger athletes that are around PHV, improvements in leg power (but not strength) may be greater when strength training is performed before aerobic training. These recommendations are based on only two studies and therefore require confirmation. Furthermore, training volume should be gradually increased with increasing age. To reduce overuse injury risk, the total number of training hours per week is recommended not to exceed the number of chronological age and the ratio of training to play time should not exceed 2:1 [29]. Training volume (dose) must be raised when age and training history increase in order to elicit an adaptive effect (response) [28]. From these guidelines, it follows that weekly training volume in children could be lower than in adolescents and thereby regeneration time is increased. This, may in fact help to reduce the risk of interfering training adaptations [90].

Summary

Systematic concurrent aerobic and strength training appears ideal to meet physical activity recommendations, to promote health- and skill-related components of physical fitness and to improve athletic performance in children and adolescents. No interference, but rather an additive effect in training adaptations was observed when youth combine aerobic and strength training compared to single-mode training. Especially adolescents improved their performance in time trials after concurrent training compared to aerobic training alone. However, preliminary evidence suggested that aerobic training should not be performed in short sequence to strength training in adolescents post PHV. Finally, concurrent aerobic and

strength training can help with weight management and reduce the risk of acute and chronic adverse outcomes in young people with inactive lifestyles, overweight, or obesity.

References

1. Williams CA. Trainability of young athletes: short-term goals or long-term mission? *Pediatr Exerc Sci.* 2016;28(4):485–7. <https://doi.org/10.1123/pes.2016-0215>.
2. Faigenbaum AD, Kraemer WJ, Blimkie CJ, Jeffreys I, Micheli LJ, Nitka M, et al. Youth resistance training: updated position statement paper from the national strength and conditioning association. *J Strength Cond Res.* 2009;23:S60–79.
3. Caspersen CJ, Powell KE, Christenson GM. Physical activity, exercise, and physical fitness: definitions and distinctions for health-related research. *Public Health Rep.* 1985;100(2):126.
4. Lesinski M, Prieske O, Granacher U. Effects and dose-response relationships of resistance training on physical performance in youth athletes: a systematic review and meta-analysis. *Br J Sports Med.* 2016;50(13):781–95. <https://doi.org/10.1136/bjsports-2015-095497>.
5. Emery CA, Roy T-O, Whittaker JL, Nettel-Aguirre A, Van Mechelen W. Neuromuscular training injury prevention strategies in youth sport: a systematic review and meta-analysis. *Br J Sports Med.* 2015;49(13):865–70.
6. Bouchard C, Blair SN, Haskell W. Physical activity and health. 2nd ed. Champaign: Human Kinetics; 2012.
7. WHO. Global recommendations on physical activity for health. Geneva: WHO Press; 2010.
8. Faigenbaum AD, Bruno LE. A fundamental approach for treating pediatric dynapenia in kids. *ACSMs Health Fitness J.* 2017;21(4):18–24.
9. Katzmarzyk PT, Barreira TV, Broyles ST, Champagne CM, Chaput JP, Fogelholm M, et al. Physical activity, sedentary time, and obesity in an international sample of children. *Med Sci Sports Exerc.* 2015;47(10):2062–9. <https://doi.org/10.1249/MSS.0000000000000649>.
10. Konstabel K, Veidebaum T, Verbestel V, Moreno LA, Bammann K, Tornaritis M, et al. Objectively measured physical activity in European children: the IDEFICS study. *Int J Obes.* 2014;38(Suppl 2):S135–43. <https://doi.org/10.1038/ijo.2014.144>.
11. Faigenbaum AD, Stracciolini A, Myer GD. Exercise deficit disorder in youth: a hidden truth. *Acta Paediatr.* 2011;100(11):1423.
12. Faigenbaum AD, Myer GD. Exercise deficit disorder in youth: play now or pay later. *Curr Sports Med Rep.* 2012;11(4):196–200.
13. Faigenbaum AD, MacDonald JP. Dynapenia: it's not just for grown-ups anymore. *Acta Paediatr.* 2017;106(5):696–7.
14. Tucker P. The physical activity levels of preschool-aged children: a systematic review. *Early Child Res Q.* 2008;23(4):547–58. <https://doi.org/10.1016/j.ecresq.2008.08.005>.
15. Currie C, Zanotti C, Morgan A, Currie D, Looze Md, Roberts C, et al. Social determinants of health and well-being among young people: Health Behaviour in School-aged Children (HBSC) study: international report from the 2009/2010 survey. Social determinants of health and well-being among young people: Health Behaviour in School-aged Children (HBSC) study: international report from the 2009/2010 survey. 2012.
16. Bompa T, Buzzichelli CA. Periodization training for sports. 3rd ed. Champaign: Human Kinetics; 2015.
17. Balyi I, Hamilton A. Long-term athlete development: trainability in childhood and adolescence. *Olympic Coach.* 2004;16(1):4–9.
18. Balyi I, Way R, Colin H. Long-term athlete development. Champaign: Human Kinetics; 2013.
19. Lloyd RS, Oliver JL. The youth physical development model: a new approach to long-term athletic development. *Strength Cond J.* 2012;34(3):61–72.
20. Lloyd RS, Oliver JL, Faigenbaum A, Howard R, De Ste Croix MBA, Williams CA, et al. Long-term athletic development-part 1: a pathway for all youth. *J Strength Cond Res.* 2015;29(5):1439–50.

21. Lloyd RS, Faigenbaum AD, Stone MH, Oliver JL, Jeffreys I, Moody JA, et al. Position statement on youth resistance training: the 2014 International Consensus. *Br J Sports Med.* 2014;48(7):498–505. <https://doi.org/10.1136/bjsports2013-092952>.
22. Mirwald RL, Baxter-Jones G, AD BDA, Beunen GP. An assessment of maturity from anthropometric measurements. *Med Sci Sports Exerc.* 2002;34(4):689–94. <https://doi.org/10.1097/00005768-200204000-00020>.
23. College of Kinesiology. https://kinesiology.usask.ca/growthutility/phv_ui.php. Accessed 18 Dec 2017.
24. Viru A, Loko J, Harro M, Volver A, Laaneots L, Viru M. Critical periods in the development of performance capacity during childhood and adolescence. *Eur J Phys Educ.* 1999;4(1):75–119.
25. Ford P, De Ste Croix M, Lloyd R, Meyers R, Moosavi M, Oliver J, et al. The long-term athlete development model: physiological evidence and application. *J Sports Sci.* 2011;29(4):389–402.
26. Wick K, Leeger-Aschmann CS, Monn ND, Radtke T, Ott LV, Rebholz CE, et al. Interventions to promote fundamental movement skills in childcare and kindergarten: a systematic review and meta-analysis. *Sports Med (Auckland, NZ).* 2017;47(10):2045–68.
27. Malina RM, Bouchard C, Bar-Or O. Growth, maturation, and physical activity. Champaign: Human Kinetics; 2004.
28. Faigenbaum AD, Lloyd RS, Myer GD. Youth resistance training: past practices, new perspectives, and future directions. *Pediatr Exerc Sci.* 2013;25(4):591–604.
29. Jayanthi NA, LaBella CR, Fischer D, Pasulka J, Dugas LR. Sports-specialized intensive training and the risk of injury in young athletes: a clinical case-control study. *Am J Sports Med.* 2015;43(4):794–801.
30. Vandendriessche JB, Vaeyens R, Vandorpe B, Lenoir M, Lefevre J, Philippaerts RM. Biological maturation, morphology, fitness, and motor coordination as part of a selection strategy in the search for international youth soccer players (age 15–16 years). *J Sports Sci.* 2012;30(15):1695–703. <https://doi.org/10.1080/02640414.2011.652654>.
31. Armstrong N, Barker AR. Endurance training and elite young athletes. In: Armstrong N, Barker AR, editors. *The elite young athlete.* Basel: Karger Publishers; 2011. p. 59–83.
32. Clark BC, Manini TM. Sarcopenia≠ dynapenia. *J Gerontol Ser A Biol Med Sci.* 2008;63(8):829–34.
33. Pichardo AW, Oliver JL, Harrison CB, Maulder PS, Lloyd RS. Integrating models of long-term athletic development to maximize the physical development of youth. *Int J Sports Sci Coach.* 2018. <https://doi.org/10.1177/1747954118785503>.
34. Faigenbaum AD, Lloyd RS, MacDonald J, Myer GD. Citius, altius, fortius: beneficial effects of resistance training for young athletes: narrative review. *Br J Sports Med.* 2016;50(1):3–7.
35. McCambridge T, Stricker P. Strength training by children and adolescents. *Pediatrics.* 2008;121(4):835–40.
36. Bergeron MF, Mountjoy M, Armstrong N, Chia M, Cote J, Emery CA, et al. International Olympic Committee consensus statement on youth athletic development. *Br J Sports Med.* 2015;49(13):843–51. <https://doi.org/10.1136/bjsports-2015-094962>.
37. Lloyd RS, Cronin JB, Faigenbaum AD, Haff GG, Howard R, Kraemer WJ, et al. National Strength and Conditioning Association position statement on long-term athletic development. *J Strength Cond Res.* 2016;30(6):1491–509.
38. Myer GD, Faigenbaum AD, Ford KR, Best TM, Bergeron MF, Hewett TE. When to initiate integrative neuromuscular training to reduce sports-related injuries and enhance health in youth? *Curr Sports Med Rep.* 2011;10(3):155–66. <https://doi.org/10.1249/JSR.0b013e31821b1442>.
39. Büsch D, Prieske O, Kriemler S, Puta C, Gabriel H, Granacher U. Krafttraining im Kindes- und Jugendalter: Bedeutung, Wirkung und Handlungsempfehlungen. *Schweizerische Zeitschrift für Sportmedizin und Sporttraumatologie.* 2017;65(3):34–42.
40. Smith JJ, Eather N, Morgan PJ, Plotnikoff RC, Faigenbaum AD, Lubans DR. The health benefits of muscular fitness for children and adolescents: a systematic review and meta-analysis. *Sports Med.* 2014;44(9):1209–23.
41. Payne VG, Morrow JR Jr, Johnson L, Dalton SN. Resistance training in children and youth: a meta-analysis. *Res Q Exerc Sport.* 1997;68(1):80–8.

42. Behm DG, Young JD, Whitten JH, Reid JC, Quigley PJ, Low J, et al. Effectiveness of traditional strength vs. power training on muscle strength, power and speed with youth: a systematic review and meta-analysis. *Front Physiol.* 2017;8:423.
43. Behringer M, Vom HA, Yue Z, Mester J. Effects of resistance training in children and adolescents: a meta-analysis. *Pediatrics.* 2010;126(5):e1199–e210.
44. Behringer M, Heede AV, Matthews M, Mester J. Effects of strength training on motor performance skills in children and adolescents: a meta-analysis. *Pediatr Exerc Sci.* 2011;23(2):186–206.
45. Falk B, Tenenbaum G. The effectiveness of resistance training in children. *Sports Med.* 1996;22(3):176–86. <https://doi.org/10.2165/00007256-199622030-00004>.
46. Harries SK, Lubans DR, Callister R. Resistance training to improve power and sports performance in adolescent athletes: a systematic review and meta-analysis. *J Sci Med Sport.* 2012;15(6):532–40. <https://doi.org/10.1016/j.jams.2012.02.005>.
47. Behm DG, Faigenbaum AD, Falk B, Klentrou P. Canadian Society for Exercise Physiology position paper: resistance training in children and adolescents. *Appl Physiol Nutr Metab.* 2008;33(3):547–61.
48. Lloyd RS, Oliver JL, Meyers RW, Moody JA, Stone MH. Long-term athletic development and its application to youth weightlifting. *Strength Cond J.* 2012;34(4):55–66.
49. Sale DG. Neural adaptation to resistance training. *Med Sci Sports Exerc.* 1988;20(5 Suppl):S135–45.
50. Sale DG. Neural adaptation to strength training. In: Komi PV, editor. *Strength and power in sport.* 2nd ed. Oxford: Blackwell Scientific; 2008. p. 281–314.
51. Powers SK, Howley ET. *Exercise physiology: theory and application to fitness and performance.* 7th ed. New York: McGraw-Hill; 2009.
52. Folland JP, Williams AG. The adaptations to strength training. *Sports Med.* 2007;37(2):145–68.
53. Tesch P. Skeletal muscle adaptations consequent to long-term heavy resistance exercise. *Med Sci Sports Exerc.* 1988;20(5 Suppl):S132–4.
54. Kraemer WJ, Deschenes MR, Fleck SJ. Physiological adaptations to resistance exercise. *Sports Med.* 1988;6(4):246–56.
55. Seynnes OR, de Boer M, Narici MV. Early skeletal muscle hypertrophy and architectural changes in response to high-intensity resistance training. *J Appl Physiol.* 2007;102(1):368–73.
56. Pette D, Staron RS. Myosin isoforms, muscle fiber types, and transitions. *Microsc Res Tech.* 2000;50(6):500–9.
57. Toigo M, Boutellier U. New fundamental resistance exercise determinants of molecular and cellular muscle adaptations. *Eur J Appl Physiol.* 2006;97(6):643–63.
58. Legerlotz K, Marzilger R, Bohm S, Arampatzis A. Physiological adaptations following resistance training in youth athletes—a narrative review. *Pediatr Exerc Sci.* 2016;28(4):501–20. <https://doi.org/10.1123/pes.2016-0023>.
59. Granacher U, Goesele A, Roggo K, Wischer T, Fischer S, Zuerny C, et al. Effects and mechanisms of strength training in children. *Int J Sports Med.* 2011;32(5):357–64. <https://doi.org/10.1055/s-0031-1271677>.
60. Ozmun JC, Mikesky AE, Surburg PR. Neuromuscular adaptations following prepubescent strength training. *Med Sci Sports Exerc.* 1994;26(4):510–4.
61. Armstrong N, Tomkinson G, Ekelund U. Aerobic fitness and its relationship to sport, exercise training and habitual physical activity during youth. *Br J Sports Med.* 2011;45(11):849–58.
62. Matos N, Winsley RJ. Trainability of young athletes and overtraining. *J Sports Sci Med.* 2007;6(3):353–67.
63. Armstrong N, Welsman JR. Assessment and interpretation of aerobic fitness in children and adolescents. *Exerc Sport Sci Rev.* 1994;22(1):435–76.
64. Payne VG, Morrow JR Jr. Exercise and VO₂max in children: a meta-analysis. *Res Q Exerc Sport.* 1993;64(3):305–13.
65. Baquet G, Van Praagh E, Berthoin S. Endurance training and aerobic fitness in young people. *Sports Med.* 2003;33(15):1127–43. <https://doi.org/10.2165/00007256-200333150-00004>.

66. Costigan SA, Eather N, Plotnikoff R, Taaffe DR, Lubans DR. High-intensity interval training for improving health-related fitness in adolescents: a systematic review and meta-analysis. *Br J Sports Med.* 2015;49:1221–2.
67. Wilson JM, Marin PJ, Rhea MR, Wilson SM, Loenneke JP, Anderson JC. Concurrent training: a meta-analysis examining interference of aerobic and resistance exercises. *J Strength Cond Res.* 2012;26(8):2293–307.
68. Docherty D, Sporer B. A proposed model for examining the interference phenomenon between concurrent aerobic and strength training. *Sports Med.* 2000;30(6):385–94.
69. Häkkinen K, Alen M, Kraemer W, Gorostiaga E, Izquierdo M, Rusko H, et al. Neuromuscular adaptations during concurrent strength and endurance training versus strength training. *Eur J Appl Physiol.* 2003;89(1):42–52.
70. Armstrong N, McManus AM. Physiology of elite young male athletes. In: Armstrong N, McManus AM, editors. *The elite young athlete.* Basel: Karger Publishers; 2011. p. 1–22.
71. McManus AM, Armstrong N. Physiology of elite young female athletes. In: Armstrong N, McManus AM, editors. *The elite young athlete.* Basel: Karger Publishers; 2011. p. 23–46.
72. Marson EC, Delevatti RS, Prado AK, Netto N, Kruel LF. Effects of aerobic, resistance, and combined exercise training on insulin resistance markers in overweight or obese children and adolescents: a systematic review and meta-analysis. *Prev Med.* 2016;93:211–8. <https://doi.org/10.1016/j.ypmed.2016.10.020>.
73. García-Hermoso A, Ramírez-Vélez R, Ramírez-Campillo R, Peterson MD, Martínez-Vizcaíno V. Concurrent aerobic plus resistance exercise versus aerobic exercise alone to improve health outcomes in paediatric obesity: a systematic review and meta-analysis. *Br J Sports Med.* 2018;52(3):161–6.
74. Gäßler M, Prieske O, Hortobagyi T, Granacher U. The effects of concurrent strength and endurance training on physical fitness and athletic performance in youth: a systematic review and meta-analysis. *Front Physiol.* [Epub]. <https://doi.org/10.3389/fphys.2018.01057>.
75. Mikkola J, Rusko H, Nummela A, Pollari T, Hakkinen K. Concurrent endurance and explosive type strength training improves neuromuscular and anaerobic characteristics in young distance runners. *Int J Sports Med.* 2007;28(7):602–11. <https://doi.org/10.1055/s-2007-964849>.
76. Ronnestad BR, Mujika I. Optimizing strength training for running and cycling endurance performance: a review. *Scand J Med Sci Sports.* 2014;24(4):603–12. <https://doi.org/10.1111/sms.12104>.
77. Alves AR, Marta CC, Neiva HP, Izquierdo M, Marques MC. Concurrent training in prepubescent children: the effects of 8 weeks of strength and aerobic training on explosive strength and V[Combining Dot Above]O_{2max}. *J Strength Cond Res.* 2016;30(7):2019–32. <https://doi.org/10.1519/JSC.0000000000001294>.
78. Marta C, Marinho DA, Barbosa TM, Izquierdo M, Marques MC. Effects of concurrent training on explosive strength and VO(2max) in prepubescent children. *Int J Sports Med.* 2013;34(10):888–96. <https://doi.org/10.1055/s-0033-1333695>.
79. Santos AP, Marinho DA, Costa AM, Izquierdo M, Marques MC. The effects of concurrent resistance and endurance training follow a detraining period in elementary school students. *J Strength Cond Res.* 2012;26(6):1708–16.
80. Santos A, Marinho DA, Costa AM, Izquierdo M, Marques MC. The effects of concurrent resistance and endurance training follow a specific detraining cycle in young school girls. *J Hum Kinet.* 2011;29A:93–103. <https://doi.org/10.2478/v10078-011-0064-3>.
81. Makhoul I, Castagna C, Manzi V, Laurencelle L, Behm DG, Chaouachi A. Effect of sequencing strength and endurance training in young male soccer players. *J Strength Cond Res.* 2016;30(3):841–50.
82. Enright K, Morton J, Iga J, Drust B. The effect of concurrent training organisation in youth elite soccer players. *Eur J Appl Physiol.* 2015;115(11):2367–81. <https://doi.org/10.1007/s00421-015-3218-5>.
83. Durlak JA. How to select, calculate, and interpret effect sizes. *J Pediatr Psychol.* 2009;34(9): 917–28.
84. McGawley K, Andersson P-I. The order of concurrent training does not affect soccer-related performance adaptations. *Int J Sports Med.* 2013;34(11):983–90.

85. Eklund D, Pulverenti T, Bankers S, Avela J, Newton R, Schumann M, et al. Neuromuscular adaptations to different modes of combined strength and endurance training. *Int J Sports Med.* 2015;36(02):120–9.
86. Baar K. Using molecular biology to maximize concurrent training. *Sports Med.* 2014;44(2):117–25.
87. Eddens L, van Someren K, Howatson G. The role of intra-session exercise sequence in the interference effect: a systematic review with meta-analysis. *Sports Med (Auckland, NZ).* 2018;48(1):177–88. <https://doi.org/10.1007/s40279-017-0784-1>.
88. Murlasits Z, Kneffel Z, Thalib L. The physiological effects of concurrent strength and endurance training sequence: a systematic review and meta-analysis. *J Sports Sci.* 2018;36(11):1212–9.
89. Ratel S, Duché P, Williams CA. Muscle fatigue during high-intensity exercise in children. *Sports Med.* 2006;36(12):1031–65.
90. Coffey VG, Hawley JA. Concurrent exercise training: do opposites distract? *J Physiol.* 2017;595(9):2883–96.
91. Bluett KA, Croix M, De Ste BA, Lloyd RS. A preliminary investigation into concurrent aerobic and resistance training in youth runners. *Isokinetics Exerc Sci.* 2015;23(2):77–85. <https://doi.org/10.3233/ies-150567>.
92. Potdevin FJ, Alberty ME, Chevutschi A, Pelayo P, Sidney MC. Effects of a 6-week plyometric training program on performances in pubescent swimmers. *J Strength Cond Res.* 2011;25(1):80–6.



Concurrent Training in Elderly

18

Eduardo Lusa Cadore and Mikel Izquierdo

Concurrent Strength and Endurance Training in Elderly

Biological aging is associated with declines in the neuromuscular and cardiovascular systems, resulting in an impaired capacity to perform daily activities [1–5]. In addition, age-related muscle power decrease is also an important predictor of functional limitations in healthy elderly [6–12].

Strength and endurance training promote specific neuromuscular and cardiovascular adaptations. The adaptations induced by strength training include muscle hypertrophy [13, 14] and an increase in both the motor unit recruitment capacity and motor unit firing rate [15–17]. These neuromuscular adaptations result in improved muscle strength and power development [18]. In contrast, endurance training induces central and peripheral adaptations that improve the cardiovascular function and the capacity of skeletal muscles to generate energy via the oxidative metabolism [19, 20]. Thus, a combination of strength and endurance training (i.e., concurrent training) in elderly populations is the most effective way to enhance both neuromuscular and cardiorespiratory functions, and consequently to preserve functional capacity [21–25]. In addition, another benefit of prescribing both strength and endurance training concurrently in elderly is that, in order to perform both modalities, the total time spent undergoing physical activity is increased, which is also beneficial to prevent and control cardiometabolic diseases [26]. However, as has been described in previous chapters of the book, the simultaneous development of both neuromuscular and cardiovascular adaptations might be challenging; and, in order to optimize the concurrent training prescription, it seems relevant to identify

E. L. Cadore (✉)

Exercise Research Laboratory, School of Physical Education, Physiotherapy and Dance,
Universidade Federal do Rio Grande do Sul, Porto Alegre, RS, Brazil

M. Izquierdo

Department of Health Sciences, Public University of Navarre, Pamplona, Navarre, Spain

the most effective combination of training variables (i.e., intensity, volume, weekly frequency, exercise order) to promote both neuromuscular and cardiovascular adaptations in the elderly.

Table 18.1 shows a summary of the methods and results from studies which compared neuromuscular, cardiorespiratory, and functional adaptations to strength, endurance, and concurrent training, as well as different concurrent training regimes in elderly populations (i.e., mean age of above 60 years).

Effects of Concurrent Training on Muscle Strength, Rate of Force Development, and Power Output

In aging populations, most of the studies reported that concurrent training induced similar strength adaptations using two sessions per week of each modality (i.e., strength and endurance) when compared with strength training alone [34–39]. However, we have previously demonstrated that three times a week of concurrent training can result in an interference effect in elderly men [25]. In addition, the time-course of strength development during a concurrent training periodization may be influenced by the weekly training frequency [40, 41]. Furthermore, we have also shown that the intra-session exercise sequence may influence the magnitude of strength adaptations in the elderly, and performing strength training prior to endurance exercise may optimize the neuromuscular adaptations in this population [27, 28].

In previous study of our laboratory, Izquierdo et al. [22] investigated the effects of 16 weeks of strength, endurance, and concurrent training among elderly men. In this study, the strength and endurance training groups performed specific training twice a week, and the concurrent training group performed strength exercises on one day and cycle ergometer training on the other day. This study demonstrated that after 16 weeks of training, similar lower-body strength gains were observed in the strength and concurrent training groups, which suggests that a minimum weekly frequency of concurrent training may promote an optimal stimulus to strength gains in previously untrained elderly subjects [22].

When similar volumes of strength training only and concurrent training were performed on separate days (i.e., four training sessions per week), Karavirta et al. [39] observed similar strength gains (i.e., 21 and 22% in dynamic leg press) and similar improvements in concentric leg extension power (~16%) after 21 weeks of training twice a week in 40–67-year-old men. Using a similar training volume, intensity, and weekly frequency, other studies have shown comparable strength and power gains induced by strength and concurrent training in older men [35–37, 39], and older women [38].

However, increasing the weekly training frequency of concurrent training from two to three sessions per week may induce an interference effect in elderly men. This was shown by our study in elderly men (65 ± 5 years), where 12 weeks of training performed three times a week led to greater dynamic and isometric strength in the leg extensor muscles in the group that performed only strength training (dynamic strength: 67%; isometric strength: 14%) when compared with a combined strength

Table 18.1 Neuromuscular, functional, and cardiorespiratory adaptations to endurance-, strength-, and concurrent training in the elderly

Authors	Period (weeks)	Weekly frequency	Volume and intensity	Main findings
Wood et al. [21]	12	ST: 3 x/wk; ET: 2 x/wk; CT: ST + ET	ST: 2 sets, 12–15 rep (75% 5 RM) of 8–12 RM ET: 60–70% of HR _{max} estimated, 20–45 min cycling CT: 1 set of 8–12 RM + 30 min cycling	ST: ↑ 5 RM (44%) CT: ↑ 5 RM (38%) No differences between CT and ST in 5 RM gains. All groups: ↑ functional fitness, but greater ↑ in CT
Izquierdo et al. [22]	16	ST: 2 x/wk; ET: 2 x/wk; CT: 1 x/wk ST + 1 x/wk ET	ST: 3–5 sets, 6–15 rep (50–80% 1 RM) slow + fast contractions (20% of total volume, 30–50% of 1 RM) ET: 30–40 min cycling, at loads (W) of 2, 3, and 4 mmol L ⁻¹ of lactate	ST: ↑ 1 RM (41%); ↑ muscle power (37%). ↑ CSA QF (11%). CT: ↑ 1 RM (38%); ↑ muscle power (38%). ↑ CSA QF (11%). No differences among CT and ST in strength and CSA gains. ↑ W _{max} (16%) in ST, CT, and ET groups
Cadore et al. [25]	12	ST: 3 x/wk; ET: 3 x/wk; CT: ST + ET, ET prior to ST at same session	ST: 18–20 RM progressing to 6–8 RM ET: 20–30 min cycling, 80–100% of HR at VT ₂	ST: ↑ 1 RM (67%); ↑ PT (14%); ↑ EMG QF (30%). CT: ↑ 1 RM (41%); ST had greater increases in the 1 RM, PT, and EMG than CT. ↑ VO _{2peak} (20%); ET: ↑ VO _{2peak} (20%); ↑ 1 RM (22%)

(continued)

Table 18.1 (continued)

Authors	Period (weeks)	Weekly frequency	Volume and intensity	Main findings
Cadore et al. [24]	12	ST: 3 x/wk; ET: 3 x/wk; CT: ST + ET, ET prior to ST at same session	ST: 18–20 RM progressing to 6–8 RM ET: 20–30 min cycling, 80–100% of HR at VT ₂	ST: ↑ dynamic NEURO ECO at 100 W of VL (14%); CT & ET: ↑ W _{max} (19%); ↑ dynamic NEURO ECO at 100 W of VL (10%) and 50, 75, and 100 W of RF (14–35%).
Cadore et al. [27]	12	ST: 3 x/wk; ET: 3 x/wk; CT: ST + ET at same day	ST: 18–20 RM progressing to 6–8 RM ET: 20–30 min cycling, 80–100% of HR at VT ₂ CT performed with ET performed prior to (ES group) vs. after ST (SE group)	SE: ↑ force per unit of muscle mass (27%); ↑ MT QF (9%); ES: ↑ force per unit of muscle mass (15%); ↑ MT QF (9%); Greater changes in the SE than in the force per unit of muscle mass (27 vs. 15%).
Cadore et al. [28]	12	ST: 3 x/wk; ET: 3 x/wk; CT: ST + ET at same day	ST: 18–20 RM progressing to 6–8 RM ET: 20–30 min cycling, 80–100% of HR at VT ₂ CT performed with ET performed prior to (ES group) vs. after ST (SE group)	SE: ↑ 1 RM (35%); ↑ PT (8%)*; ↑ MT of VL, VM, RF, and VI (4–16%); ↑ QF EMG (~20%); ↑ NEURO ECO of RF in SE (22%); ES: ↑ 1 RM (21%); ↑ PT (5.7%); ↑ MT of VL, VM, RF and VI (4–16%); ↑ QF EMG (~20%). Greater changes in the SE than in the 1 RM (35 vs. 21%).
Ferrari et al. [30]	10 after previous 20 weeks of training	2 x/wk (CT2) vs. 3 x/wk (CT3) at same day	ST: 10–12 RM progressing to 6–8 RM ET: 30 min cycling, 85 progressing to 95% of HR at VT ₂ CT performed with ST performed prior to ET	↑ upper and lower-body 1 RM (35%) in both groups; ↑ QF MT in both groups (8%); ↑ VO _{2peak} in both groups; ↑ W _{max} only in CT3

Table 18.1 (continued)

Wilhelm et al. [31]	12	ST: 2 x/wk; ET: 2 x/wk; CT: ST + ET at same day	ST: 15–18 RM progressing to 8–10 RM ET: 20–40 min cycling, 85–95% of HR at VT ₂ CT performed with ET performed prior to (ES group) vs. after ST (SE group)	↑ 1 RM; ↑ peak power; ↑ MT QF; ↑ RFEI; ↑ 30SS*; ↑ TUG performance; ↑ QF EMG; No differences between SE and ES
Ferrari et al. [32]	10 after previous 20 weeks of training	2 x/wk (CT2) vs. 3 x/wk (CT3) at same day	ST: 10–12 RM progressing to 6–8 RM ET: 30 min cycling, 85 progressing to 95% of HR at VT ₂ CT performed with ST performed prior to ET	↑ isokinetic PT at 60 and 180° s ⁻¹ ; ↑ force per unit of muscle mass; ↑ CMJ height; No differences between groups
Da Silva et al. [33]	12	2 x/wk	ST: 65% progressing to 75% of 1 RM. RFG performing repetitions to concentric failure; NFG performing 50% of possible maximal repetitions; ENFG performing 50% of possible maximal repetitions but doubling the number of sets ET: 20–30 min at 60–65% of maximal HR, progressing to 70–75%	↑ 1 RM similarly among groups; ↑ force per unit of muscle mass; similarly among groups; ↑ RTD similarly among groups; ↑ SJ and CMJ performance similarly among groups; Greater ↑ MT QF in ENFG and RFG compared to NFG

↑ increases; *min* minutes; *NEURO ECO* neuromuscular economy; *1 RM* lower-body one maximum repetition; *PT* isometric peak torque; *CSA* cross-sectional area; *MT* muscle thickness; *QF* quadriceps femoris; *VL* *vastus lateralis*; *VM* *vastus medialis*; *RF* *rectus femoris*; *VI* *vastus intermedius*; *EI* echo intensity; 30SS 30 second sit-to-stand test; *TUG* timed-up-and-go-test; *SJ* squat jump; *CMJ* counter movement jump; *x/wk* training sessions per week; *ST* strength training; *ET* endurance training; *CT* concurrent training; *ES* endurance prior to strength training; *SE* strength prior to endurance training; *RFG* repetitions to failure group; *NFG*, repetitions not to failure group; *ENFG* repetitions not to failure group with equalized volume; *EMG* electromyographic signal; *VT₁* and *VT₂* first and second ventilatory threshold, respectively; *VO_{2peak}* peak of oxygen uptake; *W_{max}* maximal power at cycle ergometer; *HR* heart rate. Significant difference: All mentioned differences are statistically significant

and cardiovascular group (dynamic strength: 41%; isometric strength: 2%), whereas similar upper-body strength gains were evidenced in the strength and concurrent training groups (30–33%) [25]. Based on these results, we suggested that the interference effect of endurance training on strength adaptations occurs only in the specific muscle groups that perform both strength and endurance exercises (i.e., lower-limbs). Although an interference effect was observed in the concurrent training group, this group exhibited a similar magnitude of strength gains in relation to the results of the abovementioned studies (i.e., approximately 20–30%) [34, 35, 37–39], and the same strength adaptations occurred in a shorter period of time (12 vs. 21 weeks). These different time courses in strength development could be explained by the different weekly frequencies of training performed. In our study [25], subjects performed three training sessions per week, while in other previous studies only two training sessions per week were performed (i.e., ~30% lower volume) [34, 35, 37–39].

In contrast, we have previously shown that a weekly frequency of three times a week did not promote greater maximal strength [30] and jump performance [32] gains in well-trained healthy elderly subjects when compared with twice per week (20–22%, respectively). In this study, we suggested that in previously concurrently trained elderly subjects, twice per week may be an optimal weekly frequency to enhance muscle strength and jump performance. However, in another study on elderly women, Fisher et al. [42] have shown that 16 weeks of 1, 2, and 3 sessions of endurance and strength training lead to similar improvements in muscle strength, cardiovascular fitness, and functional tasks performance. Therefore, it seems that the recommended weekly frequency of concurrent training may differ for elderly men and women. However, this issue needs to be further investigated.

Another factor that may influence the magnitude of strength adaptations in the elderly is the intra-session exercise sequence. Greater maximal dynamic strength gains (35 vs. 21%) and greater force per unit of muscle mass (27 vs. 15%) were observed in a concurrent group that performed strength training prior to endurance exercise, when compared with the inverse order [27, 28], after 12 weeks of concurrent training using a similar training periodization model, which had induced an interference effect in our previous study [25]. It may, thus, be suggested that the lower strength gains obtained after the endurance-strength exercise sequence could be related to lower workloads used during the training in this group, which probably was related to residual fatigue induced by high-intensity endurance training on the cycle ergometer, especially during the last 4 weeks of training [28]. Regarding explosive force, no differences in the maximal rate of force development (RFD) and that of 100 ms were observed when comparing the two exercise sequences, with both achieving similar improvements after 12 weeks of training. Conversely, Wilhelm et al. [31] observed similar strength and power output gains, irrespective of the exercise order. However, some differences between studies by Cadore et al. [28, 29] and Wilhelm et al. [31] may explain the discrepant results: in our studies [27, 28], the weekly frequency was three times per week, endurance training intensity achieved 100% of second ventilatory threshold (VT_2), and strength training was performed using 6–8 RM in the last 2 weeks. On the other hand, in the study by Wilhelm et al.

[31], the weekly frequency was twice per week, endurance training intensity achieved 95% of VT₂, and strength training was performed using 8–10 RM in the last 2 weeks, which probably means a lower strength training intensity in the final phase of training. Along with differences in the training intensity in both modalities (i.e., strength and endurance), the different weekly frequencies related on average to approximately a 50% higher training volume in the knee and hip extensors when training was performed three times per week [27, 28], which may have caused these different results. Since in young men and women no difference was observed between the two exercise orders following 24 weeks of training [43], it might well be suggested that elderly individuals may be more sensitive to residual fatigue during the subsequent strength training. Importantly, however, recently, we have shown that concurrent training performed with repetitions to concentric failure did not provide additional gains in the knee extensors maximal strength, explosive strength, in healthy elderly individuals. In addition, even when performing 50% of the possible maximal repetitions with no volume compensation, elderly men optimized maximal and explosive strength gains within 12 weeks of training [33]. From a practical standpoint, the performance of submaximal sets promoted the same magnitude of strength enhancements, showing that this is an efficient alternative for improving neuromuscular function in elderly men [33].

Effects of Concurrent Training on Muscle Hypertrophy

Although several studies have investigated the effects of strength training on muscle mass in older subjects, a lower number of studies have explored the effects of concurrent training on muscle hypertrophy in this population. In the study by Izquierdo et al. [22], no differences were observed between the strength (twice a week) and concurrent training groups (one session per week of strength and one session per week of cycle endurance training) in the magnitude of hypertrophy after 16 weeks of training (increases of ~11%). A unique finding of this study was that only one day of strength training combined with another day of endurance training performed on a cycle ergometer resulted in enhanced muscle mass in the elderly after 16 weeks.

In another study, Karavirta et al. [39], have shown increase in the cross-sectional area of type II muscle fibers of the vastus lateralis only in the strength training group (~16%), whereas no changes were observed in the concurrent training group. However, this difference did not result in different strength gains. In other studies, utilizing a weekly training frequency ranging from two to three times with intensities of 40–80% of 1 RM (progressive load during training periodization) with multiple sets produced marked increases in muscle mass (9–16%), with no differences between the strength and concurrent training interventions [34, 35, 37–39]. Moreover, although the intra-session exercise sequence influenced strength adaptations, it is important to note that the sequence of strength and endurance exercise had no influence on muscle mass gains [28, 31]. Thus, independent of the intra-session exercise sequence, the performance of endurance training does not impair the hypertrophy induced by strength training when both types of training are

performed simultaneously. As observed with muscle strength, Ferrari et al. [30] have shown similar muscle hypertrophy comparing a weekly frequency of three times a week with only twice weekly training sessions (approximately 5% in the quadriceps muscles) in previously concurrently trained elderly subjects. Regarding the use of maximal or submaximal sets (i.e., repetitions to failure or not to failure) during concurrent training in elderly, da Silva et al. [33] compared three types of concurrent training interventions in healthy elderly men: one with the strength training performed with repetitions to concentric failure (RFG); another with strength training performed with 50% of the repetitions to concentric failure (NFG); and a third, with strength training performed with 50% of the repetitions to concentric failure, but equalizing the total volume by adding more sets. We demonstrated that the groups that performed a higher training volume showed greater muscle hypertrophy, although repetitions to failure did not provide additional muscle size gains compared to repetitions not to failure using the same total load [33].

Do Changes in Anabolic and Catabolic Hormone Concentrations Explain the Interference Effect in the Elderly?

The results regarding the effects of concurrent training on muscle mass enhancements in the elderly are in agreement with the studies conducted in young populations, as no difference was observed between the strength training and concurrent training groups when imaging technics were used to evaluate these effects [44, 45]. However, studies that used muscle biopsies demonstrated the interference phenomenon in the cross-sectional area of type I fibers in young men who performed concurrent training with a high intensity and volume of both strength and endurance training [13, 46]. The interference occurred concomitantly with increases in cortisol levels, suggesting that these subjects may have been in an exacerbated catabolic state [13, 47]. In the elderly, no evidence of an overtraining state has been observed. In the study by Karavirta et al. [39], a moderate volume of training resulted in an increase in the type II fiber area only in the strength training group, while no changes were observed in the concurrent training group. Notwithstanding, no changes in the basal anabolic or catabolic hormone levels were evidenced in this study [39]. In addition, in a previous study of our laboratory, Cadore et al. [25] have shown that the interference effect on neuromuscular adaptations occurred with no changes in the levels of free and total testosterone or cortisol, suggesting that the interference phenomenon occurred with no evidence of an overtraining state in the elderly.

Effects of Concurrent Training on Maximal and Submaximal Neuromuscular Activity

Early adaptations to strength training in the elderly include increases in the maximal neuromuscular activity (i.e., EMG signal amplitude) [48–52]. These changes may suggest the occurrence of neural adaptations, such as increases in the maximal

motor unit recruitment [15], maximal motor unit firing rate [16], spinal motorneuronal excitability, and efferent motor drive [17]. Although neural adaptation impairments are suggested as a mechanism to explain the interference effect, few studies have investigated the neural adaptations to concurrent training. In elderly subjects, the interference effect may be related to impaired neural adaptations to strength training, since the lower strength gains induced by concurrent training when compared with strength training alone may occur in parallel with lower maximal neuromuscular activity adaptations induced by concurrent training [25].

When investigating the mechanisms underlying the strength adaptations to strength and concurrent training in the elderly, we observed a significant increase in the maximal EMG amplitude of the *rectus femoris* and *vastus lateralis* only in the strength training group (~30%), and these modifications were significantly greater than those observed in the concurrent training group (~1.5%, not statistically significant) [25]. In addition, we also observed greater isometric neuromuscular economy (reduced submaximal EMG to the same absolute load after training) in the *rectus femoris* and *vastus lateralis* only in the strength training group. It is important to highlight that the greater neuromuscular activity changes observed in strength training than concurrent training occurred in parallel with greater strength gains in strength training [25], which suggested that the interference effect occurred at least in part due to impairments in neural changes.

In another study, Cadore et al. [27] found significantly greater changes in the force per unit of active muscle mass (i.e., muscle quality or specific tension) in elderly individuals who performed strength training prior to an endurance exercise sequence when compared with the inverse order (27 vs. 15%, $P < 0.01$). The force per unit of active muscle mass provides an estimation of the contribution of neuromuscular factors associated with changes in strength development, as enhanced strength with the same muscle mass suggests neural adaptations to training [53–55]. In addition, Cadore et al. [28] showed greater changes in the neuromuscular economy of the *rectus femoris* in elderly individuals who performed strength training prior to an endurance exercise sequence when compared with the inverse order. Taken together, these results suggest that the interference effect in the elderly might be explained at least in part by impairments in the neural adaptations to strength training. From a practical point of view, although the concurrent training performance may impair the neuromuscular adaptations, the performance of strength prior to endurance intra-session exercise sequence seems to minimize this negative effect and should be considered to optimize the benefits of concurrent training in the neuromuscular function in elderly.

Effects of Concurrent Training on Cardiorespiratory Adaptations

Along with the decrease in the maximal cardiac output [56, 57], several authors have demonstrated that the cardiorespiratory fitness declines are also associated with strength and power decreases related with aging [1, 2, 27, 58]. In line with this, some studies have shown that the combination of strength and endurance training is a

better strategy to improve the cardiorespiratory fitness of the elderly when compared with endurance and especially strength training alone. In addition, the performance of strength training simultaneously with endurance training does not impair the aerobic adaptations produced by endurance training alone [21, 22, 34–37, 39, 58, 59].

Studies that have investigated cardiovascular adaptations to CT have demonstrated increases ranging from 10 to 18% in the maximum oxygen uptake and maximal cycle ergometer workload in elderly individuals who underwent training periods ranging from 12 to 21 weeks, and a weekly frequency ranging from two to three training sessions [21, 22, 24, 37–39, 58, 59]. Similar to the results observed in strength performance and hypertrophy mentioned above, Izquierdo et al. [22] observed similar aerobic power gains in elderly men who underwent one session per week of strength training and one session per week of cycle endurance training in the CT group (28%) and those who underwent ET twice per week (23%) after 16 weeks of training.

Interestingly, in the study by Cadore et al. [27], similar enhancements were observed in the peak oxygen uptake, maximal workload at cycle ergometer, and the workload at the second ventilatory threshold among groups that performed strength training prior to an endurance exercise sequence and the opposite exercise order. However, a greater improvement was found in the workload at the first ventilatory threshold in the group that performed strength training prior to endurance exercise in each session. It is possible that this difference was observed as a consequence of the greater increases in muscle strength achieved by performing strength training prior to endurance training, as strength gains have been associated with maximal and submaximal endurance gains [2] and dynamic neuromuscular economy in the elderly [24]. In another study, we have shown that, independent of the exercise order (i.e., SE or ES), 12 weeks of concurrent training significantly reduced the submaximal oxygen uptake at the highest submaximal intensity (i.e., 100 W) in elderly men [60]. Based on this study, we also concluded that the prevalence of non-responders in the maximal aerobic power was lower in the elderly group who performed endurance training regularly before strength training [60]. Regarding different weekly training frequencies, the aforementioned study of Ferrari et al. [30] showed similar $\text{VO}_{2\text{peak}}$ increases after 10 weeks of concurrent training performed two or three times a week in well-trained elderly men. However, greater maximal power at cycle ergometer (W_{max}) gains were observed in the group who trained three times per week, suggesting that in trained elderly, a greater weekly training frequency may be necessary to promote overall endurance gains.

Effects of Concurrent Training on Functional Capacity

Few studies have compared the effects of strength, endurance, and concurrent training on functional capacity in the elderly. In an investigation by Wood et al. [21], no differences were observed between the strength-, endurance-, and concurrent training groups in functional performance gains assessed by the sit and reach test, agility/dynamic balance assessed by repeatedly standing from a chair, walking around cones and returning to the chair (i.e., TUG test), and coordination tests. Holviala

et al. [59] showed increases in the treadmill load carrying walking test performance (10.1 kg in each hand) only in the concurrent training group (4.5%), whereas no changes were observed in the strength training and endurance training groups. In another study, Wilhelm et al. [31] have shown that concurrent training led to improved sit-to-stand ability (i.e., number of repetitions in 30 s), as well as timed-up-and-go test performance in healthy elderly men, independent of the exercise sequence. Altogether, these results suggested that the combination of strength and endurance capacities improves functional capacity in the elderly population. However, it should be also mentioned that in the oldest aged individuals, especially those individuals with frailty syndrome or at greater functional declines, the exercise intervention approach must combine balance and gait exercises along with strength and endurance stimuli, in order to improve the functional capacity and reduce the risk of falls [29, 61, 62]. In addition, in view of improving the concurrent strength and endurance training prescription, strength training should be prescribed combining slow and explosive mode contractions in order to optimize the functional capacity enhancements. This recommendation is because maximal muscle power output and rate of force development are more associated with functional capacity than maximal strength per se [12, 63, 64].

Summary

Strength training is an effective intervention to improve muscle strength, power output, and muscle mass in the elderly. Endurance training induces improvements in $\text{VO}_{2\text{max}}$ and submaximal endurance capacity in these populations. Therefore, a combination of strength and endurance training (i.e., concurrent training) seems to be the most effective way to improve both neuromuscular and cardiorespiratory functions. Based on recent evidence, concurrent training performed at a moderate weekly frequency (i.e., two times per week) may promote marked gains in muscle hypertrophy, strength and power gains in elderly subjects. The strength training should be performed at moderate to high intensity (i.e., 60–80% of 1RM), and moderate volume (i.e., 2–3 sets per exercise). Each session should target the main muscle groups of the body. Also, endurance training should be performed at moderate to high intensity (i.e., 60–85% of $\text{VO}_{2\text{max}}$), and last for 25–40 min. For concurrent training protocols in which both strength and endurance training are performed on the same day, the strength and endurance gains may be optimized with strength training being performed prior to endurance exercise. Moreover, two weekly sessions of both strength and endurance training may be an optimal weekly frequency to promote additional muscle mass and strength gains, as well as cardiorespiratory fitness in previously concurrent trained elderly. Furthermore, performing repetitions until concentric failure does not provide further neuromuscular performance gains and muscle hypertrophy compared to a lower number of repetition in this population. In terms of improving the functional capacity of the elderly, the concurrent strength and endurance training prescription should include high-velocity strength training, designed to improve muscle power output, as muscle power has been associated with the functional capacity.

References

1. Izquierdo M, Häkkinen K, Antón A, Garrues M, Ibañez J, Ruesta M, et al. Maximal strength and power, endurance performance, and serum hormones in middle-aged and elderly men. *Med Sci Sports Exerc.* 2001;33:1577–87.
2. Izquierdo M, Häkkinen K, Ibanez J, Antón A, Garrués M, Ruesta M, et al. Effects of strength training on submaximal and maximal endurance performance capacity in middle-aged and older men. *J Strength Cond Res.* 2003;17:129–39.
3. Snijders T, Verdijk LB, van Loon LJC. The impact of sarcopenia and exercise training on skeletal muscle satellite cells. *Ageing Res Rev.* 2009;8:328–38.
4. Aagaard P, Suetta C, Caserotti P, Magnusson SP, Kjaer M. Role of the nervous system in sarcopenia nad muscle atrophy with aging: strength training as a countermeasure. *Scand J Med Sci Sports.* 2010;20:49–64.
5. Cadore EL, Izquierdo M, Conceição M, Radaelli R, Pinto RS, Baroni BM, et al. Echo intensity is associated with skeletal muscle power and cardiovascular performance in elderly men. *Exp Gerontol.* 2012a;47:473–8.
6. Izquierdo M, Ibanez J, Gorostiaga EM, Garrues M, Zuñiga A, Antón A, et al. Maximal strength and power characteristics in isometric and dynamic actions of upper and lower extremities in middle-aged and older med. *Acta Physiol Scand.* 1999a;167:57–68.
7. Izquierdo M, Aguado X, Gonzalez R, López JL, Häkkinen K. Maximal and explosive force production capacity and balance performance in men of different ages. *Eur J Appl Physiol Occup Physiol.* 1999b;79:260–7.
8. Sayers SP, Bean J, Cuoco A, Le Brasseur NK, Jette A, Fielding RA. Changes in function and disability after resistance training: does velocity matter? A pilot study. *Am J Phys Med Rehabil.* 2003;82:605–13.
9. Henwood TR, Riek S, Taaffe DR. Strength versus muscle power specific resistance training in community-dwelling older adults. *J Gerontol A Biol Sci Med Sci.* 2008;63:83–91.
10. Miszko TA, Cress ME, Slade JM, Covey CJ, Agrawal SK, Doerr CE. Effect of strength and power training on physical function in community-dwelling older adults. *J Gerontol A Biol Sci Med Sci.* 2003;58:171–5.
11. Bottaro M, Machado SN, Nogueira W, Scales R, Veloso J. Effect of high versus low-velocity resistance training on muscular fitness and functional performance in older men. *Eur J Appl Physiol.* 2007;99:257–64.
12. Reid KF, Fielding RA. Skeletal muscle power and functioning in older adults. *Exerc Sport Sci Rev.* 2012;40:1–12.
13. Kraemer WJ, Patton JF, Gordon SE, Harman EA, Deschenes MR, Reynolds K, et al. Compatibility of high-intensity strength and endurance training on hormonal and skeletal muscle adaptations. *J Appl Physiol.* 1995;78:976–89.
14. Pinto RS, Correa CS, Radaelli R, Cadore EL, Brown LE, Bottaro M. Short-term strength training improves muscle quality and functional capacity of elderly women. *Age (Dordr).* 2014;36(1):365–72. <https://doi.org/10.1007/s11357-013-9567-2>.
15. Knight CA, Kamen G. Adaptations in muscle activation of the knee extensor muscle with strength training in young and older adults. *J Electromyogr Kinesiol.* 2001;11:405–12.
16. Kamen G, Knight CA. Training-related adaptations in motor unit discharge rate in young and older adults. *J Gerontol A Biol Sci Med Sci.* 2004;59:1334–8.
17. Aagaard P, Simonsen EB, Andersen JL, Magnusson P, Dyhre-Poulsen P. Neural adaptation to resistance training: changes in evoked V-wave and H-reflex responses. *J Appl Physiol.* 2002;92:2309–18.
18. Izquierdo M, Häkkinen K, Ibañez J, Garrues M, Antón A, Zúñiga A, et al. Effects of strength training on muscle power and serum hormones in middle-aged and older men. *J Appl Physiol.* 2001b;90:1497–507.
19. Seals DR, Hagberg JM, Hurley BF, Ehsani AA, Holloszy JO. Endurance training in older men and women: I. Cardiovascular responses to exercise. *J Appl Physiol.* 1984;57:1024–31.
20. Meredith CN, Frontera WR, Fisher EC, Hughes VA, Herland JC, Edwards J, et al. Peripheral effects of endurance training in young and old subjects. *J Appl Physiol.* 1989;66:2844–9.

21. Wood RH, Reyes R, Welsch MA, Favarolo-Sabatier J, Sabatier M, Lee CM, et al. Concurrent cardiovascular and resistance training in healthy older adults. *Med Sci Sports Exerc.* 2001;33:1751–8.
22. Izquierdo M, Ibañez J, Häkkinen K, Kraemer WJ, Larrión JL, Gorostiaga EM. Once weekly combined resistance and cardiovascular training in healthy older men. *Med Sci Sports Exerc.* 2004;36:435–43.
23. Izquierdo M, Häkkinen K, Ibañez J, Kraemer WJ, Gorostiaga EM. Effects of combined resistance and cardiovascular training on strength, power, muscle cross-sectional area, and endurance markers in middle-aged men. *Eur J Appl Physiol.* 2005;94:70–5.
24. Cadore EL, Pinto RS, Lhullier FLR, Correa CS, Alberton CL, Pinto SS, et al. Effects of strength, endurance and concurrent training on aerobic power and dynamic neuromuscular economy in elderly men. *J Strength Cond Res.* 2011a;25:758–66.
25. Cadore EL, Pinto RS, Lhullier FLR, Correa CS, Alberton CL, Pinto SS, et al. Physiological effects of concurrent training in elderly men. *Int J Sports Med.* 2010;31:689–97.
26. Cadore EL, Izquierdo M. Exercise interventions in polypathological aging patients that coexist with diabetes mellitus: improving functional status and quality of life. *Age (Dordr).* 2015;37:64. <https://doi.org/10.1007/s11357-015-9800-2>.
27. Cadore EL, Izquierdo M, Alberton CL, Pinto RS, Conceição M, Cunha G, et al. Strength prior to endurance intra-session exercise sequence optimizes neuromuscular and cardiovascular gains in elderly men. *Exp Gerontol.* 2012b;47:164–9.
28. Cadore EL, Izquierdo M, Pinto SS, Alberton CL, Pinto RS, Baroni BM, et al. Neuromuscular adaptations to concurrent training in the elderly: effects of intrasession exercise sequence. *Age (Dordr).* 2013a;35(3):891–903. <https://doi.org/10.1007/s11357-012-9405-y>.
29. Cadore EL, Rodríguez-Mañas L, Sinclair A, Izquierdo M. Effects of different exercise interventions on risk of falls, gait ability and balance in physically frail older adults. A systematic review. *Rejuvenation Res.* 2013b;16:105–14. <https://doi.org/10.1089/rej.2012.1397>.
30. Ferrari R, Kruel LF, Cadore EL, Alberton CL, Izquierdo M, Conceição M, et al. Efficiency of twice weekly concurrent training in trained elderly men. *Exp Gerontol.* 2013;48:1236–42.
31. Wilhelm EN, Rech A, Minozzo F, Botton CE, Radaelli R, Teixeira BC, et al. Concurrent strength and endurance training exercise sequence does not affect neuromuscular adaptations in older men. *Exp Gerontol.* 2014;60:207–14.
32. Ferrari R, Fuchs SC, Kruel LF, Cadore EL, Alberton CL, Pinto RS, et al. Effects of different concurrent resistance and aerobic training frequencies on muscle power and muscle quality in trained elderly men: a randomized clinical trial. *Aging Dis.* 2016;7(6):697–704. <https://doi.org/10.14336/AD.2016.0504>.
33. Da Silva LZN, Teodoro JL, Menger E, Lopez P, Grazioli R, Farinha J, et al. Repetitions to failure versus not to failure during concurrent training in healthy elderly men: a randomized clinical trial. *Exp Gerontol.* 2018;108:18–27. <https://doi.org/10.1016/j.exger.2018.03.017>.
34. Holviala J, Häkkinen A, Alen M, Sallinen J, Häkkinen K. Effects of prolonged and maintenance strength training on force production, walking, and balance in aging women and men. *Scand J Med Sci Sports.* 2014;24(1):224–33. <https://doi.org/10.1111/j.1600-0838.2012.01470.x>.
35. Karavirta L, Tulppo MP, Laaksonen DE, Nyman K, Laukkanen RT, Kinnunen H, et al. Heart rate dynamics after combined endurance and strength training in older men. *Med Sci Sports Exerc.* 2009;41:1436–43.
36. Sillampää E, Häkkinen A, Nyman K, Cheng S, Karavirta L, Laaksonen DE, et al. Body composition and fitness during strength and/or endurance training in older men. *Med Sci Sports Exerc.* 2008;40:950–8.
37. Sillampää E, Häkkinen A, Punnonen K, Häkkinen K, Laaksonen DE. Effects of strength and endurance training on metabolic risk factors in healthy 40–65-year-old men. *Scand J Med Sci Sports.* 2009a;19:885–95.
38. Sillampää E, Laaksonen DE, Häkkinen A, Karavirta L, Jensen B, Kraemer WJ, et al. Body composition, fitness, and metabolic health during strength and endurance training and their combination in middle-aged and older women. *Eur J Appl Physiol.* 2009b;106:285–96.
39. Karavirta L, Häkkinen A, Sillanpää E, Garcia-Lopez D, Kauhanen A, Haapasaari A, et al. Effects of combined endurance and strength training on muscle strength, power and hypertrophy in 40–67-year-old men. *Scand J Med Sci Sports.* 2011;21:402–11.

40. Cadore EL, Izquierdo M. How to simultaneously optimize muscle strength, power, functional capacity, and cardiovascular gains in elderly: an update. *Age (Dordr)*. 2013a;35:2329–44. <https://doi.org/10.1007/s11357-012-9503-x>.
41. Cadore EL, Izquierdo M. New strategies for the concurrent strength-, power-, and endurance-training prescription in elderly individuals. *J Am Med Dir Soc*. 2013b;14:623–4.
42. Fisher G, McCarthy JP, Zuckerman PA, Bryan DR, Bickel CS, Hunter GR. Frequency of combined resistance and aerobic training in older women. *J Strength Cond Res*. 2013;27(7):1868–76. <https://doi.org/10.1519/JSC.0b013e31827367e0>.
43. Schumann M, Küttismaa M, Newton RU, Sirparanta AI, Syväöja H, Häkkinen A, et al. Fitness and lean mass increases during combined training independent of loading order. *Med Sci Sports Exerc*. 2014;46:1758–68. <https://doi.org/10.1249/MSS.0000000000000303>.
44. McCarthy JP, Pozniak MA, Agre JC. Neuromuscular adaptations to concurrent strength and endurance training. *Med Sci Sports Exerc*. 2002;34:511–9.
45. Häkkinen K, Alen M, Kraemer WJ, Gorostiaga EM, Izquierdo M, Rusko H, et al. Neuromuscular adaptations during concurrent strength and endurance training versus strength training. *J Appl Physiol*. 2003;89:42–52.
46. Bell GJ, Syrotuik D, Martin TP, Burnham R, Quinney HÁ. Effect of concurrent strength and endurance training on skeletal muscle properties and hormone concentrations in humans. *Eur J Appl Physiol*. 2000;81:418–27.
47. Bell GJ, Syrotuik D, Socha T, Maclean I, Quinney HÁ. Effect of strength and endurance training on strength, testosterone, and cortisol. *J Strength Cond Res*. 1997;11:57–64.
48. Häkkinen K, Alen M, Kallinen M, Newton RU, Kraemer WJ. Neuromuscular adaptation during prolonged strength training, detraining and re-strength-training in middle-aged and elderly people. *Eur J Appl Physiol*. 2000;83:51–62.
49. Häkkinen K, Kraemer WJ, Newton RU, Alen M. Changes in electromyographic activity, muscle fibre and force production characteristics during heavy resistance/power strength training in middle-aged and older men and women. *Acta Physiol Scand*. 2001;171:51–62.
50. Häkkinen K, Kallinen M, Izquierdo M, Jokelainen K, Lassila H, Mälkiä E, et al. Changes in agonist-antagonist EMG, muscle CSA, and force during strength training in middle-aged and older people. *J Appl Physiol*. 1998;84:1341–9.
51. Cannon J, Kay D, Tarpenning KM, Marino FE. Comparative effects of resistance training on peak isometric torque, muscle hypertrophy, voluntary activation and surface EMG between young and elderly women. *Clin Physiol Funct Imaging*. 2007;27:91–100.
52. Brentano MA, Cadore EL, Silva EM, Ambrosini AB, Coertjens M, Petkowics R, et al. Physiological adaptations to strength and circuit training in postmenopausal women with bone loss. *J Strength Cond Res*. 2008;22:1816–25.
53. Frontera WR, Suh D, Krivickas LS, Hughes VA, Goldstein R, Roubenoff R. Skeletal muscle fiber quality in older men and women. *Am J Physiol Cell Physiol*. 2000;279:C611–8.
54. Narici MV, Maganaris C, Reeves N. Myotendinous alterations and effects of resistive loading in old age. *Scand J Med Sci Sports*. 2005;15:392–401.
55. Tracy BL, Ivey FM, Hurlbut D, Martel GF, Lemmer JT, Siegel EL, et al. Muscle quality. II. Effects of strength training in 65- to 75-yr-old men and women. *J Appl Physiol*. 1999;86:195–201.
56. Astrand I, Astrand PO, Hallbeck I, Kilbom A. Reduction in maximal oxygen uptake with age. *J Appl Physiol*. 1973;35:649–54.
57. Fleg JL, Lakatta EG. Role of muscle loss in the age-associated reduction in VO_{2max} . *J Appl Physiol*. 1988;65:1147–51.
58. Cadore EL, Pinto RS, Alberton CL, Pinto SS, Lhullier FLR, Tartaruga MP, et al. Neuromuscular economy, strength and endurance in healthy elderly men. *J Strength Cond Res*. 2011b;25:997–1003.
59. Holviala J, Häkkinen A, Karavirta L, Nyman K, Izquierdo M, Gorostiaga EM, et al. Effects of combined strength and endurance training on treadmill load carrying walking performance in aging men. *J Strength Cond Res*. 2010;24:1584–95.

60. Cadore EL, Pinto RS, Teodoro JL, Silva LZN, Menger E, Alberton CL, et al. Cardiorespiratory adaptations in elderly men following different concurrent training regimes. *J Nutr Health Aging.* 2018;22:483–90. <https://doi.org/10.1007/s12603-017-0958-4>.
61. Cadore EL, Casas-Herrero A, Zambom-Ferraresi F, Idoate F, Millor N, Gómez M, et al. Multicomponent exercises including muscle power training enhance muscle mass, power output, and functional outcomes in institutionalized frail nonagenarians. *Age (Dordr).* 2014;36(2):773–85. <https://doi.org/10.1007/s11357-013-9586-z>.
62. Izquierdo M, Cadore EL. Muscle power training in the institutionalized frail: a new approach to counteracting functional declines and very late-life disability. *Cur Med Res Opinion.* 2014;30:1385–90.
63. Pereira A, Izquierdo M, Silva AJ, Costa AM, Bastos E, González-Badillo JJ, et al. Effects of high-speed power training on functional capacity and muscle performance in older women. *Exp Gerontol.* 2012;47:250–5.
64. Casas-Herrero A, Cadore EL, Zambom-Ferraresi F, Idoate F, Millor N, Martínez-Ramírez A, et al. Functional capacity, muscle fat infiltration, power output and cognitive impairment in institutionalized frail oldest-old. *Rejuvenation Res.* 2013;16(5):396–403. <https://doi.org/10.1089/rej.2013.1438>.



Concurrent Aerobic and Strength Training for Body Composition and Health

19

Eurico Nestor Wilhelm and Ronei Silveira Pinto

Introduction

Concurrent endurance and strength training (CT) has been used to enhance athletic performance in a variety of sports, but its use as a health-promoting strategy for the general population should not be overlooked. By combining endurance and strength exercise modes, CT stresses both the cardiovascular and the neuromuscular systems. Besides traditional adaptation in endurance parameters (e.g. maximal aerobic capacity, lactate threshold, exercise economy) and skeletal muscle function (maximal strength, muscle power, muscular endurance, etc.), CT can also influence body composition, as well as traditional and non-traditional cardiometabolic risk factors. This chapter will discuss the effects of CT on health-related outcomes, with an emphasis on body composition and cardiometabolic biomarkers.

Body Composition

Total Fat Mass and Percentage of Body Fat

Obesity has become a worldwide problem, and besides being a modifiable risk factor estimates from the World Health Organization are that obesity has increased dramatically in the past decades, affecting approximately 13% of the world's adult

E. N. Wilhelm

Physical Education School, Federal University of Pelotas (UFPel), Pelotas, RS, Brazil

Exercise Research Laboratory, Physical Education School, Federal University of Rio Grande do Sul (UFRGS), Porto Alegre, RS, Brazil

R. S. Pinto (✉)

Exercise Research Laboratory, Physical Education School, Federal University of Rio Grande do Sul (UFRGS), Porto Alegre, RS, Brazil

e-mail: ronei.pinto@ufrgs.br

population in 2014, with nearly 39% of adults characterized as overweight [1]. Obese individuals are at greater risk for metabolic, orthopaedic and cardiovascular diseases (CVD), as well as some types of cancer [1, 2]. Reducing body fat is of particular relevance for those who are overweight and obese, and incorporating well-designed exercise training routines as part of their weight loss and management agenda can be an effective strategy [3]. Early investigations have employed skinfold thickness to estimate relative changes in body fat mass with CT [4, 5] and although this is a valid method, recent experiments have taken advantage of the more robust dual-energy X-ray absorptiometry (DXA) technique to track changes in body composition [6–8]. This section will focus on results from experiments employing DXA or imaging techniques for the assessment of total and regional fat distribution.

The effect of CT on total fat mass has been investigated in a variety of studies, with controversial results found in the literature. Donges et al. [6] reported reductions in total body fat mass of middle-aged and older men performing 3 months of endurance training (ET) or CT, while increases in muscle mass were only observed in those allocated to strength training (ST) or CT programmes. Similar benefits of CT in decreasing fat mass or percentage of body fat have been observed by others [8–11], and the superiority of CT over single-mode training routines (e.g. ST) to reduce total body fat mass has been a matter of debate, which may relate to the larger overall training volume performed by the CT group compared to ET or ST alone (i.e. participants engaged in CT performed the sum of each single-mode training routine) in some but not all experiments. Pooled data from 21 studies, however, indicate that CT brings about a similar reduction in body fat compared to ET or ST, but insufficient data precluded the analysis of performing different CT volumes in comparison to single modalities in terms of reducing body fat [12]. Furthermore, some studies have reported no alterations in body fat of individuals engaged in long-term CT [7, 9]. Instead of representing an inability of CT to ameliorate body composition, these divergent findings actually reflect differences in exercise and methodological protocols, as will be discussed below.

Several of these experiments were not designed to directly tease out the influence of exercise upon body fat mass and did not control for caloric intake, energy expenditure and potential compensatory behaviours that may increase or decrease one's energy balance. If participants' energy balance is not precisely controlled, any response (from decrease to increase) in body composition could be expected. Following thermodynamics, alterations in body mass are regulated by one's net energy balance. Loss of total body and fat mass is attributed to a prolonged negative energy balance [3, 13], with experimental evidence for this given by investigations in which energy intake, as well as expenditure, of participants is manipulated to introduce an energy deficit or surplus over a period of time. For example, Ross et al. [3] demonstrated that diet or exercise alone can bring about equivalent reductions in body fat, as long as a similar energy deficit is sustained.

That said, it seems evident that for any individual seeking exclusively for reducing his/her fat mass, one of the best options is to select exercise routines that generate the greatest total energy expenditure. Although not limited to ET (e.g. high-intensity interval training), increase in muscle aerobic capacity and mitochondrial content have been traditionally linked to chronic endurance exercise [14], and

ET may shift fuel utilization towards fat oxidation at rest and during submaximal exercise [15, 16]. Conversely, hypertrophic gains due to ST contribute to increase total energy expenditure, as fat-free mass is a major determinant of resting metabolic rate [17], although the absolute contribution of increasing skeletal muscle mass to total metabolic rate is relatively small [18]. As such, endurance exercise engaging a large muscle mass, such as walking/running and swimming, may be the most obvious choice to increase energy expenditure as it allows a relatively high metabolic demand to be sustained for prolonged periods, although similar reductions in fat mass would be expected from isocaloric strength exercise sessions. In a meta-analysis of CT studies, Wilson et al. [12] have estimated marginally superior decreases in body fat in response to strength training performed concurrently with running compared to cycling. Although running engages greater amounts of muscle mass, it may also impair hypertrophic gains to a greater extent in CT routines [12]. Hence, there is a trade-off between acutely increasing energy expenditure with running and improving fat-free mass, and thus resting metabolic rate, with cycling. Moreover, the same authors identified that intensity of the endurance exercise component was directly associated with decreases in body fat, which probably reflects a greater energy expenditure if exercise duration was matched between conditions.

It is worth noting, however, that there is always an upper limit of exercise volume that one is able to perform, and it is less likely (though possible) that ordinary individuals will engage in extensive single modality training routines (e.g. >1.5 h/session) without losing motivation, not to mention the increased risk of injury related to repetitive orthopaedic strain that may result from the same movement pattern in long duration rhythmic activities. As such, CT may be a strategic alternative to increase one's weekly energy expenditure by enabling the incorporation of additional amounts and more diverse exercises in a single training session (when CT is performed on the same day), or by increasing training frequency (when the endurance and strength exercise components are performed on alternate days).

Concurrent training can also be used to reduce one's percentage of body fat by directly reducing adipocyte mass, increasing fat-free mass or a combination of both. The percentage of body fat reflects the proportion of fat stores relative to total body mass, in a way that an increase in skeletal muscle mass can result in a reduction of the percentage of fat, irrespective of changes in lipid stores. Since long-term CT may bring about increases in muscle mass with concurrent decreases in fat mass (Fig. 19.1), this training mode may be considered an ideal alternative to reduce the percentage of body fat [11].

Abdominal Fat Depots

The site of body fat distribution plays a role in overall health, with excessive adiposity around the waistline (abdominal obesity) being a major risk factor for CVD and metabolic disorders [19, 20]. The negative influence of central obesity as a cardio-metabolic risk factor most likely derives from excessive accumulation of visceral fat (visceral obesity) than that in the subcutaneous compartment in the abdominal region [20], thus, even though decreasing total body fat content is a major goal for

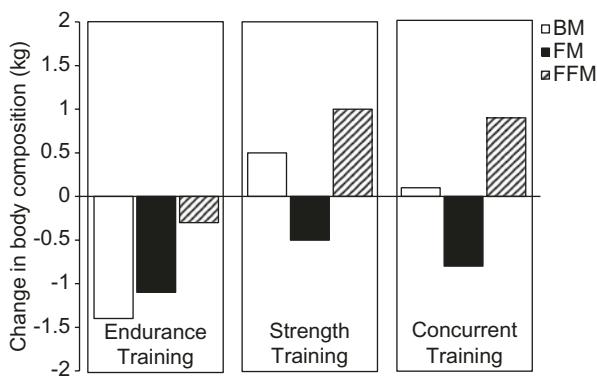


Fig. 19.1 Hypothetical model illustrating typical changes in selected body composition parameters to exercise training modalities. Endurance training engaging a large muscle mass holds a potential for large caloric expenditure, which may lead to a negative energy balance and reduce total body and fat mass (BM and FM, respectively). Strength training usually results in smaller or even an increase in total BM due to increases in fat-free mass (FFM), whereas concurrent training has the potential to ameliorate both FM and FFM. Ultimately, body composition changes will depend on a complex interaction between exercise modality and net energy balance

overweight and obese individuals, reducing or preventing excessive deposition of fat in the intra-abdominal compartment is considered of major relevance even for lean individuals. Visceral obesity is associated with waist circumference [21, 22], but it is more appropriately quantified through computerized axial tomography or magnetic resonance imaging as these techniques can be used to distinguish between fat in the subcutaneous and intra-abdominal compartment, and fair estimations can be obtained by DXA through android fat measurements [21].

Currently, a body of evidence indicates that exercise training can effectively reduce visceral fat depots. Results from a systematic review and meta-analysis reveal that endurance exercise appears to be effective in reducing abdominal fat, but the beneficial effect of ST is less evident [23]. Visceral fat reductions may be attained with CT but results are not as clear as with single-mode ET, most likely because of a reduction in the volume of the endurance exercise component during CT sessions in many studies. Nevertheless, randomized trials have confirmed the potential of CT to decrease central fat depots [6, 24] providing enough exercise volume is attained. Moreover, a recent meta-analysis of 15 trials comparing ET, ST and/or CT on metabolic and anthropometric parameters reported the latter to be effective in reducing waist circumference and suggests that CT is a more effective approach to prevent and treat obesity [25].

Recently, the distribution of strength and endurance exercise modes within a CT routine has received considerable attention from the scientific community (Fig. 19.2). Controversial results have been published regarding the influence of the CT loading order upon muscle mass and strength, with some research groups reporting greater adaptations when endurance exercise was preceded by strength exercises [26, 27], while others have found little or no exercise order effect upon neuromuscular parameters [7, 9, 28–31].

Loading Order	Day 1	Day 2	Day 3	Day 4
A				
B				
C				

Fig. 19.2 Example of concurrent endurance and strength training routines with different exercise loading orders. Same session concurrent training can be performed with the endurance component preceding strength exercises (A), or the reverse exercise sequence (B). Alternatively, each exercise mode can be performed in separate exercise sessions (C). The latter has been reported to optimize changes in android fat mass [9]

Different from the neuromuscular system, there appears to be consistent (yet limited) evidence regarding CT loading order and body composition. A series of Finnish studies has explored this topic and initially showed that the intrasession concurrent exercise sequence does not play a relevant role influencing changes in body fat, at least when an exercise routine with relatively low training volume is employed (i.e. 60–100 min of exercise per session, 2–2.5 sessions per week) [7]. A posterior study confirmed these findings and expanded the current knowledge by demonstrating that splitting the CT session so that the endurance and the strength exercise components were performed in different days resulted in superior fat mass reduction compared to volume-matched CT performed in the same session [9]. When the site of body mass change was taken into consideration, a greater reduction in android (central) fat mass was observed in both men and women performing the endurance and strength exercise on alternate days. These are intriguing results as each protocol was expected to have elicited similar exercise energy expenditure during the training sessions. One could speculate that participants performing CT in a single session could have exercised at lower relative intensity as prior endurance/high-intensity exercise can impair the performance of the subsequent strength component of CT [32], while maximal force capabilities may be less affected [32, 33]. Although excess post-exercise oxygen uptake (and rest energy expenditure) is affected by strength exercise intensity, Thornton et al. [34] estimated that the magnitude of the post-exercise energy expenditure difference between a high (e.g. 85% of 15RM) and low (45% of 15RM) intensity strength exercise session is minor. Thus, it is unlikely that intensity-related excess post-exercise oxygen uptake would account for the greater reduction in body fat when ST and ET are performed in

separate sessions. Alternatively, shorter but more frequent exercise bouts in the separate session CT group may have contributed to a greater total energy expenditure due to the cumulative effect of more frequent excess post-exercise oxygen consumption events, but this hypothesis remains speculative. Despite the uncovered underlying mechanisms, these are promising findings with practical implication for those interested in optimizing changes in body composition with exercise, but replication of these results in other populations more likely to benefit from reducing total and regional body fat (such as obese and patients with type 2 diabetes) is still necessary.

Cardiometabolic Health

Beyond increasing lean mass and reducing central fat content, CT bears the potential to improve additional risk factors for cardiovascular and metabolic diseases. Poor regulation of blood lipids, glucose metabolism, and elevated systemic blood pressure are among major modifiable cardiometabolic risk factors amenable through exercise. The next sections will focus on the interaction between CT and these health-related parameters.

Blood Lipids and Lipoproteins

Long-term exercise training is recommended to ameliorate blood lipid and lipoprotein concentrations. Results from cross-sectional studies have provided the first evidence that increased physical activity levels were associated with improved fasting lipid profile, with athletes displaying increased serum high-density lipoprotein cholesterol (HDL-c) values that may be as high as 50% greater than inactive control counterparts. Triglyceride (TG) concentrations fluctuate in the opposite direction, with those with higher fitness levels presenting lower blood TGs. There is less evidence to support consistent total cholesterol (TC) and low-density lipoprotein cholesterol (LDL-c) changes, and the benefits of being physically active is normally reduced or even disappear when results are adjusted for confounding factors [35]. Longitudinal experiments investigating exercise interventions generally agree with epidemiological data, but changes in lipids and lipoproteins are normally of smaller magnitude. Based on a meta-analysis of 25 studies, including 1404 apparently healthy participants, it seems safe to expect a modest (+2.5 mg/dL) though significant increase in HDL-c after long-term ET [36]. Conflicting results have been reported in randomized controlled trials regarding the ability of ST to alter blood lipids at rest, but an analysis of accumulated evidence suggested that ST may ameliorate basal TC, the ratio of TC/HDL-c, TG, LDL-c and non-HDL-c in adults [37]. A smaller number of studies have investigated the potential of CT to change one's fasting lipids and lipoproteins, but it is generally accepted that CT can improve parameters of dyslipidaemia in a variety of populations [10, 38, 39], which is not surprising considering the known effects of single ET and ST upon HDL-c and TC.

The protective effect of HDL-c against CVD likely reflects its role in reversal cholesterol transport, not to mention its antioxidant, anti-inflammatory and vasoactive functions. Simply put, the reversal cholesterol transport involves a mechanism by which stored cholesterol esters, for example in vascular wall macrophages, can interact with extracellular apolipoprotein A1 to form nascent HDL-c, which then continues to stock cholesterol to form mature HDL-c species [40]. Mature HDL-c can selectively deliver their cholesterol content to the liver for elimination through (1) a direct pathway, whereby efflux of cholesterol ester occurs directly from HDL-c to hepatocytes; or (2) by indirect pathways, including cholesterol-triglyceride exchange with other lipoproteins to produce cholesterol-rich LDL-c forms, which then can transfer cholesterol to hepatocytes [40].

It is reasonable to consider that the combination of endurance and strength exercise could exert an additive effect in improving fasting lipid profile. To compare the three different exercise modalities in blood lipids and lipoproteins adaptations in young overweight/obese but otherwise healthy individuals, Tseng et al. [39] conducted a 3-month training study in which participants were allocated to ET (5 day/week, ~60 min/day at 50–70% maximal heart rate), ST (5 day/week, ~60 min/session, multiple sets performed at 60–80% of one repetition maximum), CT (similar endurance training and strength training sessions performed on alternate days for a total of 5 day/week) or a control group. Although all exercise groups improved cardiometabolic parameters, the ET and CT groups presented greater increases in HDL-c compared to the ST group. Interestingly, participants in the CT group displayed greater decreases in fasting glucose and TG compared to the other two exercise modalities, even though the total training volume (estimated by exercise time in this study) of the CT group was not greater than the others. Similarly, Libardi et al. [41] reported that ST and CT benefited middle-aged men by reducing fasting TC, but only CT improved blood TG concentrations. These are important findings as they indicate that CT may be superior to ET and ST alone to improve lipid profile, but it is important to keep in mind that this premise does not always hold true as studies comparing the three modalities have also reported similar responses after an intervention period. In fact, meta-analyses by Schwingshackl and colleagues estimated that CT and ET were similar in improving blood lipids and lipoproteins in overweight and obese individuals [25], but CT was reported to be superior to ST in decreasing TG of type 2 diabetes mellitus patients [42].

Therefore, the current knowledge is that exercise training can lead to improvements in blood lipid and lipoprotein profile. Adding ST to an ET programme does not hamper these positive adaptations, and there is even evidence indicating that CT may be superior to each modality alone, although it is still uncertain whether this response reflects an additive interaction between adaptations from different training modalities or greater exercise volume with CT.

Glycaemic Control

Healthy individuals with preserved glycaemic control display fasting circulating glucose concentrations below 100 mg/dL, and glycated haemoglobin (HbA1c)

under 5.7%. Chronic impairments in normal glucose regulation, such as diabetes mellitus, place individuals at an increased risk of mortality and long-term complications as neuropathy, nephropathy, CVD and amputations. Lifestyle modifications including the adherence to a healthy diet and increasing physical activity levels are considered major non-pharmacological strategies in the prevention and treatment of type 2 diabetes mellitus and the metabolic syndrome [43–45]. Supervised exercise training has been shown to be particularly relevant to improve one's glycaemic regulation by decreasing fasting glucose and the absolute percentage of HbA1c in type 2 diabetic patients [46]. The effectiveness of ET to improve glucose metabolism in these patients has been documented for decades [47], and later evidence led to the recognition that supervised ST as well as the combination of endurance and strength exercises are effective alternatives in improving patient's glycaemic control [46].

As CT combines the benefits of ET and ST, it has the potential to optimize metabolic responses in type 2 diabetics. In a large trial comparing the three exercise modalities upon long-term changes in HbA1c, CT brought about superior improvements in glycaemic control compared to single endurance or strength exercise groups [48]. Furthermore, those with a lower initial fraction of HbA1c only benefited from CT. Although the referred work indicates superiority of CT, it is important to highlight that patients enrolled in the combined training group completed greater weekly exercise volumes compared to those allocated to single modality groups. Hence, it is difficult to determine whether the observed effects resulted from a superiority of CT modality or from a greater total work performed.

Attempting to answer the abovementioned question, Church and colleagues [49] conducted a 9-month exercise trial trying to match the total training volume between exercise programmes, so that the CT group expended less time engaged in the endurance and strength activities compared to single ET and ST groups. Only patients engaged in CT attained reductions in HbA1c compared to a non-exercise control group. A posterior study corroborated these findings by reporting greater improvements in fasting glucose concentration in healthy males after CT compared to ET or ST, even with the endurance and strength components reduced by half in the CT group [39]. These results indicate a potential superior effect of CT in glucose metabolism that is irrespective of exercise volume. Nevertheless, a meta-regression of randomized controlled trials identified CT volume, particularly of the strength component, to be associated with improvements in HbA1c of type 2 diabetes patients [50], underscoring the importance to consider the interaction between exercise volume and mode in chronic adaptations for glucose regulation.

Exercise intensity was initially identified as a predictor of improvements in HbA1c in endurance exercise trials [47], but not in a more recent meta-regression including CT trials [50]. Inconsistent results about the putative benefit of higher intensity CT programmes upon glucose regulation-related outcomes are found in the literature, probably because of the interaction between training intensity and volume which results in greater total work performed by a high-intensity compared to low-intensity groups if the same exercise duration were used. A subgroup analysis of the Italian Diabetes Exercise Study helped to shed some light upon this topic, as researchers compared the outcomes of type 2 diabetics performing energy

expenditure-matched CT at low vs. moderate-to-high intensity. After 12 months of exercise intervention, patients exercising at higher intensity displayed a greater reduction of -0.5% in Hb1Ac compared to -0.33% in the lower intensity CT subgroup. Although an intensity dose-response could be identified, the additional benefit of higher intensity CT was deemed of little clinical relevance by the researchers [38], but we stress that a $\sim 0.15\%$ difference in Hb1Ac should not be overlooked.

The benefit of CT in glycaemic control of apparently healthy individuals is less clear. There seems to be mixed results in the literature comparing CT to single exercise modalities, with greater improvements in fasting glucose concentrations of young males reported to occur after CT compared to ET or ST [39], while others found potentially greater benefits of ET in glucose disposal during an oral glucose tolerance test in men [6], or even superior effects of ST and CT in reducing fasting glucose concentrations of older women compared to ET [8]. In some situations, exercise training may not improve fasting glucose concentrations after either modality, but prevent an impairment in glycaemic control over time [41], which probably reflects a narrower range for physiological adaptation in middle-aged otherwise healthy individuals compared to patients with established metabolic disorders.

Taken together, CT seems to be at least as effective as ET and ST to improve glycaemic control (or prevent its decline) in healthy individuals. There is evidence that CT may be superior to either ST or ET alone in improving glucose-related outcomes in those with type 2 diabetes mellitus, but it is currently difficult to ascertain whether this adaptation represents a superior effect of CT per se, or simply reflects the potential greater total amount of exercise performed by concurrent trained individuals. Clearly, studies designed to directly compare different CT volumes are still necessary for more definitive conclusions to be taken.

Blood Pressure and Vascular Adaptations

High blood pressure is a major cardiovascular risk factor, associated with alterations in the structure and function of the vasculature. Traditionally, systemic hypertension has been defined as (sustained) rest office-based systolic and/or diastolic brachial artery blood pressure $\geq 140/90$ mmHg, respectively, but in 2017 the American College of Cardiology and the American Heart Association published new guidelines with more aggressive blood pressure thresholds for the US population, with hypertension characterized as systolic blood pressure ≥ 130 mmHg and/or diastolic blood pressure ≥ 80 mmHg [51]. The hypertensive population is more prone to adverse events like stroke, heart failure, peripheral artery disease and target organ damage [52]. Furthermore, increased haemodynamic forces can damage the vascular wall leading to endothelial dysfunction and result in further vascular health impairment [52]. A correlation between the increase in blood pressure and cardiovascular risk is observed even in the normotensive range, which stresses the need of well-suited approaches to prevent or delay progressive elevations in blood pressure [52].

Endurance exercise has been classically recommended as an essential part of the antihypertensive treatment and it seems safe to expect hypertensive patients to

benefit with reductions of 5–7 mmHg in resting blood pressure with long-term ET [53]. Contrary to earlier beliefs, the practice of dynamic ST does not promote chronic increases in blood pressure and can, thus, be used as an adjuvant blood pressure-lowering strategy with effects comparable to ET [53]. The combination of both modalities is well accepted and recommended for prevention and treatment of hypertension. A meta-analysis of 68 trials investigating the influence of CT on blood pressure estimated an overall reduction of −3.2 mmHg in systolic blood pressure, and −2.5 mmHg in diastolic blood pressure compared to non-exercise control groups when all participants were taken into consideration [54]. Importantly, the long-term antihypertensive effects of CT increased with baseline blood pressure levels, stacking up at −5.3 mmHg for systolic blood pressure, and −5.6 mmHg for diastolic blood pressure in hypertensive individuals, with decreases of almost 9 mmHg reported in the trials ranked as high methodological quality. These results suggest that those in greater need of blood pressure reductions will be the ones to benefit the most with training.

The mechanisms by which exercise brings about a chronic reduction in blood pressure must relate to alterations in cardiac output and/or peripheral vascular resistance [52]. Since resting cardiac output is affected minimally or not at all by exercise training [55], changes in vascular resistance may mediate most of the benefits of exercise. The long-lasting antihypertensive benefit of exercise results from a complex interaction of improved vascular responsiveness, neurohumoral adjustments and/or structural vascular adaptation [52, 55]. Several of such mechanisms are still being investigated, but particularly functional and structural vascular adjustments to exercise training have been well characterized. The vascular endothelium plays a pivotal role control in vascular health and haemostasis. Endothelial cells are prone to damage induced by chronic high blood pressure and dyslipidaemia, with endothelial dysfunction being related to myocardial infarction, hypertension, and even ageing without clinical evidence of CVD [56, 57]. The consequences of endothelial dysfunction are at least twofold: (1) an atherosclerotic-prone vascular bed; with (2) impaired vasodilatory capacity, which may contribute to development and progression of hypertension.

Impaired vascular function can be improved by either ET or ST alone [56, 58]. Acute dynamic exercise exerts direct stimulation on blood vessels by increasing vascular anterograde shear stress, which acts as a potent stimulus to trigger endothelial adaptations. Transitory increases in anti-atherogenic shear stress may occur even in non-exercising vascular beds, providing prolonged large muscle mass dynamic exercise is performed. Moreover, changes in systemic factors including an exercise-induced increase in circulating myokines (such as interleukin-6), as well as chronic reductions in pro-inflammatory agents (e.g. C-reactive protein, tumour necrosis factor α) and improvement in insulin signalling in endothelial cells all converge to exert a positive effect on the vasculature [59]. Besides acute haemodynamic adjustments, CT has the potential to ameliorate lipid and low-grade chronic inflammation markers in selected populations [6, 25] and can be considered an effective lifestyle strategy to increase endothelial function. Accordingly, individuals with risk factors for vascular dysfunction or established CVD generally display increased

endothelial-dependent vasodilation in conduit and resistance vascular beds after a short period of CT [60, 61]. Interestingly, there is evidence that the within-session CT loading order may influence vascular adaptations to exercise. Starting the CT training sessions by the strength component (i.e. strength + endurance exercise sequence) has been reported to lead to improvements in the endothelial function of young females and males, whereas no improvements in vascular function were observed with the loading order (endurance + strength) [62]. Although the precise underlying mechanisms remain elusive, it has been speculated that a potential attenuation of resistance exercise-associated increase in circulating growth hormone by prior endurance exercise [63] may have hindered endothelial adaptation in the endurance + strength training group, since growth hormone infusion has been reported to stimulate nitric oxide production (as estimated by nitrate balance) and endothelial-dependent vasodilation [64].

Although it remains debatable whether arterial stiffness contributes to or results from hypertension, it is established that augmented aortic stiffness is related to cardiovascular risk [65]. Deposition of collagen fibres and reduction of elastin content in the blood vessels eventually results in stiffer arteries with reduced capacity to accommodate pulsatile intravascular tension. High-intensity strength training is generally linked to increased arterial stiffness in young healthy adults [66] probably due to a compensatory adaptation to the large increases in blood pressure during exercise manoeuvres. Increased vascular stiffness in young individuals to ST is unlikely to represent a pathological adjustment, but alternatives to prevent this vascular remodelling process include the manipulation of ST intensity, as low to moderate intensity ST does not seem to impair central arterial compliance in young individuals [67], or selective addition of an endurance component to a ST routine [62, 68]. As reported by Kawano et al. [68], CT appears to be effective to prevent chronic reductions in arterial compliance, typically associated with high-intensity ST. Similar to vascular reactivity, Okamoto et al. [62] also observed that reductions in brachial-ankle pulse wave velocity (a surrogate marker of central arterial stiffness) after 8 weeks of CT was only evident in participants who followed the strength + endurance exercise sequence, suggesting that the CT loading order may exert some influence upon vascular function and remodelling. However, the underlying mechanisms leading to superior vascular adaptations with the strength + endurance exercise sequence reported by Okamoto and colleagues remain largely unknown.

Summary

Different from what may happen with maximal strength development, the combination of strength and endurance exercise training does not impair health-related adaptations. CT is effective to improve body composition, blood pressure, and blood lipid/lipoprotein profile, with some evidence that this exercise modality may surpass single endurance and strength exercise training for enhancing glucose regulation. Maintenance and even improvement in vascular health can also be attained

through concurrent exercise, and the endurance component of CT may be effective to prevent strength training-induced increases in arterial stiffness. In a pragmatic perspective, for reducing body fat the intensity of the CT endurance component may be a relevant variable, with short duration (20–30 min) endurance exercise performed at a higher intensity as a potential choice to reduce body fat while limiting a negative interference effect of CT on hypertrophic gains [12]. Those seeking for greater skeletal muscle and strength development may opt for combining strength and cycling training, whereas running as endurance modality may be slightly favourable to reduce body fat [12]. Even though CT volume and intensity can play a relevant role in improving glycaemic control and additional cardiometabolic risk factors in selected populations, there is evidence that CT per se has a superior effect compared to ST or ET alone. As such, a CT routine combines the benefits from each single exercise modality and may be considered an optimal training alternative for health improvement and maintenance.

References

1. WHO. Obesity and overweight—fact sheet [internet]. World Health Organization. 2017. <http://www.who.int/mediacentre/factsheets/fs311/en/>
2. Haslam D, Sattar N, Lean M. Obesity—time to wake up. *BMJ*. 2006;333(7569):640–2.
3. Ross R, Dagnone D, Jones PJH, Smith H, Paddags A, Hudson R, et al. Reduction in obesity and related comorbid conditions after diet-induced weight loss or exercise-induced weight loss in men. A randomized, controlled trial. *Ann Intern Med*. 2000;133(2):92–103.
4. Hickson RC. Interference of strength development by simultaneously training for strength and endurance. *Eur J Appl Physiol Occup Physiol*. 1980;45(2–3):255–63.
5. Häkkinen K, Alen M, Kraemer WJ, Gorostiaga E, Izquierdo M, Rusko H, et al. Neuromuscular adaptations during concurrent strength and endurance training versus strength training. *Eur J Appl Physiol*. 2003;89(1):42–52.
6. Donges CE, Duffield R, Guelfi KJ, Smith GC, Adams DR, Edge JA. Comparative effects of single-mode vs. duration-matched concurrent exercise training on body composition, low-grade inflammation, and glucose regulation in sedentary, overweight, middle-aged men. *Appl Physiol Nutr Metab*. 2013;38(7):779–88.
7. Schumann M, Küüsmaa M, Newton RU, Sirparanta A-I, Syväöja H, Häkkinen A, et al. Fitness and lean mass increases during combined training independent of loading order. *Med Sci Sport Exerc*. 2014;46(9):1758–68.
8. Sillanpää E, Laaksonen DE, Häkkinen A, Karavirta L, Jensen B, Kraemer WJ, et al. Body composition, fitness, and metabolic health during strength and endurance training and their combination in middle-aged and older women. *Eur J Appl Physiol*. 2009;106(2):285–96.
9. Eklund D, Häkkinen A, Laukkonen JA, Balandzic M, Nyman K, Häkkinen K. Fitness, body composition and blood lipids following 3 concurrent strength and endurance training modes. *Appl Physiol Nutr Metab*. 2016;41(7):767–74.
10. Monteiro PA, Chen KY, Lira FS, Saraiwa BTC, Antunes BMM, Campos EZ, et al. Concurrent and aerobic exercise training promote similar benefits in body composition and metabolic profiles in obese adolescents. *Lipids Health Dis*. 2015;14(1):153.
11. Willis LH, Slentz CA, Bateman LA, Shields AT, Piner LW, Bales CW, et al. Effects of aerobic and/or resistance training on body mass and fat mass in overweight or obese adults. *J Appl Physiol*. 2012;113(12):1831–7.
12. Wilson JM, Marin PJ, Rhea MR, Wilson SM, Loenneke JP, Anderson JC. Concurrent training: a meta-analysis examining interference of aerobic and resistance exercises. *J Strength Cond Res*. 2012;26(8):2293–307.

13. Bouchard C, Tremblay A, Nadeau A, Dussault J, Després J-P, Threiault G, et al. Long-term exercise training with constant energy intake. 1: effect on body composition and selected metabolic variables. *Int J Obes.* 1990;14:57–73.
14. Howald H, Hoppele H, Claassen H, Mathieu O, Straub R. Influences of endurance training on the ultrastructural composition of the different muscle fiber types in humans. *Pflügers Arch Eur J Physiol.* 1985;403(4):369–76.
15. Calles-Escandón J, Goran MI, O'Connell M, Nair KS, Danforth E. Exercise increases fat oxidation at rest unrelated to changes in energy balance or lipolysis. *Am J Physiol Endocrinol Metab.* 1996;270:E1009–14.
16. Friedlander AL, Casazza GA, Horning MA, Buddinger TF, Brooks GA. Effects of exercise intensity and training on lipid metabolism in young women. *Am J Physiol Endocrinol Metab.* 2011;275(5 Pt 1):853–63.
17. Sparti A, DeLany JP, de la Bretonne JA, Sander GE, Bray GA. Relationship between resting metabolic rate and the composition of the fat-free mass. *Metabolism.* 1997;46(10):1225–30.
18. Byrne HK, Wilmore JH. The effects of a 20-week exercise training program on resting metabolic rate in previously sedentary, moderately obese women. *Int J Sport Nutr Exerc Metab.* 2001;11:15–31.
19. Huxley R, Mendis S, Zheleznyakov E, Reddy S, Chan J. Body mass index, waist circumference and waist:hip ratio as predictors of cardiovascular risk—a review of the literature. *Eur J Clin Nutr.* 2010;64(1):16–22.
20. Fox CS, Massaro JM, Hoffmann U, Pou KM, Maurovich-Horvat P, Liu C-Y, et al. Abdominal visceral and subcutaneous adipose tissue compartments: association with metabolic risk factors in the Framingham Heart Study. *Circulation.* 2007;116(1):39–48.
21. Kaul S, Rothney MP, Peters DM, Wacker WK, Davis CE, Shapiro MD, et al. Dual-energy x-ray absorptiometry for quantification of visceral fat. *Obesity.* 2012;20(6):1313–8.
22. Pouliot M-C, Després J, Lemieux S, Moosani S, Bouchard C, Tremblay A, et al. Waist circumference and abdominal sagittal diameter: best simple anthropometric indexes of abdominal visceral adipose tissue accumulation and related cardiovascular risk in men and women. *Am J Cardiol.* 1994;73(1):460–8.
23. Ismail I, Keating SE, Baker MK, Johnson NA. A systematic review and meta-analysis of the effect of aerobic vs. resistance exercise training on visceral fat. *Obes Rev.* 2012;13(1):68–91.
24. Dutheil F, Lac G, Lesourd B, Chapier R, Walther G, Vinet A, et al. Different modalities of exercise to reduce visceral fat mass and cardiovascular risk in metabolic syndrome: the RESOLVE* randomized trial. *Int J Cardiol.* 2013;168(4):3634–42.
25. Schwingshackl L, Dias S, Strasser B, Hoffmann G. Impact of different training modalities on anthropometric and metabolic characteristics in overweight/obese subjects: a systematic review and network meta-analysis. *PLoS One.* 2013;8(12):e82853.
26. Cadore EL, Izquierdo M, Pinto SS, Alberton CL, Pinto RS, Baroni BM, et al. Neuromuscular adaptations to concurrent training in the elderly: effects of intrasession exercise sequence. *Age (Omaha).* 2013;35(3):891–903.
27. Pinto S, Cadore E, Alberton C, Zaffari P, Bagatini N, Baroni B, et al. Effects of intra-session exercise sequence during water-based concurrent training. *Int J Sports Med.* 2013;35(1):41–8.
28. Wilhelm EN, Rech A, Minozzo F, Botton CE, Radaelli R, Teixeira BC, et al. Concurrent strength and endurance training exercise sequence does not affect neuromuscular adaptations in older men. *Exp Gerontol.* 2014;60:207–14.
29. Collins MA, Snow TK. Are adaptations to combined endurance and strength training affected by the sequence of training? *J Sports Sci.* 1993;11(6):485–91.
30. Chtara M, Chaouachi A, Levin GT, Chaouachi M, Chamari K, Amri M, et al. Effect of concurrent endurance and circuit resistance training sequence on muscular strength and power development. *J Strength Cond Res.* 2008;22(4):1037–45.
31. Gravelle BL, Blessing DL. Physiological adaptation in women concurrently training for strength and endurance. *J Strength Cond Res.* 2000;14(1):5–13.
32. de Souza EO, Tricoli V, Franchini E, Paulo AC, Regazzini M, Ugrinowitsch C. Acute effect of two aerobic exercise modes on maximum strength and strength endurance. *J Strength Cond Res.* 2007;21(4):1286–90.

33. Wilhelm EN, Radaelli R, Perin D, Cunha GS, Cadore EL, Laitano O, et al. The influence of running and cycling on subsequent maximal muscular performance. *Isokinetics Exerc Sci.* 2014;22(2):115–22.
34. Thornton MK, Pottenger JA. Effects of resistance exercise bouts of different intensities but equal work on EPOC. *Med Sci Sport Exerc.* 2002;34(4):715–22.
35. Durstine JL, Grandjean PW, Davis PG, Ferguson MA, Alderson NL, DuBose KD. Blood lipid and lipoprotein adaptations to exercise: a quantitative analysis. *Sport Med.* 2001;31(15):1033–62.
36. Kodama S, Tanaka S, Saito K, Shu M, Sone Y, Onitake F, et al. Effect of aerobic exercise training on serum levels of high-density lipoprotein cholesterol. *Arch Intern Med.* 2007;167(10):999–1008.
37. Kelley GA, Kelley KS. Impact of progressive resistance training on lipids and lipoproteins in adults: a meta-analysis of randomized controlled trials. *Prev Med (Baltim).* 2009;48(1):9–19.
38. Balducci S, Zanuso S, Cardelli P, Salvi L, Bazuro A, Pugliese L, et al. Effect of high- versus low-intensity supervised aerobic and resistance training on modifiable cardiovascular risk factors in type 2 diabetes; the Italian Diabetes and Exercise Study (IDES). *PLoS One.* 2012;7(11):e49297.
39. Tseng M-L, Ho C-C, Chen S-C, Huang Y-C, Lai C-H, Liaw Y-P. A simple method for increasing levels of high-density lipoprotein cholesterol: a pilot study of combination aerobic- and resistance-exercise training. *Int J Sport Nutr Exerc Metab.* 2013;23(3):271–81.
40. Singh IM, Shishehbor MH, Ansell BJ. High-density lipoprotein as a therapeutic target. *J Am Med Assoc.* 2007;298(7):786–98.
41. Libardi CA, de Souza GV, Cavaglieri CR, Madruga VA, Chacon-Mikahil MPT. Effect of resistance, endurance, and concurrent training on TNF- α , IL-6, and CRP. *Med Sci Sport Exerc.* 2012;44(1):50–6.
42. Schwingshackl L, Missbach B, Dias S, König J, Hoffmann G. Impact of different training modalities on glycaemic control and blood lipids in patients with type 2 diabetes: a systematic review and network meta-analysis. *Diabetologia.* 2014;57(9):1789–97.
43. Colberg SR, Albright AL, Blissmer BJ, Braun B, Chasan-Taber L, Fernhall B, et al. Exercise and type 2 diabetes: American College of Sports Medicine and the American Diabetes Association: joint position statement. *Med Sci Sport Exerc.* 2010;42(12):2282–303.
44. Diabetes Prevention Program Research Group, Knowler WC, Barrett-Connor E, Fowler SE, Hamman RF, Lachin JM, et al. Reduction in the incidence of type 2 diabetes with lifestyle intervention or metformin. *N Engl J Med.* 2002;346(6):393–403.
45. Anderssen SA, Carroll S, Urdal P, Holme I. Combined diet and exercise intervention reverses the metabolic syndrome in middle-aged males: results from the Oslo Diet and Exercise Study. *Scand J Med Sci Sports.* 2007;17(6):687–95.
46. Umpierre D, Ribeiro PAB, Kramer C, Leitão CB, Zucatti ATN, Azevedo MJ, et al. Physical activity advice only or structured exercise training and association with HbA 1c levels in type 2 diabetes. *JAMA.* 2011;305(17):1790.
47. Boulé NG, Kenny GP, Haddad E, Wells GA, Sigal RJ. Meta-analysis of the effect of structured exercise training on cardiorespiratory fitness in type 2 diabetes mellitus. *Diabetologia.* 2003;46(8):1071–81.
48. Sigal RJ, Kenny GP, Boulé NG, Wells GA, Prud'homme D, Fortier M, et al. Effects of aerobic training, resistance training, or both on glycemic control in type 2 diabetes. *Ann Intern Med.* 2007;147:357–69.
49. Church TS, Blair SN, Cocreham S, Johnson W, Kramer K, Mikus CR, et al. Effects of aerobic and resistance training on hemoglobin A 1c levels in patients with type 2 diabetes. *JAMA.* 2010;304(20):2253–62.
50. Umpierre D, Ribeiro PAB, Schaan BD, Ribeiro JP. Volume of supervised exercise training impacts glycaemic control in patients with type 2 diabetes: a systematic review with meta-regression analysis. *Diabetologia.* 2013;56(2):242–51.
51. Whelton PK, Carey RM, Aronow WS, Casey DE, Collins KJ, Dennison Himmelfarb C, et al. 2017 ACC/AHA/APA/ABC/ACPM/AGS/APhA/ASH/ASPC/NMA/PCNA guideline for the prevention, detection, evaluation, and management of high blood pressure in adults: a report

- of the American College of Cardiology/American Heart Association Task Force on Clinical Practice guidelines. *Hypertension*. 2017;71(6):e13–e115.
52. Pescatello LS, Franklin BA, Fagard R, Farquhar WB, Kelley GA, Ray CA. American College of Sports Medicine position stand. Exercise and hypertension. *Med Sci Sport Exerc*. 2004;36(3):533–53.
53. Pescatello LS, MacDonald HV, Lamberti L, Johnson BT. Exercise for hypertension: a prescription update integrating existing recommendations with emerging research. *Curr Hypertens Rep*. 2015;17(11):87.
54. Corso LML, MacDonald HV, Johnson BT, Farinatti P, Livingston J, Zaleski AL, et al. Is concurrent training efficacious antihypertensive therapy? A meta-analysis. *Med Sci Sport Exerc*. 2016;48(12):2398–406.
55. Fagard RH, Cornelissen VA. Effect of exercise on blood pressure control in hypertensive patients. *Eur J Cardiovasc Prev Rehabil*. 2007;14(1):12–7.
56. DeSouza CA, Shapiro LF, Clevenger CM, Dinenno FA, Monahan KD, Tanaka H, et al. Regular aerobic exercise prevents and restores age-related declines in endothelium-dependent vasodilation in healthy men. *Circulation*. 2000;102(12):1351–7.
57. Rush JWE, Dennis SG, D a G. Vascular nitric oxide and oxidative stress: determinants of endothelial adaptations to cardiovascular disease and to physical activity. *Can J Appl Physiol*. 2005;30(4):442–74.
58. Olson TP, Dengel DR, Leon AS, Schmitz KH. Moderate resistance training and vascular health in overweight women. *Med Sci Sport Exerc*. 2006;38(9):1558–64.
59. Padilla J, Simmons GH, Bender SB, Arce-Esquivel AA, Whyte JJ, Laughlin MH. Vascular effects of exercise: endothelial adaptations beyond active muscle beds. *Physiology*. 2011;26(3):132–45.
60. Maiorana A, O'Driscoll G, Cheetham C, Dembo L, Stanton K, Goodman C, et al. The effect of combined aerobic and resistance exercise training on vascular function in type 2 diabetes. *J Am Coll Cardiol*. 2001;38(3):860–6.
61. Vona M, Codeluppi GM, Iannino T, Ferrari E, Bogousslavsky J, von Segesser LK. Effects of different types of exercise training followed by detraining on endothelium-dependent dilation in patients with recent myocardial infarction. *Circulation*. 2009;119(12):1601–8.
62. Okamoto T, Masuhara M, Ikuta K. Combined aerobic and resistance training and vascular function: effect of aerobic exercise before and after resistance training. *J Appl Physiol*. 2007;103(5):1655–61.
63. Goto K, Higashiyama M, Ishii N, Takamatsu K. Prior endurance exercise attenuates growth hormone response to subsequent resistance exercise. *Eur J Appl Physiol*. 2005;94(3):333–8.
64. Napoli R, Guardasole V, Angelini V, D'Amico F, Zarra E, Matarazzo M, et al. Acute effects of growth hormone on vascular function in human subjects. *J Clin Endocrinol Metab*. 2003;88(6):2817–20.
65. Mitchell GF, Hwang S-J, Vasan RS, Larson MG, Pencina MJ, Hamburg NM, et al. Arterial stiffness and cardiovascular events: the Framingham Heart Study. *Circulation*. 2010;121(4):505–11.
66. Miyachi M. Effects of resistance training on arterial stiffness: a meta-analysis. *Br J Sports Med*. 2013;47(6):393–6.
67. Rakobowchuk M, McGowan CL, de Groot PC, Bruinsma D, Hartman JW, Phillips SM, et al. Effect of whole body resistance training on arterial compliance in young men. *Exp Physiol*. 2005;90(4):645–51.
68. Kawano H, Tanaka H, Miyachi M. Resistance training and arterial compliance: keeping the benefits while minimizing the stiffening. *J Hypertens*. 2006;24(9):1753–9.



Sex Differences in Concurrent Aerobic and Strength Training

20

Olav Vikmoen

Introduction

As illustrated by the various chapters throughout this book, there are many different aspects to concurrent endurance and strength training. However, the most basic question is whether performing these two types of training concurrently will lead to different physiological adaptations compared to performing only one type of training. Most attention in the literature has been given to the potential negative effects on the traditional adaptations to a strength training program from concurrently performing endurance training, often called the interference effect. Furthermore, attention has also been given to the potential positive effects which endurance athletes may gain by adding strength training to their normal training. The latter will be discussed in depth in Part V.

Many studies have reported that concurrent training can lead to impaired neuromuscular adaptations as compared to strength training only [1–11]. Furthermore, adding strength training to endurance athletes' normal training has been reported to improve performance in many endurance sports [12–26]. However, the data are equivocal and many studies report no negative effect on strength-related adaptations after concurrent training [27–34], or no beneficial effects on endurance performance when endurance athletes additionally perform strength training [35–45]. The reasons for the different findings in these two aspects of concurrent training are discussed extensively in other parts of this book. The main focus of this chapter will be to discuss possible sex differences in the adaptations to concurrent training. Specifically this chapter aims to review whether the adaptations to concurrent

O. Vikmoen

Division for Comprehensive Defence, Norwegian Defence Research Establishment,
Kjeller, Norway

e-mail: olav.vikmoen@ffi.no

training are sex-specific. Furthermore, it will be discussed if any sex differences are apparent in the effects of adding strength training to normal endurance training for endurance athletes.

Sex Differences in Performance and Relevant Physiology

Men are on average about 5–10% taller and 20–25% heavier than their female counterparts [46, 47]. In addition, men have about 40–50% and 30% more muscle mass in the upper and lower body, respectively, while women have approximately 20–25% of body fat compared to 13–16% in men [47, 48]. Furthermore, men have been reported to have larger mean muscle fiber areas than women both in the upper (*m. biceps brachii*) and lower body (*m. vastus lateralis*) [49].

As a result, review papers report that men are 40–55% stronger than women and this difference is especially pronounced in the upper body. Men also generate greater muscular power as well as higher anaerobic power compared to women [48]. The difference in absolute strength and anaerobic performance narrows when it is related to body mass and lean body mass [47], but it does not disappear.

Women have thinner ventricular walls with less myocardial tissue, smaller cavity sizes, and smaller stroke volume than men [48]. Furthermore, women have on average 10–16% lower hemoglobin concentrations [48] and a lower total hemoglobin mass both in absolute and relative values [50, 51] compared to men. Therefore, women have on average 15–30% lower maximal oxygen consumption ($\text{VO}_{2\text{max}}$) than men [48].

When performing muscle contractions at the same relative intensities, women have been shown to be more resistant to muscle fatigue than men [48, 52]. Since one of the proposed mechanisms for the interference effect is residual fatigue induced by the endurance training compromising the subsequent strength training [53, 54], it might be speculated that sex differences in fatigability will lead to sex differences in the response to concurrent training. The reason for the lower fatigability in women is not completely understood, but it is probably related to the fact that women exert less absolute force at a relative workload, leading to a smaller compression of the microcirculation and lower muscle oxygen demands [47, 52]. When lifting the same absolute load, muscular endurance is greater in men [47, 48].

Also, the substrate utilization during exercise differs between men and women [55, 56]. During endurance exercise at submaximal intensities, women oxidize proportionally more fat and less carbohydrates and proteins than men [55]. Since it has been suggested that low glycogen stores after endurance training can lead to less effective strength training sessions and impaired anabolic signaling after strength training [53, 54, 57], sex differences in substrate utilization during endurance training sessions can in theory lead to sex differences in the adaptations to strength training sessions performed concurrently.

There are also some hormonal differences between men and women, the most obvious being different secretion of sex hormones. The abovementioned differences in muscle mass and strength are usually explained by the higher serum testosterone

levels in men [48, 58], while the higher fat oxidation in women has been attributed to estradiol secreted by the ovaries [55]. Testosterone levels in the blood may increase in both men and women in response to exercise, even though the increase often is smaller in women [59]. Exercise may also increase estradiol levels in women [59].

The menstrual cycle has a profound effect on the secretion of the ovarian hormones in women [60]. During the follicular phase there is a gradual increase in estrogen concentrations, while progesterone dominates during the luteal phase. However, it seems that the different phases of the menstrual cycle affect maximal strength, muscle fatigability, and maximal aerobic power to a small degree only, even though conflicting results exist [60, 61]. The same seems to be true for most physiological responses to submaximal exercise, even though increased oxygen consumption (VO_2) at high intensities during the mid-luteal phase has been reported [60].

Based on the differences in physical performance and hormone levels between men and women, it might be speculated that there are sex differences in the adaptations to strength and endurance training when they are performed separately. However, the typical muscular adaptations to strength training seems to be similar between the sexes, as studies show that there are no differences in the relative increase in maximal strength [62, 63], increases in muscle mass [63], and the fiber type shift from type IIX towards type IIA after strength training [62]. The same is true for the relative increase in $\text{VO}_{2\text{max}}$ after endurance training [64].

Sex Differences in Concurrent Training

Unfortunately, most of the research dealing with concurrent training has been carried out using male participants. In addition, there is a lack of studies that directly compare the effect of concurrent training between men and women. Therefore, this chapter will mainly be based on results from separate studies performed in male and female participants or results from the few studies that include both female and male participants. The challenge with the first approach is that different studies using male and female participants usually also differ in many other methodological aspects that might be relevant. Similarly, the challenge with the second approach is that most of these studies include both men and women to get a larger number of participants and the total number of each sex are often too small for meaningful comparisons. Therefore, these studies usually report pooled data from the male and female subgroups.

Are There Any Sex Differences in the Effects of Concurrent Training on the Adaptations to Strength Training?

Above it was shortly discussed that many studies report attenuated adaptations in various aspects of muscle strength and muscle growth after concurrent training, even though the results are conflicting. There are numerous variables that are

possible to manipulate in the design of these studies and the conflicting results are probably related to many different methodological aspects that vary between studies. For example, it seems that the improvement in maximal power and explosive strength are more attenuated than maximal strength and muscle hypertrophy after concurrent training [11, 65, 66]. It might also be speculated that the use of male and female participants might explain some of the different findings. Unfortunately, there are not many studies in this area that are performed with female participants [29, 67–69], and some of these studies do not directly investigate if an interference effect exists [68, 69]. However, the studies investigating the interference effect using female participants do not report compromised neuromuscular adaptations [29, 67]. Thus, based on these studies it might be concluded that there is no interference effect or that it at least is smaller in women compared to men. However, it should be noted that in these studies the total training volume was quite low and no impairment in training adaptations is also common in male participants performing a low total training volume or a low number of training sessions per week [27, 28, 30–34]. Therefore, it is difficult to interpret if the lack of an interference effect is sex-specific or just simply due to a low training volume or other aspects related to the study design.

In recent work from our group we investigated if well-trained female endurance athletes with no strength training experience adding 11 weeks of strength training to their training would have different changes in muscle cross sectional area (CSA), maximal strength, and explosive strength compared to a group of untrained women performing the same heavy strength training program [70]. We observed similar increases in the lean mass of the legs, one repetition maximum (RM) in one-legged leg press, and maximal isometric knee extension torque in both groups. However, the improvement in isokinetic torque at a contraction velocity of $240^{\circ} \text{ s}^{-1}$ and the improvement in squat jump height were smaller in the female endurance athletes compared to the untrained participants. The results from this study can be compared to a study including male participants with a similar design and strength training program [71]. Here it was reported that well-trained male cyclists showed smaller increases in 1RM and CSA of the thigh muscles, squat jump height, and maximal rate of force development (RFD) after 12 weeks of concurrent training compared to a group of recreational active individuals only performing strength training. These two studies again suggest that the magnitude of the interference effect may be smaller in women than in men, at least in terms of maximal strength at slow contraction velocities and muscle growth. However, the different findings in these two studies might again be explained by the amount of endurance training performed. The female athletes performed about 5 h of endurance training per week, whereas the male cyclists performed endurance training for about 10 h per week. It is therefore unclear if the different findings are explained by the amount of endurance training or solely by sex. Reports that 1–3 h of weekly endurance training in recreationally active male and female runners did not lead to any impaired strength adaptations [5] suggest that the amount of endurance training probably is most important. Furthermore, the smaller improvement in power-related measurements in the female athletes compared to the untrained individuals illustrates that an interference effect

also occurred in the female athletes [70]. The finding that negative effects of concurrent training are most pronounced in the development of power and explosive strength compared to maximal strength is in accordance with studies using predominantly male participants [65, 66].

As described, there are studies that investigate the concurrent training phenomenon that include small subsets of both male and female participants [1, 2, 4, 5, 8, 27, 65, 72]. Unfortunately, most of these studies report pooled data for both sexes. The reason for this is usually that preliminary analyses showed that there were similar patterns of results for the male and female participants [1, 5, 8, 65, 72]. Furthermore, other of these studies report no sex differences in regard to the interference effect [2]. Even though these analyses are carried out with small sample sizes, these studies further indicate that the interference effect is similar between the sexes.

Based on the considerations above it appears that the possible interference effect of concurrent strength and endurance in most cases are similar between men and women. However, there might be other aspects of concurrent training that can differ, for example how to optimal organize concurrent training for the smallest possible interference effect to occur. Two recent studies, including both male and female participants, investigated if it is best to perform strength and endurance training on different days or on the same day, and whether the exercise sequence matters when aerobic and strength training are performed in the same session [73, 74]. These studies reported similar changes in both men and women after the different training modes and no sex differences in which of the training modes that were best for the measured outcomes. Further support for this is given when comparing separate studies with male and female participants using almost identical training programs [68, 75–77]. Therefore, it seems that the optimal organization of concurrent training is similar between men and women.

Are There Any Sex Differences in the Effects of Strength Training on Performance in Endurance Sports?

As described above, adding strength training to a normal endurance training routine has been reported to improve running performance in some studies, while other studies did not report any beneficial effects. However, there do not appear to be any sex differences in the effects of strength training on running performance based on these studies. Improved running performance or running economy has been reported in studies using male [13, 15, 18, 19, 78] and female athletes [37, 79], as well as in studies reporting pooled data from both male and female athletes [12, 16, 80, 81]. Furthermore, no effect of strength training on running performance has also been reported in male [36, 39] and female athletes [82] or mixed groups of athletes [35, 83]. Even though the abovementioned studies do not indicate any sex differences in the effects of strength training on running performance, none of these studies were designed to directly answer this question. One of the few studies including a large enough number of both male and female runners to make meaningful comparisons is the study by Barnes et al. [12]. In this study, the effect of 7–10 weeks of

traditional heavy strength training or heavy strength training in combination with plyometric training on laboratory measures of performance and performance during the competition season in male and female collegiate runners was assessed. This study reported that both the male and female runners had improvements in peak treadmill running speed and running economy, and that both sexes had larger improvement in these measures after traditional heavy strength training. However, it was only the female runners that improved actual competition times and this was evident after both types of strength training. Both types of strength training were possibly harmful to competition times in men. The apparent sex difference in this study is somewhat difficult to explain but the authors speculate that it might be related to a larger proportion of training above 80% of $\text{VO}_{2\text{max}}$ and shorter race distances in the female runners. However, the results may also indicate that the effect of strength training on real-world running performance is somewhat larger in women than in men.

Improved performance after addition of strength training to normal endurance training has also been reported in cycling, but as described, the results are equivocal. Unfortunately, to the best of the author's knowledge, there are no studies comparing the effects of adding strength training to endurance athlete's normal training on cycling performance between men and women. In addition, until recently, almost all research has been performed using male cyclists, and one of the few studies including female cyclists reported no improvement in cycling performance or cycling economy [41]. However, the cyclists in this study only included one strength training exercise twice a week making the training volume quite low. This might explain the lack of improved performance since studies using low strength training volume usually do not report any enhanced cycling performance even in men [44, 84].

Therefore, some years ago, our group conducted a more thorough investigation on the effects of strength training on various aspects of cycling performance and performance determinants in female cyclists [25, 26]. Furthermore, we used a strength training program identical to what has previously been reported to improve performance in male cyclists [21, 23]. The strength training program lasted for 12 weeks with two sessions per week with a training load of 10–4 RM. The effects of 12 weeks of heavy strength training on muscle strength, muscle hypertrophy, and various aspects of cycling performance were very similar in both the male [21, 23] and the female cyclists [25, 26] in these studies, and the results from these studies are summed up in Table 20.1. In neither men nor women did strength training have any effect on $\text{VO}_{2\text{max}}$ compared to control cyclists only performing their normal endurance training. Furthermore, performance in a 40 min all-out test, lactate threshold, and performance in the Wingate test improved similarly in both male and female cyclists after strength training. On the other hand, strength training did only improve cycling economy in the female cyclists. However, this is likely because the male cyclists were on a somewhat higher performance level than the female cyclists and it appears that it is difficult to improve cycling economy in very well trained cyclists [20]. There have been reported improved cycling economy after heavy strength training in male cyclists on a lower performance level [17]. To simulate a typical mass start race in cycling we performed a test consisting of a 3 h submaximal cycling trial

Table 20.1 Percent change in strength and cycling performance after 12 weeks of heavy strength training in male and female cyclists

	Male cyclists	Female cyclists
1RM	$26.0 \pm 6.6\%$	$38.6 \pm 19.0\%$
CSA	$4.6 \pm 1.7\%$	$7.4 \pm 5.3\%$
$\text{VO}_{2\text{max}}$	$3.3 \pm 4.6\%$	$-1.1 \pm 2.6\% (\text{ns})$
Cycling economy	No change	$3.5 \pm 3.1\%$
Lactate threshold	$4.1 \pm 5.1\%$	$7.3 \pm 12\%$
40 min all-out	$6.0 \pm 5.6\%$	$6.4 \pm 7.9\%$
VO_2 last hour, 3 h submax	$-2.2 \pm 2.0\%$	$-3.3 \pm 4.4\%$
5 min all-out	$7.2 \pm 6.6\%$	$7.0 \pm 4.5\%$
Wingate peak power	$9.4 \pm 9.6\%$	$12.7 \pm 12.6\%$
Wingate average power	$1.2 \pm 3.6\% (\text{ns})$	$3.4 \pm 4.3\%$

The results from the male cyclists are from Ronnestad et al. [21, 23], and the results from the female cyclists are from Vikmoen et al. [25, 26]

Values are mean \pm SD. RM repetition maximum, $\text{VO}_{2\text{max}}$ maximal oxygen consumption, VO_2 last hour, 3 h submax oxygen consumption during the last hour of a 3 h submaximal cycling trial, ns not statistically significant change

followed by a 5 min all-out test. The effect of strength training on the results from this test was also strikingly similar between the male and female cyclists. Both had showed a lower VO_2 and hence an improved work economy during the last hour of the submaximal trial, compared to before the strength training intervention. This probably led to a lower magnitude of fatigue during the 3 h submaximal trial and both the male and female cyclists improved similarly in the 5 min all-out test after the strength training program (Table 20.1). None of these changes were observed in neither male nor female control cyclists. The results from these studies in both male and female cyclists indicate that there are no sex differences in the improvements in cycling performance when cyclists add strength training to their normal training. However, caution is warranted since these studies did not directly investigate if sex differences exist. Future studies should include sufficient numbers of both male and female cyclists that in parallel carries out the same strength training program to directly compare the effects between sexes.

Several adaptations to strength training have been suggested as important mechanisms for the improved cycling performance after strength training. These include an increased muscle CSA, leading to increased muscle strength, a muscle fiber transformation from type IIX towards type IIA, increased RFD that makes cyclists capable of reaching their peak torque earlier in the pedal stroke, reduced motor unit recruitment on the same absolute power output, and other neuromuscular factors [25, 26, 84, 85]. These adaptations to strength training appear to be similar between men and women and further support that the improvements in endurance performance resulting from these adaptations should be similar. For example, a fiber type shift from type IIX to type IIA has been reported in both male and female cyclists after heavy strength training [20, 25], and increases in muscle mass after strength training is also similar in men and women [63].

Summary

This chapter has discussed if the physical and physiological differences between men and women will lead to any sex differences in concurrent endurance and strength training. Men have more muscle mass and are leaner than age matched women. Furthermore, men are stronger, have greater muscular power, higher anaerobic power, and higher $\text{VO}_{2\text{max}}$ compared to women. However, women are less fatigable than men on the same relative intensities and have a better ability to burn fat on submaximal intensities. In addition, there are also hormonal differences between men and women.

Unfortunately, the existing literature is not sufficient to provide a definitive answer if there are sex differences in concurrent training. However, based on studies including participants of only one sex and studies including small numbers of participants of each sex indicate that the interference effects will be similar in both men and women, even though some findings points towards a smaller interference effect in women. It is more likely that other factors concerning the training program will be more important than sex to determine if an interference effect will occur. This is thoroughly discussed in other chapters of this book. Based on the current literature, it also appears that both male and female endurance athletes will similarly benefit from strength training added to their endurance training routine, even though one study indicates that female runners might have a better transformation of gains made in laboratory tests to real competition running performance. However, the research on sex differences in these areas is limited and more studies that directly investigate possible sex differences in concurrent training should be performed. These studies should include enough participants of both sexes that perform exactly the same concurrent training programs, so that meaningful comparisons between men and women can be made.

References

1. Hickson RC. Interference of strength development by simultaneously training for strength and endurance. *Eur J Appl Physiol Occup Physiol*. 1980;45(2–3):255–63.
2. Bell GJ, Syrotuik D, Martin TP, Burnham R, Quinney HA. Effect of concurrent strength and endurance training on skeletal muscle properties and hormone concentrations in humans. *Eur J Appl Physiol*. 2000;81(5):418–27.
3. Cadore EL, Pinto RS, Lhullier FL, Correa CS, Alberton CL, Pinto SS, et al. Physiological effects of concurrent training in elderly men. *Int J Sports Med*. 2010;31(10):689–97. <https://doi.org/10.1055/s-0030-1261895>.
4. Gergley JC. Comparison of two lower-body modes of endurance training on lower-body strength development while concurrently training. *J Strength Cond Res*. 2009;23(3):979–87. <https://doi.org/10.1519/JSC.0b013e3181a0629d>.
5. Hunter G, Demment R, Miller D. Development of strength and maximum oxygen uptake during simultaneous training for strength and endurance. *J Sports Med Phys Fitness*. 1987;27(3):269–75.
6. Izquierdo-Gabarren M, Gonzalez De Txabarri Exposito R, Garcia-pallares J, Sanchez-medina L, De Villarreal ES, Izquierdo M. Concurrent endurance and strength training not to failure optimizes performance gains. *Med Sci Sports Exerc*. 2010;42(6):1191–9. <https://doi.org/10.1249/MSS.0b013e3181c67eec>.

7. Jones TW, Howatson G, Russell M, French DN. Performance and neuromuscular adaptations following differing ratios of concurrent strength and endurance training. *J Strength Cond Res.* 2013;27(12):3342–51. <https://doi.org/10.1519/JSC.0b013e3181b2cf39>.
8. Putman CT, Xu X, Gillies E, MacLean IM, Bell GJ. Effects of strength, endurance and combined training on myosin heavy chain content and fibre-type distribution in humans. *Eur J Appl Physiol.* 2004;92(4–5):376–84. <https://doi.org/10.1007/s00421-004-1104-7>.
9. Karavirta L, Hakkinen A, Sillanpaa E, Garcia-Lopez D, Kauhanen A, Haapasaari A, et al. Effects of combined endurance and strength training on muscle strength, power and hypertrophy in 40–67-year-old men. *Scand J Med Sci Sports.* 2011;21(3):402–11. <https://doi.org/10.1111/j.1600-0838.2009.01059.x>.
10. Kraemer WJ, Patton JF, Gordon SE, Harman EA, Deschenes MR, Reynolds K, et al. Compatibility of high-intensity strength and endurance training on hormonal and skeletal muscle adaptations. *J Appl Physiol.* 1995;78(3):976–89.
11. Hakkinen K, Alen M, Kraemer WJ, Gorostiaga E, Izquierdo M, Rusko H, et al. Neuromuscular adaptations during concurrent strength and endurance training versus strength training. *Eur J Appl Physiol.* 2003;89(1):42–52. <https://doi.org/10.1007/s00421-002-0751-9>.
12. Barnes KR, Hopkins WG, McGuigan MR, Northuis ME, Kilding AE. Effects of resistance training on running economy and cross-country performance. *Med Sci Sports Exerc.* 2013;45(12):2322–31. <https://doi.org/10.1249/MSS.0b013e31829af603>.
13. Damasceno MV, Lima-Silva AE, Pasqua LA, Tricoli V, Duarte M, Bishop DJ, et al. Effects of resistance training on neuromuscular characteristics and pacing during 10-km running time trial. *Eur J Appl Physiol.* 2015; <https://doi.org/10.1007/s00421-015-3130-z>.
14. Hickson RC, Dvorak BA, Gorostiaga EM, Kurowski TT, Foster C. Potential for strength and endurance training to amplify endurance performance. *J Appl Physiol.* 1988;65(5):2285–90.
15. Sedano S, Marin PJ, Cuadrado G, Redondo JC. Concurrent training in elite male runners: the influence of strength versus muscular endurance training on performance outcomes. *J Strength Cond Res.* 2013;27(9):2433–43. <https://doi.org/10.1519/JSC.0b013e318280cc26>.
16. Storen O, Helgerud J, Stoa EM, Hoff J. Maximal strength training improves running economy in distance runners. *Med Sci Sports Exerc.* 2008;40(6):1087–92.
17. Sunde A, Storen O, Bjerkaas M, Larsen MH, Hoff J, Helgerud J. Maximal strength training improves cycling economy in competitive cyclists. *J Strength Cond Res.* 2010;24(8):2157–65. <https://doi.org/10.1519/JSC.0b013e3181aeb16a>.
18. Paavolainen L, Hakkinen K, Hamalainen I, Nummela A, Rusko H. Explosive-strength training improves 5-km running time by improving running economy and muscle power. *J Appl Physiol.* 1999;86(5):1527–33.
19. Spurrs RW, Murphy AJ, Watsford ML. The effect of plyometric training on distance running performance. *Eur J Appl Physiol.* 2003;89(1):1–7. <https://doi.org/10.1007/s00421-002-0741-y>.
20. Aagaard P, Andersen JL, Bennekou M, Larsson B, Olesen JL, Crameri R, et al. Effects of resistance training on endurance capacity and muscle fiber composition in young top-level cyclists. *Scand J Med Sci Sports.* 2011;21(6):e298–307. <https://doi.org/10.1111/j.1600-0838.2010.01283.x>.
21. Ronnestad BR, Hansen EA, Raastad T. Effect of heavy strength training on thigh muscle cross-sectional area, performance determinants, and performance in well-trained cyclists. *Eur J Appl Physiol.* 2010;108(5):965–75.
22. Ronnestad BR, Hansen EA, Raastad T. In-season strength maintenance training increases well-trained cyclists' performance. *Eur J Appl Physiol.* 2010;110(6):1269–82. <https://doi.org/10.1007/s00421-010-1622-4>.
23. Ronnestad BR, Hansen EA, Raastad T. Strength training improves 5-min all-out performance following 185 min of cycling. *Scand J Med Sci Sports.* 2011;21(2):250–9. <https://doi.org/10.1111/j.1600-0838.2009.01035.x>.
24. Koninckx E, Van Leemputte M, Hespel P. Effect of isokinetic cycling versus weight training on maximal power output and endurance performance in cycling. *Eur J Appl Physiol.* 2010;109(4):699–708. <https://doi.org/10.1007/s00421-010-1407-9>.
25. Vikmoen O, Ellefsen S, Troen O, Hollan I, Hanestadhaugen M, Raastad T, et al. Strength training improves cycling performance, fractional utilization of VO₂max and cycling economy in female cyclists. *Scand J Med Sci Sports.* 2016;26(4):384–96. <https://doi.org/10.1111/sms.12468>.

26. Vikmoen O, Ronnestad BR, Ellefsen S, Raastad T. Heavy strength training improves running and cycling performance following prolonged submaximal work in well-trained female athletes. *Physiol Rep.* 2017;5(5) <https://doi.org/10.14814/phy2.13149>.
27. Abernethy PJ, Quigley BM. Concurrent strength and endurance training of the elbow extensors. *J Strength Cond Res.* 1993;7(4):234–40.
28. Cantrell GS, Schilling BK, Paquette MR, Murlasits Z. Maximal strength, power, and aerobic endurance adaptations to concurrent strength and sprint interval training. *Eur J Appl Physiol.* 2014;114(4):763–71. <https://doi.org/10.1007/s00421-013-2811-8>.
29. Gravelle BJ, Blessing DI. Physiological adaptations in women concurrently training for strength and endurance. *J Strength Cond Res.* 2000;14(1):5–13.
30. Holviala J, Kraemer WJ, Sillanpaa E, Karppinen H, Avela J, Kauhanen A, et al. Effects of strength, endurance and combined training on muscle strength, walking speed and dynamic balance in aging men. *Eur J Appl Physiol.* 2012;112(4):1335–47. <https://doi.org/10.1007/s00421-011-2089-7>.
31. McCarthy JP, Agre JC, Graf BK, Pozniak MA, Vailas AC. Compatibility of adaptive responses with combining strength and endurance training. *Med Sci Sports Exerc.* 1995;27(3):429–36.
32. McCarthy JP, Pozniak MA, Agre JC. Neuromuscular adaptations to concurrent strength and endurance training. *Med Sci Sports Exerc.* 2002;34(3):511–9.
33. Nelson AG, Arnall DA, Loy SF, Silvester LJ, Conlee RK. Consequences of combining strength and endurance training regimens. *Phys Ther.* 1990;70(5):287–94.
34. Shaw BS, Shaw I, Brown GA. Comparison of resistance and concurrent resistance and endurance training regimes in the development of strength. *J Strength Cond Res.* 2009;23(9):2507–14. <https://doi.org/10.1519/JS.0b013e3181bc191e>.
35. Bertuzzi R, Pasqua LA, Bueno S, Damasceno MV, Lima-Silva AE, Bishop D, et al. Strength-training with whole-body vibration in long-distance runners: a randomized trial. *Int J Sports Med.* 2013;34(10):917–23. <https://doi.org/10.1055/s-0033-1333748>.
36. Ferrauti A, Bergermann M, Fernandez-Fernandez J. Effects of a concurrent strength and endurance training on running performance and running economy in recreational marathon runners. *J Strength Cond Res.* 2010;24(10):2770–8. [https://doi.org/10.1519/JSC.0b013e3181d64e9c.00124278-201010000-00026 \[pii\]](https://doi.org/10.1519/JSC.0b013e3181d64e9c.00124278-201010000-00026).
37. Kelly CM, Burnett AF, Newton MJ. The effect of strength training on three-kilometer performance in recreational women endurance runners. *J Strength Cond Res.* 2008;22(2):396–403.
38. Mikkola J, Vesterinen V, Taipale R, Capostagno B, Hakkinen K, Nummela A. Effect of resistance training regimens on treadmill running and neuromuscular performance in recreational endurance runners. *J Sports Sci.* 2011;29(13):1359–71. <https://doi.org/10.1080/02640414.2011.589467>.
39. Schumann M, Mykkonen OP, Doma K, Mazzolari R, Nyman K, Hakkinen K. Effects of endurance training only versus same-session combined endurance and strength training on physical performance and serum hormone concentrations in recreational endurance runners. *Appl Physiol Nutr Metab.* 2015;40(1):28–36. <https://doi.org/10.1139/apnm-2014-0262>.
40. Bastiaans JJ, van Diemen AB, Veneberg T, Jeukendrup AE. The effects of replacing a portion of endurance training by explosive strength training on performance in trained cyclists. *Eur J Appl Physiol.* 2001;86(1):79–84.
41. Bishop D, Jenkins DG, Mackinnon LT, McEniry M, Carey MF. The effects of strength training on endurance performance and muscle characteristics. *Med Sci Sports Exerc.* 1999;31(6):886–91.
42. Bishop D, Jenkins DG. The influence of resistance training on the critical power function & time to fatigue at critical power. *Aust J Sci Med Sport.* 1996;28(4):101–5.
43. Jackson NP, Hickey MS, Reiser RF 2nd. High resistance/low repetition vs. low resistance/high repetition training: effects on performance of trained cyclists. *J Strength Cond Res.* 2007;21(1):289–95. <https://doi.org/10.1519/R-18465.1>.
44. Levin GT, McGuigan MR, Laursen PB. Effect of concurrent resistance and endurance training on physiologic and performance parameters of well-trained endurance cyclists. *J Strength Cond Res.* 2009;23(8):2280–6. <https://doi.org/10.1519/JSC.0b013e3181b990c2>.

45. Psilander N, Frank P, Flockhart M, Sahlin K. Adding strength to endurance training does not enhance aerobic capacity in cyclists. *Scand J Med Sci Sports.* 2014; <https://doi.org/10.1111/sms.12338>.
46. Janssen I, Heymsfield SB, Wang ZM, Ross R. Skeletal muscle mass and distribution in 468 men and women aged 18–88 yr. *J Appl Physiol (1985).* 2000;89(1):81–8. <https://doi.org/10.1152/jappl.2000.89.1.81>.
47. Nindl BC, Jones BH, Van Arsdale SJ, Kelly K, Kraemer WJ. Operational physical performance and fitness in military women: physiological, musculoskeletal injury, and optimized physical training considerations for successfully integrating women into combat-centric military occupations. *Mil Med.* 2016;181(1 Suppl):50–62. <https://doi.org/10.7205/MILMED-D-15-00382>.
48. Epstein Y, Yanovich R, Moran DS, Heled Y. Physiological employment standards IV: integration of women in combat units physiological and medical considerations. *Eur J Appl Physiol.* 2013;113(11):2673–90. <https://doi.org/10.1007/s00421-012-2558-7>.
49. Miller AE, MacDougall JD, Tarnopolsky MA, Sale DG. Gender differences in strength and muscle fiber characteristics. *Eur J Appl Physiol Occup Physiol.* 1993;66(3):254–62.
50. Boning D, Cristancho E, Serrato M, Reyes O, Mora M, Coy L, et al. Hemoglobin mass and peak oxygen uptake in untrained and trained female altitude residents. *Int J Sports Med.* 2004;25(8):561–8. <https://doi.org/10.1055/s-2004-820963>.
51. Boning D, Rojas J, Serrato M, Ulloa C, Coy L, Mora M, et al. Hemoglobin mass and peak oxygen uptake in untrained and trained residents of moderate altitude. *Int J Sports Med.* 2001;22(8):572–8. <https://doi.org/10.1055/s-2001-18530>.
52. Hunter SK. Sex differences in human fatigability: mechanisms and insight to physiological responses. *Acta Physiol (Oxf).* 2014;210(4):768–89. <https://doi.org/10.1111/apha.12234>.
53. Leveritt M, Abernethy PJ, Barry BK, Logan PA. Concurrent strength and endurance training. A review. *Sports Med.* 1999;28(6):413–27.
54. Fyfe JJ, Bishop DJ, Stepto NK. Interference between concurrent resistance and endurance exercise: molecular bases and the role of individual training variables. *Sports Med.* 2014;44(6):743–62. <https://doi.org/10.1007/s40279-014-0162-1>.
55. Tarnopolsky MA. Gender differences in substrate metabolism during endurance exercise. *Can J Appl Physiol.* 2000;25(4):312–27.
56. Hausswirth C, Le Meur Y. Physiological and nutritional aspects of post-exercise recovery: specific recommendations for female athletes. *Sports Med.* 2011;41(10):861–82. <https://doi.org/10.2165/11593180-00000000-00000>.
57. Wilson JM, Marin PJ, Rhea MR, Wilson SM, Loenneke JP, Anderson JC. Concurrent training: a meta-analysis examining interference of aerobic and resistance exercises. *J Strength Cond Res.* 2012;26(8):2293–307. <https://doi.org/10.1519/JSC.0b013e31823a3e2d>.
58. Shephard RJ. Exercise and training in women, Part I: influence of gender on exercise and training responses. *Can J Appl Physiol.* 2000;25(1):19–34.
59. Kraemer WJ, Ratamess NA. Hormonal responses and adaptations to resistance exercise and training. *Sports Med.* 2005;35(4):339–61.
60. Janse de Jonge XA. Effects of the menstrual cycle on exercise performance. *Sports Med.* 2003;33(11):833–51.
61. Shephard RJ. Exercise and training in women, Part II: influence of menstrual cycle and pregnancy. *Can J Appl Physiol.* 2000;25(1):35–54.
62. Staron RS, Karapondo DL, Kraemer WJ, Fry AC, Gordon SE, Falkel JE, et al. Skeletal muscle adaptations during early phase of heavy-resistance training in men and women. *J Appl Physiol.* 1994;76(3):1247–55.
63. Abe T, DeHoyos DV, Pollock ML, Garzarella L. Time course for strength and muscle thickness changes following upper and lower body resistance training in men and women. *Eur J Appl Physiol.* 2000;81(3):174–80. <https://doi.org/10.1007/s004210050027>.
64. Skinner JS, Jaskolski A, Jaskolska A, Krasnoff J, Gagnon J, Leon AS, et al. Age, sex, race, initial fitness, and response to training: the HERITAGE Family Study. *J Appl Physiol (1985).* 2001;90(5):1770–6.

65. Dudley GA, Djamil R. Incompatibility of endurance- and strength-training modes of exercise. *J Appl Physiol.* 1985;59(5):1446–51.
66. Glowacki SP, Martin SE, Maurer A, Baek W, Green JS, Crouse SF. Effects of resistance, endurance, and concurrent exercise on training outcomes in men. *Med Sci Sports Exerc.* 2004;36(12):2119–27.
67. Silva RF, Cadore EL, Kothe G, Guedes M, Alberton CL, Pinto SS, et al. Concurrent training with different aerobic exercises. *Int J Sports Med.* 2012;33(8):627–34. <https://doi.org/10.1055/s-0031-1299698>.
68. Eklund D, Schumann M, Kraemer WJ, Izquierdo M, Taipale RS, Hakkinen K. Acute endocrine and force responses and long-term adaptations to same-session combined strength and endurance training in women. *J Strength Cond Res.* 2016;30(1):164–75. <https://doi.org/10.1519/JSC.00000000000001022>.
69. Davitt PM, Pellegrino JK, Schanzer JR, Tjionas H, Arent SM. The effects of a combined resistance training and endurance exercise program in inactive college female subjects: does order matter? *J Strength Cond Res.* 2014;28(7):1937–45. <https://doi.org/10.1519/JSC.0000000000000355>.
70. Vikmoen O. Effects of heavy strength training on performance determinants and performance in cycling and running [Doctoral dissertation]. Oslo: Norwegian School of Sports Sciences; 2015.
71. Ronnestad BR, Hansen EA, Raastad T. High volume of endurance training impairs adaptations to 12 weeks of strength training in well-trained endurance athletes. *Eur J Appl Physiol.* 2012;112(4):1457–66. <https://doi.org/10.1007/s00421-011-2112-z>.
72. Sale DG, MacDougall JD, Jacobs I, Garner S. Interaction between concurrent strength and endurance training. *J Appl Physiol.* 1990;68(1):260–70.
73. Eklund D, Hakkinen A, Laukkanen JA, Balandzic M, Nyman K, Hakkinen K. Fitness, body composition and blood lipids following 3 concurrent strength and endurance training modes. *Appl Physiol Nutr Metab.* 2016;41(7):767–74. <https://doi.org/10.1139/apnm-2015-0621>.
74. Schumann M, Yli-Peltola K, Abbiss CR, Hakkinen K. Cardiorespiratory adaptations during concurrent aerobic and strength training in men and women. *PLoS One.* 2015;10(9):e0139279. <https://doi.org/10.1371/journal.pone.0139279>.
75. Eklund D, Pulverenti T, Bankers S, Avela J, Newton R, Schumann M, et al. Neuromuscular adaptations to different modes of combined strength and endurance training. *Int J Sports Med.* 2015;36(2):120–9. <https://doi.org/10.1055/s-0034-1385883>.
76. Schumann M, Kuusmaa M, Newton RU, Sirparanta AI, Syvaoja H, Hakkinen A, et al. Fitness and lean mass increases during combined training independent of loading order. *Med Sci Sports Exerc.* 2014;46(9):1758–68. <https://doi.org/10.1249/MSS.0000000000000303>.
77. Schumann M, Walker S, Izquierdo M, Newton RU, Kraemer WJ, Hakkinen K. The order effect of combined endurance and strength loadings on force and hormone responses: effects of prolonged training. *Eur J Appl Physiol.* 2014;114(4):867–80. <https://doi.org/10.1007/s00421-013-2813-6>.
78. Saunders PU, Telford RD, Pyne DB, Peltola EM, Cunningham RB, Gore CJ, et al. Short-term plyometric training improves running economy in highly trained middle and long distance runners. *J Strength Cond Res.* 2006;20(4):947–54. <https://doi.org/10.1519/R-18235.1>. R-18235 [pii].
79. Johnston RE, Quinn TJ, Kertzer R, Vroman NB. Strength training in female distance runners: impact on running economy. *J Strength Cond Res.* 1997;11(4):224–9.
80. Turner AM, Owings M, Schwane JA. Improvement in running economy after 6 weeks of plyometric training. *J Strength Cond Res.* 2003;17(1):60–7.
81. Guglielmo LG, Greco CC, Denadai BS. Effects of strength training on running economy. *Int J Sports Med.* 2009;30(1):27–32. <https://doi.org/10.1055/s-2008-1038792>.
82. Vikmoen O, Raastad T, Seynnes O, Bergstrom K, Ellefsen S, Ronnestad BR. Effects of heavy strength training on running performance and determinants of running performance in female endurance athletes. *PLoS One.* 2016;11(3):e0150799. <https://doi.org/10.1371/journal.pone.0150799>.

83. Roschel H, Barroso R, Tricoli V, Batista MA, Acuesta FM, Serrao JC, et al. Effects of strength training associated with whole-body vibration training on running economy and vertical stiffness. *J Strength Cond Res.* 2015;29(8):2215–20. <https://doi.org/10.1519/JSC.00000000000000857>.
84. Ronnestad BR, Mujika I. Optimizing strength training for running and cycling endurance performance: a review. *Scand J Med Sci Sports.* 2014;24(4):603–12. <https://doi.org/10.1111/sms.12104>.
85. Ronnestad BR, Hansen J, Hollan I, Ellefsen S. Strength training improves performance and pedaling characteristics in elite cyclists. *Scand J Med Sci Sports.* 2015;25(1):e89–98. <https://doi.org/10.1111/sms.12257>.

Part V

Concurrent Aerobic and Strength Training for Athletic Performance



Long-Term Effects of Strength Training on Aerobic Capacity and Endurance Performance

21

Øyvind Sandbakk

Introduction

Strength training is currently regarded as an important part of endurance athletes' long-term training program. However, the scientific evidence on long-term effects of concurrent strength and endurance training is sparse and only a few strength training interventions in endurance athletes last more than 15 weeks. This chapter: (1) summarizes the current scientific evidence on the effects of long-term strength training (i.e., defined as interventions lasting above 12 weeks) on aerobic capacity and endurance performance, and (2) discusses the potential neural and cellular mechanisms related to these effects, in order to provide a framework for generating new hypotheses in this exiting area.

Scientific Evidence

The requirements of strength for endurance performance in sport depend on the competitive duration and format, as well as the exercise mode employed. Endurance training is the essential stimulus for endurance athletes and they do traditionally not prioritize high volumes of strength training (i.e., training aimed to increase the muscles ability to generate maximum force). However, as highlighted in other chapters in this book, recent research has demonstrated positive short-term intervention effects of supplementing strength training concurrent to endurance training on aerobic capacity and performance. These studies have shown that aerobic capacity is mainly enhanced by improvements in exercise economy/efficiency and delayed fatigue when strength training is added. Partly because of the rising evidence

Ø. Sandbakk

Department of Neuromedicine and Movement Science, Centre for Elite Sports Research,
Norwegian University of Science and Technology, Trondheim, Norway
e-mail: oyvind.sandbakk@ntnu.no

showing its positive effects, strength training has become part of the training regime of many successful endurance athletes over the last years. However, since the majority of training interventions lasted only 8–12 weeks, caution should still be used when long-term effects are considered. We do currently not know the exact impact of long-term strength training on endurance performance. However, based on knowledge from power-based sports, it is logical to assume that progression and periodization in load, velocity, and/or changes in types of exercises would stimulate further long-term adaptations in strength in endurance athletes aiming to optimize their aerobic capacity.

The longest strength training intervention on endurance athletes to date is done by Rønnestad et al. [1], who performed a 25-week intervention in highly endurance trained cyclists. This study showed substantial positive effects on maximal strength and power variables, as well as power output at 4 mmol/L blood lactate concentration and maximal aerobic power. However, the effect sizes are in line with studies of shorter duration, and no mid-test was performed to analyze the effect of intervention duration on subsequent responses. A recent meta-analysis by Beattie et al. [2] confirms that, aside from Rønnestad et al.'s [1] 25-week strength intervention, the intervention periods used in the literature were 16 weeks or less, and the average duration approximately 10 weeks. Hence, much of what we know about neurological and structural adaptations from strength training derives from short-term interventions, and otherwise the interventions involve relatively untrained or inexperienced subjects. In fact, there are only a few studies investigating the long-term strength adaptations in well-trained athletes; however, these are from strength and power sports, e.g., rugby players [3]. Future research in well-trained endurance athletes should focus on long-term strength interventions and the subsequent changes in endurance performance.

Interestingly, Berryman et al.'s [4] recent meta-analysis of strength training on well-trained endurance athletes revealed a significant effect of the duration of the strength training, where protocols including more than 24 sessions led to greater improvements in work economy compared to protocols of less than 24 sessions. In addition, one case study used a scientific approach to combine strength and endurance training and, additionally, measured both strength and endurance variables systematically over the annual cycle [5]. In this study, the authors found an increase in 6RM leg press over 10 weeks before the progression plateaued over the rest of the year. Although there were further improvements in peak aerobic power over the year, it is unknown whether the strength training or other types of training affected this.

Another important question is whether the effects from an intensive period of strength training would be maintained in subsequent periods without or with less strength training. This is highly interesting with relation to periodization of strength training over the annual training cycle. Research shows that only a small part of the strength gained during an intervention is maintained after 8–12 weeks without strength training, which is accompanied by a relatively rapid reduction in muscle cross-sectional area and peak power output. Even after the 25-week training intervention by Rønnestad et al. [1], there was a rapid decline of adaptations during the

subsequent 8 weeks. Thus, in the long-term periodization of strength training for endurance athletes, “maintenance training,” as previously shown effective by Rønnestad et al. [6], seems to be required. However, strength training over longer periods often have to replace other types of training in highly trained athletes with already full training schedules to avoid overtraining. It can be argued that replacement of endurance training with strength training may have negative effects on endurance capacity. However, this was not the case in the study by Paavolainen et al. [7], who replaced endurance training by a mix of plyometric and explosive strength training and found beneficial effects over a relatively short intervention period (around 10 weeks). However, no studies have currently examined whether such a replacement would positively or negatively affect overall performance over longer time-scales. Thus, the question is not only what the possible positive effects of strength training is, but also whether this compromises with a negative effect due to less of the replaced training.

There are currently no reports of a negative effect of heavy strength training on exercise economy, maximal oxygen uptake or lactate threshold in endurance sports. Furthermore, a study performed on top-level endurance athletes did not observe a negative effect after 16 weeks of concurrent heavy strength training and endurance training on muscle capillarization [8], and after a period of concurrent strength and endurance training, there seems to be no impairment of the oxidative enzyme activity in endurance-trained athletes [9, 10]. Thus, with regard to muscle vascularization and oxidative potential, there seems to be no indications of negative effect of strength training—at least not when strength training is added over a shorter period. In fact, increased muscle mass without any reduced capillarization would in theory increase the overall oxidative potential of the muscle and thereby improve endurance performance. In this setting, muscle hypertrophy can be a “long-term” mechanism for improved aerobic capacity and Vikmoen et al. [11] recently reported a correlation between increased muscle mass and fractional utilization of $\text{VO}_{2\text{max}}$ (and performance) in female cyclists.

Even though strength training can be added to endurance training without a concomitant increase in total body mass, there seems to be a small, ~3–6%, increase in measurements of muscle hypertrophy in the main target muscles over 10–12 weeks [6, 8, 12, 13]. If this trend continues over longer strength training regimes, it might potentially have some negative side-effects, especially if strength exercises increase the mass of non-functional muscles. It can therefore be assumed that it is particularly important that strength-training exercises should involve similar muscle groups and imitate the sports-specific movements when performed over longer time-periods.

Based on the overall scientific evidence, endurance athletes are currently advised to build up maximal strength in the important muscles during the preparatory period by two strength training sessions per week, using a “daily undulating periodized program” [14]. Loads between 4RM and 10RM are typically used, with 2–3 sets per exercise and approximately 2–3 min of rest between sets. However, during the subsequent training periods and even during the competitive season, where development of strength is not prioritized, approximately one strength training session per

week (low volume) with high intensity seems to be needed to maintain the previous strength training adaptations [6]. However, for all these aspects, the athletes' training history, modality of aerobic training, and intervention duration might represent important variables potentially explaining individual effects. Since these recommendations are mainly based on short-term studies combined with practical work with elite endurance athletes, future research should be conducted to study the actual effects of different long-term periodization strategies. This would be helpful to provide the practitioner with more precise guidelines regarding, for example, the appropriate timing for the implementation of strength development within the annual training plan for different individuals.

Although sport-specific requirements of strength and endurance are relatively well understood in many endurance sports, we understand less of the optimal mix of strength and endurance training puzzled into the daily training plan of elite endurance athletes. How should it optimally be periodized in micro and macro cycles with changing volume of strength versus endurance training? How could employment of different muscle groups in strength and endurance training be done? Should different types of nutrition and overall energy availability be prioritized before, during, and after strength vs endurance training? These are examples of areas that are relatively unexplored, at least in a long-term perspective. The reality might be that science has not caught up with the sophistication of modern training and recovery techniques used by the best athletes. For example, world-class rowers or XC skiers can build up and sustain a large and strong muscle mass while, at the same time, developing an outstanding aerobic endurance capacity.

Potential Neural and Cellular Mechanisms

Although there is currently limited scientific evidence for the positive effects of long-term strength training on endurance performance, many of today's top athletes in endurance sports use various types of strength training over longer time-scales in order to enhance performance. Together with the results from short-term studies, we therefore suggest that similar effects are present also over longer time-spans although progression and periodization of both strength and endurance training is possibly needed to gain long-term progress. However, as with other types of training, it is likely that the acceleration of these effects reduces over time, as the body adapts to the "new" load. In the following, some of the main long-term mechanisms that may be present when endurance athletes supplement their endurance training with heavy strength training will be discussed. Still, the reader should be aware of the limited evidence in this area and researchers should use this to generate new hypotheses that can be tested in future studies.

The muscle fiber recruitment pattern may change with long-term strength training. Strengthening the type I fibers may lead to lower relative activity of the muscle and postpone their fatigue over long-duration work, thereby also postponing the employment of type II fibers that are normally less economical. The type II fibers can subsequently be used later, which may be the reason why some studies show

positive effects of strength training only after 2 h of submaximal cycling or skiing [15]. A reduced reliance of type II fibers may also increase economy through longer maintenance of glycogen stores that subsequently increase performance after prolonged exercise. However, long-term strength training may also increase the portion of type IIA fibers, thereby reducing type IIX, as previously shown by Aagaard et al. [8]. The type IIA fibers are more fatigue resistant, but still have the possibility to produce relatively high power. The findings in this area are conflicting [9], so future research needs to confirm the potential effect.

Increased maximum force and/or increased rate of force development capability following strength training may facilitate better blood flow to the working muscles [8, 14]. Increased rate of force development is likely caused by increased neural activation and has been linked to improvements in movements/sports where faster force development is positive for performance, e.g., to improve force effectiveness, leading to less relative load on the muscle or longer recovery phases during a cycle, thereby inducing less time with constriction of the blood flow. Although this has not yet been shown directly, we suggest that it would lead to improved delivery of oxygen and substrates during exercise.

Another area with conflicting theories is how strength training may influence the activation of muscle fibers during endurance exercise. One theory says that less muscle mass can generate the same work when the muscle is stronger, thereby reducing the oxygen cost of exercise. Other theories say that the same muscle mass can do the same work at lower relative activation levels when stronger, subsequently improving the ability to increase power at the end of an endurance competition. However, long-term adaptations might occur also on the muscle-tendon level. In some sports, such as running, increased muscle-tendon stiffness due to strength training may improve performance for some individuals [14]. However, this effect is influenced by the technical demands of running and the baseline stiffness of the individual. In other sports, such as cycling, this mechanism is unlikely to have an effect on performance.

There are also cellular effects of strength training occurring on a long-term perspective, such as activation of the phosphatidylinositol 3-kinase (PI3-k)-Akt-mammalian target of rapamycin (mTOR) signaling pathway. This is regarded to regulate the rate of protein synthesis and may, with long-term training, induce muscle hypertrophy. However, activation of adenosine monophosphate-activated protein kinase (AMPK) caused by high levels of endurance exercise may inhibit mTOR and suppress myofibrillar protein synthesis. Thus, large volumes of endurance exercise may negatively affect intracellular pathways of importance for myofibrillar protein synthesis [16], and placing strength sessions optimally will be especially important for endurance athletes in periods where the goal is to increase muscle mass. This also highlights the importance of sufficient amount of strength training to maintain muscle mass and strength in periods with high volumes of endurance training or competitions. However, note that the molecular research in the area is in its infancy and can currently not be directly applied to the physical preparation of endurance athletes.

While sufficient mechanical loading is important for gaining optimal strength training effects, also the movement pattern during training is important. This should

be similar to the movement in the corresponding discipline, to trigger specifically the optimal activation patterns of the involved muscles and inducing cellular adaptations. In addition, training models should aim to avoid strength- and endurance-training interference during periods of concurrent aerobic and strength training by planning training with awareness of the possible molecular interference and by including optimal nutrition. Overall, these different mechanisms should likely be triggered in different individuals and different sports, depending on the demands of the sport in relationship to the individual's capacity. This subsequently influences the choice of load, series, repetitions, and type of exercise that should be chosen for a given athlete—indicating that there is no “ideal” strength training program for a give sport but rather a toolbox that coaches and athletes should choose from in different contexts.

Summary

Overall, both scientific and practical evidence suggest that strength training could be successfully included in elite endurance athletes' training program, twice weekly to build up strength in the preparation period and once per week to maintain strength in the competition period. By using sport-specific strength programs, aerobic capacity seems to mainly be improved through exercise economy/efficiency and sometimes by delayed fatigue. Currently no negative effects of strength training on aerobic capacity has been shown. The possible neural and cellular mechanisms include: (1) a change in the muscle fiber recruitment pattern that postpones the muscle's fatigue over long-duration work and leads to longer maintenance of glycogen stores, (2) possible increase in the portion of type IIA fibers that are able to combine high strength and endurance capacities simultaneously, (3) increased rate of force development that facilitates better blood flow to the working muscles, thereby improving delivery of oxygen and substrates during exercise, (4) increased muscle-tendon stiffness in movements where this is beneficial, and (5) maintained signaling from intracellular pathways of importance for myofibrillar protein synthesis, induced by a training pattern with low negative inference from the large amounts of endurance training. However, the effects of long-term strength training on these factors, as well as how progression and periodization strategies can be used to prolong the positive effects of strength training on endurance performance, are not shown in scientific studies and need to be further examined.

References

1. Ronnestad BR, Hansen J, Hollan I, Spencer M, Ellefsen S. Impairment of performance variables after in-season strength-training cessation in elite cyclists. *Int J Sports Physiol Perform.* 2016;11(6):727–35.
2. Beattie K, Kenny IC, Lyons M, Carson BP. The effect of strength training on performance in endurance athletes. *Sports Med.* 2014;44(6):845–65.
3. Appleby B, Newton RU, Cormie P. Changes in strength over a 2-year period in professional rugby union players. *J Strength Cond Res.* 2012;26(9):2538–46. National Strength & Conditioning Association.

4. Berryman N, Mujika I, Arvisais D, Roubeix M, Binet C, Bosquet L. Strength training for middle- and long-distance performance: a meta-analysis. *Int J Sports Physiol Perform.* 2018;13(1):57–63.
5. Ronnestad BR, Hansen J. A scientific approach to improve physiological capacity of an elite cyclist. *Int J Sports Physiol Perform.* 2018;13(3):390–3.
6. Ronnestad BR, Hansen EA, Raastad T. In-season strength maintenance training increases well-trained cyclists' performance. *Eur J Appl Physiol.* 2010;110(6):1269–82.
7. Paavolainen L, Hakkinen K, Hamalainen I, Nummela A, Rusko H. Explosive-strength training improves 5-km running time by improving running economy and muscle power. *J Appl Physiol* (1985). 1999;86(5):1527–33.
8. Aagaard P, Andersen JL, Bennekou M, Larsson B, Olesen JL, Crameri R, et al. Effects of resistance training on endurance capacity and muscle fiber composition in young top-level cyclists. *Scand J Med Sci Sports.* 2011;21(6):e298–307.
9. Bishop D, Jenkins DG, Mackinnon LT, McEniry M, Carey MF. The effects of strength training on endurance performance and muscle characteristics. *Med Sci Sports Exerc.* 1999;31(6):886–91.
10. Hickson RC, Dvorak BA, Gorostiaga EM, Kurowski TT, Foster C. Potential for strength and endurance training to amplify endurance performance. *J Appl Physiol* (1985). 1988;65(5):2285–90.
11. Vikmoen O, Ellefsen S, Troen O, Hollan I, Hanestadhaugen M, Raastad T, et al. Strength training improves cycling performance, fractional utilization of VO₂max and cycling economy in female cyclists. *Scand J Med Sci Sports.* 2016;26(4):384–96.
12. Losnegard T, Mikkelsen K, Ronnestad BR, Hallen J, Rud B, Raastad T. The effect of heavy strength training on muscle mass and physical performance in elite cross country skiers. *Scand J Med Sci Sports.* 2011;21(3):389–401.
13. Taipale RS, Mikkola J, Nummela A, Vesterinen V, Capostagno B, Walker S, et al. Strength training in endurance runners. *Int J Sports Med.* 2010;31(7):468–76.
14. Ronnestad BR, Mujika I. Optimizing strength training for running and cycling endurance performance: a review. *Scand J Med Sci Sports.* 2014;24(4):603–12.
15. Mujika I, Ronnestad BR, Martin DT. Effects of increased muscle strength and muscle mass on endurance-cycling performance. *Int J Sports Physiol Perform.* 2016;11(3):283–9.
16. Hawley JA. Molecular responses to strength and endurance training: are they incompatible? *Appl Physiol Nutr Metab.* 2009;34(3):355–61.



Strength Training for Endurance Cyclists

22

Bent R. Rønnestad

Effects of Strength Training on Important Determinants of Endurance Performance

Hickson et al. [1] were amongst the first to give us the idea that heavy strength training could positively affect cycling performance. Their study was performed on untrained individuals, but lately the knowledge of the effects of adding strength training to the endurance training in recreationally, well-trained and elite cyclists has increased. This chapter will mainly focus on the effect of adding strength training to the ongoing endurance training in well-trained cyclists. To do this, the effects of strength training on important physiological determinants of performance will be evaluated. The interaction between maximal oxygen consumption ($\text{VO}_{2\text{max}}$), fractional utilization of $\text{VO}_{2\text{max}}$ (% $\text{VO}_{2\text{max}}$), and the anaerobic capacity explains how long a given rate of aerobic and anaerobic metabolism can be sustained, which altogether determines the performance VO_2 [2]. The cycling economy or efficiency then determines the power output at a given amount of energy consumption and thus majorly determines the performance power output [2]. We will now look closer on how strength training affects these performance determinants and performance power output.

Combining heavy strength training with normal endurance training seems to have neither a positive nor a negative effect on the development of $\text{VO}_{2\text{max}}$ [3–15]. When it comes to gross efficiency or cycling economy, the findings are more equivocal. When cycling economy is measured by the traditional method (i.e., short, 3–5 min, submaximal bouts of cycling), no additive effect of supplemented strength training was observed in well-trained and elite cyclists [3, 10–12]. However, by using the same approach to measure cycling economy, improvements were shown

B. R. Rønnestad

Department of Sports Sciences, Lillehammer, Inland Norway University of Applied Sciences, Lillehammer, Norway

e-mail: bent.ronnestad@inn.no

after adding heavy strength training in moderately trained cyclists [4, 9, 14]. Interestingly, during 3 h submaximal cycling in well-trained male and female cyclists no benefit of heavy strength training on cycling economy was observed during the first hour, but during the last hour there was an improvement in cycling economy in the strength training group [16, 17]. The latter indicates that also well-trained cyclists may improve cycling economy when measured during prolonged, and maybe more ecologically valid, cycling.

In order to calculate the fractional utilization of $\text{VO}_{2\text{max}}$, a common practice is to use the percentage of $\text{VO}_{2\text{max}}$ at the lactate threshold. Unlike the impression of the name, there is in practice no single unique lactate threshold, as it can be calculated in numerous ways [18]. However, in order to measure training-induced changes, it is important to use the same calculation method before and after the training period [19]. In theory, the lactate threshold describes an estimation of a breakpoint on the blood lactate concentration ($[\text{la}^-]$) curve as a function of exercise intensity [19]. Lactate threshold expressed as a percentage of $\text{VO}_{2\text{max}}$ is largely unaffected by exercise economy and $\text{VO}_{2\text{max}}$, which might explain the small correlation between lactate threshold expressed as % $\text{VO}_{2\text{max}}$ and time trial cycling performance in cyclists [20]. The few studies that have reported the effect of concurrent training on lactate threshold expressed as % $\text{VO}_{2\text{max}}$ in cyclists observe neither a positive nor negative effect [12, 14]. However, we recently reported that concurrent training in well-trained female cyclists improved fractional utilization of $\text{VO}_{2\text{max}}$ during a 40-min all-out trial, while no changes occurred in the group that performed endurance training only [15]. Interestingly, in the same study, no significant change was observed when the lactate threshold was expressed as % $\text{VO}_{2\text{max}}$, indicating that this method of expression fractional utilization of $\text{VO}_{2\text{max}}$ might not be sensitive enough to detect small changes [15].

There are numerous methods to determine the power output at the lactate threshold, resulting in diverse “thresholds” on the $[\text{la}^-]$ vs. power curve which all seem to correlate well with long-term endurance performance [18, 19]. The power output at the lactate threshold is, amongst others, affected by the cycling economy. Therefore, the finding of improved lactate threshold power output in several studies after combined heavy strength- and endurance training is expected [10–13, 15, 21]. However, there are also studies observing no improvements in power output at a defined $[\text{la}^-]$ [3, 14, 22].

The traditional way of measuring cycling performance is to perform all-out tests lasting between 30 and 60 min, where mean power output typically is the performance measure. When positive effects of concurrent training are reported, heavy strength training is performed with multiple leg exercises during a period of minimum 8 weeks [3, 7, 11–13, 15, 17, 21]. In contrast, studies failing to show much improvement in measurement of performance were typically either short term in duration, included a low volume of strength training or used explosive strength training [5, 6, 8, 22]. A measurement which can be looked at as a performance measurement is the power output at $\text{VO}_{2\text{max}}$ (W_{max}), which is influenced by $\text{VO}_{2\text{max}}$, cycling economy, anaerobic capacity, and neuromuscular characteristics [23]. Accordingly, W_{max} has been shown to predict endurance performance in cyclists [24],

[25] and to distinguish the endurance performance in well-trained cyclists [25]. Concurrent endurance and heavy strength training are reported to increase W_{\max} or time to exhaustion at W_{\max} in trained to well-trained cyclists [7, 10–12, 14, 26]. A relatively new method of assessing cycling performance in the lab is an attempt to imitate road cycling competitions, by performing prolonged submaximal cycling for many hours followed by a short, 5-min, all-out trial which is the main performance outcome. Combining heavy strength training with usual endurance training has improved 5-min all-out power after 3 h submaximal cycling in both well-trained female and male cyclists [16, 17].

Another factor important for the outcome of a cycling race is the ability to close a gap, break away from the pack, or perform well in the final sprint. The outcome of these crucial moments of a race is largely decided by the size of the involved muscle mass and the maximal leg strength [27]. The ability to generate high power output for a short period is often measured in the lab as mean and peak power output in a 30-s all-out test. Based on the beneficial effects of heavy strength training on muscle strength and muscle mass, it is expected that concurrent training improves the ability to generate a high power output for a short period of time [10–13]. A related variable is the curvature constant (W') of the power–duration relationship and it has recently been observed that W' has a strong positive relationship with both thigh muscle size and maximal knee extensors force in elite cyclists [28]. This has practical implications, since the ability to generate high power output during a short period of time is an important aspect of overall cycling performance [29].

Potential Mechanisms Behind the Effects of Strength Training on Cycling Performance

There are multiple potential mechanisms behind the positive effects on cycling performance of adding heavy strength training to the ongoing endurance training. A potential mechanism for improved performance after combined strength and endurance training is an increased force potential in the efficient muscle fiber type I and thus postponed activation of the less efficient type II muscle fibers, resulting in improved cycling economy and performance [30]. Since mainly type I fibers are activated during traditional submaximal measurements of cycling economy, this might explain why the literature is equivocal on improvements in cycling economy in well-trained cyclists. Postponed activation of type II muscle fibers is a plausible explanation for the findings of improved cycling economy in well-trained cyclists after a period of concurrent training after 2 h of submaximal cycling [16, 17]. It is likely that prolonged cycling exhausts some of the type I fibers and therefore can postpone activation of the less efficient type II fibers explain improved cycling economy. The latter is in agreement with the observation of strength training induced reduction in the increased muscle activity during the second hour of a 2-h cycling test [31], indicating postponed activation of type II fibers. The latter may have a glycogen sparing effect that might contribute to explain improved 5-min all-out performance after 3 h submaximal cycling after

12 weeks of concurrent training [16, 17]. Another potential mechanism related to muscle fiber recruitment is an increased proportion of type IIA fibers at the expense of type IIX fibers. It has been observed increased proportion of type IIA fibers at the expense of type IIX fibers after 12–16 week heavy strength training in both well-trained female and top-level male cyclists [3, 15]. The increase in the more fatigue resistant, yet high capability of power output, type IIA fibers may contribute to improved endurance performance. Indeed, recent data from our lab reveals a large correlation between change in mean power output during a 40-min all-out test and change in IIX fibers ($r = -0.63, p < 0.05$). This means that reduced proportion of type IIX fibers after 12 weeks of heavy strength training (and endurance training) was associated with improved power output during a 40-min all-out trial in well-trained female cyclists [15].

Another putative mechanism explaining improvement in endurance-related measurements after concurrent training is increased maximum force, and/or increased rate of force development (RFD) facilitating better blood flow to exercising muscles [3, 14, 32]. Improvement in maximum force and/or RFD might lower the relative exercise intensity and induce less constriction of the blood flow. Alternatively, improved RFD may reduce time to reach the desired force in each movement cycle and thereby potentially increase the relaxation phase with improved blood flow. Interestingly, 25 weeks of combined strength and endurance training in elite cyclists led to earlier occurrence of peak torque during the pedal stroke, while endurance training only did not [12]. Whether blood flow is enhanced after a period of concurrent training has not been thoroughly investigated, but in theory will increased blood flow lead to increased delivery of O_2 and substrates to working muscles and thus contribute to increased power output at a fixed $[Ia^-]$, but not necessarily improved cycling economy. Accordingly, it has been observed that improvement in power output at $4 \text{ mmol} \cdot L^{-1} [Ia^-]$ and mean power in 40-min all-out trial correlated largely with changes towards earlier peak torque during the pedal stroke ($r = -0.50$ and $r = -0.63$, respectively, $p < 0.05$; [12]). On the other hand, a recent study on moderately trained cyclists by Barrett-O'Keefe et al. [4] showed that 8 weeks of heavy strength training improved work economy at a cadence of 60 rpm, reduced muscular blood flow, while maintaining muscular arterial-venous oxygen difference. The latter indicates that improvement in muscular efficiency is an important mechanism behind improved work economy and improved endurance performance.

Coyle et al. [33] observed a positive relationship between lean body mass and 1-h all-out power output in well-trained and elite cyclists, suggesting that improved ability to recruit a relatively large quantity of muscle mass in each pedal stroke was associated with elite performance. Furthermore, cyclists that use a larger amount of their muscles mass have been observed to have a larger fractional utilization of $VO_{2\max}$ [33]. This was related to increased amounts of mitochondria sharing the power production and leading to less metabolic strain at a certain power output. Increased fractional utilization was actually indicated in a study where elite cyclists improve 45-min all-out performance after 16 weeks of added heavy strength training. The authors estimated that the power output during the

test had increased from 76% to 83% of the power output at $\text{VO}_{2\text{max}}$ [3]. It might thus be speculated that increased lean mass and increased absolute amounts of aerobic enzymes, with no change in the concentration of aerobic enzymes, could give a contribution to improved performance after adding heavy strength training to normal endurance training. This is in agreement with the recent results from our lab, where there was a very large correlation between change in mean power output during the 40-min all-out test and change in the cross-sectional area of m. quadriceps ($r = 0.73$, $p < 0.05$) with no change in the concentration of aerobic enzymes [15]. Furthermore, in the later study, fractional utilization of $\text{VO}_{2\text{max}}$ during the 40-min all-out test improved larger in the concurrent group than the control group [15].

Practical Recommendations for Implementing Strength Training

In this chapter, we have shown that adding heavy strength training to the normal endurance training can have a positive effect on cycling performance, at least when it is performed above 8 weeks, with multiple exercises for the power generating muscles in cycling. Nevertheless, it is important to remember that endurance training on the bike is the most important focus for a cyclist. If you normally have only three training sessions available during the week, is it likely that you will have the largest performance increments they are spent on the bike. However, if more time is available, then the scientific literature indicates that adding some heavy strength training *can* improve your cycling performance.

When choosing strength training exercises, you should have the specificity principle in mind. That means that the muscle action, the muscles engaged, and the movement pattern should be somewhat similar to the action on the bike. Specificity is recommended partly due to adaptations in the neural system (like optimal activation of the involved muscles) and partly due to structural adaptations (like optimizing the number of active cross-bridges in the particular range of motion). The latter is indicated by findings from an isometric strength training study where the strength improvement at the trained muscle length was twice the improvement of other muscle lengths [34]. The major contribution to the power output during cycling is achieved from concentric muscle actions during the pedaling down stroke. Peak force during pedaling occurs when the crank arm reaches an angle of approximately 90° , which is usually equal to a knee angle of approximately 100° . Therefore, a general rule is to focus on strength training exercises with a knee angle between 90° and almost full knee extension. That being said, the exercises should not be so difficult to perform that the mechanical loading and muscle mass involved is too low. Mechanical loading is an important stimulus for strength training adaptations. For instance, it has been shown that what somebody call “strength training” on the bike or “power pedaling” which consists of cycling with a low cadence (around 40 rpm) with relatively high force has no effect on neither maximal force capacity of the legs nor cycling performance [35].

It seems like it is the intended rather than the actual velocity that determines the velocity-specific training response [36]. This means that even though the actual movement velocity is quite low, you may increase your RFD if you focus on performing the lift as quick as possible. Therefore, you are recommended to have maximal effort in the concentric, cycling specific phase; performing the concentric phase as quickly as possible, while the eccentric, non-cycling specific phase should be performed more slowly (lasting around 2–3 s).

In terms of training periodization, it is recommended to build up the maximal strength during the first phase of the preparatory period leading up to the competition season. Two strength training sessions per week are normally enough to achieve a sufficient increase in strength during a 8–12 week period [10, 13–15]. We have seen an increase in maximum strength of 23–26% after 10–12 weeks with a strength training program designed as a “daily undulating periodized program” with progression in intensity, starting with 10 repetition maximum (RM) and ending at 4RM. This program varies the training load from session to session and progresses towards heavier loads and fewer repetitions. It is recommended to perform between 4RM and 10RM and 2–3 sets with approximately 2–3 min of rest between sets. Before you start with heavy loads, you must ensure that you have first developed a proper lifting technique with lower loads.

Note that in the beginning of the strength training period, it is common to get “heavy” and “sore” legs after the strength training sessions. Therefore, it is important to take it easy with the endurance training during the first two to 3 weeks of the strength training. It may be a good advice to start strength training rather quickly after the end of a competition season, when endurance training has a lower priority. Some potential exercises to choose amongst when designing your strength training program can be: half squat, single leg half squat, step-up, leg press with one foot at a time, one-legged hip flexion (imitating the pedaling upstroke), and toe raises (to ensure proper force transmission from the large thigh muscles into the pedal). You should perform 5–10 min of general warm-up followed by a specific warm-up with a gradual increase in loading of the strength training exercises. It is recommended to start the session with the exercise that involves the largest muscle mass, often the most coordinative demanding exercise. Thereafter, complete 2–3 more exercises that focus on the important muscles for the pedaling action. Strength training sessions to increase cycling performance do not have to be time consuming, including warm-up which can be done within 45 min.

There are phases during the preparatory period where you want to increase the focus on endurance training. In these phases, you should try to maintain the strength training adaptations. It seems like this can be done by performing one heavy strength training session every 7–10th day [11, 12]. To avoid detraining effects, it is recommended that you perform high intensity muscle actions and maximal mobilization in the concentric phase, but you do not need to follow the repetition maximum principle. That means that you for example can perform 2–3 × 5 repetitions at a load which you can perform maximally 8–10 repetitions. It is also recommended to perform strength maintenance training during the competition season. We have recently seen that if you stop all strength training from the middle of April until the middle of June, you will lose almost all your strength training adaptations [37].

Summary

This chapter provides an updated review on the effects of adding heavy strength training to the ongoing endurance training on the major physiological determinants of endurance performance in well-trained cyclists. Although not universal, the scientific literature present findings of improved cycling economy, improved fractional utilization of $\text{VO}_{2\text{max}}$, and improvement in indices of anaerobic power after adding heavy strength training to well-trained cyclists. More important, and more consistent, is the finding of improved cycling performance and/or improved W_{max} or time to exhaustion at W_{max} after adding heavy strength training with multiple exercises targeting the important muscles for power output during the pedal stroke for a longer duration (above 8 weeks).

References

1. Hickson RC, Rosenkoetter MA, Brown MM. Strength training effects on aerobic power and short-term endurance. *Med Sci Sports Exerc.* 1980;12:36–9.
2. Joyner MJ, Coyle EF. Endurance exercise performance: the physiology of champions. *J Physiol.* 2008;586:35–44.
3. Aagaard P, Andersen JL, Bennekou M, Larsson B, Olesen JL, Cramer R, Magnusson SP, Kjaer M. Effects of resistance training on endurance capacity and muscle fiber composition in young top-level cyclists. *Scand J Med Sci Sports.* 2011;21:e298–307.
4. Barrett-O'Keefe Z, Helgerud J, Wagner PD, Richardson RS. Maximal strength training and increased work efficiency: contribution from the trained muscle bed. *J Appl Physiol.* 2012;113:1846–51.
5. Bastiaans JJ, van Diemen AB, Veneberg T, Jeukendrup AE. The effects of replacing a portion of endurance training by explosive strength training on performance in trained cyclists. *Eur J Appl Physiol.* 2001;86:79–84.
6. Bishop D, Jenkins DG, Mackinnon LT, McEniry M, Carey MF. The effects of strength training on endurance performance and muscle characteristics. *Med Sci Sports Exerc.* 1999;31:886–91.
7. Hickson RC, Dvorak BA, Gorostiaga EM, Kurowski TT, Foster C. Potential for strength and endurance training to amplify endurance performance. *J Appl Physiol.* 1988;65:2285–90.
8. Levin GT, McGuigan MR, Laursen PB. Effect of concurrent resistance and endurance training on physiologic and performance parameters of well-trained endurance cyclists. *J Strength Cond Res.* 2009;23:2280–6.
9. Louis J, Hausswirth C, Easthope C, Brisswalter J. Strength training improves cycling efficiency in master endurance athletes. *Eur J Appl Physiol.* 2012;112(2):631–40.
10. Rønnestad BR, Hansen EA, Raastad T. Effect of heavy strength training on thigh muscle cross-sectional area, performance determinants, and performance in well-trained cyclists. *Eur J Appl Physiol.* 2010a;108:965–75.
11. Rønnestad BR, Hansen EA, Raastad T. In-season strength maintenance training increases well-trained cyclists' performance. *Eur J Appl Physiol.* 2010b;110:1269–82.
12. Rønnestad BR, Hansen J, Hollan I, Ellefsen S. Strength training improves performance and pedaling characteristics in elite cyclists. *Scand J Med Sci Sports.* 2015;25(1):e89–98.
13. Rønnestad BR, Hansen J, Nygaard H. 10 weeks of heavy strength training improves performance-related measurements in elite cyclists. *J Sports Sci.* 2017;35(14):1435–41.
14. Sunde A, Støren O, Bjerkaas M, Larsen MH, Hoff J, Helgerud J. Maximal strength training improves cycling economy in competitive cyclists. *J Strength Cond Res.* 2010;24:2157–65.
15. Vikmoen O, Ellefsen S, Trøen Ø, Hollan I, Hanestadhaugen M, Raastad T, Rønnestad BR. Strength training improves cycling performance, fractional utilization of $\text{VO}_{2\text{max}}$ and cycling economy in female cyclists. *Scand J Med Sci Sports.* 2016;26:384–96.

16. Rønnestad BR, Hansen EA, Raastad T. Strength training improves 5-min all-out performance following 185 min of cycling. *Scand J Med Sci Sports.* 2011;21:250–9.
17. Vikmoen O, Rønnestad BR, Ellefsen S, Raastad T. Heavy strength training improves running and cycling performance following prolonged submaximal work in well-trained female athletes. *Physiol Rep.* 2017;5(5). pii: e13149.
18. Faude O, Kindermann W, Meyer T. Lactate threshold concepts: how valid are they? *Sports Med.* 2009;39(6):469–90.
19. Tokmakidis SP, Leger LA, Pilianidis TC. Failure to obtain a unique threshold on the blood lactate concentration curve during exercise. *Eur J Appl Physiol Occup Physiol.* 1998;77:333–42.
20. Støren Ø, Ulevåg K, Larsen MH, Støa EM, Helgerud J. Physiological determinants of the cycling time trial. *J Strength Cond Res.* 2013;27(9):2366–73.
21. Koninckx E, Van Leemputte M, Hespel P. Effect of isokinetic cycling versus weight training on maximal power output and endurance performance in cycling. *Eur J Appl Physiol.* 2010;109:699–708.
22. Psilander N, Frank P, Flockhart M, Sahlin K. Adding strength to endurance training does not enhance aerobic capacity in cyclists. *Scand J Med Sci Sports.* 2015;25(4):e353–9.
23. Jones AM, Carter H. The effect of endurance training on parameters of aerobic fitness. *Sports Med.* 2000;29:373–86.
24. Hawley JA, Noakes TD. Peak power output predicts maximal oxygen uptake and performance time in trained cyclists. *Eur J Appl Physiol Occup Physiol.* 1992;65:79–83.
25. Lucía A, Pardo J, Durántez A, Hoyos J, Chicharro JL. Physiological differences between professional and elite road cyclists. *Int J Sports Med.* 1998;19(5):342–8.
26. Beattie K, Carson BP, Lyons M, Kenny IC. The effect of maximal- and explosive-strength training on performance indicators in cyclists. *Int J Sports Physiol Perform.* 2017;12(4):470–80.
27. Izquierdo M, Ibanez J, Hakkinen K, Kraemer WJ, Ruesta M, Gorostiaga EM. Maximal strength and power, muscle mass, endurance and serum hormones in weightlifters and road cyclists. *J Sports Sci.* 2004;22:465–78.
28. Kordi M, Menzies C, Parker Simpson L. Relationship between power-duration parameters and mechanical and anthropometric properties of the thigh in elite cyclists. *Eur J Appl Physiol.* 2018;118(3):637–45.
29. Atkinson G, Davison R, Jeukendrup A, Passfield L. Science and cycling: current knowledge and future directions for research. *J Sports Sci.* 2003;21:767–87.
30. Mujika I, Rønnestad BR, Martin DT. Effects of increased muscle strength and muscle mass on endurance-cycling performance. *Int J Sports Physiol Perform.* 2016;11(3):283–9.
31. Hausswirth C, Argentin S, Bieuzen F, Le Meur Y, Couturier A, Brisswalter J. Endurance and strength training effects on physiological and muscular parameters during prolonged cycling. *J Electromyogr Kinesiol.* 2010;20(2):330–9.
32. Heggelund J, Fimland MS, Helgerud J, Hoff J. Maximal strength training improves work economy, rate of force development and maximal strength more than conventional strength training. *Eur J Appl Physiol.* 2013;113:1565–73.
33. Coyle EF, Feltner ME, Kautz SA, Hamilton MT, Montain SJ, Baylor AM, Abraham LD, Petrek GW. Physiological and biomechanical factors associated with elite endurance cycling performance. *Med Sci Sport Exer.* 1991;23:93–107.
34. Mansell S, Phillips SK, Rutherford OM. Muscle length changes following strength training of the adductor pollicis muscle. *J Physiol.* 1997;499P:83P.
35. Kristoffersen M, Gundersen H, Leirdal S, Iversen VV. Low cadence interval training at moderate intensity does not improve cycling performance in highly trained veteran cyclists. *Front Physiol.* 2014;5:34.
36. Behm DG, Sale DG. Intended rather than actual movement velocity determines velocity-specific training response. *J Appl Physiol (1985).* 1993;74(1):359–68.
37. Rønnestad BR, Hansen J, Hollan I, Spencer M, Ellefsen S. Impairment of performance variables after in-season strength-training cessation in elite cyclists. *Int J Sports Physiol Perform.* 2016;11(6):727–35.



Strength Training for Endurance Runners

23

Kris Beattie

Introduction

Since the 1960s, maximal oxygen uptake ($\dot{V}O_{2\max}$) has been the most popular measurement for assessing performance in distance runners. Early assessments of $\dot{V}O_{2\max}$ recorded values greater than 80 mL kg $^{-1}$ min $^{-1}$ in champion athletes [1]. Research has shown strong relationships between $\dot{V}O_{2\max}$ and middle- (800 m, $r = 0.75$) and long-distance (marathon, $r = 0.78$) running performance in heterogeneous groups [2, 3]. However, this relationship is trivial in elite populations (marathon time <2:30, $r = 0.01$) [3]. While a high $\dot{V}O_{2\max}$ (>70 mL kg $^{-1}$ min $^{-1}$) may be a pre-requisite to be an elite distance runner, additional physical qualities are needed to succeed at this level. Therefore, other physiological markers such as running economy, fractional utilisation of $\dot{V}O_{2\max}$, velocity at maximal oxygen uptake ($v_{\dot{V}O_{2\max}}$) and sprinting ability play a vital role in world-class performances [4]. This is often demonstrated in middle- and long-distance championship finals, where after a period of high-intensity racing, the winner is generally the runner who can produce the best ‘kick’ during the final lap. For example, during the 2016 Rio Olympic Games 5000 and 10,000 m finals, the gold medallist sprinted at a velocity of over 7.5 m/s during the final stages of each race (see Fig. 23.1).

Strength Training

In addition to a superior cardiovascular system, limitations to world-class distance running performance may therefore be dictated by the neuromuscular system’s rate of force production (RFD). One training technique for improving force production qualities in distance runners is through strength training (see Fig. 23.2). The

K. Beattie

Department of Sport and Health Sciences, Athlone Institute of Technology, Athlone, Ireland
e-mail: kbeattie@ait.ie

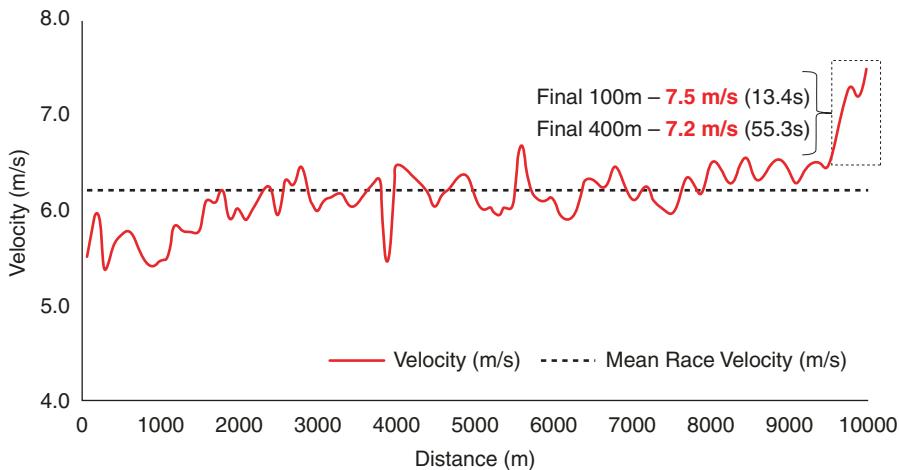


Fig. 23.1 Velocity of the 2016 Rio Olympic Games gold medallist during the 10,000 m final. Note the sudden increase in velocity during the sprint finish (mean race velocity: 6.2 m/s)

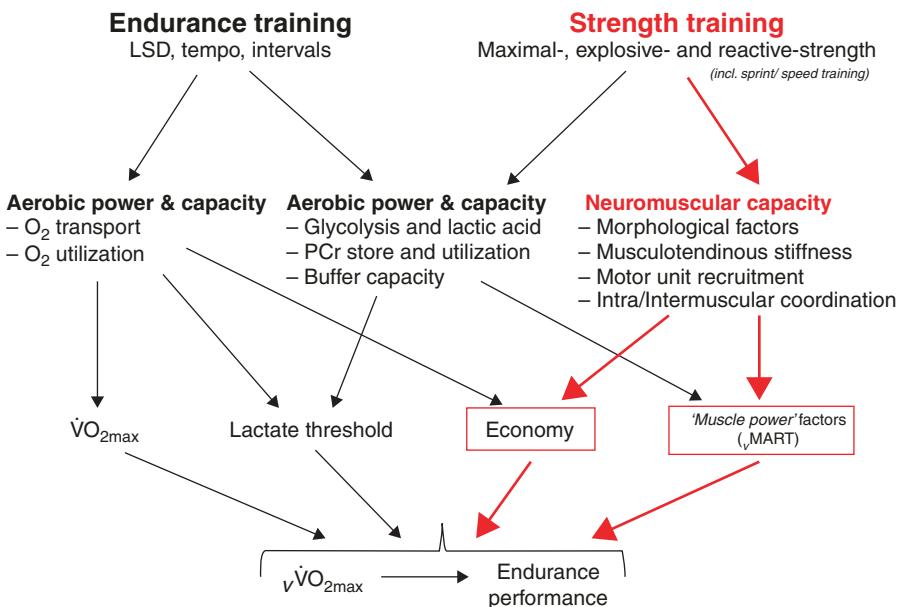


Fig. 23.2 Hypothetical model of the determinants for elite endurance performance and the potential benefits from strength and speed training. Red font and bold arrows highlight the potential benefit of strength and speed training on distance running performance [5] [LSD: long slow distance training; intervals: repeated bouts of exercise lasting 1–8 min and eliciting an oxygen demand equal to 90–100% of $\dot{V}O_{2\text{max}}$; PCr: phosphocreatine; $\dot{V}O_{2\text{max}}$: maximal O₂ uptake; vMART: peak velocity in maximal anaerobic running test; $v\dot{V}O_{2\text{max}}$: velocity at $\dot{V}O_{2\text{max}}$]

subcategories for strength training include: (1) maximal-strength (targets maximal force development through high-load, low-velocity movements i.e. squats, trap-bar deadlifts, Bulgarian split-squat); (2) explosive-strength (targets RFD through medium-to-high load, medium-to-high velocity movements i.e. Olympic lifts, jump-squats and squat-jumps); and (3) reactive-strength training (targets musculotendinous stiffness and ‘fast’ stretch-shortening cycle function (SSC) through low-load, high-velocity exercises i.e. pogo-jumps, drop-jumps, bounds, sprints). By utilising all three strength methods in an appropriate manner, a ‘strength-trained’ distance runner would theoretically (1) be more economical as the sub-maximal forces produced during each stride would decrease to a lower percentage of maximal force values, and (2) be able to produce higher maximum-velocities through an improved ability to rapidly absorb and create force against the ground.

Research has shown that all types of strength training (maximal-, explosive- and/or reactive-strength) can improve 3 km [6] and 5 km time-trial performance [4], running economy [4, 6–12], $\dot{V}O_{2\text{max}}$ [7, 8, 10] and maximum anaerobic running velocity ($v\text{MART}$) in competitive distance runners [4, 10]. However, it is important to note that most of the strength interventions in previous research studies were relatively short-term (~8 weeks). Additionally, there is a lack of research investigating the effect of sprint training in distance runners. For long-term strength and speed development in distance runners, it is important to prescribe a holistic mixed-methods approach to programming, utilising all strength-qualities (maximal-, explosive- and reactive-strength) and sprint training methods (technical drills, maximum-velocity sprinting) [13, 14]. However, the proportion of each strength quality, and the intensity of sprint training prescribed, will differ depending on the training age of the athlete and the training phase of the macrocycle (i.e. general preparation phase [GPP], special preparation phase [SPP], competition) (see Table 23.4).

Maximum-Strength

Maximal-strength is the ability to voluntarily generate maximum force without a time constraint [15]. Maximal-strength training (also known as the ‘max-effort’ method) targets maximal force development through high-load (>80% one repetition maximum [RM]), low-velocity exercises such as squats and trap-bar deadlifts. The prescription of maximal-strength training has long been a hot topic of debate within the track and field community, with some coaches viewing that maximal-strength training lacks specificity for distance running [7]. However, there has been a growing amount of research demonstrating the effectiveness of maximal-strength training on running economy, $\dot{V}O_{2\text{max}}$ and overall distance running performance [7, 9, 12, 16]. Additionally, maximum-strength training can concurrently improve other strength qualities [17–19] and sprinting ability [20] in relatively weak athletes.

It is important to note that for long-term maximal-strength development, the athlete eventually needs to be exposed to relatively high loads (>80% 1 RM) [21]. High

loads create slow velocities, therefore enabling high forces to be expressed (i.e. the force–velocity relationship). With this in mind, exercise selection may be important. Some track and field coaches contend that for optimal transference, a strength exercise should be ‘specific’ to the running movement (i.e. a low-load, single-leg exercise). However, the aim of maximum-strength training is to promote specific neuromuscular adaptations (e.g. motor-unit recruitment, intramuscular coordination) to increase maximal force capabilities [22]. Consequently, to create an environment where high forces can be expressed, the athlete must be stable. Therefore, traditional multi-joint exercises such as back squats and trap-bar deadlifts provide adequate stability to lift relatively large loads. If the athlete cannot squat or deadlift competently, a single-leg exercise such as a Bulgarian split-squat can provide a stable unilateral alternative. Otherwise, these single-leg exercises can be utilised as an ‘assistance’ exercise following squats or deadlifts to target further strength development (see ‘Assistance Exercises’ section) [23].

A simple linear loading progression provides a sound programming strategy for maximal-strength development in distance runners. During GPP, there may be an initial period where loading is <80% 1 RM (i.e. 5–8 reps per set). These relatively extensive sets allow technical competency and prepare the musculature for more intensive loading in subsequent training phases. During the latter mesocycles of the GPP, or during the SPP, loading can be increased >80% 1 RM (i.e. 3–5 reps per set). For distance runners who have an advanced strength training age, partial lifts such as $\frac{1}{2}$ squats and $\frac{1}{4}$ squats can be progressively introduced to increase transfer to explosive-strength and sprinting adaptations [24]. During the competition phase where racing is precedence, concentric or isometric lifts can be incorporated to maintain maximum-strength but reduce likelihood of soreness or fatigue (see Table 23.4).

Maximum-strength can be monitored throughout the macrocycle by RM tests (i.e. 2–5 RM), sub-maximal load-velocity equations or isometric mid-thigh pulls/ squats [25]. When the transfer of training diminishes (i.e. lack of improvement in economy, $\dot{V}O_{2\max}$ or maximum-velocity sprinting), the athlete has achieved an adequate level of maximum-strength for distance running. At this point maximum-strength should be maintained, and training should emphasise more specific stimuli such as reactive-strength and sprint training. However, this threshold for diminishing returns may vary between athletes (e.g. >1.6 kg*kg⁻¹ of bodyweight back squat 1RM) and highlights the importance of economy and $\dot{V}O_{2\max}$ monitoring.

Explosive-Strength

Explosive-strength is the ability to produce large forces in minimal time [15]. Explosive-strength training improves RFD and impulse through medium-to-high load, medium-to-high velocity movements (i.e. Olympic lifts, jump-squats, squat-jumps) [15]. However, maximal-strength training is a foundational component of explosive-strength development [21]. Research has shown that the neuromuscular adaptations from maximal-strength training can improve both explosive-strength

and maximal-strength in relatively weak athletes [17–19]. A simple explosive-strength exercise such as the countermovement jump provides a time-efficient exercise prior to (or between sets of) maximal-strength exercises (see Table 23.4). Additionally, the countermovement jump produces the highest maximal power values when compared to other explosive exercises [26]. Regular monitoring of countermovement jump metrics (i.e. jump height, relative peak power), using force platforms, contact mats or phone apps, may help to gain a quick and informative insight into explosive-strength adaptations [25].

Reactive-Strength

Reactive-strength is the ability of the musculotendinous unit to produce a powerful concentric contraction immediately following a rapid eccentric contraction (the stretch-shortening cycle [SSC]) [27]. Research in competitive distance runners has shown that interventions focusing on reactive-strength can improve 3 km [6] and 5 km time-trial performance [4], running economy [4, 6] and vMART [4]. Reactive-strength training is commonly referred to as ‘plyometrics’. Plyometrics, originally coined the ‘shock regime’ by Yuri Verkhoshansky, is a method of jump training that involves a rapid eccentric ‘shock’ stimulation to the musculotendinous unit [28]. The kinematic and kinetic characteristics of fast SSC plyometrics (i.e. bounding, hurdle hops) are similar to that of running (i.e. elastic force production; acute knee and hip angular displacement) [29].

Extensive Plyometrics

Traditional ‘shock’ plyometrics can be demanding on the ankle and knee musculotendinous structures. Therefore, to prepare the athlete for these intensive jumps, it is important to condition the musculotendinous structure during GPP through basic and sub-maximal plyometrics (i.e. pogo-jumps—stiff leg jumps with acute ankle, knee and hip angular displacement). These foundational jumps are also an excellent teaching tool to improve yielding ability (timing of ankle, knee and hip pre-activation prior to ground contact), limb position, coordination and rhythm—characteristics that are required for intensive plyometrics and competent sprinting [30]. Extensive pogo-jumps should be performed in a sub-maximal and rhythmical manner, focusing on dorsi-flexed and flat-footed landings [30]. Pogo-jump height is seldom more than 10 cm, and jump distance between 20 and 50 cm (see Table 23.1).

Intensive Plyometrics

Once the athlete attains an appropriate physiological and technical foundation, jumps can be intensified during the SPP. The [double-leg] pogo-jump from the extensive phase can be intensified by focusing on fast ground contacts and maximal jump height. Due to the increased jump height, there will be an increase in eccentric loading on the landing phase, therefore targeting further SSC adaptations. For distance runners with an intermediate plyometric training age, maximal pogo-jumps can be progressed to tuck jumps (again focusing on fast ground contacts and

Table 23.1 Extensive plyometric suggestions during GPP and SPP for distance runners with a beginner, intermediate, or advanced plyometric training age

Intensity	Sub-maximal (low/moderate)
Frequency per week	2
Distance	2 × 10 m per exercise
Surface	Grass or soft track surface
Reps	20–40 contacts per exercise (i.e. 10–20 contacts per 10 m)
Beginner	Pogo-jumps (double-leg) – 2 × 10 m forwards – 2 × 10 m side-ways – 2 × 10 m backwards
Intermediate/advanced	Pogo-jumps (double-leg) – 2 × 10 m forwards – 2 × 10 m side-ways – 2 × 10 m backwards Pogo-jumps (single-leg) – 2 × 10 m forwards – 2 × 10 m medial side-ways – 2 × 10 m backwards
Cues	<i>'bouncy'</i> <i>'relaxed'</i> <i>'rhyth�ical'</i> <i>'land flat-footed'</i>

Table 23.2 Intensive plyometric suggestions during the SPP and competition phases for distance runners with a beginner, intermediate or advanced plyometric training age

Intensity	Maximal (high)
Frequency per week	1–2
Reps	3–8 jumps
Sets	3–5
Recovery	>3 min per set
Beginner	Pogo-jumps
Intermediate	Tuck jumps or hurdle hops
Advanced	Drop-jumps (box height greater than jump height)
Cues	<i>'get off the ground as quick as possible & jump as high as possible'</i> <i>'bouncy'</i> <i>'land flat-footed'</i>

maximal jump height). Tuck jumps involve ‘tucking’ or flexing the hip and knee during flight (as if the athlete is jumping over hurdles), with a rapid extension prior to landing [29]. Once the athlete is competent at tuck jumping, they can be progressed to hurdle hops. Appropriately spaced hurdles give an excellent external cue to promote jump height while keeping ground contacts low. Lastly, the most intense jumps in the plyometric progression are drop-jumps [28]. Drop-jumps consist of the athlete stepping off a box, landing with minimum ground contact time and jumping for maximum height. Drop-jumps are true ‘shock’ plyometrics due to the supra-maximal eccentric loading (especially when box drop heights exceeds the athlete’s normal vertical jump height) and should only be administered to distance runners with an advanced plyometric training age (see Table 23.2).

It is important to note that throughout the macrocycle (GPP → competition), there should be a fluid and logical progression from extensive to intensive jumps (see Table 23.4). Depending on the athlete's jumping competency and plyometric training age, some elements of the extensive jumps may remain throughout the SPP and competition phases. Reactive-strength is commonly monitored utilising the drop-jump 'reactive-strength index' (RSI). Originally developed at the Australian Institute of Sport in the early 1990s, the drop-jump RSI ($\text{RSI} = \text{jump height} \div \text{contact time}$) is usually assessed from a set box height (i.e. 0.3 m) to control the eccentric stretch loads [31]. Regular monitoring of RSI using force platforms, contact mats or phone apps provide a quick and informative insight into reactive-strength adaptations [25].

Assistance Exercises

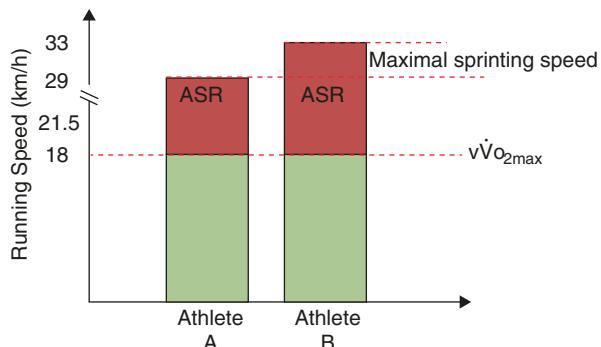
Assistance exercises can be carried out in a circuit format utilising the 'sub-maximal effort' method (8–15 repetition range, 50–80% 1RM) [15]. Depending on the phase of the macrocycle and the physical readiness of the athlete, 1–5 assistance exercises are performed at the end of a strength session. Assistance exercises target the muscles utilised within the 'competition exercise', such as the quadriceps (e.g. split-squat, goblet squat), hamstrings (e.g. short- and long-lever hamstring bridges, Nordics, single-leg RDLs), glutes (e.g. hip thrusts, X-band walks), core (e.g. planks, crunches, lower back) and calves (e.g. straight- and bent-leg calf raises). The aim of assistance exercises is to (1) target further strength development through specific musculature hypertrophy (i.e. quadriceps, hamstring, calves, glutes, abdominals and lower back) [15], (2) improve localised muscular endurance [28] and (3) reduce injury prevalence through improved musculotendinous adaptations and increased pelvic, femoral and overall postural control [32].

Sprint Training

Speed is a vital component of world-class distance running performance. As mentioned earlier, successful world-class distance runners can sprint at velocities over 7.5 m/s during long-distance races, and over 8.5 m/s during middle-distance races [33]. Speed can be enhanced in developmental athletes through general means such as maximal-strength training and plyometrics [20]. However, for optimal speed development, progressive and consistent sprint training is needed [14]. Nevertheless, sprinting is a complex skill. Like most skills, sprinting can be improved through sound technical coaching and appropriate programming. Competent sprint coaching and technical knowledge is common within the track and field sprinting community, however lesser so within distance running.

The neuromuscular adaptations from sprint training (i.e. intermuscular coordination, rate coding, musculotendinous stiffness) may have the potential to improve important physiological factors such as running economy, $\dot{V}\text{O}_{2\text{max}}$ and anaerobic

Fig. 23.3 An illustration highlighting the importance of anaerobic speed reserve (ASR) in distance runners with similar $\dot{V}O_{2\max}$ differing maximal sprinting velocities (adapted from [34])



speed reserve (ASR) [7]. The anaerobic speed reserve (ASR) is the difference between a distance runner's velocity at $\dot{V}O_{2\max}$ ($\dot{V}O_{2\max}$) and their maximal sprinting velocity [34]. Figure 23.3 demonstrates the importance of ASR for two athletes possessing similar $\dot{V}O_{2\max}$, but differing maximal sprinting velocities [34]. During a race (especially middle-distance events where mean race velocities can exceed $\dot{V}O_{2\max}$), an athlete with a large ASR (i.e. Athlete B) will theoretically work at a lower percentage of their maximum-velocity, and will therefore have a lower metabolic load compared to other competitors (i.e. Athlete A). Additionally, a higher maximum-velocity increases an athlete's potential to 'kick' and be successful at the end of a race.

Sprinting Drills

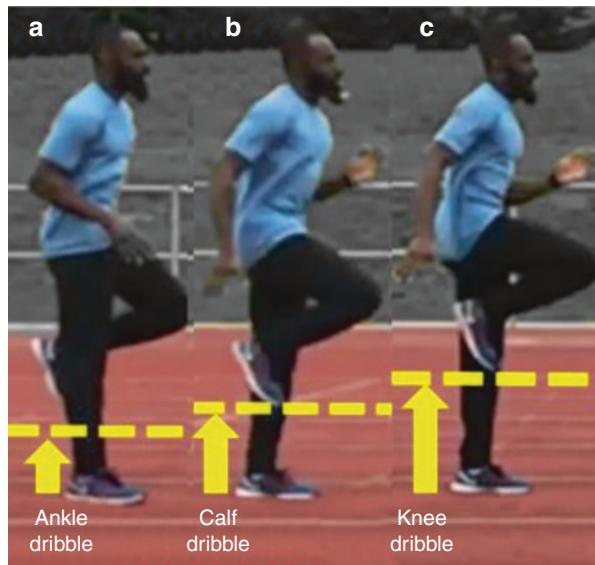
Sprint drills are intended to serve as a simplified or broken-down version of a technically sound sprint cycle [14]. Sprint drills such as dribbles and straight-leg scissors (see below) can be effective for distance runners in rehearsing limb position, rhythm and coordination strategies needed for competent maximum-velocity running. Additionally, these drills provide a specific plyometric conditioning stimulus in areas such as the hamstring and ankle musculotendinous structures.

Dribbles

The mechanics of dribbles are similar to maximum-velocity sprinting; however, the range of motion and velocity of the sprint cycle is truncated. Dribbles reinforce sprint cycle coordination, timing and front-side leg positioning [35]. Additionally, dribbles are less intensive than maximal-velocity sprints, therefore offering an excellent opportunity to practise technically sound sprint mechanics on a regular basis.

There are three types of dribbles in the progression series: ankle-, calf- and knee-dribbles. Teaching progression can start with the ankle-dribble, which has the shortest 'swing-phase' range of motion (see Fig. 23.4a). Once an athlete is competent, they can progress to calf-dribbles (Fig. 23.4b), knee-dribbles (Fig. 23.4c) and finally

Fig. 23.4 The difference in the height of the swing-leg foot during the (a) ankle-dribble, (b) calf-dribble, (c) knee-dribble



dribble-bleeds (blending of a dribble to a full sprint) [35]. Coaching points during a dribble should focus on (1) stepping over the ankle/calf/knee (see Fig. 23.4) (e.g. ‘imagine you are running through knee-high surf/long-grass’), (2) flat-foot strike directly under centre of mass (see Fig. 23.4), (3) ‘bouncing’ vertically, and (4) circular and symmetrical leg cycles (see Fig. 23.5).

Straight-Leg Scissors

The straight-leg scissor bound drill focuses on the latter part of the late-swing phase of a sprint cycle, emphasising the long-lever ‘down-strike’, pre-activation of posterior leg musculature prior to ground contact, and hip projection during the stance phase. Additionally, this drill provides a specific plyometric stimulus for conditioning the hamstring musculature at long lengths. Coaching points during a straight-leg scissor bound should focus on (1) straight leg, (2) ‘snapping’ the leg/foot downwards and backwards, and (3) ‘bouncing’ vertically and horizontally (i.e. projecting the hip vertically and horizontally) (Fig. 23.6).

Warm-Ups and ‘Bleed’ Drills

Dribbles and scissor drills are best utilised during the warm-ups of sprint and strength sessions, endurance sessions and races (see Table 23.4). Towards the end of the warm-up, ‘bleed’ drills can be incorporated to blend the dribble or scissor drill into the full sprint cycle. For example, a dribble-bleed would start off as a knee-dribble (see Fig. 23.5c), however once the athlete is dribbling at a high speed (i.e. around 20–30 m), the knee-dribble is smoothly ‘bleded’ into a full sprint cycle. The kinaesthetic feeling of rhythmically stepping over the knee and bouncing off the ground during a knee-dribble is instantaneously incorporated into a full sprint cycle.

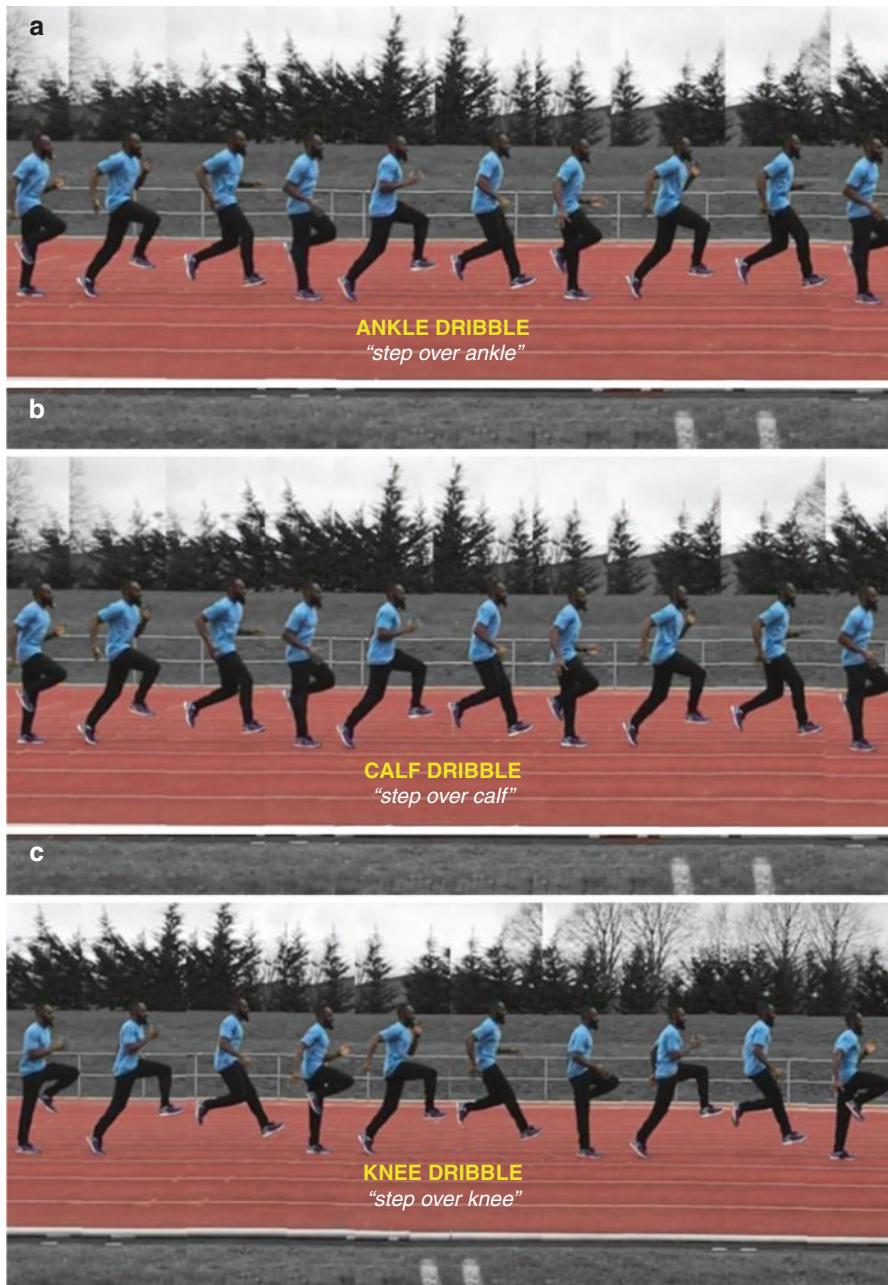


Fig. 23.5 The circular and symmetrical leg cycle during the (a) ankle-dribble, (b) calf-dribble, (c) knee-dribble



Fig. 23.6 The leg cycle during a straight-leg scissor bound

Table 23.3 Sprint training and warm-up suggestions for distance runners during GPP, SPP and competition

Intensity	Maximal (high)
Frequency per week	1–2
Reps	5–10
Recovery	3–5 min
GPP	5–10 × [10–20 m accelerations or sub-max flying runs]
SPP/competition	5 × [30–40 m sprints or flying runs]
Warm-up	<p>2 × 20 m:</p> <ul style="list-style-type: none"> – Ankle-dribble – Calf-dribble – Knee-dribble – Straight-leg scissors – Dribble-bleed – Scissor-bleed

Sprint Training

To prepare distance runners for running at maximal velocities, sprinting should be introduced in a gradual and progressive manner. One approach to speed training is to initially focus on short, maximal accelerations (from a standing start) during the GPP phase (i.e. 10–20 m), and progress by building sprint distances every micro-/mesocycle until maximum-velocity is attained (i.e. 30 or 40 m). Another approach is to perform ‘flying sprints’ from a rolling start, with a longer sub-maximal (and less intensive) acceleration. This type of run-up allows maximum-velocity to be reached without excessive anaerobic cost and fatigue. Once maximum-velocity is attained, it is held for a set distance (i.e. 10 m). This session can be introduced in a progressive manner during GPP, where the athlete initially focuses on accelerating to 80% of maximum, and progressing their velocity every mesocycle (see Table 23.4). Once the athlete is conditioned for sprinting at maximum-velocity for 10 m, this distance can be gradually progressed (i.e. 20–30 m). To ensure speed development, it is important that each repetition consists of maximal effort, with full recoveries in between repetitions (5–10 repetitions, with 3–5 min recovery between). Sprint development requires quality, not quantity (see Table 23.3).

Programming

There has been a growth in the literature investigating the compatibility of strength and aerobic training (i.e. concurrent training) and the effect on the mechanisms underpinning protein synthesis [36, 37]. Therefore, it is important that coaches are aware of this potential ‘interference effect’ associated with combined strength and endurance training. While it has been demonstrated that high volume endurance training may compromise the absolute gains in maximal-strength [38], the neuromuscular gains achieved through regular strength training in endurance athletes have been shown to be sufficient for improving endurance performance. However, for optimal adaptation and development of a distance runner, speed and strength sessions (both combined together, see Table 23.4) should be carefully programmed around ‘intense’ aerobic endurance training (i.e. zone 4 and 5, $>LT2 > 80\% \dot{V}O_{2\max}$) —possibly on the same days as recovery sessions or low-intensity aerobic training. Research has found that successful elite distance runners spend approximately 80% of their training in these low-intensity, aerobic-dominant training zones [39], therefore giving opportunities to programme strength and speed training sessions without hampering the preparation or recovery of more specific and intense aerobic sessions.

For long-term neuromuscular development in distance runners, it is advised to prescribe a mixed-methods approach to programming, utilising all strength-qualities (maximal-, explosive- and reactive-strength) and sprint training methods (technical drills, maximum-velocity sprinting) within the same session [13, 14]. However, the proportion and volume of each strength quality (including speed training) will differ depending on the training age of the athlete and the training phase of the macrocycle (i.e. general preparation phase [GPP], special preparation phase [SPP], competition)

Table 23.4 Strength and speed programming design during GPP, SPP and competition

	GPP	SPP	Competition
Warm-Up (Sprint Drills)		Sprint Drills (i.e. dribbles, straight-leg scissors, bleeds)	
1. Speed	Sub-max sprints (i.e. 80% of max V)	→ 10m ‘Flying’ sprints (i.e. 90% of max V)	→ 10m ‘Flying’ sprints (i.e. 100% of max V)
2. Reactive-Strength	Extensive Plyometrics (i.e. sub-max pogo-jumps)	→ Ext / Int Plyometrics (i.e. maximal pogo-jumps)	→ Intensive Plyometrics (i.e. tuck jumps)
3. Explosive-Strength		Countermovement Jumps (i.e. 3 × 3 – can be implemented between sets of squats)	
4. Maximal-Strength	Squats (full ROM)* (i.e. 3 × 8)	→ $\frac{1}{2}$ Squat* (i.e. 3 × 5)	→ $\frac{1}{4}$ Squat (Con / Iso)* (i.e. 3 × 3)
5. Assistance		Single-leg squats, hamstrings, glutes, core, calves (i.e. 1–5 exercises ‘circuit’ style, 8–15 repetitions)	

max V maximum-velocity, ext extensive, int intensive, ROM range of motion, con concentric, iso isometric

*Can be replaced with trap-bar deadlift or a single-leg squat alternative

(see Table 23.4). When programmed and coached appropriately, the combined speed and strength session (including sprint drills warm-up) should last no more than 45–60 min. For full-time distance runners, it is advised that the combined speed and strength session should be prescribed 1–2 times per week during the GPP and SPP, and once every 7–10 days during competition phases [7]. However, for experienced distance runners who are already ‘strong’ and have high force capabilities, there may need to be greater emphasis on intensive plyometrics and maximal-velocity sprinting to gain further improvements in speed, economy and $\dot{V}O_{2\max}$.

Summary

Exercise economy, $\dot{V}O_{2\max}$ and sprinting ability play a vital role in elite distance running performance. Research has shown that the neuromuscular adaptations from strength training can improve these key performance indicators. Therefore, strength and sprint training can be useful for improving elite distance running performance. For long-term strength and speed development, it is important to prescribe a mixed-methods approach to strength (maximal-, explosive- and reactive-strength) and speed programming (technical drills and maximum-velocity training). However, the focus of each strength quality, and the intensity of speed training prescribed, will depend on the phase of the macrocycle (i.e. GPP, SPP, competition) and the training age of the athlete. Additionally, for optimal adaptations, strength and speed sessions should be carefully programmed around ‘intense’ aerobic training and racing.

References

1. Saltin B, Åstrand PO. Maximal oxygen uptake in athletes. *J Appl Physiol*. 1967;23(3):353–8.
2. Ingham SA, Whyte GP, Pedlar C, et al. Determinants of 800m and 1500m running performance using allometric models. *Med Sci Sports Exerc*. 2008;40(2):345–50.
3. Sjödin B, Svedenhag J. Applied physiology of marathon running. *Sports Med*. 1985;2:83–9.
4. Paavolainen LM, Nummela AT, Rusko HK. Neuromuscular characteristics and muscle power as determinants of 5 km running performance. *Med Sci Sports Exerc*. 1999;31:124–30.
5. Beattie K, Kenny IC, Lyons M, Carson BP. The effect of strength training on performance in endurance athletes. *Sports Med*. 2014;44(6):845–65.
6. Spurrs RW, Murphy AJ, Watsford ML. The effect of plyometric training on distance running performance. *Eur J Appl Physiol*. 2003;89:1–7.
7. Beattie K, Carson BP, Lyons M, Rossiter A, Kenny IC. The effect of strength training on performance indicators in distance runners. *J Strength Cond Res*. 2017;31(1):9–23.
8. Berryman N, Maurel D, Bosquet L. Effect of plyometric vs. dynamic weight training on the energy cost of running. *J Strength Cond Res*. 2010;24(7):1818–25.
9. Johnston RE, Quinn TJ, Kertzer R. Strength training in female distance runners: impact on running economy. *J Strength Cond Res*. 1997;11(4):224–9.
10. Mikkola J, Rusko H, Nummela A, et al. Concurrent endurance and explosive type strength training improves neuromuscular and anaerobic characteristics in young distance runners. *Int J Sports Med*. 2007;28(7):602–11.
11. Saunders PU, Telford RD, Pyne DB, et al. Short-term plyometric training improves running economy in highly trained middle and long distance runners. *J Strength Cond Res*. 2006;20(4):947–54.

12. Støren O, Helgerud J, Støa EM, et al. Maximal strength training improves running economy in distance runners. *Med Sci Sports Exerc.* 2008;40:1089–94.
13. Haff GG, Nimphius S. Training principles for power. *Strength Cond J.* 2012;34(6):2–12.
14. Hansen D. Successfully translating strength into speed. In: Joyce D, Lewindon D, editors. *High-performance training for sports*. Leeds: Human Kinetics; 2014. p. 145–66.
15. Zatsiorsky VM, Kraemer WJ. *Science and practice of strength training*. Champaign: Human Kinetics; 2004.
16. Fletcher JR, Esau SP, MacIntosh BR. Changes in tendon stiffness and running economy in highly trained distance runners. *Eur J Appl Physiol.* 2010;110:1037–46.
17. Cormie P, McGuigan MR, Newton RU. Adaptations in athletic performance after ballistic power versus strength training. *Med Sci Sports Exerc.* 2010;42(8):1582–98.
18. Cormie P, McGuigan MR, Newton RU. Changes in eccentric phase contribute to improved stretch-shorten cycle performance after training. *Med Sci Sports Exerc.* 2010;42(9):1731–44.
19. Cormie P, McGuigan MR, Newton RU. Influence of strength on magnitude and mechanisms of adaptation to power training. *Med Sci Sports Exerc.* 2010;42(8):1566–81.
20. Seitz LB, Reyes A, Tran TT, de Villarreal EZ, Haff GG. Increases in lower-body strength transfer positively to sprint performance: a systematic review with meta-analysis. *Sports Med.* 2014;44(12):1693–702.
21. Stone MH, Cormie P, Lamont H, Stone M. Developing strength and power. In: Jeffreys I, Moody J, editors. *Strength and conditioning for sports performance*. New York: Routledge; 2016. p. 230–49.
22. Cormie P, McGuigan MR, Newton RU. Developing maximal neuromuscular power. Part 1—biological basis of maximal power production. *Sports Med.* 2011;41(1):17–38.
23. Wendler J. *5/3/1 forever—simple and effective programming for size, speed and strength*. London: Jim Wendler LLC; 2017. p. 24–34.
24. Rhea MR, Kenn JG, Peterson MD, Massey D, Simão R, Marin PJ, Favero M, Cardozo D, Krein D. Joint-angle specific strength adaptations influence improvements in power in highly trained athletes. *Hum Mov.* 2016;17(1):43–9.
25. McMaster DT, Gill N, Cronin J, McGuigan M. A brief review of strength and ballistic assessment methodologies in sport. *Sports Med.* 2014;44(5):603–23.
26. Cormie P, McCauley GO, Triplett NT, McBride JM. Optimal loading for maximal power output during lower-body resistance exercises. *Med Sci Sports Exerc.* 2007;39(2):340–9.
27. Newton RU, Laursen PB, Young W. Clinical exercise testing and assessment of athletes. In: Schwellnus MP, editor. *Olympic textbook of medicine in sport*. Oxford: Wiley-Blackwell; 2008.
28. Verkhoshansky Y, Verkhoshansky N. Special strength training manual for coaches. Rome: Verkhoshansky SSTM; 2011. p. 274.
29. Wild J, Bezodis N, Blagrove R, Bezodis IA. Biomechanical comparison of accelerative and maximum velocity sprinting: specific strength training considerations. *Strength Cond J.* 2011;21:23–36.
30. Pfaff D. Alternate methods for developing strength, power and mobility. 2008. <http://speed-endurance.com/2008/09/19/dan-pfaff-alternate-methods-for-developing-strength-power-and-mobility/>. Accessed June 2017.
31. Young WB. Laboratory assessment of athletes. *IAAF.* 1995;10(1):89–96.
32. Wiley RW, Davis IS. The effect of a hip-strengthening program on mechanics during running and during a single-leg squat. *J Orthop Sports Phys Ther.* 2011;41(9):625–32.
33. Sandford GN, Pearson S, Allen SV, Malcata RM, Kilding AE, Ross A, Laursen PB. Tactical behaviours in men's 800m olympic and world championship medallists: a changing of the guard. *Int J Sports Physiol Perform.* 2018;13(2):246–9.
34. Buchheit M, Laursen PB. High-intensity interval training, solutions to the programming puzzle: part I: cardiopulmonary emphasis. *Sports Med.* 2013;43(5):313–38.
35. McMillan S. Why we dribble. 2016. <http://spyre.co.za/dribbles/>. Accessed June 2017.
36. Baar K. Using molecular biology to maximise concurrent training. *Sports Med.* 2014;44:S117–25.

37. Schuman M, Pelttari P, Doma K, Karavirta L, Häkkinen K. Neuromuscular adaptations to same-session combined endurance and strength training in recreational endurance runners. *Int J Sports Med.* 2016;37(14):1136–43.
38. Wilson JM, Marin PJ, Rhea MR, Wilson SM, Loenneke JP, Anderson JC. Concurrent training: a meta-analysis examining interference of aerobic and resistance exercises. *J Strength Cond Res.* 2012;26(8):2293–307.
39. Seiler S, Tønnessen E. Intervals, thresholds, and long slow distance: the role of intensity and duration in endurance training. *Sportscience.* 2009;13:32–53. <http://www.sportsci.org/2009/ss.htm>. Accessed June 2017.



Strength Training for Cross-Country Skiers

24

Thomas Losnegard

Introduction

Remarkable changes have occurred in cross-country (XC) skiing in recent decades, with the introduction of races such as the sprint event and mass start, as well as better track preparation, improved skiing equipment, and changes in course profiles [1]. As an example, the race velocity in distance skiing (>10/15 km for women and men respectively) has increased by ~5–8% in World Cup races over the last decade and in sprint skiing (<1.8 km; ~3 min), a ~20% higher average velocity is evident compared to distance skiing [2]. Moreover, in World Championships and Olympics, five of six race events for each gender are sprints or mass starts and the placings are often determined by a final sprint. Therefore, the ability to conserve power for the final sprint and consequently perform supramaximal workloads is an important determinant of performance in today's XC skiing. Although aerobic endurance training has always been mandatory for skiers, the “high speed techniques,” such as double poling (DP) and the V2 skating technique, also demand well-developed upper-body power. Therefore, specific upper-body training, performed as speed, strength and muscular endurance training, has gained increased attention over the past decade [3–7]. This chapter therefore provides an updated synopsis of the demands for muscle strength in today's XC skiers, with a special focus on the upper body. It also provides an overview of the effect of training models in enhancing upper-body power, with a special emphasis on heavy strength training in endurance performance in highly trained XC skiers. In addition, alternative models such as sport-specific speed training and muscular endurance training are addressed. Finally, a practical application of efficient strength training is provided based on the distinctiveness of movement patterns in skiing techniques, and thus, the specificity of training for XC skiers.

T. Losnegard

Department of Physical Performance, Norwegian School of Sport Sciences, Oslo, Norway
e-mail: thomas.losnegard@nih.no

Performance in XC Skiing

XC skiing is a typical endurance sport where the average speed (m s^{-1}) for a required distance is mainly determined by energy turnover (J s^{-1}) and work economy (J m^{-1}) [8].

$$\text{Speed}(\text{m}\cdot\text{s}^{-1}) = \frac{\text{Energy turnover}(\text{J}\cdot\text{s}^{-1})}{\text{Work economy}(\text{J}\cdot\text{m}^{-1})}$$

Accordingly, a greater energy turnover (aerobic and/or anaerobic) and/or an improved work economy will increase speed and thus improve performance. Although it is widely accepted that aerobic energy turnover is closely related to performance in XC skiing (e.g., [9–11]), the importance of a high anaerobic energy turnover rate has gained increased attention in recent years (e.g., [12, 13]). In particular, sprints and mass starts require the ability to perform supramaximal workloads during parts of the races. Hence, the combination of a high aerobic power and anaerobic power/capacity coupled with an efficient technique is a distinctive feature of today's skiers [12, 13]. This complexity of energy sources used during races demands different training models to target specific adaptations. Although aerobic endurance training has always been mandatory, skiers have developed different strength training regimes over the years, aiming to optimize performance. It is well documented that skiers can initially increase their strength by 0.5–1.2% per session when they start systematic heavy strength training, despite their already large volume of endurance training [4, 6]. Further, increased cross-sectional area can be expected, at least in upper-body muscles, which seem as an important factor for achieving further strength gains [4]. However, in order to utilize the strength gain into enhanced skiing performance, the energy turnover and/or economy must be enhanced. The following section will discuss the potential effects of strength training on performance and show how strength training may influence skiers' energy turnover and work economy.

The Effect of Strength Training on Skiing Performance

An overview of the effect of heavy strength training on XC skiing performance is shown in Fig. 24.1. The early studies conducted by Hoff et al. [3, 14] and Østerås et al. [15] found large effects of heavy strength training on XC performance, while more recent investigations [4, 6, 16, 17] found mostly trivial effects. The reason for the discrepancy is unknown, but different outcome measures (i.e., time to exhaustion vs. constant duration tests) might explain some of the differences. In addition, testing equipment is an important factor when translating a specifically increased ability into actual performance. In most studies that found a “significant” effect of heavy strength training on performance (Fig. 24.1) [3, 4, 14, 15], a double poling ergometer was used. However, results from more sport-specific movements (such as rollerskiing outdoors) indicate that the effect of strength

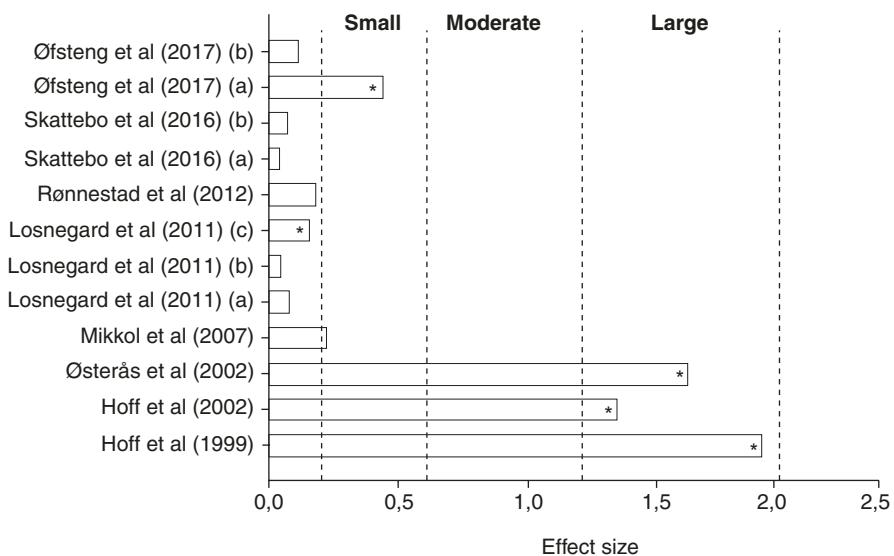


Fig. 24.1 The effect size of adding strength training to endurance training on performance in comparison to the control group. Calculated as the difference in change score between groups (raw data) standardized by the pooled standard deviation from baseline. *Significant differences from pre- to post-test between strength and control group ($P < 0.05$). Hoff et al. [3, 14] and Østerås et al. [15]: double poling ergometer with a time to exhaustion test (~ 4 min); Mikkola et al. [16]: 2-km time trial in double poling (~ 4.5 min); Losnegard et al. [4]: (a) 1.1 time trial classic style uphill (~ 4.5 min), (b) 1.3-km time trial freestyle uphill (~ 5 min), (c) double poling ergometer (5-min all-out); Rønnestad et al. [17]: 7.5-km time trial freestyle (~ 19 min); 6: (a) 3-min all-out double poling ergometer from “rested state”, (b) 3-min all-out double poling ergometer from fatigued state; [19]: (a) Time to exhaustion followed by a prolonged submaximal test in double poling on a roller ski treadmill. (b) Time to exhaustion in double poling in “rested state” on a roller ski treadmill

training is less pronounced [4, 16, 17]. This is probably attributed to the finding that rollerskiing outdoors demands a higher technical ability than a double poling ergometer, which in turn demands a higher technical ability than a strength test (e.g., more complex timing of force application). Thus, the effect of increased muscle strength on performance clearly reduces, and sometimes vanishes, when the exercise modes demand a higher degree of coordination of skiing movements.

The trivial effects shown in Fig. 24.1 could also be related to the duration of the performance tests. The nature of today’s competition format such as mass starts has increased the importance to conserve power for the final sprint, which has also been the interest in some recent studies [6, 18, 19]. Recently, Øfsteng et al. [19] investigated the effect of heavy strength training on DP performance in “rested state” and after a prolonged 90-min submaximal intensity. Although no significant effects were found in the “rested state”, the strength training group improved performance after submaximal intensity more than the control group (Fig. 24.1). Further, Børve

et al. [18] performed a similar study (DP performance test following 50-min submaximal test), but with focus on muscular endurance training (4×30 rep twice a week). Here, we found similar effects on DP performance as in Øfsteng et al. [19]. Taken together, these studies indicate that upper-body training (maximal strength or muscular endurance) could enhance “finishing abilities” after a prolonged exercise in XC skiers. However, the mechanisms behind these improvements are to date not clear and if these tests conducted on a treadmill are valid on snow needs to be further examined.

In a comprehensive study, aiming to investigate the effect of heavy strength training on XC skiing performance, we found a strong correlation between maximal strength and performance in females, whereas this relationship was trivial in men [4]. We argued that female skiers (and perhaps weaker male skiers) could benefit from adding strength training to their normal training. As differences in performance between gender are larger with exercises that involves a significant upper-body contribution [20], improved upper-body strength can potentially improve skiing performance more in female than in male skiers. Therefore, we conducted a new controlled study on elite junior female skiers (~16 years) and investigated their sprint abilities during both a rested 3-min all-out test and a 3-min all-out test after 27 min of DP on an ergometer [6]. Surprisingly, despite a significant increase in strength (~24% in 8 weeks), no beneficial but also no harmful effects of strength training was found on the 3-min performance tests, work economy, $\text{VO}_{2\text{max}}$, or 20-s all-out DP. We concluded that athletes and coaches should carefully consider whether young skiers should prioritize such training. Further, it was also found that skiers experienced the strength training as very demanding, indicating that an accumulated fatigue influenced the post-test. Thus, coaches should carefully plan and evaluate strength training in order to minimize the risk of unplanned “overload,” especially during the late preparation phase when the intensity of endurance training is increased. Hence, this study highlights what type of training young skiers should perform to optimize performance. In contrast to their senior counterparts, these athletes have limited time for training due to school and other activities in addition to the developmental factors accompanying puberty. It is well documented that aerobic energy turnover and work economy (including technique development) are the most important factors in achieving world-class level [9, 11, 13, 21, 22]. Clearly, these aspects must be prioritized and strength training may therefore be considered individually and perhaps differently (including endurance training) than in adult athletes.

For adult athletes, skiers have to plan their strength training in conjunction with their endurance training to maximize potential strength gains. Notably, strength training for XC skiers is preferably executed during the pre-season, while during the competition season body mass is reduced to optimize performance [22]. This is clearly challenging since muscle strength and muscle cross-sectional area are highly related [4]. Personal communications with world-class athletes and unpublished data from our lab indicate that the strength level is reduced in line with the anthropometrical changes.

Aerobic Energy Turnover

Aerobic energy turnover is the product of the maximal aerobic power ($\text{VO}_{2\text{max}}$) and the fractional utilization of $\text{VO}_{2\text{max}}$, also called the “performance VO_2 ”. A number of studies in various sports, including XC skiing, have shown that $\text{VO}_{2\text{max}}$ is not affected by heavy strength training e.g., [6, 17, 23]. The fractional utilization of $\text{VO}_{2\text{max}}$ is closely related to performance in numerous endurance sports such as running, on- and off-road cycling, and possibly XC skiing [24, 25]. Recent studies involving cycling suggested that the fractional utilization during a 40-min time trial was improved after adding heavy strength training [26]. Due to no changes in mitochondrial density, the authors proposed that the increased cross-sectional area of the muscles led to increased numbers of activated mitochondria and thus increased fractional utilization. In XC skiing, no data is available on the effect of strength training on fractional utilization $\text{VO}_{2\text{max}}$.

A unique aspect of XC skiing is the variety of techniques used during a competition, with different use of the upper and lower body. This affects the maximal aerobic power achieved in the sub-techniques, where skiers normally exhibit 3–10% lower peak aerobic power ($\text{VO}_{2\text{peak}}$) during ski skating and the DP technique than during running [27]. Therefore, for already highly trained XC skiers where the $\text{VO}_{2\text{max}}$ during a whole body exercise does not seem to change over time [22], reducing the “gap” between other techniques has been speculated to be one of the possible training benefits of increased upper-body training [28]. These aspects have received attention in recent decades, especially with increasing use of the V2 ski skating and DP techniques in certain terrains. The lower $\text{VO}_{2\text{peak}}$ in DP has been found to be related to intrinsic factors (e.g., O_2 -extraction) in the arm muscles compared to the legs, even in highly trained XC skiers [29]. It has also been proposed that the upper body has a great potential to increase its aerobic energy turnover rate, with a subsequently enhanced upper-body $\text{VO}_{2\text{peak}}$, in response to intensive endurance training [29]. However, to date no studies have been able to demonstrate such an effect [5, 18, 30]. In addition to intrinsic factors, the muscle mass involved is a limiting factor for $\text{VO}_{2\text{peak}}$ in many exercises [31], and in DP specifically [32]. Hegge et al. [32] investigated the $\text{VO}_{2\text{peak}}$ in DP with different muscle masses involved and found that the $\text{VO}_{2\text{peak}}$ increased sequentially with increased body mass contributions. Hence, theoretically, an increased muscle mass could increase the $\text{VO}_{2\text{peak}}$ and reduce the “gap” between sub-techniques such as DP or skating and running. Losnegard et al. [4] found that 12 weeks of heavy strength training increased trunk lean body mass in XC skiers. Interestingly, the $\text{VO}_{2\text{peak}}$ in skating also increased with no changes in running $\text{VO}_{2\text{max}}$. However, later studies have not verified this assumption [6, 17] and the findings should therefore be approached with caution. In summary, little data supports the suggestion that specific upper-body training in general (heavy, explosive or muscular endurance) leads to enhanced $\text{VO}_{2\text{peak}}$ in skiing sub-techniques.

Anaerobic Energy Turnover

Anaerobic energy turnover is divided into anaerobic power and anaerobic capacity. While anaerobic power is an important determinant of performance during short spurts of activity and acceleration, anaerobic capacity is more related to performance in middle distance competitions [33]. Due to the nature of XC skiing competitions, with repeated high-intensity periods, the O₂-demand is well beyond VO_{2peak} during parts of the competition [12, 13, 34–37]. This influences the energy system contribution during a race and suggests that anaerobic power and capacity are important determinants of performance. Losnegard et al. [12] found a strong correlation between performance and accumulated oxygen deficit ($\Sigma\text{O}_2\text{-deficit}$) in a simulated sprint race on a rollerski treadmill in a group consisting of long-distance (>50 km), distance (>15 km), and sprint skiers (<1.8 km). Moreover, sprint skiers have a higher body mass and body mass index than distance skiers due to the nature of the competition format and subsequently the race demands [2, 13]. Since $\Sigma\text{O}_2\text{-deficit}$ is related to the muscle mass involved in the exercise [38, 39], long-term heavy strength training with a subsequent increase in muscle cross-sectional area could increase the $\Sigma\text{O}_2\text{-deficit}$. Moreover, the total volume of strength and speed training in international-level sprint skiers seems to be significantly higher compared to international-level distance skiers (~ 12% vs. 7% of total training time) in the preparation phase (6 months before the season), but similar with respect to total time of training during the year [2]. Thus, it can be suggested that some of the differences in $\Sigma\text{O}_2\text{-deficit}$ (and body mass) between skiers are related to differences in training focus regarding maximal strength, speed, and endurance training.

Several studies in XC skiing have investigated the relationship between “strength” and short performance tests where anaerobic power turnover represents the main energy source [6, 4, 13, 40–42]. Sandbakk et al. [13] investigated physiological and training differences between world-class and national class sprint skiers and found that acceleration (30-m test) and maximal strength did not differ between groups. This is supported by the findings of Losnegard et al. [4] who found no effect of heavy strength training on the acceleration phase during skating on roller skis. However, a tendency towards a reduced time during a 100-m test for the strength training group was found, indicating that strength training could potentially improve maximal speed [4]. Stöggel et al. [41] analyzed the relationship between general strength and “maximal speed” (test duration of ~60 s) with related kinetic and kinematical variables. They concluded that maximal strength had only a low to moderate correlation with “maximal speed,” whereas timing of the force application was the main discriminating factor between different levels of skiers. However, they proposed that strength ability is technique dependent, indicating that movement pattern is an important factor to consider during strength training.

Work Economy

The importance of work economy is emphasized by the finding of a close relationship with performance in groups of heterogeneous XC skiers (e.g., [43]). Further,

recent studies have shown that a within subject change in work economy (O_2 -cost), based on changes in equipment and technique, leads to enhanced speed at $VO_{2\max}$ and thus improved performance [44, 45]. Several studies in various sports indicate that both intrinsic factors (muscle fiber types, neuromuscular characteristics) and biomechanical factors (technique) contribute significantly to the variation in exercise economy seen between highly trained subjects (see review by [23]). Further, it has been shown that strength training influences work economy in endurance sports such as cycling [46, 47] and running [23]. In XC skiing, Mikkola et al. [16], Østerås et al. [15], and Rønnestad et al. [17] showed significant reductions in the O_2 -cost between pre- and post-tests in the strength groups, but the changes did not significantly differ from that of the control groups. Skattebo et al. [6], Carlsson et al. [48], Øfsteng et al. [19], and Losnegard et al. [4] found no effect of strength training on work economy on a double poling ergometer, double poling or ski skating on a rollerski treadmill. In addition, Hoff et al. [3, 14] used unconventional methods to measure work economy and it has recently been argued that they actually did not measure the O_2 -cost (see Skattebo et al. [6] for details). Overall, no study has found a convincing beneficial effect of heavy strength training on work economy in XC skiing. The discriminating findings between endurance sports might be related to the fact that XC is an extremely technically demanding exercise, involving both arms and legs to different extents. Moreover, in elite skiers it has been shown that the O_2 -cost is typically reduced by ~3% during the preparation phase with a “traditional Norwegian training regime.” In this period, skiers included ~7% strength training as part of the total training volume [22], although it should be noted that no clear evidence for a “cause-effect” exists. Nevertheless, the reduced O_2 -cost corresponds to 0.5% per month or 1–1.5% during a typical strength training intervention period (8–12 weeks) used in research. This implies that an eventual effect of strength training is difficult to detect, and that future research should use appropriate methods to evaluate whether such effects exist.

Practical Recommendations

In order to elicit the desired physical adaptations, it is important to evaluate correct muscle use and movement pattern before implementing strength training. In XC skiing, DP and V2 skating are the most-used techniques in races and are both very technically demanding exercises. Here, the joints are engaged in a sequential pattern before and during the poling phase to optimize propulsion and transfer potential and rotational energy as forward kinetic energy (e.g., [44, 49]). The upper-body muscles are therefore engaged in a “first in-first out pattern” involving (I) the abdominal muscles and hip extensors, followed by (II) the shoulder extensors latissimus dorsi, teres major, delta and pectoralis major, and (III) the shoulder and elbow extensor triceps brachii [49–51]. Such timing of force application is, thus, considered one of the most important characteristics of effective technique and resulting performance [41, 45]. To optimize strength training it is therefore necessary to (I) elicit an exercise mode covering the correct muscle use and (II) simulate the specific movement

patterns used in the respective techniques. During indoor maximal strength training, Losnegard et al. [4] used two relatively simple exercises: “seated pull-down” and “standing double poling.” These two exercises served as main exercises and supplemental exercises for core stability (including the use of Swiss balls, sling exercises, and various mat exercises) as additional training models either before or after the main program.

As stated previously, it is generally agreed that “stronger is not necessarily better” in optimizing performance in XC skiing [4, 6, 13, 41]. Hence, for skiers who already have high strength levels, the overall goal might be to maintain maximal strength and improve other physiological or technical mechanisms. One factor of interest is the metabolic response during DP, which seems to be different for the arms and legs [29, 52, 53], indicating that intense upper-body endurance training may increase the arms’ ability to extract oxygen and thus enhance DP performance. To enhance muscular endurance, the number of repetitions is high, while the loads are relatively low (20–100 reps/set; [54]). Such training for endurance performance has received attention in various sports including running [55, 56] and rowing [57, 58] as it seems to target different muscular and neurological adaptations compared to maximal strength training [54]. Specifically for XC skiing, Nilsson et al. [5] showed that 20-s or 180-s interval training in a DP ergometer increased both 30-s and 6-min power output in well-trained XC skiers, while Vandbakk et al. [30] demonstrated increased time to exhaustion after 8 weeks of 30-s DP intervals. The short duration speed training (“explosive”; >30 s) is a widely used training model for competitive XC skiers and could serve as a training model to maintain or enhance performance. However, such training methods are relative new in XC skiing, and further studies are encouraged to develop such models (combined with technique training) directly for XC skiing.

Carlsson et al. [48] tested two different training regimes in junior skiers (adding heavy strength training or interval training on a ski ergometer to their normal training routines) and found that both groups improved maximal speed during DP on a treadmill. However, there were no differences between groups in DP VO_{2peak}, maximal speed, or work economy. Moreover, Børve et al. [18] showed that replacing part of high-intensity running intervals with training using the “standing double poling” exercise, 4 × 30 reps twice a week, improved well-trained skiers’ finishing abilities during a simulated race on a rollerski treadmill. Further, even though the aim of the training was to increase muscular endurance, the strength gain (1RM) per session was in the range to studies using heavy strength training for XC skiers with similar strength exercise mode (0.6% vs. 0.5–1.2% per session) [4, 6, 17]. This implies that low-resistance strength training with high mobilization could be an alternative to heavy strength training in well-trained skiers, at least for short-term adaptations prior to competitions or during short block periodization. Together, these studies indicate that short-term upper-body endurance training may be a promising training model that could have direct applications for well-trained skiers aiming to improve their DP performance. From a practical point of view, outdoor rollerskiing with extra weight (e.g., a weight-west), uphill

Table 24.1 Example of a 6-week training program for heavy strength training

Week	1–2	3–4	5–6
Day 1 (sets/reps)	4/10RM	4/8RM	4/6RM
Day 2 (sets/reps)	4/6RM	4/5RM	4/4RM

Note: RM; repetition maximum. When athletes manage more repetitions than planned, the loads increase. Test of 1RM is performed before and after the training period

Table 24.2 Example of a 6-week muscular endurance training program

Week	1–2	3–4	5–6
Day 1 (sets/reps)	4/40	4/35	4/30
Day 2 (sets/reps)	4/30	4/25	4/20

Note: Loads represent 60–70% of 1RM, depending on the level of the athletes. Tests of 1RM/60% of 1RM are performed before and after the training period

skiing or slow resistance (manipulation of rollerski wheels) might serve as appropriate exercise modes to enhance sport-specific “muscular endurance training” for XC skiers.

A detailed training program for strength and muscular endurance training, respectively, as used by world-class skiers, is presented in Tables 24.1 and 24.2. Both programs consist of a 6-week period in a linear periodized fashion.

Summary

This chapter provides an updated review, based on scientific evidence, of the specific needs and effects of strength training on performance in high-level cross-country skiing. Based on the available literature, a certain level of strength is necessary for optimizing performance in XC skiing, based on skiers’ race preferences and techniques. In sprint skiing, a higher level of strength seems necessary than in distance skiing due to the ~20% higher average speeds and very high intermittent workloads. Further, the strength level seems to be dependent on technique with respect to different contributions from the upper and lower body. Specifically, the V2 ski skating and classic DP techniques are the major techniques used in today’s races. These techniques demand well-developed upper-body power; therefore, developing specific upper-body training seems important. However, most studies investigating the effect of heavy strength training have shown trivial effects on performance in XC skiing, implying that a substantial individual variation exists. These findings emphasize that in general “stronger is not necessarily better” in optimizing performance in XC skiing. Coaches and athletes are therefore encouraged to develop training programs that include: (I) ways to combine strength training with skiers’ endurance training to minimize the risk of unplanned overload and subsequently achieve optimal performance development; (II) training stimuli (heavy, explosive or muscular endurance) based on the needs of the individual skier; (III) sport-specific strength exercises designed to stimulate correct muscle use in the required

techniques, but simple enough to achieve the necessary overload; and (IV) ways to translate the movement patterns and timing of force applications needed in specific techniques to strength exercises to optimize technique.

Acknowledgements The author thanks Prof Øyvind Sandbakk for valuable comments on the manuscript and Ph.D. student Øyvind Skattebo for his ideas to Fig. 24.1 in this chapter.

References

1. Sandbakk Ø. The evolution of champion cross-country-skier training: from Lumberjacks to Professional Athletes. *Int J Sports Physiol Perform.* 2017;12(2):254–9. <https://doi.org/10.1123/ijsspp.2016-0816>. Epub 2017 Jan 17.
2. Losnegard T, Hallén J. Physiological differences between sprint- and distance-specialized cross-country skiers. *Int J Sports Physiol Perform.* 2014;9(1):25–31. <https://doi.org/10.1123/ijsspp.2013-0066>.
3. Hoff J, Helgerud J, Wisløff U. Maximal strength training improves work economy in trained female cross country skiers. *Med Sci Sports Exerc.* 1999;31(6):870–7.
4. Losnegard T, Mikkelsen K, Ronnestad BR, Hallén J, Rud B, Raastad T. The effect of heavy strength training on muscle mass and physical performance in elite cross country skiers. *Scand J Med Sci Sports.* 2011;21(3):389–401.
5. Nilsson J, Holmberg HC, Tveit P, Hallén J. Effects of 20-s and 180-s double poling interval training in cross-country skiers. *Eur J Appl Physiol.* 2004;92:121–7. <https://doi.org/10.1007/s00421-004-1042-4>.
6. Skattebo Ø, Hallen J, Rønnestad BR, Losnegard T. Upper body heavy strength training does not affect performance in junior female crosscountry skiers. *Scand J Med Sci Sports.* 2015;29:1007–16. <https://doi.org/10.1111/sms.12517>.
7. Terzis G, Stattin B, Holmberg HC. Upper body training and the triceps brachii muscle of elite cross country skiers. *Scand J Med Sci Sports.* 2006;16:121–6. <https://doi.org/10.1111/j.1600-0838.2005.00463.x>.
8. di Prampero PE, Atchou G, Brückner JC, Moia C. The energetics of endurance running. *Eur J Appl Physiol Occup Physiol.* 1986;55(3):259–66.
9. Ingjer F. Maximal oxygen uptake as a predictor of performance ability in women and men elite cross-country skiers. *Scand J Med Sci Sports.* 1991;1(1):25–30.
10. Saltin B, Astrand PO. Maximal oxygen uptake in athletes. *J Appl Physiol.* 1967;23(3):353–8.
11. Sandbakk Ø, Hegge AM, Losnegard T, Skattebo Ø, Tønnessen E, Holmberg HC. The physiological capacity of the world's highest ranked female cross-country skiers. *Med Sci Sports Exerc.* 2016;48(6):1091–100.
12. Losnegard T, Myklebust H, Hallén J. Anaerobic capacity as a determinant of performance in sprint skiing. *Med Sci Sports Exerc.* 2012;44(4):673–81.
13. Sandbakk O, Holmberg HC, Leirdal S, Ettema G. The physiology of world-class sprint skiers. *Scand J Med Sci Sports.* 2011;21(6):e9–16.
14. Hoff J, Gran A, Helgerud J. Maximal strength training improves aerobic endurance performance. *Scand J Med Sci Sports.* 2002;12(5):288–95.
15. Østerås H, Helgerud J, Hoff J. Maximal strength-training effects on force velocity and force-power relationships explain increases in aerobic performance in humans. *Eur J Appl Physiol.* 2002;88(3):255–63.
16. Mikkola JS, Rusko HK, Nummela AT, Paavolainen LM, Häkkinen K. Concurrent endurance and explosive type strength training increases activation and fast force production of leg extensor muscles in endurance athletes. *J Strength Cond Res.* 2007;21(2):613–20.
17. Rønnestad BR, Kojedal O, Losnegard T, Kvamme B, Raastad T. Effect of heavy strength training on muscle thickness, strength, jump performance, and endurance performance in well-trained Nordic Combined athletes. *Eur J Appl Physiol.* 2012;112(6):2341–52.

18. Børve J, Jevne SN, Rud B, Losnegard T. Upper-body muscular endurance training improves performance following 50 min of double poling in well-trained cross-country skiers. *Front Physiol.* 2017;22(8):690.
19. Øfsteng S, Sandbakk Ø, van Beekvelt M, Hammarström D, Kristoffersen R, Hansen J, Paulsen G, Rønnestad BR. Strength training improves double-poling performance after prolonged submaximal exercise in cross-country skiers. *Scand J Med Sci Sports.* 2017;28(3):893–904. <https://doi.org/10.1111/sms.12990>.
20. Sandbakk Ø, Ettema G, Holmberg HC. Gender differences in endurance performance by elite cross-country skiers are influenced by the contribution from poling. *Scand J Med Sci Sports.* 2014;24(1):28–33.
21. Sandbakk Ø, Losnegard T, Skattebo Ø, Hegge A, Tønnesen E, Kocbach J. Analysis of classical time-trial performance and technique-specific physiological determinants in elite female cross-country skiers. *Front Physiol.* 2016b;7:326. <https://doi.org/10.3389/fphys.2016.00326>.
22. Losnegard T, Myklebust H, Spencer M, Hallén J. Seasonal variations in VO₂max, O₂-cost, O₂-deficit and performance in elite cross-country skiers. *J Strength Cond Res.* 2013;27(7):1780–90.
23. Saunders PU, Pyne DB, Telford RD, Hawley JA. Factors affecting running economy in trained distance runners. *SportsMed.* 2004;34:465–85. <https://doi.org/10.2165/00007256-200434070-00005>.
24. Costill DL, Thomason H, Roberts E. Fractional utilization of the aerobic capacity during distance running. *Med Sci Sports Exerc.* 1973;5(4):248–52.
25. Impellizzeri FM, Marcora SM, Rampinini E, Mognoni P, Sassi A. Correlations between physiological variables and performance in high level cross country off road cyclists. *Br J Sports Med.* 2005;39(10):747–51.
26. Vikmoen O, Ellefsen S, Trøen Ø, Hollan I, Hanestadhaugen M, Raastad T, Rønnestad BR. Strength training improves cycling performance, fractional utilization of VO₂max and cycling economy in female cyclists. *Scand J Med Sci Sports.* 2016;26(4):384–96.
27. Losnegard T, Hallén J. Elite cross-country skiers do not reach their running VO₂max during roller ski skating. *J Sports Med Phys Fitness.* 2014;54(4):389–93.
28. Sandbakk Ø, Holmberg HC. Physiological capacity and training routines of elite cross-country skiers: approaching the upper limits of human endurance. *Int J Sports Physiol Perform.* 2017;12(8):1003–11. <https://doi.org/10.1123/ijsspp.2016-0749>.
29. Rud B, Secher NH, Nilsson J, Smith G, Hallen J. Metabolic and mechanical involvement of arms and legs in simulated double pole skiing. *Scand J Med Sci Sports.* 2014;24:913–9.
30. Vandbakk K, Welde B, Kruken AH, Baumgart J, Ettema G, Karlset T, et al. Effects of upper-body sprint-interval training on strength and endurance capacities in female cross-country skiers. *PLoS One.* 2017;12:e0172706. <https://doi.org/10.1371/journal.pone.0172706>.
31. Bergh U, Kanstrup IL, Ekblom B. Maximal oxygen uptake during exercise with various combinations of arm and leg work. *J Appl Physiol.* 1976;41(2):191–6.
32. Hegge AM, Bucher E, Ettema G, Faude O, Holmberg HC, Sandbakk Ø. Gender differences in power production, energetic capacity and efficiency of elite cross-country skiers during whole-body, upper-body, and arm poling. *Eur J Appl Physiol.* 2016;116(2):291–300.
33. Spencer M, Gastin PB. Energy system contribution during 200- to 1500-m running in highly trained athletes. *Med Sci Sports Exerc.* 2001;33(1):157–62.
34. Karlsson Ø, Gilgien M, Gløersen ØN, Rud B, Losnegard T. Exercise Intensity During Cross-Country Skiing Described by Oxygen Demands in Flat and Uphill Terrain. *Front. Physiol.* 2018;9:846. <https://doi.org/10.3389/fphys.2018.00846>.
35. Andersson E, Holmberg HC, Ørtenblad N, Björklund G. Metabolic responses and pacing strategies during successive sprint skiing time trials. *Med Sci Sports Exerc.* 2016;48(12):2544–54.
36. McGawley K, Holmberg HC. Aerobic and anaerobic contributions to energy production among junior male and female cross-country skiers during diagonal skiing. *Int J Sports Physiol Perform.* 2014;9(1):32–40. <https://doi.org/10.1123/ijsspp.2013-0239>.
37. Norman RW, Ounpuu S, Fraser M, Mitchell R. Mechanical power output and estimated metabolic rates of Nordic skiers during Olympic competition. *Int J Sports Biomech.* 1989;5:169–84.

38. Bangsbo J, Gollnick PD, Graham TE, Juel C, Kiens B, Mizuno M, Saltin B. Anaerobic energy production and O₂ deficit-debt relationship during exhaustive exercise in humans. *J Physiol.* 1990;422:539–59.
39. Bangsbo J, Michalsik L, Petersen A. Accumulated O₂ deficit during intense exercise and muscle characteristics of elite athletes. *Int J Sports Med.* 1993;14(4):207–13.
40. Stögg T, Lindinger S, Müller E. Biomechanical validation of a specific upper body training and testing drill in cross-country skiing. *Sports Biomech.* 2006;5(1):23–46.
41. Stögg T, Müller E, Ainegren M, Holmberg HC. General strength and kinetics: fundamental to sprinting faster in cross country skiing? *Scand J Med Sci Sports.* 2011;21(6):791–803.
42. Østerås S, Welde B, Danielsen J, van den Tillaar R, Ettema G, Sandbakk Ø. Contribution of upper-body strength, body composition, and maximal oxygen uptake to predict double poling power and overall performance in female cross-country skiers. *J Strength Cond Res.* 2016;30(9):2557–64. <https://doi.org/10.1519/JSC.0000000000001345>.
43. Ainegren M, Laaksonen MS, Carlsson P, Tinnsten M. Skiing economy and efficiency in recreational and elite cross-country skiers. *J Strength Cond Res.* 2012;27(5):1239–52.
44. Losnegard T, Myklebust H, Skattebo Ø, Stadheim HK, Sandbakk Ø, Hallén J. The influence of pole length on performance, O₂-cost and kinematics in double poling. *Int J Sports Physiol Perform.* 2017a;12(2):211–7.
45. Losnegard T, Myklebust H, Ehrhardt A, Hallén J. Kinematical analysis of the V2 ski skating technique: a longitudinal study. *J Sports Sci.* 2017b;35(12):1219–27.
46. Montero D, Lundby C. The effect of exercise training on the energetic cost of cycling. *Sports Med.* 2015;45(11):1603–18.
47. Rønnestad BR, Mujika I. Optimizing strength training for running and cycling endurance performance: a review. *Scand J Med Sci Sports.* 2014;24(4):603–12.
48. Carlsson T, Wedholm L, Nilsson J, Carlsson M. The effects of strength training versus ski-ergometer training on double-poling capacity of elite junior cross-country skiers. *Eur J Appl Physiol.* 2017;117(8):1523–32.
49. Holmberg HC, Lindinger S, Stögg T, Eitzlmair E, Müller E. Biomechanical analysis of double poling in elite cross-country skiers. *Med Sci Sports Exerc.* 2005;37(5):807–18.
50. Bojsen-Møller J, Losnegard T, Kempainen J, Viljanen T, Kalliokoski KK, Hallén J. Muscle use during double poling evaluated by positron emission tomography. *J Appl Physiol.* 2010;109(6):1895–903.
51. Lindinger SJ, Holmberg HC, Müller E, Rapp W. Changes in upper body muscle activity with increasing double poling velocities in elite cross-country skiing. *Eur J Appl Physiol.* 2009;106(3):353–63.
52. Calbet JA, Holmberg HC, Rosdahl H, van Hall G, Jensen-Urstad M, Saltin B. Why do arms extract less oxygen than legs during exercise? *Am J Physiol Regul Integr Comp Physiol.* 2005;289(5):R1448–58.
53. Calbet JA, Jensen-Urstad M, van Hall G, Holmberg HC, Rosdahl H, Saltin B. Maximal muscular vascular conductances during whole body upright exercise in humans. *J Physiol.* 2004;558(Pt 1):319–31.
54. Campos GE, Luecke TJ, Wendeln HK, Toma K, Hagerman FC, Murray TF, et al. Muscular adaptations in response to three different resistance-training regimens: specificity of repetition maximum training zones. *Eur J Appl Physiol.* 2002;88:50–60.
55. Mikkola J, Vesterinen V, Taipale R, Capostagno B, Häkkinen K, Nummela A. Effect of resistance training regimens on treadmill running and neuromuscular performance in recreational endurance runners. *J Sports Sci.* 2011;29:1359–71. <https://doi.org/10.1080/02640414.2011.589467>.
56. Sedano S, Marin PJ, Cuadrado G, Redondo JC. Concurrent training in elite male runners: the influence of strength versus muscular endurance training on performance outcomes. *J Strength Cond Res.* 2013;27:2433–43. <https://doi.org/10.1519/JSC.0b013e318280cc26>.
57. Ebben WP, Kindler AG, Chirdon KA, Jenkins NC, Polichnowski AJ, Ng AV. The effect of high-load vs. high-repetition training on endurance performance. *J Strength Cond Res.* 2004;18:513–7. <https://doi.org/10.1519/R-12722.1>.
58. Gallagher D, DiPietro L, Visek AJ, Bancheri JM, Miller TA. The effects of concurrent endurance and resistance training on 2,000-mrowing ergometer times in collegiate male rowers. *J Strength Cond Res.* 2010;24:1208–14.



Strength Training for Swimmers

25

Iñigo Mujika and Emmet Crowley

Concurrent training is nowadays an integral part of most competitive swimmers' preparation process, as they often combine their long, mostly aerobic swimming sessions with some form of strength training, either on dry-land or in the water. Swimming events at World Championships range in duration between approximately 21 s in the men's 50 m freestyle and 5 h 15 min in the women's 25 km open water event. This huge range in distance and duration, along with the contribution to swimming performance of explosive actions such as starts and turns, makes the relative contribution of aerobic and anaerobic pathways to power production highly variable. Therefore, training to improve both muscle strength and aerobic endurance seems to be essential to enhance competitive swimming performance.

Interest of Strength Training for Swimmers

To achieve competitive success at national or international level, swimmers must include a year-round resistance training programme to either maintain or increase strength and power, improve movement patterns, and limit the risk of injury [1, 2]. The application of muscular force in swimming results in a horizontal displacement

I. Mujika (✉)

Department of Physiology, Faculty of Medicine and Odontology,
University of the Basque Country, Leioa, Basque Country, Spain

Exercise Science Laboratory, School of Kinesiology, Faculty of Medicine,
Universidad Finis Terrae, Santiago, Chile
e-mail: inigo.mujika@inigomujika.com

E. Crowley

Biomechanics Research Unit, Department of Physical Education and Sport Sciences,
University of Limerick, Limerick, Ireland

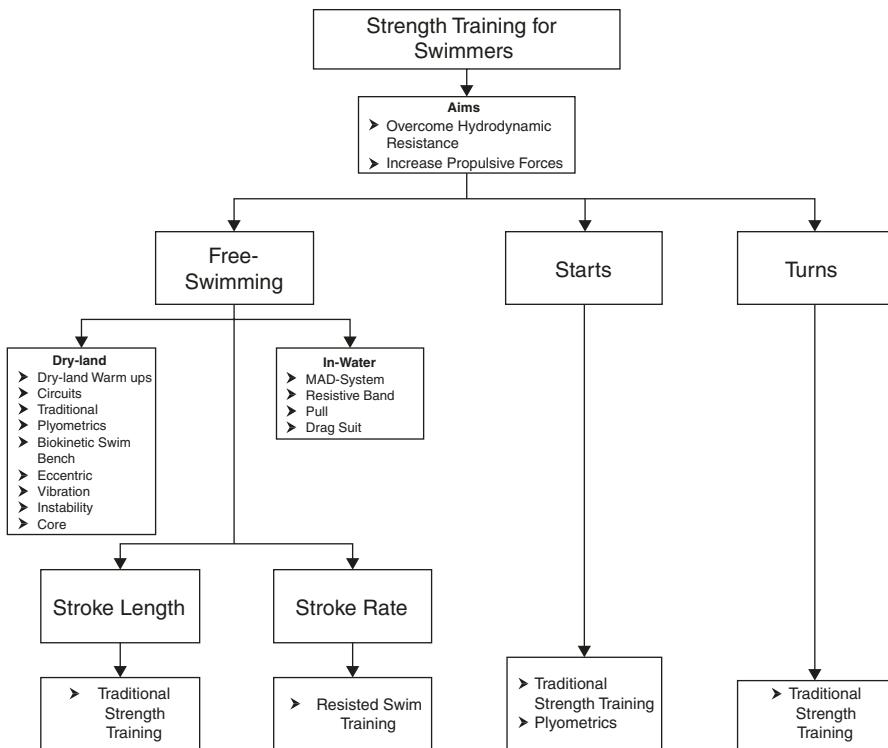


Fig. 25.1 Illustration of the strength training methods prescribed to improve swimming performance and results from the literature

of the athlete at a velocity proportional to the magnitude, direction, and duration of the resulting force. The main aim of the mechanical work performed by a swimmer is to overcome hydrodynamic resistance, which increases proportionally with the square of velocity, whereas the metabolic power required is proportional to the cube of the velocity. Therefore, any increase in swimming velocity demands a proportional increment of muscular force to overcome active drag and increase propulsive force, suggesting that muscular strength could be considered a performance determining factor in swimming [3].

Increments in muscular strength should theoretically translate into increased ability to generate propulsive force in the water, but technical aspects of swimming stroke mechanics will also determine the extent to which increased force transfers into faster swimming velocity [4–10] (Fig. 25.1). In this respect, it is important to keep in mind that strength training for swimmers should complement, not replace, sport-specific in-water training, and it should enhance, not hinder, the swimmer's in-water sessions by improving the quality of training, contributing to recovery and reducing the risk of overuse injury [2].

Impact of Strength and Power on Swimming Performance

Strength training is employed to manipulate the force-velocity curve and the ability to apply large amounts of muscular force under sport-specific conditions. A positive transfer to swimming performance should be achieved through improvements in both physiological and biomechanical parameters. Upper-body strength in particular is imperative in swimming, as most of the propulsive forces [11–13] and swimming velocity [11, 14–16] are generated by the upper-body musculature. Indeed, Carl et al. [17] reported a strong correlation between one repetition maximal lift (1RM) for the bench press, in-water force generation as measured during tethered swimming, and a timed 22.9 m swim. Such correlations were particularly relevant in male swimmers. Leg press 1RM, on the other hand, showed a weak correlation with swimming performance and did not correlate with tethered swimming force. Morouço et al. [18] assessed the mean power of the propulsive phase in three dry-land tests (squat, concentric phase of the bench press and latissimus pull down back), and analysed their associations with force production in water (mean force production during 30 s maximal effort tethered swimming in front crawl using whole body, arms only, and legs only) and swimming velocity in a maximal bout of 50 m front crawl. Mean propulsive power of bench press and latissimus pull down showed moderate–strong relationships with mean force production in whole body and arms only, whereas swimming performance was related with mean power of latissimus pull down back. The authors concluded that latissimus pull down back is the dry-land test most related with swimming performance, whereas bench press best related with force production in-water arms only, and work during counter-movement jump with tethered forces legs only. These and other similar findings [19] emphasized the need for separate evaluation of arms' and legs' force-velocity characteristics and the consideration of these measures in training design.

However, an increase in force generation capacities needs to be performed in a swimming-specific manner. Neuromuscular adaptations such as improved motor unit recruitment, synchronization, co-contraction, rate coding, intra- and inter-neuromuscular coordination, and neural inhibition have been thought to be responsible for an improvement in swimming performance. Whether a transfer-training method, based on a combination of dry-land weight training immediately followed by maximum velocity swimming could be a useful means to increase swimming power requires confirmation [20].

Pool swimming is comprised of three distinct phases: free swimming, starts, and turns (Fig. 25.1). The impact of strength training on free swimming performance has been widely researched. A recent review by Crowley et al. [21] reported that low volume, high velocity and/or force, and swim-specific strength training programmes showed a positive transfer to swimming performance, but the lack of high quality methodological studies using elite swimmers makes the literature hard to interpret. In addition, in spite of the similarities between the arm actions

in dry-land swim simulations and sprint swimming, only the power measurements made in the water are specific to the propulsive forces of front crawl swimming. Besides, the power contribution from each limb [22, 23], as well as intra-cycle force production and power output vary during different propulsive phases of front crawl swimming [24, 25].

Starts

Swimming starts are comprised of the unique coordinative effort of reaction time, vertical forces, and horizontal forces. The key component of start performance is lower-body strength, which is strongly correlated to swimming start performance [26]. The peak velocity reached during jumps with external loads relative to body mass is a good indicator of swimming start performance [27], and swimmers that possess the capacity to generate high levels of force have the ability to swim faster to 10 m [28]. Indeed, elite swimmers generate higher horizontal and vertical impulses than non-elite counterparts [29]. Lower-body plyometric interventions have resulted in positive effects on swimming start performance [30–32], which also highlights the key role of lower-body strength and power for start performance.

Turns

Swimming turning literature is sparse and does not provide a clear insight into the benefits of strength training for turning performance. Reduced drag forces, high peak propulsive forces, and increased wall push-off time produce the fastest turn performance, i.e. 2.5 m on approach and push off [33]. Lyttle et al. [34] studied the net forces created when towing swimmers while gliding and kicking underwater to establish an appropriate speed for initiating underwater kicking, and the most effective gliding position and kicking technique to be applied after a turn (prone streamline glide, lateral streamline glide, prone freestyle kick, prone dolphin kick, lateral dolphin kick). The optimal range of speeds to begin underwater kicking to prevent energy loss from excessive active drag was 1.9–2.2 m/s, but no differences were found between the prone and lateral streamline glide positions or between the three underwater kicking techniques. Faster swimmers, however, show greater squat jump power, counter-movement jump height, vertical height, and velocity at push off [35]. Elite male and female swimmers also possess ~30–50% superior leg extensor strength/power characteristics during dry-land jumping (particularly unloaded squat jump peak velocity and power) and in-water turning tasks when compared to sub-elite counterparts [36]. Short-term ballistic training and maximal strength training can enhance leg extensor force characteristics and improve aspects of the push-off stage of the swim turn in elite swimmers [37]. A well-planned and executed strength and conditioning programme is therefore needed for emerging and elite swimmers to develop these qualities [36, 37].

Impact of Strength Training on Swimming Biomechanical Parameters

Swimming velocity is the product of stroke length and stroke rate and has an important role to play in improving swimming performance. Factors such as training, intensity, physiological capabilities, race distances, sex and swimming technique influence the relationship between stroke length and rate [38–40], and coaches often prescribe training to improve either of these technical parameters [41–43]. Unfortunately, no research to date has specifically looked at improving either stroke length or stroke rate through the application of strength training.

Stroke length maintains swimming propulsive forces in the horizontal direction, improves swimming efficiency, and determines swimming velocity [13, 44–50]. Although some studies suggest that low repetition and high force strength training induced an increase in stroke length [51, 52], others showed no significant increase [10, 53], so further investigation is warranted. Nevertheless, real-life examples show that swimmers achieving the fastest times in the world have the greatest stroke length, which requires high levels of strength. Stroke rate has a great impact on swimming velocity over shorter duration events, such as 50 m performance [10, 46, 49, 54]. A training intervention using resisted swims can improve 100 m swimming performance, as the swimmer has to produce sufficient propulsive forces to move forward by increasing stroke rate, rather than being pulled back by the resisted band. In addition, a faster second half of the 100 m swimming performance suggests that resisted swims improve muscular strength endurance [48].

Concurrent Training in Swimming

Berryman et al. [55] recently assessed the net effects of strength training on middle- and long-distance performance through a meta-analysis of the available literature. Results indicated that the implementation of a strength training programme was associated with moderate performance improvements in running, cycling, cross-country skiing, and swimming. Such performance benefits were mainly due to improvements in the energy cost of locomotion, maximal force, and maximal power. Maximal force training (sets of 1–5 repetitions of isoinertial contractions at 80% of 1RM or more) and a combination of methods produced greater benefits than submaximal (sets of 6–25 repetitions of isoinertial contractions between 60 and 80% of 1RM) and maximal power (plyometric training, sprint training, and sets of 4–6 repetitions at the load that elicits maximal power during a specific isoinertial movement) training, and the beneficial effects on performance were consistent irrespective of the athletes' calibre. Strength training volume was associated with energy cost reductions, and concurrent programmes including more than 24 strength training sessions led to greater effects on energy cost than shorter programs. All sports included in the analyses, including swimming, seemed to benefit similarly from such a training strategy [55].

Dry-Land Strength Training

Improvements in a swimmer's strength and power are predominately generated during dry-land training (i.e. in the gym), but an adequate programme incorporating the right exercises can improve the in-water results attainable from strength and power training [1] (Fig. 25.1). Swimmers performing a combined intervention consisting of maximal strength and high-intensity interval endurance training twice per week over 11 weeks, in addition to their regular swimming training, improved dry-land strength, tethered swimming force and 400 m freestyle performance more than a control group that continued regular training within their teams. The improvement in 400 m performance correlated with the gain in tethered swimming force only in the female swimmers, and there were no changes in stroke rate and length, performance in 50 or 100 m freestyle, swimming economy or peak oxygen uptake. These results suggest that this type of strength training may be effective for improving middle-distance swimming performance [53].

Given the beneficial effects of strength training on anaerobic performance, a better understanding is needed of the relationship between strength training, anaerobic factors, and middle- and long-distance performance in endurance events in general and swimming events in particular. A better understanding is also needed regarding the influence of strength training duration. Berryman et al. [55] reported greater benefits on cost of locomotion after longer training protocols (>24 sessions), but the chronic effects of such a training regimen are less understood. More research is required to study the effects of different long-term periodization strategies to provide the athletes and coaches with detailed guidelines regarding, for example, the most appropriate timing for the implementation of strength development within the annual training plan [55].

In-Water Strength Training

Mujika et al. [56] reported on the training contents of a group of 18 elite 100 and 200 m swimmers over a 44-week season. Training volume in these swimmers ranged between 749 and 1475 km, 95% of which were swam at intensities below, at, or slightly above the onset of blood lactate accumulation. There was a huge variability in dry-land strength training, with some swimmers performing up to 40 h in the season, whereas some others performed no dry-land training at all. Interestingly, the amount of dry-land training bore no relationship with performance outcomes over the season. All swimmers, however, carried out large amounts of in-water submaximal strength training, such as arm pulling, kicking, and swim-specific strength training by swimming against an increased resistance to advance. Interestingly, swim-specific strength training seemed to have a negative impact on performance capacity in the short-run, but its medium- to long-term contribution to performance could not be determined [41].

Methods of Strength Training for Swimmers

Swimmers today include a wide variety of strength training practices in their preparation for competition. These include, but are not limited to, dry-land warm-ups, circuit training, traditional strength training, plyometrics, biokinetic swim bench training, measurement of active drag system (i.e. MAD-system), core training, resistive band training, pull training and drag suit training, eccentric overload training, vibration training, and instability training. A systematic review of the available controlled training intervention studies found indications that heavy strength training on dry-land (1–5 repetitions maximum with pull-downs for 3 sets with maximal effort in the concentric phase), or sprint swimming with resistance towards propulsion (maximal pushing with the arms against fixed points or pulling a perforated bowl) may be efficient for enhanced performance. Such strategies may also have positive effects on stroke mechanics, with largest effect size in 50 m freestyle after a dry-land strength training programme of 3 sets of 6 repetitions maximum in relevant muscle groups, and after resisted- and assisted-sprint training with elastic surgical tubes [57]. In the following section, we discuss the scientific evidence behind these training practices, where available, as well as their practical applications.

Dry-Land Warm-Ups

Dry-land warm-ups are an integral part of every elite swimming programme. They are prescribed for activation purposes as well as injury prevention. The inclusion of dry-land-based activation exercises before a race can improve freestyle sprint performance by 0.7–0.8% [58, 59]. The dry-land warm-up routine in these studies consisted of 3 × medicine ball (2 kg) throw downs, 3 × 10 s simulated underwater butterfly kick with an oscillation device above the swimmers head, and 3 × 0.4 m box jumps. The dynamic component of this warm-up routine would result in improved total body temperature, metabolic, neural, and psychological mechanisms [60]. This suggests that dry-land warm-ups are an important component of a swimmer's training schedule to compete at the highest level, and provide a great opportunity for both pre-habilitation and rehabilitation.

Circuit Training

Circuit training is included in many sports as an additional strength and aerobic stimulus. It encompasses a range of exercises and can be prescribed in various manners. The implementation of light loads (40–60% 1RM), brief rest intervals and repeated circuits, 3–5 sets, is a typical circuit training structure [61, 62]. Circuit training has been prescribed to improve body composition, muscular strength, muscular endurance, and cardiovascular fitness in recreational participants [63, 64].

Untrained individuals show large improvements in $\text{VO}_{2\text{max}}$ as a result of this type of training, but trained athletes show no improvement [65]. Similar outcomes are seen for power and strength measures. Although circuit training does not seem to provide clear improvements for elite athletes, it does provide several practical benefits, such as early season conditioning (aerobic, body composition, buffering capacity, etc.), structure for novice strength training swimmers, and time efficiency. Therefore, circuit training should not be overseen and can be an effective training tool for swimming programmes at the beginning of the season or for swimmers that require additional aerobic conditioning.

Traditional Strength Training

Traditional strength training is most frequently prescribed in elite swimming programmes and encompasses the prescription of conventional gym-based strength training exercises such as bench press, latissimus pull-downs, triceps extensions, triceps dips, bent arm flies, pull ups, and squats. Low volume, high velocity/force resistance training programmes result in significant improvements in swimming performance [21]. Indeed, Girold et al. [52] found a 2% increase in 50 m performance after 4 weeks of strength training; Strass [51] reported a 2.1% improvement and Girold et al. [10] a 2.8% increase after a 12-week programme. Strass [51] prescribed a power programme, whereas Girold et al. [10, 52] and Aspenes et al. [53] prescribed traditional strength training. Aspenes et al. [53] found large improvements in strength (20.7%) and this is not uncommon across all strength training programmes for swimmers and other sports. The need for high velocities during the concentric phase should be emphasized, as this can elicit greater neuromuscular adaptations and a higher recruitment of type II muscle fibres [66–68].

The practical application of traditional strength training programmes should be sport specific (e.g. joint angular ranges, muscles recruited, contraction mode, strength quality required), but specific training for muscular endurance, which is a critical component of swimming performance, does not need to be part of a strength training programme for swimmers. The focus should be on getting swimmers stronger and more powerful, while leaving the development of muscular endurance for the in-water swim training [1].

Plyometrics

Plyometrics is a sport-specific training modality used across a wide variety of sports, especially those requiring sprint and jumping performance, that utilizes the stretch-shortening cycle to produce high levels of force and power [69]. Plyometrics can improve swimming start performance and may also improve turning performance. The underlining principles of plyometrics require an eccentric contraction followed rapidly by a concentric contraction, therefore improving muscle function, coordination, and the direction of the resultant force [32]. Research by Rebutini

et al. [32] found that plyometric long jump training improved lower limb joint torque and improved swimming start performance. Bishop et al. [31] showed positive effects of an 8-week intervention period of plyometric training on swimming start performance through explosive power training. Potdevin et al. [30] found an increase in swimming velocity over 50 and 400 m swimming performance, but the influence of start performance is unknown. Adolescent swimmers' turning performance, on the other hand, did not seem to improve after a plyometric training programme [70].

Taken together, the above data suggest that plyometric training has a significant role to play in increasing swimming performance in general and start performance in particular. The large eccentric contribution due to plyometric training may also aid in kicking performance. Greater eccentric strength allows the swimmer to maintain greater knee and hip extension resulting in the retention of more water. However, it is important to include gradual progressions when prescribing plyometric training and the exercises should be specific and progressive in both intensity and volume [32].

Biokinetic Swim Bench

The biokinetic swim bench is a training tool used in many swimming programmes to simulate swimming techniques on dry-land [5]. The swimmer lies prone on a sliding bench with a slight incline, arms outstretched over his/her head and hands secured in hand-paddles. The swimmer is then able to pull along the sliding bench and therefore mimic the kinematics of front crawl swimming. The maximal power output produced on the biokinetic swim bench has a strong relationship ($r = 0.92$) with swimming velocity in semi-tethered conditions [71]. There are, however, limitations to the biokinetic swim bench. Its lack of specificity has been highlighted several times. This is due to the longer pulling pathway and the distribution of pulling forces throughout a range of joint angles which are not similar to free swimming [72]. Roberts et al. [73] designed a 3-week intervention using the biokinetic swim bench three times weekly. Results showed no improvement in swimming performance. Tanaka et al. [8] used the biokinetic swim bench to monitor improvements in strength due to a traditional strength training programme, but even though there was a significant improvement in swimming performance, there was no improvement in power outputs on the biokinetic swim bench. These results show no beneficial outcomes of the biokinetic swim bench, but similar dry-land tools may be advantageous when it comes to improving swimmer's technical and strength deficiencies.

MAD-System

The Measurement of Active Drag system (MAD-system) directly measures the forces of the hand as it pushes off from a series of pads placed 1.35 m apart and

attached to a 22-m long rigid aluminium rod mounted 0.8 m below the water surface. The rod is connected to a force transducer enabling direct measurement of push-off forces. Swimmers use their arms only for propulsion, and their legs are floated with a small buoy [74]. The MAD-system has previously been used to predict individual power requirements for swimming a world record in the 50-m free-style [75], but also as a water-based strength training device. A study reported that swimmers sprinting on the MAD-system 3 times a week simultaneously improved power and free swimming 50, 100, and 200 m race time significantly more than a control group [76]. However, the MAD-system should be used with caution, as swimmers are known to adapt their high speed stroke and usual head position to carefully adapt to the spatial arrangements of the pads [77].

Core Training

Core training is a widely used training method across a variety of sports and should be considered part of any strength training programme. Swimming performance requires a unique balance and stability in order to overcome the unstable and dynamic nature of water. During each stroke cycle, propulsive forces are produced through the hand which creates a dynamic reaction of the rotational aspects of the vertebrae causing an increase in lateral movement and excessive kicking movements, which results in a decrease in propulsive efficiency. Overcoming this instability requires a high level of core strength and stability. It is important to note that the best swimmers accelerate themselves in the horizontal direction and minimize vertical and lateral deviations. Any excessive movement, vertically or laterally is counterproductive for the swimmer's overall performance. Weston et al. [78] incorporated a 12-week core training programme and found significant improvements in swimming performance, as well as an increase in electromyography data. Dingley et al. [79] who employed a similar programme on paraplegic swimmers also found a significant improvement in swimming performance. It can be presumed that this improvement must be largely associated to an improvement in overall core strength and stability. It would seem plausible, and Weston et al. [78] alluded to this, that core strength increases stability in the lumbar and thoracic regions through a variety of exercises which in turn result in greater control through the rotational axes.

Resistive Band Training

Resistive bands are often used by swimmers during training for assistive purposes, but can also be used as a resistive tool. The resistive band is attached around the swimmer's waist using a belt and then secured to the diving block. The athlete swims out against the resistance of the elastic band and then maintains his or her position in the pool. Girold et al. [48] showed a 1.9% improvement in performance over 100 m following resistive band training over a 3-week period and followed up this research with another study showing significant improvements in 50 m swimming

performance [10]. Juárez Santos-García et al. [80] also showed that four rounds of resistive bands followed by a maximum sprint improve swimming performance. This training method implies that swim-specific resistance training [81, 82] is necessary to elicit improvements in swimming performance. Sport-specific resistance training has also been seen in water polo, and it was speculated that the reason for an improvement in performance was the development of specific performance skills, again emphasizing the necessity for specificity. It is important to note, however, that this type of training can lead to overuse injuries and needs to be monitored carefully.

Pull Training

The isolation of the arms during swimming training is a commonly used training technique, as the majority of the impulse in swimming comes from the upper-body. It is thought that the isolation of the arms will result in an increase in upper-body strength, and, therefore, an improvement in swimming performance. Unfortunately, this seems to be untrue as in comparison to whole-body swimming, arms-only swimming reduces maximal oxygen uptake [83, 84], which is assumed to occur due to the increased buoyancy provided by the pull-buoy. Konstantaki et al. [85] confirmed this as they replaced regular swimming training with arms-only training, three times weekly. The arms-only training consisted of breathing drills, one arm only, hand-paddles, pull-buoy, etc. The findings of this study showed that arms-only peak exercise intensity, ventilatory threshold, and movement economy improved, but no improvement was observed in swimming performance. This lack of transfer may be due to numerous reasons, including loss of coordination between the arms and legs, additional buoyancy and, therefore, a reduction in core strength and stability, and changes in torque due to the changes in body-roll and stability in the water. However, arms-only training can be advantageous for novice swimmers to improve upper-body strength, emphasizing technical constraints, or allowing swimmers to swim more without expending high levels of energy. In order to elicit greater results from arms-only swimming, the exclusion of the pull-buoy and the inclusion of an elastic band around the ankles may result in greater core activation in order to maintain an optimal body position [86]. It is important to note that many coaches prescribe hand-paddles within their swimming programmes, but unfortunately no study has investigated the effects of hand-paddle interventions on swimming performance. From an observational perspective, hand-paddles do provide a swim-specific strength stimulus for swimmers, but their overuse can result in poor propulsive mechanics and overuse of the shoulder joint. It is advised that hand-paddles are used in moderation and are carefully monitored.

Drag Suit Training

Training specificity is a key element in the enhancement of swimming performance, and drag suits provide swimmers with an additional training tool. The

logic behind drag suits is that the mesh clothing retains water and therefore increases the resistive drag forces, resulting in the swimmer applying more propulsive forces to the water to achieve the same time for a specific distance. A study by Dragunas et al. [87] found no significant improvement in swimming performance when the drag suit stimulus was removed. Training under this condition can result in swimmers losing their “feel for the water” [88], which may result in altered body position and, therefore, slower swimming times. It must be documented that most elite swimmers today have moved away from using drag suits due to the aforementioned concerns. Another training tool used is parachutes, which have been shown to induce no alterations in kinematic characteristics of front crawl swimming [89]. Further investigation is needed in this area, but parachutes may be the optimal training tool to increase resistive drag forces, resulting in the swimmer having to apply more propulsive forces to the water to achieve the same time for a specific distance.

Eccentric Overload Training

Concentric-eccentric actions are the most common modalities of dry-land strength training, but eccentric overload training could also be used as an alternative training stimulus for competitive swimmers. Eccentric muscle actions occur when the load applied to the muscle exceeds the force produced, resulting in a lengthening action and high muscle forces. During traditional concentric-eccentric resistance training, load is prescribed on the basis of concentric strength, which leads to the eccentric phase of movement being insufficiently loaded. Eccentric training is a potent stimulus to enhance muscle mechanical function, and muscle-tendon unit morphological and architectural adaptations. Recent research suggests that eccentric overload training can be superior to traditional resistance training at improving variables associated with strength, power, and speed performance for several groups of athletes [90], and it could represent an interesting addition to strength training programmes for swimmers.

To this aim, the use of flywheel inertial resistance is an effective way to induce an eccentric overload. Flywheel inertial devices generate resistance as a function of the mass, distribution of mass, and angular acceleration of the flywheel, and they require a mechanical demand most suited for exercises involving dynamic lower and upper extremity muscle actions [91].

Vibration and Instability Training

Whole-body and upper-body vibration training has recently become a popular alternative and/or complementary method to resistance training because of its potential beneficial effects on the neuromuscular, endocrine, cardiovascular, sensory, circulatory, and bone systems [92, 93]. Similarly, resistance training involving base or platform instability by standing, sitting, kneeling or lying on balls, discs, wobble

and rocker boards, foam rollers, low-density mats, and similar devices inducing varying degrees of instability has become a popular training method in recent times. Because swimmers perform their activity in an unstable fluid environment, this training modality could be particularly suitable for them, as it forces the athlete to stress and coordinate synergistic, stabilizing, and antagonistic muscle groups [94, 95]. The impact of such training methods on power production during swimming, however, has not been assessed.

Periodization of Strength Training for Swimming Performance

A well-planned and periodized strength training programme should allow proper long-term athlete development, limit the risk of injury and maximize competition performance [4]. Both dry-land and in-water strength training may have a direct impact on a swimmer's ability to apply force and move through the water, therefore strength training plans should adequately complement swim training throughout a season.

Hellard et al. [96] recently carried out a systematic examination of the relationships between periodized training loads and performance in a large cohort of elite swimmers over the final 11 weeks of training prior to a major competition. Although dry-land strength loads during the taper phase were shown to be detrimental to performance, relatively higher loads in the medium- (6–8 weeks before competition) and long-term (9–11 weeks before competition) meso-cycles were typically associated with faster competition performance. Differences were also observed among various distance specialists. Sprinters' priority was maximal strength and power in the long-term meso-cycle (weeks 9, 10, and 11 before competition). This was followed by a period of low-to-medium intensity training in the medium-term meso-cycle (weeks 6, 7, and 8). The peak high-intensity load was periodized in the medium-term and in the short-term meso-cycles (3–8 weeks before the main competition). For the middle-distance swimmers, the maximum concentration of strength training occurred typically in the long-term cycle, whereas low-to-medium intensity training was most effective in the medium- and long-term cycles, and the high-intensity load exerted the greatest positive effects 3–5 weeks before the final competition of the season. Taken as a whole, these data indicated that swimmers' strength and power capacities should be developed progressively in the medium- and long-term training meso-cycles, maintained in the short-term meso-cycle, and loads finally reduced to avoid detrimental effects during the taper period [96].

Newton et al. [1] suggested that in a periodized progression, the training programme should change before competition to emphasize neural activation and help swimmers in the taper process to be more coordinated and be able to deliver forces where they need to. Taper periods leading to major competitions are known to induce gains in swimming force and power [97–99], even in the absence of dry-land strength and power training stimuli. All of the above is consistent with the practices of leading international swimmers and indicates that periodization plans should be adapted to the distance specialty of swimmers.

Summary

Current evidence indicates that concurrent strength and endurance training could be a beneficial strategy for a majority of competitive swimmers. Increments in upper-body muscular strength and power should translate into increased ability to generate propulsive force in the water, improved stroke length and/or stroke rate, and increased free swimming speed. Lower-body strength and power can translate into faster start and turns. The ability of a swimmer to execute these performance components with high levels of technique, skill, and power will result in a greater overall performance. Both dry-land and in-water strength training can be beneficial to swimming performance. Swimmers today include a wide variety of strength training practices in their preparation for competition, including dry-land warm-ups, circuit training, traditional strength, plyometrics, biokinetic swim bench, MAD-system, core training, resistive band, pull and drag suit training, eccentric overload, vibration, and instability training. A well-planned and periodized strength training programme should adequately complement swim training throughout a season, allow proper long-term athlete development, limit the risk of injury, and eventually maximize competition performance.

References

1. Newton RU, Jones J, Kraemer WJ, Wardle H. Strength and power training in Australian Olympic swimmers. *Strength Cond J*. 2002;24:7–15.
2. Pelot T, Darmiento A. Strength and power training for the elite swimmer: can weights positively impact elite swim performance when “elite performance” requires 15 – 25 hours/week of practice? *Olympic Coach*. 2012;23:22–31.
3. Vorontsov A. Strength and power training in swimming. In: Seifert L, Chollet D, Mujika I, editors. *World book of swimming: from science to performance*. New York: Nova Science Publishers Inc.; 2011. p. 313–43.
4. Riewald S. Strength and conditioning for performance enhancement. In: Riewald S, Rodeo S, editors. *Science of swimming faster*. Champaign: Human Kinetics; 2015. p. 401–48.
5. Sharp RL, Troup JP, Costill DL. Relationship between power and sprint freestyle swimming. *Med Sci Sports Exerc*. 1981;14:53–6.
6. Costill D, Rayfield F, Kirwan J, Thomas R. A computer based system for the measurement of force and power during front crawl swimming. *J Swim Res*. 1986;2:16–9.
7. Hawley JA, Williams MM, Vickovic MM, Handcock PJ. Muscle power predicts freestyle swimming performance. *Br J Sports Med*. 1992;26:151–5.
8. Tanaka H, Costill DL, Thomas R, Fink WJ, Widrick JJ. Dry-land resistance training for competitive swimming. *Med Sci Sports Exerc*. 1993;25:952–9.
9. Tanaka H, Swensen T. Impact of resistance training on endurance performance. *Sports Med*. 1998;25:191–200.
10. Girold S, Maurin D, Dugué B, Chatard J-C, Millet G. Effects of dry-land vs. resisted-and assisted-sprint exercises on swimming sprint performances. *J Strength Cond Res*. 2007;21:599–605.
11. Hollander AP, de Groot G, van Ingen Schenau GJ, Kahman R, Toussaint HM. Contribution of the legs to propulsion in front crawl swimming. In: Ungerechts BE, Wilke K, Reischke K, editors. *Swimming science V*, vol. 5. Champaign: Human Kinetics; 1988. p. 39–44.
12. Toussaint HM, Beek PJ. Biomechanics of competitive front crawl swimming. *Sports Med*. 1992;13:8–24.

13. Smith DJ, Norris SR, Hogg JM. Performance evaluation of swimmers. *Sports Med.* 2002;32:539–54.
14. Bucher W. The influence of the leg kick and the arm stroke on the total speed during the crawl stroke. In: Lewillie L, Clarys JP, editors. *Swimming II*. Brussels: University Park Press; 1975. p. 180–7.
15. Deschodt V, Arsac L, Rouard A. Relative contribution of arms and legs in humans to propulsion in 25-m sprint front-crawl swimming. *Eur J Appl Physiol Occup Physiol.* 1999;80:192–9.
16. Zamparo P, Pendergast D, Mollendorf J, Termin A, Minetti A. An energy balance of front crawl. *Eur J Appl Physiol.* 2005;94:134–44.
17. Carl DL, Leslie N, Dickerson T, Griffin B, Marksteiner A. Bench press and leg press strength and its relationships with in-water force and swimming performance when measured in-season in male and female age-group swimmers. In: Kjendlie PL, Stallman RK, Cabri J, editors. *Biomechanics and medicine in swimming XI*. Oslo: Norwegian School of Sport Science; 2010. p. 247–8.
18. Morouço P, Neiva H, González-Badillo JJ, Garrido N, Marinho DA, Marques MC. Associations between dry land strength and power measurements with swimming performance in elite athletes: a pilot study. *J Hum Kinet.* 2011;29A:105–12. <https://doi.org/10.2478/v10078-011-0065-2>.
19. Nikolaidis PT. Age- and sex-related differences in force-velocity characteristics of upper and lower limbs of competitive adolescent swimmers. *J Hum Kinet.* 2012;32:87–95. <https://doi.org/10.2478/v10078-012-0026-4>.
20. Gatta G, Leban B, Paderi M, Padulo J, Migliaccio GM, Pau M. The development of swimming power. *Muscles Ligaments Tendons J.* 2015;4:438–45.
21. Crowley E, Harrison AJ, Lyons M. The impact of resistance training on swimming performance: a systematic review. *Sports Med.* 2017;47(11):2285–307. <https://doi.org/10.1007/s40279-017-0730-2>.
22. Swaine IL, Hunter AM, Carlton KJ, Wiles JD, Coleman D. Reproducibility of limb power outputs and cardiopulmonary responses to exercise using a novel swimming training machine. *Int J Sports Med.* 2010;31:854–9. <https://doi.org/10.1055/s-0030-1265175>.
23. Toubekis AG, Gourgoulis V, Tokmakidis SP. Tethered swimming as an evaluation tool of single arm-stroke force. In: Kjendlie PL, Stallman RK, Cabri J, editors. *Biomechanics and medicine in swimming XI*. Oslo: Norwegian School of Sport Science; 2010. p. 296–9.
24. Domínguez-Castells R, Izquierdo M, Arellano R. An updated protocol to assess arm swimming power in front crawl. *Int J Sports Med.* 2013;34:324–9. <https://doi.org/10.1055/s-0032-1323721>.
25. Formosa DP, Mason B, Burkett B. The force-time profile of elite front crawl swimmers. *J Sports Sci.* 2011;29:811–9. <https://doi.org/10.1080/02640414.2011.561867>.
26. West DJ, Owen NJ, Cunningham DJ, Cook CJ, Kilduff LP. Strength and power predictors of swimming starts in international sprint swimmers. *J Strength Cond Res.* 2011;25:950–5.
27. García-Ramos A, Tomazin K, Feriche B, Strojnik V, De la Fuente B, Argüelles-Cienfuegos J, et al. The relationship between the lower-body muscular profile and swimming start performance. *J Hum Kinet.* 2016;50:157–65. <https://doi.org/10.1515/hukin-2015-0152>.
28. Beretić I, Đurović M, Okićić T, Dopsaj M. Relations between lower body isometric muscle force characteristics and start performance in elite male sprint swimmers. *J Sports Sci Med.* 2013;12:639.
29. Vantorre J, Seifert L, Fernandes RJ, Boas JP, Chollet D. Comparison of grab start between elite and trained swimmers. *Int J Sports Med.* 2010;31:887–93. <https://doi.org/10.1055/s-0030-1265150>.
30. Potdevin FJ, Alberty ME, Chevutschi A, Pelayo P, Sidney MC. Effects of a 6-week plyometric training program on performances in pubescent swimmers. *J Strength Cond Res.* 2011;25:80–6.
31. Bishop DC, Smith RJ, Smith MF, Rigby HE. Effect of plyometric training on swimming block start performance in adolescents. *J Strength Cond Res.* 2009;23:2137–43.
32. Rebutini VZ, Pereira G, Bohrer RC, Ugrinowitsch C, Rodacki AL. Plyometric long jump training with progressive loading improves kinetic and kinematic swimming start parameters. *J Strength Cond Res.* 2016;30:2392–8.

33. Lyttle AD, Blanksby BA, Elliott BC, Lloyd DG. Investigating kinetics in the freestyle flip turn push-off. *J Appl Biomech.* 1999;15:242–52.
34. Lyttle AD, Blanksby BA, Elliott BC, Lloyd DG. Net forces during tethered simulation of underwater streamlined gliding and kicking techniques of the freestyle turn. *J Sports Sci.* 2000;18:801–7. <https://doi.org/10.1080/026404100419856>.
35. Cronin J, Jones J, Frost D. The relationship between dry-land power measures and tumble turn velocity in elite swimmers. *J Swim Res.* 2007;17:17–23.
36. Jones JV, Pyne DB, Haff GG, Newton RU. Comparison between elite and sub-elite swimmers on dry-land and tumble turn leg extensor force-time characteristics. *J Strength Cond Res.* 2018;32(6):1762–9. <https://doi.org/10.1519/JSC0000000000002041>.
37. Jones JV, Pyne DB, Haff GG, Newton RU. Comparison of ballistic and strength training on swimming turn and dry-land leg extensor characteristics in elite swimmers. *Int J Sports Sci Coach.* Volume 13, p. 262–69; <https://doi.org/10.1177/1747954117726017>
38. Craig AB, Pendergast DR. Relationships of stroke rate, distance per stroke, and velocity in competitive swimming. *Med Sci Sports Exerc.* 1979;11:278–83.
39. Schnitzler C, Seifert L, Chollet D. Arm coordination and performance level in the 400-m front crawl. *Res Q Exerc Sport.* 2011;82:1–8.
40. Laffite LP, Vilas-Boas JP, Demarle A, et al. Changes in physiological and stroke parameters during a maximal 400-m free swimming test in elite swimmers. *Can J Appl Physiol.* 2004;29:17–31.
41. Mujika I, Chatard JC, Busso T, Geyssant A, Barale F, Lacoste L. Use of swim-training profiles and performance data to enhance training effectiveness. *J Swim Res.* 1996;11:23–9.
42. Alberty M, Potdevin F, Dekker J, et al. Changes in swimming technique during time to exhaustion at freely chosen and controlled stroke rates. *J Sports Sci.* 2008;26:1191–200.
43. Huot-Marchand F, Nesi X, Sidney M, et al. Is improvement in performance linked to higher stroke length values in top-level 100-m front crawl swimmers? *J Hum Mov Stud.* 2005;6:12–8.
44. Costill D, Sharp R, Troup J. Muscle strength: contributions to sprint swimming. *Swim World.* 1980;21:29–34.
45. Hay J, Guimaraes A, Grimston S. A quantitative look at swimming biomechanics. *Swim Tech.* 1983;20(2):11–7.
46. Craig AB, Skehan PL, Pawelczyk JA, Boomer WL. Velocity, stroke rate, and distance per stroke during elite swimming competition. *Med Sci Sports Exerc.* 1985;17:625–34.
47. Chatard J-C, Mujika I. Training load and performance in swimming. In: Keskinen KL, Komi PV, Hollander AP, editors. *Biomechanics and medicine in swimming VIII.* Jyväskylä: University of Jyväskylä; 1999. p. 429–34.
48. Girold S, Calmels P, Maurin D, Milhau N, Chatard J-C. Assisted and resisted sprint training in swimming. *J Strength Cond Res.* 2006;20:547–54.
49. Figueiredo P, Zamparo P, Sousa A, Vilas-Boas JP, Fernandes RJ. An energy balance of the 200 m front crawl race. *Eur J Appl Physiol.* 2011;111:767–77.
50. Fernandes RJ, Marinho DA, Barbosa TM, Vilas-Boas JP. Is time limit at the minimum swimming velocity of VO₂ max influenced by stroking parameters? *Percept Mot Skills.* 2006;103:67–75.
51. Strass D. Effects of maximal strength training on sprint performance of competitive swimmers. In: *Swimming science V: international series on sport sciences*, vol 18; 1988. p. 149–56.
52. Girold S, Jalab C, Bernard O, Carette P, Kemoun G, Dugué B. Dry-land strength training vs. electrical stimulation in sprint swimming performance. *J Strength Cond Res.* 2012;26:497–505.
53. Aspenes S, Kjendlie PL, Hoff J, Helgerud J. Combined strength and endurance training in competitive swimmers. *J Sports Sci Med.* 2009;8:357–65.
54. Wakayoshi K, D'Acquisto L, Cappaert J, Troup J. Relationship between oxygen uptake, stroke rate and swimming velocity in competitive swimming. *Int J Sports Med.* 1995;16:19–23.
55. Berryman N, Mujika I, Arvisais D, Roubeix M, Binet C, Bosquet L. Strength training for middle- and long-distance performance: a meta-analysis. *Int J Sports Physiol Perform.* 2018;13(1):57–63. <https://doi.org/10.1123/ijssp.2017-0032>.

56. Mujika I, Chatard JC, Busso T, Geyssant A, Barale F, Lacoste L. Effects of training on performance in competitive swimming. *Can J Appl Physiol.* 1995;20:395–406.
57. Aspenes ST, Karlsen T. Exercise-training intervention studies in competitive swimming. *Sports Med.* 2012;42:527–43. <https://doi.org/10.2165/11630760-00000000-00000>.
58. McGowan CJ, Pyne DB, Thompson KG, Raglin JS, Osborne M, Rattray B. Elite sprint swimming performance is enhanced by completion of additional warm-up activities. *J Sports Sci.* 2017;35:1493–9. <https://doi.org/10.1080/02640414.2016.1223329>.
59. McGowan CJ, Thompson KG, Pyne DB, Raglin JS, Rattray B. Heated jackets and dryland-based activation exercises used as additional warm-ups during transition enhance sprint swimming performance. *J Sci Med Sport.* 2016;19:354–8.
60. McGowan CJ, Pyne DB, Thompson KG, Rattray B. Warm-up strategies for sport and exercise: mechanisms and applications. *Sports Med.* 2015;45:1523–46.
61. Gettman LR, Ayres JJ, Pollock ML, Jackson A. The effect of circuit weight training on strength, cardiorespiratory function, and body composition of adult men. *Med Sci Sports.* 1977;10:171–6.
62. Tabata I, Nishimura K, Kouzaki M, Hirai Y, Ogita F, Miyachi M, et al. Effects of moderate-intensity endurance and high-intensity intermittent training on anaerobic capacity and VO_{2max}. *Med Sci Sports Exerc.* 1996;28:1327–30.
63. Katch FI, Freedson PS, Jones CA. Evaluation of acute cardiorespiratory responses to hydraulic resistance exercise. *Med Sci Sports Exerc.* 1985;17:168–73.
64. Ballor DL, Becque MD, Katch VL. Metabolic responses during hydraulic resistance exercise. *Med Sci Sports Exerc.* 1987;19:363–7.
65. La Torre A, Vernillo G, Fiorella P, Mauri C, Agnello L. Combined endurance and resistance circuit training in highly trained/top-level female race walkers: a case report. *Sport Sci Health.* 2008;4:51–8.
66. Coyle EF, Feiring D, Rotkis T, Cote R, Roby F, Lee W, et al. Specificity of power improvements through slow and fast isokinetic training. *J Appl Physiol.* 1981;51:1437–42.
67. Kanehisa H, Miyashita M. Specificity of velocity in strength training. *Eur J Appl Physiol Occup Physiol.* 1983;52:104–6.
68. Sadowski J, Mastalerz A, Gromisz W, Niżnikowski T. Effectiveness of the power dry-land training programmes in youth swimmers. *J Hum Kinet.* 2012;32:77–86.
69. Markovic G. Does plyometric training improve vertical jump height? A meta-analytical review. *Br J Sports Med.* 2007;41:349–55.
70. Cossor JM, Blanksby BA, Elliott BC. The influence of plyometric training on the freestyle tumble turn. *J Sci Med Sport.* 1999;2:106–16.
71. Shimanagata S, Taguchi M, Miura M. Effect of swimming power, swimming power endurance and dry-land power on 100 m freestyle performance. In: Chatard JC, editor. Biomechanics and medicine in swimming IX. Saint Etienne: University of Saint-Etienne; 2003. p. 391–6.
72. Clarys J. Hydrodynamics and electromyography: ergonomics aspects in aquatics. *Appl Ergon.* 1985;16:11–24.
73. Roberts AJ, Termin B, Reilly M, Pendergast D. Effectiveness of biokinetic training on swimming performance in collegiate swimmers. *J Swim Res.* 1991;7:5–11.
74. Hollander AP, de Groot G, van Ingen Schenau GJ, Toussaint HM, de Best H, Peeters W. Measurement of active drag forces during swimming. *J Sports Sci.* 1986;4:21–30.
75. Toussaint HM, Truijens M. Power requirements for swimming a world-record 50-m front crawl. *Int J Sports Physiol Perform.* 2006;1:61–4.
76. Toussaint HM, Vervoorn K. Effects of specific high resistance training in the water on competitive swimmers. *Int J Sports Med.* 1990;11:228–33.
77. David A, Poizat G, Gal-Petitfaux N, Toussaint H, Seifert ML. Analysis of elite swimmers' activity during an instrumented protocol. *J Sports Sci.* 2009;27:1043–50. <https://doi.org/10.1080/02640410902988669>.
78. Weston M, Hibbs AE, Thompson KG. Isolated core training improves sprint performance in national-level junior swimmers. *Int J Sports Physiol Perform.* 2015;10:204–10.

79. Dingley AA, Pyne DB, Youngson J, Burkett B. Effectiveness of a dry-land resistance training program on strength, power, and swimming performance in paralympic swimmers. *J Strength Cond Res.* 2015;29:619–26.
80. Juárez Santos-García D, González-Ravé JM, Legaz Arrese A, Portillo Yabar LJ, Clemente Suárez VJ, Newton RU. Acute effects of two resisted exercises on 25~ m swimming performance. *Isokinetics Exerc Sci.* 2013;21:29–35.
81. Costill D. Training adaptations for optimal performance. In: Keskinen KL, Komi PV, Hollander AP, editors. *Biomechanics and medicine in swimming VIII.* Jyväskylä: University of Jyväskylä; 1999. p. 381–90.
82. Stewart AM, Hopkins WG. Seasonal training and performance of competitive swimmers. *J Sports Sci.* 2000;18:873–84.
83. Ribeiro J, Figueiredo P, Sousa A, Monteiro J, Pelarigo J, Vilas-Boas J, et al. VO₂ kinetics and metabolic contributions during full and upper body extreme swimming intensity. *Eur J Appl Physiol.* 2015;115:1117–24.
84. Rodríguez F, Lätt E, Jürimäe J, Maestu J, Purge P, Räimson R, et al. VO₂ kinetics in all-out arm stroke, leg kick and whole stroke front crawl 100-m swimming. *Int J Sports Med.* 2016;37:191–6.
85. Konstantaki M, Winter E, Swaine I. Effects of arms-only swimming training on performance, movement economy, and aerobic power. *Int J Sports Physiol Perform.* 2008;3(3):294–304.
86. Morris KS, Osborne MA, Shephard ME, Skinner TL, Jenkins DG. Velocity, aerobic power and metabolic cost of whole body and arms only front crawl swimming at various stroke rates. *Eur J Appl Physiol.* 2016;116:1075–85.
87. Dragunas AJ, Dickey JP, Nolte VW. The effect of drag suit training on 50-m freestyle performance. *J Strength Cond Res.* 2012;26:989–94.
88. McGowan CJ, Pyne DB, Raglin JS, Thompson KG, Rattray B. Current warm-up practices and contemporary issues faced by elite swimming coaches. *J Strength Cond Res.* 2016;30:3471–80.
89. Telles T, Barbosa AC, Campos MH, Junior OA. Effect of hand paddles and parachute on the index of coordination of competitive crawl-strokers. *J Sports Sci.* 2011;29:431–8.
90. Douglas J, Pearson S, Ross A, McGuigan M. Chronic adaptations to eccentric training: a systematic review. *Sports Med.* 2017;47:917–41. <https://doi.org/10.1007/s40279-016-0628-4>.
91. Chiu LZ, Salem GJ. Comparison of joint kinetics during free weight and flywheel resistance exercise. *J Strength Cond Res.* 2006;20:555–62.
92. Moras G, Rodríguez-Jiménez S, Tous-Fajardo J, Ranz D, Mujika I. A vibratory bar for upper body: feasibility and acute effects on EMG rms activity. *J Strength Cond Res.* 2010;24: 2132–42. <https://doi.org/10.1519/JSC.0b013e3181aa3684>.
93. Wilcock IM, Whatman C, Harris N, Keogh JW. Vibration training: could it enhance the strength, power, or speed of athletes? *J Strength Cond Res.* 2009;23:593–603. <https://doi.org/10.1519/JSC.0b013e318196b81f>.
94. Behm DG, Anderson KG. The role of instability with resistance training. *J Strength Cond Res.* 2006;20:716–22.
95. Serra N, Carvalho DD, Fernandes RJ. The importance of agonistic, antagonist, and synergistic muscles coordination on swimming dry land training. *Trends Sport Sci.* 2017;3(24):101–4.
96. Hellard P, Scordia C, Avalos M, Mujika I, Pyne DB. Modelling of optimal training load patterns during the 11 weeks preceding major competition in elite swimmers. *Appl Physiol Nutr Metab.* 2017;42(10):1106–17. <https://doi.org/10.1139/apnm-2017-0180>.
97. Trappe S, Costill D, Thomas R. Effect of swim taper on whole muscle and single muscle fiber contractile properties. *Med Sci Sports Exerc.* 2000;32:48–56.
98. Trinity JD, Pahnke MD, Reese EC, Coyle EF. Maximal mechanical power during a taper in elite swimmers. *Med Sci Sports Exerc.* 2006;38:1643–9.
99. Papoti M, Martins LEB, Cunha SA, Zagatto AM, Gobatto CA. Effects of taper on swimming force and swimmer performance after an experimental ten-week training program. *J Strength Cond Res.* 2007;21:538–42.



General Aspects of Concurrent Aerobic and Strength Training for Performance in Team Sports

26

Julien Robineau

Introduction

Many team sports require players to perform high-intensity efforts repeatedly and intermittently in competition. Specific training strategies such as concurrent strength and aerobic training are proposed to improve players' ability to repeat high-intensity efforts [1]. Development of the aerobic system aids in improving recovery between efforts by replenishing phosphocreatine and improving muscle buffer capacity, factors which are critical to performance in team sports [2, 3]. The aerobic energy system is also suggested to aid in post-match recovery following match-play. This quality has implications for team sport schedules where multiple matches are performed over a week (e.g. basket-ball, handball, volleyball, rugby, futsal, water polo) or a day and over consecutive days with only few hours separating matches (rugby sevens) [1]. While there is good evidence to suggest that resistance training could be beneficial for performance in a single maximal effort (sprint, jump, tackle etc.), the impact of this training format on player capacity to successively repeat these efforts is less clear [3]. However, several studies have reported that resistance training produces similar increases in mean work capacity during a repeated sprint test (~12%) [4] compared with high-intensity interval training (~13%) [5]. Resistance training also improved both initial sprint performance (8–9%) and the sprint decrement score (~20%) [5] in a repeated sprint test. The increases in repeated sprint ability (RSA) previously reported are likely to be linked to strength gains [3].

The issue of concurrent strength and aerobic training is seemingly at the center of attention of many contemporary team sport practitioners. A survey led by Jones et al. [6] examined training and monitoring strategies of strength and conditioning coaches of rugby union players. The results showed that 77% of respondents accounted for the aforementioned interference effect while programming training

J. Robineau

Research and Performance Department, French Rugby Union Federation, Marcoussis, France
e-mail: Julien.ROBINEAU@ffr.fr

for rugby union players. In addition, 47% of coaches believed it was very important to consider possible incompatibilities between aerobic and strength training when generating conditioning plans. The findings of this survey emphasized periodization would be the most effective means of avoiding any potential effect of aerobic type stimulus on strength and power development [6].

Influence of Concurrent Training Variables on the Interference Effect: A Case Study with the French Rugby Union

Previous studies showed that strength training combined with aerobic exercises in a single program is known to impair strength and power gains in comparison with strength training alone, if training frequency is high [7–9]. This was discussed in previous chapters of the present book as well as in a meta-analysis by Wilson et al. [10]. Modality, duration and frequency of endurance exercises were identified as the main factors supporting the interference effects of endurance training on the expected improvement of strength and power in response to concurrent resistance training. Moreover, the influence of several training factors such as intensity and volume of concurrent exercises as well as the order of training sessions have been previously addressed to minimize this neuromuscular interference [11–13]. An important factor potentially affecting the magnitude of interference in team sport athletes might also be the duration of the recovery period between strength and endurance exercises.

Recovery Delay Between Sequences

In a previous study in rugby union players [14], we assessed whether the recovery between strength and aerobic high-intensity interval exercises would determine the magnitude of possible interference. The sequence of performing strength training prior to aerobic exercise was chosen to avoid residual fatigue induced by the metabolic session and, therefore, maintaining the intensity of strength training. The question of recovery duration is warranted because the training load in elite team sport has increased over recent years. Sessions are often scheduled twice-a-day, separated by none or only a few hours. In our aforementioned study, daily training without recovery between sequences and, to a lesser extent, training twice-a-day with 6 h recovery between strength and aerobic training sessions did not seem to be optimal for strength and power gains, nor for adaptations in $\text{VO}_{2\text{peak}}$, while daily training with 24-h recovery between sessions appeared to be favorable. These results suggest that strength and conditioning coaches should avoid scheduling two different exercise modalities (strength vs. aerobic) in close proximity but rather aim for a 24-h recovery period in order to assure optimal neuromuscular and cardiovascular adaptations.

In team sports like rugby, coaches also have to program specific technical and tactical training sessions. These can generate high aerobic demands similar to those observed during traditional endurance training. Thus, care should be taken when scheduling specific training sessions in close proximity to strength exercise sessions. Therefore, it is recommended to monitor the specific technical and tactical training load and the induced physiological responses, e.g., by means of global

positioning system technology, and portable HR monitors. These devices allow regulation of the intensity of specific training and, thus, may help to minimize the risk of interference in strength development [14].

Type of Aerobic Training

High-intensity interval training (HIT) of various modes (i.e., different lengths of exercise and recovery bouts) is today considered one of the most effective means of improving cardiorespiratory and metabolic function and, in turn, the physical performance of athletes. HIT involves repeated short-to-long bouts of high-intensity exercise interspersed with recovery periods (short and long intervals). For team sport athletes, the inclusion of sprints and all-out efforts into HIT programs has also been shown to be an effective methodology. These types of HIT (short and long intervals, repeated sprint and sprint interval training) elicit different acute physiological metabolic responses and neuromuscular strain [15]. In light of this, it would seem relevant to determine whether the type of endurance exercise would influence the magnitude of interference on neuromuscular adaptations. The research and development department of the French Rugby Union Federation investigated the impact of 2 HIT protocols (i.e., short interval vs. sprint interval, Fig. 26.1) in amateur rugby sevens players, performed over 8 weeks on maximal strength and power, and RSA [16] (Fig. 26.1). The main finding of this study was that strength development was not compromised following concurrent training with short intervals (INT) but showed a slight impairment of slow concentric torque production gains following concurrent training with sprint interval (SIT). However, while strength gains were somewhat compromised in the strength and SIT group, this training actually led to the largest gains in VO₂ peak. Thus, according to these findings, coaches may need to carefully consider the needs of a given athlete as both optimal VO₂peak and strength gains may be difficult to achieve in amateur rugby sevens players. Tables 26.1 and 26.2 gives an example of how rugby

		Monday	Tuesday	Wednesday	Thursday	Friday
Familiarization		Session 1			Session 2	
Initial tests		MVC	Graded maximal aerobic test			RSA
Training duration 8 weeks	SIT	Strength	Sprint-interval	Strength	Sprint-interval	
	INT	Strength	Short-interval	Strength	Short-interval	
	CON	Strength	–	Strength	–	
Final tests		MVC	Graded maximal aerobic test			RSA

Fig. 26.1 Experimental design of the study. Abbreviations: CON strength training, INT concurrent strength and short interval training, MVC maximal voluntary contraction, RSA repeated sprint ability, SIT concurrent strength and sprint interval training. Sprint interval workload: 4–8 run all-out efforts interspersed by 4 min passive recovery. Short interval workload: two series of 8–12 min 30 s run at maximal aerobic velocity (MAV) interspersed by 30 s of active recovery at 50% MAV, 3 min of passive recovery between the series

Table 26.1 A sample rugby sevens weekly training schedule with short-/long interval training

	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Morning	Well-being/ Medical Resistance (LB)	Warm-up Rugby—tech/act Aerobic (short/long interval)	Warm-up Agility/Sprint Rugby—tactical Recovery	Warm-up Rugby—tech/tact Aerobic (short/long interval)	Warm-up Core training Running skills	Warm-up Rugby—tech Active recovery (swimming pool)	
Afternoon	Nap Rugby—tactical Recovery	Nap Resistance (UB) Recovery		Nap Resistance (L& UB) Recovery	Nap Rugby—tactical Aerobic suppl. Recovery		

Table 26.2 A sample rugby sevens weekly training schedule with sprint interval training (SIT)

	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Morning	Well-being/ Medical Resistance (L&UB)	Warm-up Rugby—tactical	Warm-up Running skills Rugby—technical Recovery	Warm-up Resistance (L&UB)	Warm-up Rugby—tech/tact	Warm-up Rugby—tech	Active recovery (swimming pool)
Afternoon	Nap Running skills Rugby—tactical Recovery	Nap Core training Aerobic (SIT) Recovery		Nap Rugby—tactical Recovery	Nap Core training Aerobic (SIT) Recovery		

sevens schedule a weekly training INT or SIT. The observed interference effect could be explained by an exacerbated residual fatigue mechanism. While we allowed 48 h of rest between subsequent training sessions in this study, Howatson and Milak [17] suggested that this may be insufficient. In their study, it was shown that repeated sprint exercises may induce a significant decrement of quadriceps MVC and a significant increase in muscle soreness lasting for up to 48 h. These results further confirm that sprint interval training-induced muscle fatigue can impair the quality of a subsequent resistance training sessions, even though this is performed multiple days later.

Therefore, it is recommended to consistently monitor the fatigue generated by repeated sprint or sprint interval training in order to limit the likelihood of neuromuscular interference. Many variables, such as increased recovery time between sequences or different recovery strategies (ice bath, cryotherapy, and nutritional strategies) can be manipulated to optimize recovery at baseline performance. The one-sequence a day training configuration, with prolonged recovery between aerobic and strength exercises has to be programmed especially when HIT is composed of repeated short or long sprints. Another solution is to reduce muscle soreness and damage and, therefore, exacerbated residual fatigue caused through intense efforts by performing SIT on a bicycle. Indeed, it was shown that performing concurrent cycle sprint interval and resistance training does not seem to attenuate the strength response when compared to resistance training alone [18].

Effects of Concurrent Training During Pre- and In-Season in Other Team Sports

The effects of pre- and in-season concurrent training on maximal strength and power have been observed in other team sports during real training conditions and account for technical and tactical workload. The effects of two different HIT programs (long intervals, i.e., 4×4 min vs. short intervals, i.e., 16×100 m) performed concurrently with maximum strength and specific water polo training during pre-season has been compared [19]. The results demonstrated that improvements in swimming endurance parameters and maximum strength occurred following both programs in national elite players. It should, however, be noted that the training frequency with two combined sessions per week was rather low but may have been adequate and effective to elicit significant strength and endurance increments in national elite water polo players [19]. Similar results were also shown in futsal players performing concurrent strength and repeated sprint training (RST). The main results of this study emphasized faster mean RSA time following concurrent training than after only specific futsal training [20]. Hence, additional strength and RST can be an effective strategy to improve futsal-specific performance.

Although strength and power may be relatively easy to develop during preseason training periods as observed in the two previous studies [21, 22], there is some disagreement as to whether preseason levels of strength and power can be maintained during the long in-season playing periods, especially when a large amount of energy system (aerobic and anaerobic) conditioning or lengthy team practices are

performed [23–25]. Scheidner et al. [23] and dos Remedios et al. [24] reported a significant reduction in maximal strength 13–14 weeks into the in-season in college football players. Legg and Burnham [25] reported losses in shoulder strength by as much as 25% over the course of a 10-week in-season period in college-aged football players. Beyond aiming to develop neuromuscular qualities in-season, the main objective of concurrent training for team sport athletes should, therefore, be to maintain strength, power, and speed performances. In this way, Baker [26] investigated the effects of an in-season program of concurrent training in professional rugby league football players and noted that maximal strength and power can be maintained at the maximum preseason levels for long periods of up to 29 weeks. The key to maintaining strength and power during the in-season may lie in:

- Having athletes initially better conditioned to perform concurrent training
- It has been postulated that athletes who typically perform little metabolic aerobic training in the preseason and who may possess low aerobic capacities may experience greater decreases in maximal strength during the in-season compared to athletes with a long training history of concurrent strength and aerobic training [26]. If athletes are better conditioned to perform concurrent resistance and endurance training, then the interference effects of training, game, and practice demands on strength development or maintenance may be reduced to some degree.
- A sufficient workload
- According to practical recommendations in professional soccer players edited by Rønnestad et al. [27], one strength maintenance session per week, during a 12-week period, may be sufficient to maintain initial gain in strength and sprint performance achieved during a preceding preparatory period. In contrast, performing only 1 strength maintenance session every 2 weeks seemed too low to maintain leg strength and 40-m sprint performance.
- The prioritization of training goals, sequencing, and timing of training
- Leveritt and Abernethy [28] suggested that training goals need to be prioritized so that the primary training goal should be trained first in an unfatigued state. This prioritization of training goals would then dictate the sequencing and/or timing of other training sessions.
- Utilizing an appropriate periodization model that allows for periods of high, medium, and low training volumes and intensities. This variation of training load would avoid overreaching and stimulate physiological adaptations [22].

A common training method in team sport, called small-sided games (SSGs), has recently become the focus of scientific research because of its ability to develop physical capacities together with sport-specific tactical and technical skills [29]. The primary benefits of SSGs training are that the game can replicate the movement patterns, physiological demands, and technical requirements of competitive match play [29], while also requiring players to make decisions under pressure and fatigue. In addition, compared with traditional fitness training sessions, SSGs training is thought to increase player compliance and motivation because it is perceived to be sport-specific exercise that maximizes the training time spent with the ball [29].

Iacono et al. [30] have shown that HIT and SSGs training were equally effective in developing aerobic capabilities and supra-maximal intermittent performance (according to the Yo-Yo intermittent recovery level 1 test) in elite handball players. Moreover, 8 weeks of SSGs training led to greater improvement in anaerobic performance assessed by 10 and 20-m sprints, vertical jumps and agility test compared with HIT. Consequently, during the in-season period, handball coaches may prefer the SSGs training instead of HIT to optimize anaerobic and aerobic training. Finally, coaches and players could simultaneously stimulate higher physical demands than those presented in official match-play (maximal aerobic power, changes of directions, and high-intensity actions) to continually develop handball players' fitness components while also encompassing handball-specific technical and tactical elements. Other studies, achieved notably in junior elite basket [31] and volleyball players [32], corroborated these results emphasizing significant improvements in fitness and technical skills following the SSGs training period. Therefore, SSGs could be considered as an optimal training method during in-season period, not only to maintain but also develop aerobic and anaerobic physical qualities.

Summary

In conclusion, concurrent training variables such as the exercise order, recovery period as well as the type and modality (run or cycle) of HIT may influence the interference effect. Practitioners have to keep in mind that the training program should be structured according to the prioritized objective. Moreover, they have to be cautious to aid the recovery process when recovery time is restricted.

Strategies and objectives with regard to managing concurrent training-induced interference should be different according to the phase of the season. In preseasong, the main objective is to maximize the development of physical qualities whereas practitioners seek to maintain these during in-season period. However, we emphasized that SSGs training could allow development of both aerobic and anaerobic qualities (through agility and vertical jump) even in the competitive phase. Its effect on muscular strength however remains to be proven.

All previous studies mentioned in this chapter showed the large complexity when implementing concurrent training. Sometimes, this would be mainly dependent on the coach's preferences, the philosophy of the sports science staff, the demands of the competition, and the availability of facilities [33]. The aim of further studies should be to stimulate the interest of practitioners to objectively develop periodization models for concurrent aerobic and strength training, especially for team sport athletes.

References

1. Ross A, Gill N, Cronin J. Match analysis and player characteristics in rugby sevens. *Sports Med.* 2014;44:357–67.
2. Tomlin DL, Wenger HA. The relationship between aerobic fitness and recovery from high intensity intermittent exercise. *Sports Med.* 2001;31:1–11.

3. Bishop D, Girard O, Mendez-Villanueva A. Repeated-sprint ability part II: recommendations for training. *Sports Med.* 2011;41:741–56.
4. Edge J, Bishop D, Goodman C. Effects of high- and moderate-intensity training on metabolism and repeated sprints. *Med Sci Sports Exerc.* 2005;37:1975–82.
5. Edge J, Hill-Haas S, Goodman C, et al. Effects of resistance training on H⁺ regulation, buffer capacity, and repeated sprints. *Med Sci Sports Exerc.* 2006;38:2004–11.
6. Jones TW, Smith A, Macnaughton LS, French DN. Strength and conditioning and concurrent training practices in elite rugby union. *J Strength Cond Res.* 2016;30:3354–66.
7. Hickson RC. Interference of strength development by simultaneously training for strength and endurance. *Eur J Appl Physiol.* 1980;45:255–63.
8. Dudley GA, Djamil R. Incompatibility of endurance- and strength-training modes of exercise. *J Appl Physiol.* 1985;59:1446–51.
9. Hennessy LC, Watson AWS. The interference effects of training for strength and endurance simultaneously. *J Strength Cond Res.* 1994;8:12–9.
10. Wilson JM, Marin PJ, Rhea MR, Wilson SMC, Loenneke JP, Anderson JC. Concurrent training: a meta-analysis examining interference of aerobic and resistance exercises. *J Strength Cond Res.* 2012;26:2293–307.
11. Collins MA, Snow TK. Are adaptations to combined endurance and strength training affected by the sequence of training? *J Sports Sci.* 1993;11:485–91.
12. Chtara M, Chamari K, Chaouachi M, Chaouachi A, Koubaa D, Feki Y, Millet GP, Amri M. Effects of intra-session concurrent endurance and strength training sequence on aerobic performance and capacity. *Br J Sports Med.* 2005;39:555–60.
13. Chtara M, Chaouachi A, Levin GT, Chaouachi M, Chamari K, Amri M, Laursen PB. Effect of concurrent endurance and circuit resistance training sequence on muscular strength and power development. *J Strength Cond Res.* 2008;22:1037–45.
14. Robineau J, Babault N, Piscione J, Lacome M, Bigard AX. The specific training effects of concurrent aerobic and strength exercises depend on recovery duration. *J Strength Cond Res.* 2016;30:672–83.
15. Buchheit M, Laursen PB. High-intensity interval training, solutions to the programming puzzle: part 1: cardiopulmonary emphasis. *Sports Med.* 2013;43:313–38.
16. Robineau J, Lacome M, Piscione J, Bigard X, Babault N. Concurrent training in Rugby Sevens: effects of high-intensity interval exercises. *Int J Sports Physiol Perform.* 2017;12: 336–44.
17. Howatson G, Milak A. Exercise-induced muscle damage following a bout of sport specific repeated sprint. *J Strength Cond Res.* 2009;23:2419–24.
18. Cantrell GS, Schilling BK, Paquette MR, Murlasits Z. Maximal strength, power, and aerobic endurance adaptations to concurrent strength and sprint interval training. *Eur J Appl Physiol.* 2014;114:763–71.
19. Botonis PG, Toubekis AG, Platanou TI. Concurrent strength and interval endurance training in Elite Water Polo Players. *J Strength Cond Res.* 2016;30:126–33.
20. Phongsri K, Tongnillpant N, Ajijimaporn A, Silalertdetkul. Effect of additional concurrent specific strength and repeated sprint training during preseason on performance in futsal players. In: ECSS MetropolisRuhr; 2017.
21. Baker D. Applying the in-season periodisation of strength and power training to football. *Strength Cond J.* 1998;20:18–24.
22. Fleck SJ, Kraemer WJ. Designing resistance training programs. Champaign: Human Kinetics; 1997.
23. Scheidner V, Arnold B, Martin K, Bell D, Crocker P. Detraining effects in college football players during the competitive season. *J Strength Cond Res.* 1998;12:42–5.
24. Dos Remedios KA, Dos Remedios RL, Loy SF, Holland GF, Vincent WJ, Conley LM, Hing M. Physiological and field test performance changes of community college football players over a season. *J Strength Cond Res.* 1995;9:211–5.
25. Legg D, Burnham D. In-season shoulder abduction strength changes in football players. *J Strength Cond Res.* 1999;13:4381–3.

26. Baker D. The effects of an in-season of concurrent training on the maintenance of maximal strength and power in professional and college-aged rugby league football players. *J Strength Cond Res.* 2001;15:172–7.
27. Rønnestad BR, Nymark BS, Raastad T. Effects of in-season strength maintenance training frequency in professional soccer players. *J Strength Cond Res.* 2011;25:2653–60.
28. Leveritt M, Abernethy PJ. Acute effects of high-intensity endurance exercise on subsequent resistance activity. *J Strength Cond Res.* 1999;13:47–51.
29. Buchheit M, Laursen PB, Kuhnle J, Ruch D, Renaud C, Ahmaidi S. Game-based training in young elite handball players. *Int J Sports Med.* 2009;30:251–8.
30. Iacono AD, Eliakim A, Meckel Y. Improving fitness of elite handball players: small-sided games vs. high-intensity intermittent training. *J Strength Cond Res.* 2015;29(3):835–43.
31. Delextrat A, Martinez A. Small-sided game training improves aerobic capacity and technical skills in basketball players. *Int J Sports Med.* 2014;35(5):385–91.
32. Gabbett TJ. Do skill-based conditioning games offer a specific training stimulus for junior elite volleyball players? *J Strength Cond Res.* 2008;22(2):509–17.
33. Enright K, Morton J, Iga J, Drust B. The effect of concurrent training organisation in youth elite soccer players. *Eur J Appl Physiol.* 2015;115:2367–81.



Concurrent Aerobic and Strength Training for Performance in Soccer

27

Joao Renato Silva

Soccer as a Concurrent Modality

Demands of Football

Elite soccer players cover 8–13 km during matches [1] with an average intensity near the anaerobic threshold (70–75% of VO_{2max}) [1–3], which suggests that performance at the elite level may, in part, be determined by aerobic fitness [2]. However, despite low- to medium intensity running being the predominant activity pattern of soccer players, high-impulsive efforts, such as sprints, jumps, duels, and kicking, require maximal neuromuscular efforts [4]. These have the goal of maximizing the impulse produced [5] as this determines the decisive decision-making situations in professional football (e.g., speed) [6]. Moreover, the acceleration and deceleration activity profile in soccer results in high neuromuscular strains, even when speed is low [7]. Nowadays, players are experiencing an increase in match-play physical demands in part due to shorter between-match recovery periods and high neuromuscular demands (e.g., greater number of high-intensity running actions and acceleration requirements) [2, 8, 9]. Competitive soccer places a considerable stress on the physiological and biomechanical load (e.g., stress in joints and muscles) adaptation pathways. It seems that match-play represents an important component of the strength/power training stimulus; indeed higher match exposure is associated with improved neuromuscular qualities such as jumping height and power [10–12].

In soccer, potentiated neuromuscular and endurance-related qualities provide a competitive advantage, as they are associated with improved fatigue resistance

J. R. Silva

National Sports Medicine Programme, Excellence in Football Project, Aspetar—Qatar Orthopaedic and Sports Medicine Hospital, Doha, Qatar

Center of Research, Education, Innovation and Intervention in Sport (CIFI2D), Porto, Portugal

during the game [13, 14] faster post-match recovery [15] and injury prevention [16–18]. Therefore, players perform intense training programs (e.g., strength/power, endurance, speed endurance) aiming to improve neuromuscular and specific endurance performance.

Methodological Considerations

Recently, it has been highlighted that particular attention should be given to the selection of the modes of strength/power and endurance training [19]. It is believed that when they are at opposite ends of the biomechanical and neuro-coordinative spectrum, the anatomical and performance adaptations may be reduced, and the accuracy of the intended movement, fluidity, and elegance that characterize excellence may be compromised [19]. These methodological considerations call for the adoption of an integrated approach in training design (e.g., exercise, session plan), involving all technical staff such as the coach, the physical coach, and the physiologist. For example, two “physical conditioning” training exercises (e.g., 4 × 4' speed running at 15 km/h vs. 4 × 4' situational drill) may result in similar internal load (e.g., 90% maximal heart rate), but may differ in the highly impulsive requirements (e.g., more acceleration/decelerations during the drills). As so, manipulation of exercise structure is key for strength gains transfer to the high-impulsive actions required during soccer [19]. In fact, coaches adopt small-sided games to develop player's endurance qualities [20], but usually, even more to prepare next game strategic plan and consolidate players and team technical-tactical behaviors. The later aspect comprises the greater proportion of training time in strategic sports. In fact, different game structures (pitch size and player numbers) may influence the frequency and fatigue development of high-impulsive actions [21, 22]. Consequently, the neuromuscular involvement during the “overall” training sessions is an important consideration in soccer. Notably, the physiological and molecular events associated with endurance fitness development and maintenance (expression of PGC-1 α mRNA) [23] are usually targeted during the typical soccer training (e.g., tactical exercise, technical circuits that often involve frequent displacements or small-sided game exercises performed during a 90-min soccer competition/training session) [19].

Research in Concurrent Training in Soccer

The physiological and performance adaptations to different CT program (Tables 27.1 and 27.2) have been investigated in youth (13–15 years), [24] young adults (17–19 years), [25, 26] and adult soccer players [27–30]. Generally, studies have examined the training effects of two sessions per week [24–27, 30]. Nevertheless, the effect of higher frequency of concurrent training sessions (i.e., three) [29] and a combination of different frequencies of endurance and strength session during the CT (endurance block composed of two endurance training sessions and one strength training session by week and *vice versa*) have been investigated [28].

Table 27.1 Physiological and functional adaptations to concurrent training on alternating sessions

Study	Level/Country/ <i>n</i> (age)	Type of training	D	P	Physiological adaptations	Performance changes
Nunez et al. [25]	Semi-professional/ Spain/16 (28 ± 3.7)	Strength and Endurance with 24 h rest between sessions; SE and END —a sequence of general, special, and specific exercises incorporated in different training blocks. ET block (2 sessions END + 1 session SET) SET block (1 session END + 2 session SE)	4 blocks of 12 weeks	S		↑73–80% Probst test ↑11.1–16.2% SJ ↑8–8.7% CMJ ↑6–7% CMJWAS
Wong et al. [24]	Professional/ Hong-Kong/9 (24.6 ± 1.5)	Strength in the morning and Endurance in the afternoon (5 h interval) SE : 5 exercises; high-pull, jump squat, bench press, back half-squat, and chin-up; 4 sets at 6RM with 3-min rest between sets) END : 16 × 15 s at 120% of MAS with 15 s rest	2×/ week/8 weeks	PS		↑4% VJ, 15.9% T _{10m} 12.8% T _{30m} ↑119.7% YYIR1, ↑3.1% MAS ↑9.2% MAS _{distance}
Makhlouf et al. [30]	Elite youth/ Tunisia/14 (13.7 ± 0.5)	Strength and Endurance with 24 h rest between sessions SE : traditional resistance exercises, olympic lifts, plyometrics, 3 sets, 5–10 reps) END : 2 × 12–16 runs at 110–120%MAS)	2×/ week/12 weeks	IS	↑40.1% 1RM _{Squat}	↑6.9% T _{10m} ↑5.7% T _{30m} ↑5.7% Agility _{15m} ↑13.6% SJ ↑8% CMJ ↑4.1% MAV ↑54.5% YYIR1 ↔5JT

(continued)

Table 27.1 (continued)

Study	Level/Country/n (age)	Type of training	D	P	Physiological adaptations	Performance changes
Enright et al. [29]	Professional/ Premiere League Club/7 (17 ± 2)	Endurance and Strength and with 120-min rest between training components, SE: 5 traditional resistance exercises, 4 sets \times 6reps 85% 1RM) END: small-sided games, 4 V 4, 4 \times 4 min/3-min rec, 85–95% maximal heart rate	2x/ week/5 weeks	IS	19.1%1RM _{Squat} * \uparrow 27.3%IMVC LR \uparrow 13.3%ConcQuads _{180°} \uparrow 11–19.2%ConcHams _{90–180°} \uparrow 23.1%EccHams _{120°} \uparrow 14.3%AoP* \leftrightarrow MVIC _{peak force} , EccQuads _{120°} , ConcQuads _{90°} , FL, MT _{distal/} medial/proximal	\uparrow 8.2%SJ \uparrow 5.6%10 m* \leftrightarrow T _{30m} , CMJ

*significantly different between groups [29]

Table 27.2 Physiological and functional adaptations to different within-sessions order concurrent training (strength plus endurance and endurance plus strength)

Study	Level/Country/ <i>n</i> (age)	Type of training	D	P	Physiological adaptations	Performance changes
Strength plus endurance						
McGawley and Andersson [26]	Semi-and professional/ Sweden/9 (23 ± 4)	5-min rest between training components END: repeated sprint ability, speed endurance, high-intensity interval dribbling track and speed agility, and quickness circuits SE: (olympic lifts and traditional resistance exercises, 2–3 sets/5–10 reps, 75–85% 1RM; plyometrics 3–4 sets/4–15 reps, core strength)	3×/ week/5 weeks	PS	↑6–7.6% fat (%), kg ↑1.5–3% lean mass (% and KG) ↑11.1% Agility ↑18.7% 1RM Half-squat ↑28.5% 1RM Lunge ↑97.3% Iliopsoas (°) ↑5.3% Hamstrings (°)	↑1.4% T ₁₀ ↑7% CMJ
Helgerud et al. [27]	Elite/Spain/23 (25; range 20–31)	15-min rest between training components END: 4 × 4-min runs in a treadmill (5.5% inclination) 90–95% maximal heart rate separated by 3-min jogging at 50–60% maximal heart rate SE: 4 sets × 4 RM half-squats 90° with 3-min rest between sets	2×/ week/8-weeks	PS	↑8.6% VO _{2max} ↑3.7% RE _(1 km/h) ↑52% 1RM _{Squat} ↑49% 1RM/BW	↑3.2% T ₁₀ ↑1.6% T ₂₀ ↑5.2% CMJ
Makhoul et al. [30]	14 (13.7 ± 0.5)	15-min rest between training components SE: traditional resistance exercises, olympic lifts, plyometrics, 3 sets, 5–10 reps END: 2 × 12–16 runs at 110–120% maximal aerobic speed	2×/ week/12 weeks	IS	↑47.2% 1RM _{Squat}	↑5.8% T ₁₀ ↑2.6% T ₃₀ ↑4.3% Agility _{15m} ↑78.6% YIR1 ↑5.3% MAS ↔ SJ, CMJ, 5JT

(continued)

Table 27.2 (continued)

Study	Level/Country/ <i>n</i> (age)	Type of training	D	P	Physiological adaptations	Performance changes
Makhlof et al. [30]	Elite youth/Tunisia/15 (13.7 ± 0.5)	15-min rest between training components SE: traditional resistance exercises, olympic lifts, plyometrics, 3 sets, 5–10 reps) END: 2 × 12–16 runs at 110–120% maximal aerobic speed	2×/ week/12 weeks	IS	↑40.5% 1RM _{Squat}	↑3.2–4.3% T ₁₀ and T ₃₀ ↑11.6% Agility _{15m} ↑7–11% SJ and CMJ ↑4.7% MAS ↑58.8% YYIR1 ↔5IT
McGawley and Andersson [26]	Semi-and professional/Sweden/9 (23 ± 4)	5-min rest between training components END: repeated sprint ability, speed endurance, high-intensity interval dribbling track and speed agility, and quickness circuits) SE: (olympic lifts and traditional resistance exercises, 2–3 sets/5–10 reps, 75–85% 1RM; plyometrics 3–4 sets/4–15 reps, core strength)	3×/ week/5 weeks	PS	↑5.2–7.1% fat (% and kg) ↑1.6–3.6% lean (% and KG) ↑19.1% 1RM Half-squat ↑19.1% 1RM Lunge ↑165.2% Iliopsoas (°) ↑10.3% Hamstrings (°)	↑2.2% T ₁₀ ↑11.9% CMJ ↑0.9% Agility ↑0.8% RSA ↑16.8% perf dec RSA ↑22.9% YYIR2
Lopez-Segovia et al. [28]	Elite/Spain/19 (18.4 ± 0.6)	SE + END SE: jumps with and without external loads, traditional resistance exercises. Speed agility and quickness exercises with and without external loads END: high-intensity runs, physical-technical circuits and small-sided games, with maximal intensity during 4–6-min periods.	2×/ week/16-weeks	PS-IS	↑5.8% Fsquats _{20kg} ↑7.1% Fsquats _{30kg} ↑5.2% Fsquats _{40kg}	↑6.8% CMJ _(20kg) ↓2.3% T ₂₀ and T ₃₀ ↓3.2% T _{suj0–20-} ↓11.6% T _{suj0–30-} ↓2.6% T _{suj20–30-}

Enright et al. [29]	Professional/ Premiere League Club8 (17 ± 2)	SE + END with 30–45-min rest between training components SE: 5 traditional resistance exercises, 4 sets × 6reps 85% 1RM) END: small-sided games, 4 V 4, 4 × 4 min/3-min rec, 85–95% maximal heart rate	2×/week/ 5 weeks	IS	↑10.3% 1RM _{Squat*} ↑20.3% IMVC _{LR} ↑2.6% ConcQuads _{180°} ↑9–12% ConChams _{60–180°} ↑16.5% EccChams _{120°} ↑7.5% AoP _{20°} ↔MVIC _{peak force*} EccQuads _{120°} , ConcQuads _{60°} , FL, and MT distal, media and proximal	↑7.5% SJ ↔ T _{10m*} , T _{30m} CMJ
------------------------	--	---	---------------------	----	--	---

↑ significant improvement, ↓ significant decrement, ↔ no significant alterations, ~ approximately, NS not specified, F/D frequency and duration of training protocols, P period of the soccer season, SE strength training, END endurance training, SJ squat jump, CMJ WAS countermovement jump with arm swing, MAS maximal aerobic speed, VJ vertical jump, Fsquats_{(20–40kg)*} speed of movement during full squats exercise (range of the external load); T_{5–30m} sprint performance; T_{sprint(10–30s)} sprint performance in predetermined split distances; VO_{2max}, maximal oxygen consumption; RE_(1 km/h), running economy (velocity); 1RM_{HHS}, one repetition maxim in half-squat strength exercise; 1RM/BW, strength per kg of body weight; Rec recovery, C/S continuous jumps with legs extended, YYR1 Yo-Yo intermittent recovery level one, M_{Sdistance} maximal aerobic distance, SSG small-sided game, CMJ_(20kg) countermovement jump (external load), SAQ speed, agility, and quickness, HR_{max} maximal heart rate, PS performed during in-season, RSA repeated sprint ability, PT plyometric training, perf dec RSA performance decrement in the repeated sprint ability test, YYTR2 Yo-Yo intermittent recovery level two, FL fascicle length, MT muscle thickness, AoP Pennation Angle; Traditional resistance exercises such as squats, dead lifts, lunges)

* significantly different between groups [29]

The training-induced adaptations of CT performed in alternating sessions (e.g., strength training on Tuesday followed by endurance on Wednesday or endurance in the morning and strength in the afternoon, Table 27.1) [24, 26–28], or within the training session (strength plus endurance-based drills or endurance plus strength-based drills, SE + END, and END + SE, respectively) [24–26, 29] have been investigated (Table 27.2 and Fig. 27.2).

Strength/power training component of CT involved isolated (e.g., closed-chain multi-joint traditional resistance exercises, TRE) or a combination of distinct movement patterns (e.g., TRE, ballistic exercises, plyometrics, and sport-specific force-based actions within the same workout) with distinct loads (e.g., 4RM, 6RM, and 75% 1RM) and a wide range of movement velocities to improve player's performance in relevant motor tasks (Tables 27.1 and 27.2). Endurance-based element consisted of isolated (high-intensity aerobic training, HIA) or a combination of high-intensity training methods (e.g., HIA + speed endurance + repeated sprint ability, Tables 27.1 and 27.2). These loading schemes involved different intensity ranges (e.g., % of maximal heart rate and % of maximal sprinting speed) and exercises formats/structures (running based, dribbling tracks and small-sided games). Moreover, the independent variables (e.g., intensity, frequency, volume, work:rest ratio) of the strength or endurance loading scheme were manipulated in different ways, resulting in different training stimulus (Part II). Being so, players were exposed to a wide range of CT combinations (Tables 27.1 and 27.2). Small differences in the manipulation of the different mechano-biological descriptors of strength/power stimulus (e.g., load magnitude, volume) may result in distinct performance adaptations in soccer players [19]; determines the responses of cellular and molecular signaling pathways [31] (Part II). Consequently, the drawing of precise conclusions regarding the role of the different individual CT variables results in a complex equation. This is related to: (1) the wide variety of adopted training methods; (2) the short-term duration of the interventions; (3) the distinct season time lines used throughout the pre-season [25, 27–30] and/or in-season periods [24–26, 28]; (4) the different weekly loading schemes applied (endurance vs. strength); and (5) the different players' standard.

In fact, from the authors' knowledge just one study detailed the overall exposure (e.g., total distance covered, volume) during the exercise intervention [26]. Nevertheless, as discussed below, independently of the manipulation of the different concurrent variables, CT programs may result in substantial short-term physiological and performance improvements (Tables 27.1 and 27.2). Moreover, the magnitude of physiological and performance enhancements is comparable to the ones reported after strength/power studies conducted in soccer [19].

Physiological and Performance Adaptations to Concurrent Training in Soccer

Data related to the players' physiological parameters (e.g., % 1RM) and performance parameters (e.g., soccer-specific endurance tests and jump tests) were extracted and presented as the percentage of change, training efficiency, and corrected effect sizes (see [Appendix](#) for formulas).

Physiological Adaptations

The effectiveness of a training program is evaluated by the magnitude of sport-specific improvements (e.g., jumping, sprinting, and intermittent running capacity). Our analysis suggests that CT may result in improvements in different motor tasks and performance qualities in high- and low-level players (Tables 27.1 and 27.2 and Fig. 27.1). CT promote improvements in body composition (increased lean mass and decreased body fat) [29] endurance-related (VO_{2max} and running economy) [30] and neuromuscular-related characteristics (e.g., 1RM, rate force development) [24–26, 29, 30]. In fact, independent of the players' standard, enhanced (large magnitude) dynamic maximal force production [24, 26, 29, 30] can be obtained during different concurrent approaches [24, 26–30] (e.g., alternative days and within-session order). Specifically, increases in 1RM were observed during the performance of bilateral (Squat, Fig. 27.1) [24, 26, 29, 30] and unilateral (lunge) multi-joint exercises [29]. CT may also result in increases in relative maximal strength and peak torque during knee extension and flexion tasks both during concentric and eccentric isokinetic muscle actions [26]. Particularly, the increase in eccentric hamstring strength capabilities is especially relevant given the high rate of injury and subsequent recurrence that target this specific “vulnerable” muscle in soccer [32–34].

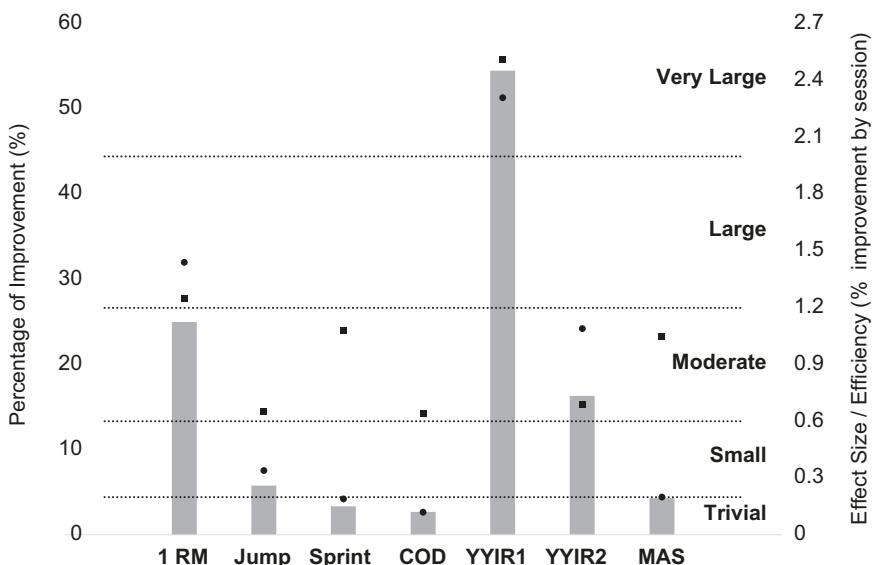


Fig. 27.1 Performances gains (solid bars), training efficiency (% improvement by session, circles), and magnitude of change (Weighted Effect Size, ES, squares) in 1 RM [24, 26, 29, 30], Jump [24, 26, 27, 29, 30], Sprint [24, 26, 27, 29, 30], COD [24, 29], YYIR1 [24, 27], YYIR2 [29], and MAS [24, 27] after short-term concurrent training interventions (5–12 weeks); studies included had to report changes in 1 RM. Training efficiency = % performance improvement/number of training sessions; *1RM* one repetition maximum, *COD* change of direction ability, *YYIR1* Yo-Yo intermittent recovery test level 1, *YYIR2* Yo-Yo intermittent recovery test level 2, *MAS* maximal aerobic speed. Dashed horizontal lines represent the threshold values for corrected effect sizes (see Appendix)

Performance Adaptations

Pooled data from different studies (Fig. 27.1) [24–30] reveals an enhancement of neuromuscular performance (moderate magnitude) when measured by the performance of different multi-joint tasks such as jumping (SJ, CMJ, and CMJ-WAS), sprinting (10–30 m) [24, 26–30], and COD abilities (*t*-test and agility15 s test) [24, 29]. Although a similar magnitude of change is observed between these different motor tasks, the training efficiency is greater for jumping abilities followed by sprinting and COD abilities (Fig. 27.1). There are systematic [19] and meta-analytic evidences [35] showing that strength increases during the performance of traditional resistance exercises (e.g., squats and lunges) transfer positively to the performance of sprint-and-jump-related actions [19, 35]. In fact, associations between the measures of maximal (1RM) [36] and relative strength (1RM/BM) [37], as well as between mechanical properties of specific muscles (e.g., quadriceps), such as peak torque [19, 38] and peak power [39], and the ability of soccer players to perform complex multi-joint dynamic movements (e.g., jumping and sprinting actions) have been reported [11, 36–39]. Additionally, CT results in substantial gains in the performance of nonspecific (Fig. 27.1, Probs-test and MAS, extremely large and moderate magnitudes, respectively) [24, 27] and specific endurance tests (Fig. 27.1, YYIR1 and YYIR2, very large and moderate magnitudes, respectively) [24, 27, 29]. Notably, these performance improvements are relevant to optimize soccer players' match performance. Improved neuromuscular capacity (e.g., strength and power) and soccer-specific endurance (assessed by the Yo-Yo tests) have been linked to a greater fatigue resistance (e.g., during a worst-case match scenario) [13, 14], faster post-match recovery (e.g., lower match-related muscle-damage markers) [15, 40] and injury prevention (e.g., offers greater injury protection when players are exposed to rapid changes in workload) [16–18].

Considerations for Concurrent Training Design

There is a multitude of potential CT variables (within-session exercise order, between-mode recovery length, endurance training intensity, and endurance training volume) that may play a role in the acute and chronic interference [41] consequently influencing the chronic adaptations (Part II).

Within-Session Order

Clubs' obligations may involve team travelling and competing frequently within the in-season, limiting structured training and recovery opportunities within this important period [42]. The limited time for training results in coaches prescribing training sessions involving the training of different physical components (strength and football-specific endurance training) within the same day (e.g., morning and afternoon sessions during training camps) or within the same session. Nevertheless,

it's believed that the order in which these exercise modes are performed may potentially modulate interference and so, result in different training stimuli [41]. Although scarce, researchers have examined the short-term influence of SE + END [24–26, 29] and END + SE [24, 29, 30] within the same session. Generally, both forms of within-session order result in substantial improvements in neuromuscular performance assessed by means of 1RM (squat lunge and knee extension and flexion tasks), jumping, sprinting, and COD abilities (Table 27.2, Fig. 27.2b). Particularly, pooled data of the studies measuring strength gains revealed that END + SE results in a greater magnitude (Fig. 27.2a) of change in 1RM, acceleration (10 m sprint), and COD actions. Nevertheless, both organizations resulted in similar magnitude of gains on CMJ performance. The superior training effect of END + SE in sprinting abilities is further confirmed when pooling the different sprint distances (Fig. 27.2b). Notably, sprint "training efficiency" scores, representing the percentage of improvement by session, is higher for the END + SE

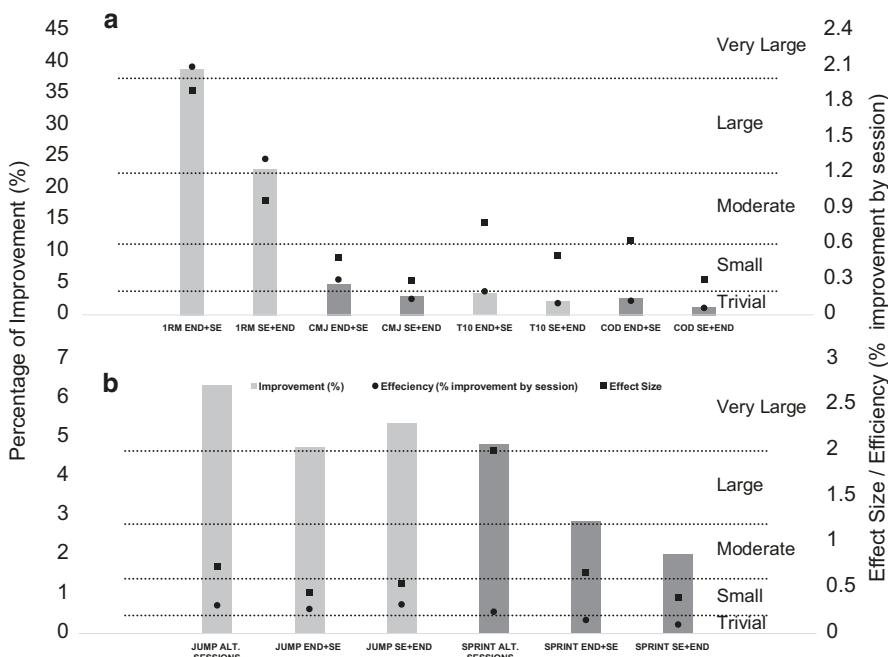


Fig. 27.2 Performances gains (solid bars), training efficiency (% improvement by session, circles), and magnitude of change (Weighted Effect Size, ES, squares) after (a) Concurrent training within-session order END + SE [24, 29, 30] and SE + END [24, 26, 29] within the same session (5–12 weeks). (b) Concurrent training performed in alternating sessions [24, 26–28] (5–12 weeks) and within-session order (5–12 weeks). Training efficiency = % performance improvement/number of training sessions, END + SE endurance plus strength, SE + END strength plus endurance, 1RM one repetition maximum, CMJ countermovement jump, T10 10 m sprint time. Dashed horizontal lines represent the threshold values for corrected effect sizes (see Appendix); Note: data extracted from study [28] are from the second season block (SE—6 sets/8 RM/fast loads, END—6 medium extensive intervals of 8 min)

independently of the method of analysis (10 m sprint vs. sprinting pooled data, Fig. 27.2a, b).

Almost 90% of all muscle injuries of professional soccer players are localized in lower limbs [34] with hamstrings muscle strains accounting for 12–16% of all injuries [34, 43, 44]. Particularly, the injury rate is higher in the last parts of the soccer matches [45]. Eccentric hamstring strength is a fundamental etiological factor associated with hamstring muscle strains [46]. As so, researchers investigate the short-term [46, 47] and acute [48] timing-induced effect (PRE vs. POST training session) of eccentric-based strength exercises (Nordic hamstrings exercises, NHE) targeting this soccer-specific “vulnerable” muscles. Lovell and colleagues [47] examined the short-term (2 times a week during 12 week) timing-induced effect of NHE within the session order. The authors observed that training adaptations were independent of the within-session exercise order; similar gains in strength, flexibility, architectural (pen-nation angle), and morphological changes (muscle thickness) were observed. Nevertheless, Small and colleagues [46] applying an identical research design in a shorter exposure period (8 weeks, 2 times a week, 3 sets of 12–10–8 reps) observed that the performance of NHE exercises at POST significantly reduced the negative influence of fatigue during soccer-specific exercise; players significantly increase eccentric hamstrings peak torque and the functional ratio (eccentric hamstrings; concentric quadriceps) at half-time (45 min) and post (90 min) soccer-specific simulation protocol (SAFT90) compared to the PRE group. However, PRE had a greater improvement in eccentric hamstrings strength and functional ratio (eccHams:concQuads) after the training intervention (assessments performed prior the soccer-specific protocol). Lovel and colleagues [48] investigated the acute neuromuscular and performance responses to NHE completed PRE vs. POST training session. The authors observed that PRE increased sprint performance but had a greater fatiguing effect on hamstrings strength (decreased eccentric peak torque) during 60-min soccer-specific exercise (peak torque assessed in 15-min intervals) [48].

Therefore, this greater fatiguing effect may render the players more susceptible to hamstring strain injury acutely during the remaining training session [48]. Specially, a higher injury predisposition might occur in the high-loaded players. Accordingly, the external load completed by players is highly variable within and between soccer-specific exercises, such as small-sided games and team strategic combinations. Different tactical and technical roles dispose to a high inter-player variability in specific locomotor activities [49, 50]. These previous factors (fatigue responses and inter-player variability within a session) along with the similar or greater gains of POST organization should be considered by coaches when defining the timing of the strength component. Nevertheless, it is important to highlight that these previous studies [46–48] were performed with amateur soccer players that are subject to a smaller training exposure (2–3 sessions a week) than professional players [46–48]. We believe that soccer-related technical staff should adopt an integrated approach when defining the exercise timing of the strength-based element of the session. Some of these are:

- Is the player returning from injury or not?
- Is the target increasing player's maximal strength or strength endurance?

- Is the team in a congestive schedule period or not?
- What is the expected metabolic/mechanical stress of the “overall” session?
- Does the player show enough technical competency to perform a complex strength exercise in fatigued state?

Between-Mode Recovery Length (Proximity)

The recovery length allowed between concurrent exercise sessions is another important practical consideration [41]. Increasing training time available, as the observed within specific periods of the season (e.g., in-season periods with one competition per week or during pre-season and transition period) may allow coaches to implement isolated mechanical-and metabolic-based sessions [42] on alternating days [24, 28] or within the same day (morning and afternoon training sessions) [26, 27]. It's believed that an increase in recovery length will allow to not compromise the resistance training stimulus (via residual fatigue and/or substrate depletion) and anabolic response (via molecular interference, Part II) that is thought to occur when undertaking concurrent exercise sessions [41]. Enright and colleagues [26] observed small but substantial improvements (larger corrected effect sizes, ESs) in physical performance parameters in the END + SE vs. SE + END concurrent organization. Importantly, the recovery time allocated between the training of the two physical components was very different between exercises modes. The time allocated between the END + SE was of 120 min and of 45 min between the SE + END organization. As so, the authors attributed the superior results of the END + SE organization to the higher recovery time allocated between training bouts and the superior nutritional arrangements that could be applied when a greater interval period occurs [26]. The relevance of the between-mode recovery length is further confirmed in the study of Wong and colleagues [27] (5 h recovery between the strength and endurance session). In this study [27], were observed the greater improvements in jumping (large ESs) and sprinting abilities (very large ESs) among the seven selected studies. This is particularly relevant given that in professional football unexpected changes in team's training schedule occur that alter the organization of CT and the timing of food intake around each exercise session [51]. Nutrition plays a key role in modulating the physiological adaptations to CT (Part III) [51].

CT performed in alternating sessions [24, 27, 28, 52] may result in greater magnitude of changes in overall sprint and jump performance (Fig. 27.2b) than within same session arrangements [24, 29, 30, 51] or within the day [26]. This greater magnitude of change could be explained not only by a decrease in the interference effect (e.g., decrease training proximity) but as well as by a possible superior organization of the overall training session. Coaches may be able to structure the individual training sessions with the strategic and technical-tactical exercises that are dependent of strength or endurance qualities. This type of organization (strength/power vs. endurance-based sessions) may allow a greater input in the independent physiological and biomechanical load pathways of neuromuscular or endurance-related adaptations as well as in other relevant factors of soccer performance (technical-tactical) [42].

Intensity and Volume

Another practical consideration is the intensity and volume of the endurance component applied in the CT [53]. It has been suggested that given the conditional concurrent nature of soccer, concurrent high-intensity strength (high load few repetitions), and high-intensity endurance training modes (e.g., speed endurance) may enhance a player's overall performance [19]. In this regard, CT studies have mostly analyzed different combinations of these training methods (Tables 27.1 and 27.2).

A combination of resistance exercises, plyometric, and sport-specific strength exercises (e.g., accelerations and deceleration drills) is recommended to target a broad range of the force–velocity spectrum [19, 42]. This type of approach has been suggested not only due to its superior efficiency but also due to its ecological value [19]. Coaches should be conscious that a reduced transfer of strength gains to high-impulsive actions of soccer may occur when the prescribed exercises have a “poor” biomechanical specificity [54]. In this regard, open-chain, isolated and machine-based exercises (i.e., leg extension, leg press,) may target differently the intra-muscular and inter-muscular aspects of athletic performance; they may not provide adequate movement pattern specificity for optimal performance improvements in closed-chain sporting movements (e.g., sprinting and COD) [55]. Given the scarcity of studies in CT in soccer, an analysis of strength training studies performed in soccer may allow to draw better conclusions regarding the efficiency of different strength and endurance training methods. In fact, the majority of strength training studies in soccer have been performed during the pre-season period (for references, see [19]). The detraining during the transition period results in large reductions in endurance-markers (e.g., $\text{VO}_{2\text{max}}$ and time to exhaustion) and performance of soccer-specific endurance exercise (Yo-Yo intermittent endurance exercise level 2) [42]. Therefore, a substantial amount of endurance-based work is prescribed during pre-season [42]. In this regard, Bogdanis and colleagues [56, 57] analyzed the effects of high-repetition/moderate-load (hypertrophy) and low-repetition/high-load (neural adaptations) programs on anthropometric, neuromuscular, and endurance performance; a considerable amount of interval training and small-sided games were performed [56, 57]. The hypertrophic mode was associated with increases in lower limb muscle mass, while the neural mode was more effective in improving relative strength, sprint, and COD performance, running economy, and fatigue resistance measured with a repeated cycle ergometer sprint test [56, 57]. Other researchers [58] found that explosive-strength training performed in parallel with endurance training resulted in improvements in the individual anaerobic threshold and neuromuscular parameters (e.g., low-force portion of the load-vertical jumping curve). These results suggest, at least in part, a better efficacy of neural-based programs in high-level players [56, 57, 59].

High-intensity endurance training modes (single and combined forms of HIT, Tables 27.1 and 27.2) have been suggested to better fit in the soccer training periodization puzzle than the adoption of high volumes/low intensity endurance modes [19]. This rational is based on the following observations: (1) the acute anabolic

(e.g., growth hormone and insulin-like growth factor-I) [60–64] and redox environment; (2) HIT maintains a muscle fiber phenotype associated with strength and power capabilities [65]; (3) commonality of muscle action (brief and intense muscle contractions) [19]; (4) the adaptations in skeletal muscle and improvements in laboratory and field endurance-related parameters that are comparable to the observed after high-volume endurance training [66–71]; (5) increase in endurance and neuromuscular-related outcomes [72]; and (6) may improve muscle power-based actions [71–73]. Nevertheless, independent of the HIT training mode, exercise design should recreate the high-impulsive structure/nature of soccer (e.g., acceleration and deceleration, multidirectional running patterns).

Summary

Research in concurrent training in soccer reveals similar physiological and performance adaptations than the typically observed after strength/power training studies in soccer. Concurrent high-intensity strength and high-intensity endurance training modes may represent the most efficient combination to implement in soccer periodized training program. Within a CT, the observed magnitude of change and training efficiency seems as follows: alternating sessions>endurance plus strength within the same session>strength plus endurance within the same session. As discussed in this chapter, coaches should adopt an integrated approach considering the exercise timing of the strength element of the session (e.g., individual player, exercise structure, training methods, performance constructs, moment of the season). In fact, soccer is a concurrent sport by nature, due to the associated-endurance related demands triggered by the training of the other relevant constructs of performance (technical-tactical) and competition format (volume and intensity).

Appendix: Analysis and Interpretation of Results

To evaluate the magnitude of the effects, percent change was calculated for each dependent variable for each study using the below equation:

$$\left[M_{\text{post}} - M_{\text{pre}} \right] / M_{\text{pre}} \times 100 \quad (\text{Eq. 27.1})$$

where M_{post} was the post-training mean and M_{pre} the baseline mean. ESs (Effect size) were computed to present standardized training-related effect on the outcome variables [74]. The different ES within individual studies were calculated with Cohen's d , by dividing the raw ES (difference in means) by the pooled standard deviations, as proposed by Bornstein et al. [75] as followed (Eq. 27.1):

$$\text{ES} = g = \frac{\left(M_{\text{post}} - M_{\text{pre}} \right)}{\text{SD}_{\text{pooled}}} \quad (\text{Eq. 27.2})$$

SD_{pooled} is the pooled SD of the measurements and was calculated as follows (Eq. 27.2):

$$SD_{\text{pooled}} = \sqrt{\frac{(n-1) \times SD_{\text{Pre}}^2 + (n-1) \times SD_{\text{Post}}^2}{(2n-2)}} \quad (\text{Eq. 27.3})$$

where SD_{Pre}^2 is the standard deviation of the performance test completed before the training intervention and SD_{Post}^2 is the standard deviation of the performance test completed after the training intervention. To account for possible overestimation of the true population, ESs were corrected accounting for the magnitude of the sample size of each study [76]. Therefore, a correction factor (CF) was calculated as proposed by Hedges and Olkin [76].

$$CF = 1 - \frac{3}{4df - 1} \quad (\text{Eq. 27.4})$$

where $df = n - 1$. The corrected ES was calculated as follows:

$$\text{Corrected ES}_c = g \times CF \quad (\text{Eq. 27.5})$$

Threshold values for ES_c were defined as trivial (<0.2), small (0.2–0.6), moderate (0.6–1.2), large (1.2–2.0), and very large (>2.0) [77].

Training efficiency for each dependent variable was calculated as follows:

$$\text{Efficiency} = \frac{\% \text{ of improvement} [M_{\text{post}} - M_{\text{pre}}] / M_{\text{pre}} \times 100}{\text{Number of training sessions} (\text{number of weeks} \times \text{number of sessions per week})} \quad (\text{Eq. 27.6})$$

References

- Bangsbo J, Mohr M, Krustrup P. Physical and metabolic demands of training and match-play in the elite football player. *J Sports Sci.* 2006;24(7):665–74.
- Reilly T, Ekblom B. The use of recovery methods post-exercise. *J Sports Sci.* 2005;23(6):619–27.
- Stolen T, Chamari K, Castagna C, Wisloff U. Physiology of soccer: an update. *Sports Med.* 2005;35(6):501–36.
- Cometti G, Maffuletti NA, Pousson M, Chatard JC, Maffulli N. Isokinetic strength and anaerobic power of elite, subelite and amateur soccer players. *Int J Sports Med.* 2001;22:45–51.
- Winter EM, Abt G, Brookes FB, Challis JH, Fowler NE, Knudson DV, et al. Misuse of “Power” and other mechanical terms in sport and exercise science research. *J Strength Cond Res.* 2016;30(1):292–300.
- Faude O, Koch T, Meyer T. Straight sprinting is the most frequent action in goal situations in professional football. *J Sports Sci.* 2012;30(7):625–31.
- Akenhead R, Hayes PR, Thompson KG, French D. Diminutions of acceleration and deceleration output during professional football match play. *J Sci Med Sport.* 2013;16(6):556–61.
- Barnes C, Archer DT, Hogg B, Bush M, Bradley PS. The evolution of physical and technical performance parameters in the english premier league. *Int J Sports Med.* 2014;35(13):1095–100.

9. Bush M, Barnes C, Archer DT, Hogg B, Bradley PS. Evolution of match performance parameters for various playing positions in the English Premier League. *Hum Mov Sci.* 2014;39C:1–11.
10. Sporis G, Jovanovic M, Omrcen D, Matkovic B. Can the official soccer game be considered the most important contribution to player's physical fitness level? *J Sports Med Phys Fitness.* 2011;51(3):374–80.
11. Silva JR, Magalhaes JF, Ascenso AA, Oliveira EM, Seabra AF, Rebelo AN. Individual match playing time during the season affects fitness-related parameters of male professional soccer players. *J Strength Cond Res.* 2011;25(10):2729–39.
12. Morgans R, Di Michele R, Drust B. Soccer match-play represents an important component of the power training stimulus in premier league players. *Int J Sports Physiol Perform.* 2018;13(5):665–7.
13. Bangsbo J, Iaia FM, Krstrup P. The Yo-Yo intermittent recovery test: a useful tool for evaluation of physical performance in intermittent sports. *Sports Med.* 2008;38(1):37–51.
14. Silva JR, Magalhaes J, Ascenso A, Seabra AF, Rebelo AN. Training status and match activity of professional soccer players throughout a season. *J Strength Cond Res.* 2013;27(1):20–30.
15. Tofari P, Kemp J, Cormack S. A self-paced team sport match simulation results in reductions in voluntary activation and modifications to biological, perceptual and performance measures at half-time, and for up to 96 hours post-match. *J Strength Cond Res.* 2017; <https://doi.org/10.1519/JSC.0000000000001875>.
16. Malone S, Owen A, Newton M, Mendes B, Collins KD, Gabbett TJ. The acute:chronic workload ratio in relation to injury risk in professional soccer. *J Sci Med Sport.* 2017;20(6):561–5.
17. Al Attar WSA, Soomro N, Sinclair PJ, Pappas E, Sanders RH. Effect of injury prevention programs that include the nordic hamstring exercise on hamstring injury rates in soccer players: a systematic review and meta-analysis. *Sports Med.* 2017;47(5):907–16.
18. Zouita S, Zouita AB, Kebbi W, Dupont G, Ben Abderrahman A, Ben Salah FZ, et al. Strength training reduces injury rate in elite young soccer players during one season. *J Strength Cond Res.* 2016;30(5):1295–307.
19. Silva JR, Nassis GP, Rebelo A. Strength training in soccer with a specific focus on highly trained players. *Sports Med Open.* 2015;2(1):1–27.
20. Hill-Haas SV, Dawson B, Impellizzeri FM, Coutts AJ. Physiology of small-sided games training in football: a systematic review. *Sports Med.* 2011;41(3):199–220.
21. Rebelo AN, Silva P, Rago V, Barreira D, Krstrup P. Differences in strength and speed demands between 4v4 and 8v8 small-sided football games. *J Sports Sci.* 2016;34(24):2246–54.
22. Hodgson C, Akenhead R, Thomas K. Time-motion analysis of acceleration demands of 4v4 small-sided soccer games played on different pitch sizes. *Hum Mov Sci.* 2014;33:25–32.
23. Jeong TS, Bartlett JD, Joo CH, Louhelainen J, Close GL, Morton JP, et al. Acute simulated soccer-specific training increases PGC-1alpha mRNA expression in human skeletal muscle. *J Sports Sci.* 2015;33(14):1493–503.
24. Makhlouf I, Castagna C, Manzi V, Laurencelle L, Behm DG, Chaouachi A. Effect of sequencing strength and endurance training in young male soccer players. *J Strength Cond Res.* 2016;30(3):841–50.
25. Lopez-Segovia M, Palao Andres JM, Gonzalez-Badillo JJ. Effect of 4 months of training on aerobic power, strength, and acceleration in two under-19 soccer teams. *J Strength Cond Res.* 2010;24(10):2705–14.
26. Enright K, Morton J, Iga J, Drust B. The effect of concurrent training organisation in youth elite soccer players. *Eur J Appl Physiol.* 2015;115(11):2367–81.
27. Wong PL, Chaouachi A, Chamari K, Dellal A, Wisloff U. Effect of preseason concurrent muscular strength and high-intensity interval training in professional soccer players. *J Strength Cond Res.* 2010;24(3):653–60.
28. Nunez VM, Da Silva-Grigoletto ME, Castillo EF, Poblador MS, Lancho JL. Effects of training exercises for the development of strength and endurance in soccer. *J Strength Cond Res.* 2008;22(2):518–24.

29. McGawley K, Andersson PI. The order of concurrent training does not affect soccer-related performance adaptations. *Int J Sports Med.* 2013;34(11):983–90.
30. Helgerud J, Rodas G, Kemi OJ, Hoff J. Strength and endurance in elite football players. *Int J Sports Med.* 2011;32(9):677–82.
31. Spiering BA, Kraemer WJ, Anderson JM, Armstrong LE, Nindl BC, Volek JS, et al. Resistance exercise biology: manipulation of resistance exercise programme variables determines the responses of cellular and molecular signalling pathways. *Sports Med.* 2008;38(7):527–40.
32. Ekstrand J, Walden M, Hagglund M. Hamstring injuries have increased by 4% annually in men's professional football, since 2001: a 13-year longitudinal analysis of the UEFA Elite Club injury study. *Br J Sports Med.* 2016;50(12):731–7.
33. Hagglund M, Walden M, Ekstrand J. Previous injury as a risk factor for injury in elite football: a prospective study over two consecutive seasons. *Br J Sports Med.* 2006;40(9):767–72.
34. Hawkins RD, Hulse MA, Wilkinson C, Hodson A, Gibson M. The association football medical research programme: an audit of injuries in professional football. *Br J Sports Med.* 2001;35(1):43–7.
35. Seitz LB, Reyes A, Tran TT, Saez de Villarreal E, Haff GG. Increases in lower-body strength transfer positively to sprint performance: a systematic review with meta-analysis. *Sports Med.* 2014;44(12):1693–702.
36. Wisloff U. Strong correlation of maximal squat strength with sprint performance and vertical jump height in elite soccer players. *Br J Sports Med.* 2004;38(3):285–8.
37. Keiner M, Sander A, Wirth K, Schmidbleicher D. Long-term strength training effects on change-of-direction sprint performance. *J Strength Cond Res.* 2014;28(1):223–31.
38. Dauty M, Potiron Josse M. Corrélations et différences de performance entre des footballeurs, professionnels, en formation et amateurs à partir du test de sprint (10 mètres départ arrêté) et de tests isocinétiques du genou. *Sci Sports.* 2004;19(2):75–9.
39. Requena B, Gonzalez-Badillo JJ, de Villareal ES, Ereline J, Garcia I, Gapeyeva H, et al. Functional performance, maximal strength, and power characteristics in isometric and dynamic actions of lower extremities in soccer players. *J Strength Cond Res.* 2009;23(5):1391–401.
40. Owen A, Dunlop G, Rouissi M, Chtara M, Paul D, Zouhal H, et al. The relationship between lower-limb strength and match-related muscle damage in elite level professional European soccer players. *J Sports Sci.* 2015;33(20):2100–5.
41. Fyfe JJ, Bishop DJ, Stepto NK. Interference between concurrent resistance and endurance exercise: molecular bases and the role of individual training variables. *Sports Med.* 2014;44(6):743–62.
42. Silva JR, Brito J, Akenhead R, Nassis GP. The transition period in soccer: a window of opportunity. *Sports Med.* 2016;46(3):305–13.
43. Arnason A, Andersen TE, Holme I, Engebretsen L, Bahr R. Prevention of hamstring strains in elite soccer: an intervention study. *Scand J Med Sci Sports.* 2008;18(1):40–8.
44. Woods C, Hawkins RD, Maltby S, Hulse M, Thomas A, Hodson A. The Football Association Medical Research Programme: an audit of injuries in professional football--analysis of hamstring injuries. *Br J Sports Med.* 2004;38(1):36–41.
45. Rahnama N, Reilly T, Lees A. Injury risk associated with playing actions during competitive soccer. *Br J Sports Med.* 2002;36(5):354–9.
46. Small K, McNaughton L, Greig M, Lovell R. Effect of timing of eccentric hamstring strengthening exercises during soccer training: implications for muscle fatigability. *J Strength Cond Res.* 2009;23(4):1077–83.
47. Lovell R, Knox M, Weston M, Siegler JC, Brennan S, Marshall PWM. Hamstring injury prevention in soccer: before or after training? *Scand J Med Sci Sports.* 2018;28(2):658–66.
48. Lovell R, Siegler JC, Knox M, Brennan S, Marshall PW. Acute neuromuscular and performance responses to Nordic hamstring exercises completed before or after football training. *J Sports Sci.* 2016;34(24):2286–94.
49. Gregson W, Drust B, Atkinson G, Salvo VD. Match-to-match variability of high-speed activities in premier league soccer. *Int J Sports Med.* 2010;31(4):237–42.

50. Bradley PS, Carling C, Archer D, Roberts J, Dodds A, Di Mascio M, et al. The effect of playing formation on high-intensity running and technical profiles in English FA Premier League soccer matches. *J Sports Sci.* 2011;29(8):821–30.
51. Enright K, Morton J, Iga J, Drust B. Implementing concurrent-training and nutritional strategies in professional football: a complex challenge for coaches and practitioners. *Sci Med Football.* 2017;1(1):65–73.
52. Enright K, Morton J, Iga J, Drust B. Hormonal responses during two different concurrent-training trials in youth elite soccer players: does changing the organisation of training impact the hormonal response to concurrent exercise? *J Sports Med Phys Fitness.* 2018;58(5):699–706.
53. Wilson JM, Marin PJ, Rhea MR, Wilson SM, Loenneke JP, Anderson JC. Concurrent training: a meta-analysis examining interference of aerobic and resistance exercises. *J Strength Cond Res.* 2012;26(8):2293–307.
54. Beattie K, Kenny IC, Lyons M, Carson BP. The effect of strength training on performance in endurance athletes. *Sports Med.* 2014;44(6):845–65.
55. Stone M, Stone M. Resistance training modes: a practical perspective. In: Cardinale M, Newton R, Nosaka K, editors. *Strength and conditioning: biological principles and practical application.* Oxford: Wiley-Blackwell; 2011. p. 353.
56. Bogdanis GC, Papaspyprou A, Souglis AG, Theos A, Sotiropoulos A, Maridaki M. Effects of two different half-squat training programs on fatigue during repeated cycling sprints in soccer players. *J Strength Cond Res.* 2011;25(7):1849–56.
57. Bogdanis GC, Papaspyprou A, Souglis A, Theos A, Sotiropoulos A, Maridaki M. Effects of hypertrophy and a maximal strength training programme on speed, force and power of soccer players. In: Reilly T, Korkusuz F, editors. *Science and Football VI. The proceedings of the sixth world congress on science and football.* New York: Routledge; 2009. p. 290–5.
58. Los Arcos A, Yancı J, Mendiguchia J, Salinero JJ, Brughelli M, Castagna C. Short-term training effects of vertically and horizontally oriented exercises on neuromuscular performance in professional soccer players. *Int J Sports Physiol Perform.* 2013;9(3):480–8.
59. Gorostiaga EM, Izquierdo M, Ruesta M, Iribarren J, Gonzalez-Badillo JJ, Ibanez J. Strength training effects on physical performance and serum hormones in young soccer players. *Eur J Appl Physiol.* 2004;91(5–6):698–707.
60. Meckel Y, Nemet D, Bar-Sela S, Radom-Aizik S, Cooper DM, Sagiv M, et al. Hormonal and inflammatory responses to different types of sprint interval training. *J Strength Cond Res.* 2011;25(8):2161–9.
61. Wahl P. Hormonal and metabolic responses to high intensity interval training. *J Sports Med Doping Stud.* 2013;3(1):e132.
62. Wahl P, Mathes S, Achtzehn S, Bloch W, Mester J. Active vs. passive recovery during high-intensity training influences hormonal response. *Int J Sports Med.* 2014;35(7):583–9.
63. Wahl P, Mathes S, Kohler K, Achtzehn S, Bloch W, Mester J. Acute metabolic, hormonal, and psychological responses to different endurance training protocols. *Horm Metab Res.* 2013;45(11):827–33.
64. Zinner C, Wahl P, Achtzehn S, Reed JL, Mester J. Acute hormonal responses before and after 2 weeks of HIT in well trained junior triathletes. *Int J Sports Med.* 2014;35(4):316–22.
65. Gunnarsson TP, Christensen PM, Holse K, Christiansen D, Bangsbo J. Effect of additional speed endurance training on performance and muscle adaptations. *Med Sci Sports Exerc.* 2012;44(10):1942–8.
66. Gibala MJ, Little JP, van Essen M, Wilkin GP, Burgomaster KA, Safdar A, et al. Short-term sprint interval versus traditional endurance training: similar initial adaptations in human skeletal muscle and exercise performance. *J Physiol.* 2006;575.(Pt 3):901–11.
67. Burgomaster KA, Hughes SC, Heigenhauser GJ, Bradwell SN, Gibala MJ. Six sessions of sprint interval training increases muscle oxidative potential and cycle endurance capacity in humans. *J Appl Physiol.* 2005;98(6):1985–90.
68. Gibala M. Molecular responses to high-intensity interval exercise. *Appl Physiol Nutr Metab.* 2009;34(3):428–32.

69. Jensen L, Bangsbo J, Hellsten Y. Effect of high intensity training on capillarization and presence of angiogenic factors in human skeletal muscle. *J Physiol.* 2004;557(Pt 2):571–82.
70. Christensen PM, Krstrup P, Gunnarsson TP, Kiilerich K, Nybo L, Bangsbo J. VO₂ kinetics and performance in soccer players after intense training and inactivity. *Med Sci Sports Exerc.* 2011;43(9):1716–24.
71. Ingebrigtsen J, Shalfawi SA, Tonnessen E, Krstrup P, Holtermann A. Performance effects of 6 weeks of aerobic production training in junior elite soccer players. *J Strength Cond Res.* 2013;27(7):1861–7.
72. Iaia FM, Rampinini E, Bangsbo J. High-intensity training in football. *Int J Sports Physiol Perform.* 2009;4(3):291–306.
73. Dupont G, Akakpo K, Berthoin S. The effect of in-season, high-intensity interval training in soccer players. *J Strength Cond Res.* 2004;18(3):584–9.
74. Rhea MR. Determining the magnitude of treatment effects in strength training research through the use of the effect size. *J Strength Cond Res.* 2004;18(4):918–20.
75. Borenstein M, Higgins J, Rothstein H. Introduction to meta-analysis (statistics and practice). London: Wiley; 2009.
76. Hedges L, Olkin I. Statistical methods for meta-analysis. New York: Academic Press; 1985.
77. Hopkins WG, Marshall SW, Batterham AM, Hanin J. Progressive statistics for studies in sports medicine and exercise science. *Med Sci Sports Exerc.* 2009;41(1):3–13.