European Journal of Sport Science

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tejs20

Resistance training-induced improvement in exercise tolerance is not dependent on muscle mass gain in post-menopausal women

Gersiel Nascimento de Oliveira Júnior , Jairo de Freitas Rodrigues de Sousa , Marcelo Augusto da Silva Carneiro , Fernanda Maria Martins , Samarita Beraldo Santagnello & Fábio Lera Orsatti

To cite this article: Gersiel Nascimento de Oliveira Júnior , Jairo de Freitas Rodrigues de Sousa , Marcelo Augusto da Silva Carneiro , Fernanda Maria Martins , Samarita Beraldo Santagnello & Fábio Lera Orsatti (2020): Resistance training-induced improvement in exercise tolerance is not dependent on muscle mass gain in post-menopausal women, European Journal of Sport Science, DOI: 10.1080/17461391.2020.1798511

To link to this article: https://doi.org/10.1080/17461391.2020.1798511

Accepted author version posted online: 17 Jul 2020.

Publisher: Taylor & Francis & European College of Sport Science

Journal: *European Journal of Sport Science*

DOI: 10.1080/17461391.2020.1798511

The article was proofread by an English language science writing service.

31st March, 2020

To whom it may concern

I hereby declare that I have proofread the following article "Resistance training-induced improvement in exercise tolerance is not dependent on muscle mass gain in post-menopausal women" by Gersiel Nascimento de Oliveira Júnior, Jairo de Freitas Rodrigues de Sousa, Marcelo Augusto da Silva Carneiro, Fernanda Maria Martins, Samarita Beraldo Santagnello and Fábio Lera Orsatti.

Yours faithfully,

Jane Godwin Coury

M.A. in Applied Linguistics

Resistance training-induced improvement in exercise tolerance is not dependent on muscle mass gain in post-menopausal women

Resistance training volume and exercise tolerance

Gersiel Nascimento de Oliveira Júnior[1], Jairo de Freitas Rodrigues de Sousa[1], Marcelo Augusto da Silva Carneiro[1], Fernanda Maria Martins[1], Samarita Beraldo Santagnello[1], Fábio Lera Orsatti[1,2*]

[1]Exercise Biology Research Group (BioEx), Federal University of Triangulo Mineiro (UFTM), Uberaba, Minas Gerais, Brazil.

[2] Department of Sport Sciences, Health Science Institute, Federal University of Triangulo Mineiro (UFTM), Uberaba, Minas Gerais, Brazil.

***Corresponding author:**

Fábio Lera Orsatti
Federal University of Triangulo Mineiro (UFTM), Post Graduate Program in Physical Education, Exercise Biology Research Laboratory (BioEx), Uberaba, Minas Gerais. Brazil. Tutunas Avenue, 490 - CEP: 38061-500 - Phone: +55 (34) 3318-5504.
E-mail: fabiorsatti@gmail.com and fabio.orsatti@uftm.edu.br

Abstract

Menopause transition may impair muscle function, decreasing exercise tolerance. The torque–duration relationship (hyperbolic curve) forms a practical framework within which exercise tolerance may be explored. In this regard, resistance training (RT) increases the curvature constant of this relationship (W′). Muscle hypertrophy and strength gains have been suggested as possible mediators of RT-induced improvement in W′, however, it is unclear what the main mediator is. Higher-volume RT (HV-RT), beyond that recommended by RT-guidelines (i.e. three sets per exercise), may promote greater hypertrophy, but not higher strength gains. Hence, this study aimed to investigate whether greater hypertrophy in HV-RT maximizes W′ gain when compared to LVRT in postmenopausal women (PW). Fifty-eight PW were randomized to the control group (CTRL), HV-RT (six sets per exercise) or LV-RT (three sets per exercise). They underwent a 12-week RT program and were assessed for W′, thigh lean body mass (TLBM) and maximal isometric voluntary contraction (MIVC). The TLBM gain was higher ($P < 0.001$) in the HV-RT (9.4%) than LV-RT (3.7%). However, both HV-RT and LV-RT similarly increased MIVC (9.7% vs. 16.5%, $P= 0.063$) and W′ (26.4 % vs. 34.6 % $P= 0.163$). Additionally, the changes in W′ were associated with the changes in TLBM (31%, $P= 0.003$) and MIVC (52%, $P= <0.001$). However, when the changes in TLBM and MIVC were inserted into the predictive model, only the MIVC (33%, $P= 0.002$) was a predictor of W′. Thus, although HV-RT promoted greater hypertrophy than LV-RT, HV-RT does not seem to maximize W′ in PW.

Keywords: tolerance exercise, W prime, strength training, muscle strength and older

Introduction

Physical performance declines with aging. The rate of decline in physical performance differs by sex, women showing more rapid decline than men during the menopause transition (1-3). A portion of the accelerated loss physical performance with menopause transition is a result of accelerated losses of muscle mass and strength with menopause transition (1, 4-6). Another important factor for accelerated loss physical performance with menopause transition is a lower exercise tolerance (7, 8). Although young women are less fatigued than young men, the gender difference in performance fatigue is

reduced at advanced ages (7, 9). Decline in estrogen levels during the menopause transition can impair the vascular function and reduce the blood flow (10, 11), which can increase intracellular metabolites (i.e. H+ and Pi), determinants of capacity to maintain the exercise (8, 12). In addition, the amount of muscle mass and strength have been positively associated with exercise tolerance (13-17), therefore accelerated muscle mass and strength losses with menopause transition seems to contribute to the lower exercise tolerance in postmenopausal women (PW).

The torque–duration relationship (hyperbolic curve) during intermittent isometric maximal voluntary contractions forms a practical framework within which exercise tolerance is explored (18-20). The asymptote of the hyperbolic curve represents the critical threshold [i.e. Critical Torque (CT)] between the heavy- and severe-intensity domains and this threshold defines the boundary between tolerable and not tolerable exercise. The curvature constant of this hyperbola, the W prime (W′), represents the total amount of impulse [the product of force over a period of time] that can be done above CT (18-20). From a practical point of view, this method is suited to the study of neuromuscular fatigue and exercise tolerance mechanisms in vivo (18-20). In this regard, resistance training (RT) may improve exercise tolerance (i.e. enhance W′) in young adults and patients with low exercise tolerance (19, 21-26). However, the determinants (i.e. mediators) of RT-induced improvement in exercise tolerance is unclear. Cross-sectional and longitudinal studies have shown that the amount of W′ is positively associated with muscle mass and strength (13-20, 26). In this regard, the increase in muscle mass mediated-by RT could be associated with elevated stored energy sources (PCr, ATP, and glycogen), which may allow the maintenance of force across time. At the same time, the strength increase mediated-by RT due to neurological adaptations (27) and improvements in ATP flux (24), which would promote a lower metabolic disturbance and (or) accumulation of metabolites and, consequently, attenuation of firing frequency of group III/IV afferents, increases exercise tolerance during severe-intensity exercise. As RT increases W′, but not CT, (26, 28, 29) and also increases muscle mass and strength (26, 30), muscle mass and strength gains may be possible mediators of RT-induced improvement in W′(26). However, although RT increases both muscle mass and muscle strength, these adaptations may occur irrespective of each other (31-33). Thus, it is unclear which adaptation induced by RT (gains in muscle strength or mass) potentially affects the W′ gain.

Evidence has shown a dose–response relationship between RT volume and hypertrophy (32-35). Particularly, two meta-analysis have reported a dose–response relationship of volume and hypertrophy in older adults (34, 35). Additionally, higher-volume RT (HV-RT), beyond that recommended by public guidelines for RT (i.e. 1-3 sets per exercise) (30, 36), has been shown to promote superior gains in muscle mass (32), but not muscle strength gains (32, 37, 38). Regarding this, it would seem reasonable to assume that if W′ is influenced by muscle mass, additional muscle mass gain with a HV-RT leads to additional W′ gains when compared to a lower-volume resistance training (LV-RT). Therefore, this study aimed to investigate whether higher muscle mass gain in a HV-RT maximizes W′ gains when compared to a LVRT in post-menopausal women (PW).

Materials and methods

Subjects

This study was approved by the local ethical committee (85052218.0.0000.5154) and all participants signed an informed consent form before participation.

Three studies investigating the effect of TR on W′ have shown a medium to large effect (26, 28, 29). Based on data from these three studies, we adopted an alpha level of 0.05, a power of 80% and a medium effect size (Mixed-ANOVA: effect size f = 0.25). Thus, a minimum number of 42 participants was required for this study. The sample size was estimated using the G-Power® software (version 3.1.2).

Out of the 70 volunteers who were screened for participation, 58 postmenopausal women (PW; aged > 50 years) met the inclusion criteria. Inclusion criteria were: postmenopausal women (characterized by spontaneous amenorrhea for at least 12 months), to be untrained (did not engage in exercise program in the last 6 months), no use of hormone therapy or phytoestrogens; controlled blood pressure and glycaemia; absence of myopathies, arthropathies, and neuropathies; absence of muscle, thromboembolic and gastrointestinal disorders; absence of cardiovascular and infection diseases; non-drinkers (no alcohol intake whatsoever in their diet), and non-smokers.

Following this screening, we used a Medcalc® tool (Create random group) to assign cases to random groups (the randomization was blinding to participants and researchers). PW were randomized into one of the following conditions: HV-RT, LV-RT, and control group (CTRL).

Body composition assessments

Body composition [total body fat mass, and right thigh lean body mass (TLBM)] was assessed by dual-energy X-ray absorptiometry (Lunar iDXA; GE, Madison, WI, USA) and quantified by Encore Software, version 14.10. TLBM was defined by a distal demarcation set at the tibiofemoral joint and the proximal demarcation set as a diagonal bifurcation through the femoral neck (39). DXA assessments were performed after 8-10 hours of fasting. To standardize the level of body hydration, the subjects were instructed to consume 2-L of water during the day before the DXA assessments. The volunteers dressed in light and comfortable clothes without any metal fastenings. All DXA measurements were performed by the same experienced examiner. The TLBM quantified by DXA is strongly correlated ($R^2 = 0.88$; $p<0.001$) with TLBM quantified by magnetic resonance imaging (39).

Maximum Strength Assessment (1RM)

Previously, all volunteers participated in a 1-week familiarization period (3 sessions) with low-loads (no consecutive days) to become familiar with the exercise technique.

Before the one repetition maximum (1-RM) test, a warm-up was performed using a subjective load, determined during the familiarization, with approximately 15 repetitions of 30–40 % of 1RM. After 1.5-min of rest, the load was increased, and eight to twelve repetitions were performed with a subjective load of 50–60 % of 1RM. After 1.5-min of rest, the load was increased, and three to five repetitions were performed with a subjective load of 80–90 % of 1RM. After 3 to 5-min. of rest, the load was considerably increased, and the subjects were encouraged to overcome resistance using full motion. When the load was overestimated or underestimated, the subjects rested 3 to 5-min. before a new attempt was performed with a lower or higher load, respectively. This procedure was performed to find the equivalent load of 1RM, which ranged between 2 and 5 attempts. The load that was adopted as the maximum load was the load used for the last execution of the exercises that were performed with no more than one repetition by the subject. The leg extension (movement range: 90º – 180º), leg curl (movement range: 180º – 90º), and 45º leg press (movement range: 0º – 90º) exercises were used to determine the muscle strength gains. The exercises were performed on separate days to avoid residual effect (fatigue) of the previous test.

Training protocols

Both groups started the RT program performing 1 set per exercise, in four dynamic exercises (Moldmac®, Franca, SP, Brazil): leg press 45°, leg extension, leg curl, and standing calf raise (using the body weight) three times per week. Progressively, 1 set per exercise was added per week up to 3 sets in the LV-RT and up to 6 sets in HV-RT. All volunteers were instructed to perform the maximal of repetitions until the concentric failure in each set. In the first session of the first week, all volunteers performed the maximum number of repetitions (with 80% of 1-RM) until the point of momentary concentric failure, that is, the inability to perform another concentric repetition while maintaining the proper form of exercise. In the following sessions, when the participant performed more than 12 repetitions in the first set, the load was increased (5-10%) to ensure that subjects achieved momentary failure in the target repetition range (8-12 repetitions). On the other hand, when the participant performed less than 8 repetitions in the first set, the load was decreased (5-10%) to ensure the target repetition range (8-12 repetitions). The cadence of repetitions was carried out in a controlled fashion, with a concentric action of approximately 1 s and an eccentric action of approximately 2 s. Subjects were afforded 90-s rest between sets and exercises (36). No cluster rest (i.e. intra-set rest) was allowed. All workouts were supervised by a qualified professional. No exercise other than RT was allowed.

Maximal Isometric Voluntary Contraction Assessment

The maximal isometric voluntary contractions (MIVC) were performed in a climate-controlled (21–25°C) laboratory. The S-beam load cell (maximum tension-compression = 200 kgf, precision of 0.1 kgf, maximum error of measurement = 0.33%, Miotec®, Brazil) (40) was attached just above the malleolus without static fixation of the ankle joint. The participants were placed in a sitting position and securely strapped into the test chair, with the hip and knee joints at angles of 100° and 70°, respectively. The trunk movement was limited by two cross-shoulder harnesses and an abdomen belt. The hands were positioned over (holding) cross-shoulder harnesses. Initially, the participants did a warm-up over a period of 2 min (i.e. 24 contractions with 3 s contraction, 2 s rest) with submaximal effort described as comfortable. After a rest of 5 min, the individuals were instructed to perform the MIVC as fast and as hard as possible. The MIVC measurements were performed three times, with one minute of rest between each measurement. Contractions and rest time were controlled by a metronome

and preceded by verbal commands "go and stop" respectively. The signal was captured using an analogic-to-digital converter (Miotol, Miotec®, Brazil), with a sampling frequency of 2000 Hz. and analyzed in a specific software MioGraph (Miotec®, Brazil). To avoid the measurement errors, before starting daily assessments, the load cell was calibrated using a known load.

CT and W′ Assessments

The CT and W′ procedures were performed after 5 minutes of rest from the last MIVC. The CT and W′ were evaluated in the same apparatus used for the MIVC. The participants were required to perform 60 MIVCs (3 s contraction, 2 s rest) over a period of 5 min (Supplementary figure) (18). Participants were not informed of the time or number of contractions during the test. The muscle strength of each contraction was recorded with the average of the values obtained in the contraction plateau (2 - 2.5 s). The CT was defined as the average of the last six contractions of the 60 MIVCs (18). W′ was defined as all impulses done above CT. The software GraphPad Prism (version 5.0, GraphPad Software Inc., San Diego, CA) was used to calculate the area under the curve (force vs time), using the CT as the threshold.

To evaluate the test-retest reliability of W′ and CT, we selected a part of the sample (n = 21). Both W′ and CT had excellent test-retest reliability [ICC = 0.970, CI 95%= (0.928 – 0.988), and ICC = 0.986; CI95% = (0.983 – 0.997)], respectively.

Statistical analysis

Shapiro Wilk and Levene tests were used to verify the data distribution and the homogeneity of variances. Mixed-analysis of variance (ANOVA) was used to observe the effect of group, time and interaction between the group and the time. The effect size [eta squared (η^2)] and observed power (OP) were also calculated. The post hoc [Fisher's Least Significant Difference (LSD)] were used to identifier the with-group effect. To avoid regression to the mean, ANCOVA, correcting the gains (delta, Δ) by the pre values, were used to compare the group and the effect size [eta squared (η^2)] and OP were also calculated. The LSD was used to identify the difference between groups. To determine whether the gains in muscle strength and TLBM across the intervention within the individual was associated with the gains in W′ across the intervention, we used multiple regression as recommended by Bland and Altman (41). The significant

level was set at 5%. The values are shown as the mean and standard deviation or confidence interval of 95% (CI95%).

Results

Eighteen PW dropped out of the study. Seven from HV-RT [osteoarticular problems (n=2); problems of moving to the training site (n = 1); family problems (n = 1); did not meet the minimum frequency (n=3)], six volunteers were excluded from LV-RT [osteoarticular problems (n=2); problems of moving to the training site (n = 1); family problems (n = 3)] and five from CTRL (n=5 personal reasons). All subjects included in the statistical analysis (CTRL = 14, LV-RT = 13 and HV-RT = 13) completed >80% of training sessions (overall average attendance of 89%).

There were no differences between the groups for general characteristics at baseline (Table 1). No volunteers reported muscular or joint damage.

The LV-RT and HV-RT increased W′ [ANOVA interaction (group vs. time): F (2.37) = 7.909; p = 0.001; η^2 = 0.03; OP= 0.94] and MIVC [F(2.37) = 7.990; p = 0.001; η^2 = 0.01; OP = 0.94] from pre to post intervention (post-hoc LSD: p = < 0.05). When the magnitude of increase in the W′ (Δ = delta values adjusted by pre-values) were compared between the groups [ANCOVA: F (2.36) = 7.633; p = 0.002; η^2 = 0.30; OP= 0.93], the post-hoc revealed that both groups of training increased W′ (P < 0.05), however without differences (P = 0.163) between the LV-RT and HV-RT. (CTRL: Δ = -90.2 N.m.s and CI95%: -644.9 - 465.3 N.m.s; LV-RT: Δ = 1436.1 N.m.s and CI95% = 855.9 - 2016.3 N.m.s and HV-RT: Δ = 857.1 N.m.s and CI95% = 277.3 - 1436.8 N.m.s) (Figure 1, panel A). Similarly, when the magnitude of increase in the MIVC were compared between the groups [ANCOVA: F (2.36) = 8.046; p = 0.001; η^2 = 0.31; OP = 0.94], the post-hoc revealed that both groups of training increased MIVC (P < 0.05) no differences (P = 0.063) between the LV-RT and HV-RT (CTRL: Δ = 1.6 N.m and CI95% = -4.4 – 7.6 N.m; LV-RT: Δ = 18.7 N.m and CI95% = 12.5 - 24.9 N.m and HV-RT: Δ = 10.3 N.m and CI95% = 4.1 - 16.6 N.m) (Figure 1, panel B).

The LV-RT and HV-RT increased TLBM [ANOVA interaction (group vs. time): F (2.37) = 17.490; p= <0,001; η^2 = 0.01; OP= 1.00] from pre to post intervention (post-hoc LSD: p = < 0.05). Although both groups of RT, increased TLBM when compared with CTRL [ANCOVA: F (2.36) = 22.522; p < 0,001; η^2 = 0.50; OP= 0.81, pos-hoc LSD: P = < 0.001], a higher magnitude of increase (Δ) in the TLBM was observed in

the HV-RT group when compared to the LV-RT. The TLBM increased 0.43 kg (IC 95% = 0.34 - 0.53 kg) and 0.17 kg (IC 95% = 0.08 - 0.27 kg) in the HV-RT and LV-RT, respectively (Figure 1, panel C).

The pre to post within subject changes in MIVC (B = 67.4; IC 95% 40.8; 93.9) and TLBM (B = 2251.1; IC 95% 863.6; 3638.5) were associated with pre to post within subject changes in W′. However, when the changes in TLBM and MIVC were inserted into the predictive model, only the MIVC (33%, P = 0.002 vs. 3%, P = 0.363) was a predictor of W′ (Table 3).

Discussion

The main findings of the current study were that both RT groups increased W', strength and TLBM in PW. However, the HV-RT maximized the TLBM gains (but not W′ and muscle strength gains) when compared to LV-RT. Besides, the W' were associated only with the muscle strength gains when the muscle mass gains were added to the regression model. Thus, our study contributes to the previous literature indicating that RT-induced increase in W′ is not dependent on muscle mass gains but seems to be on muscle strength gains.

Cross-sectional studies have reported an association between W′ and muscle mass (13, 15, 16). In the current study, we observed an association (31%) between the changes in TLBM and the changes in W′ following RT. The association between muscle and W′ has been attributed to energy storage muscle capacity (15). However, recently, Clark et al., (42) have shown that a change in W′ was not significantly correlated with a change in muscle glycogen concentration following 2 h of heavy-intensity exercise. Indeed, even with greater TLBM gains in the HV-RT group than the LV-RT group, W′ gains were similar between the groups (HV-RT and LV-RT). This suggests that another factor other than muscle mass changes may be mediating W′ gains following RT. Thus, Kordi et al. showed, in a cross-sectional study, that muscle strength explained the highest amount of variance (75%) in the magnitude of W′, whilst muscle explains only 36% (13). Broxterman et al., (43) showed a high correlation between the magnitude of W′ and fatigue-induced declines in MVC, suggesting that muscle strength can determine the extension of W′. Consistent with these previous studies, our intervention study found that changes in muscle strength explained 52% of changes in W′ induced by RT, while changes in muscle mass explained only 33%. When the changes in muscle mass

and strength were inserted together into the predictive model (multiple regression), only the muscle strength remained as a predictor of W′. Therefore, collectively, it is reasonable to suppose that an RT-induced increase in W′ is not dependent on muscle mass gains, but is, at least in parts, dependent on strength gains in PW.

The role of neurological adaptations of muscle strength gains induced-by RT has been well documented (27). Thus, due to the association between pre to post within subject changes in W′ and muscle strength, it seems reasonable to suppose that adaptation generated-by RT in muscle strength and W′ can be attributed to neural adaptations. However, in the current study, RT-induced an increase in muscle strength explained only 33% of the increase in W′. This suggests that other factors besides the maximal strength gains affect the W′ gains. Although several factors affect W′, recently the central projection of afferent feedback from the group III/IV muscle, linked to the accumulation of fatigue-related metabolites (H + and Pi), has been suggested to control the W′ (12, 19, 44, 45). Regarding this, it is reasonable to suppose that that RT may decrease the accumulation of end products of anaerobic metabolism during high-intensity exercise (12, 23, 25). Recently, Berg et al. (2018) (24) showed that RT improved anaerobic ATP synthesis flux (anaerobic glycolysis and creatine kinase reaction), which allowed higher force production during sustained maximal contraction in older adults. Therefore, it seems that the RT-induced increase in W′ is also associated with muscle adaptations that lead to an improvement in anaerobic ATP synthesis flux, lower metabolic disturbance and (or) accumulation of metabolites and, consequently, attenuation of firing frequency of group III/IV afferents, increasing exercise tolerance during severe-intensity exercise.

This study has limitations that should be acknowledged. The small number of participants due to the nature of the intervention may have underpowered the statistical analyses. However, we performed the observed power analyses which demonstrated large power. Moreover, our present study is a randomized controlled trial, the eligibility of volunteers was based on inclusion criteria, all training variables were recorded (volume, and frequency) and the outcome variables (W′ and isometric maximal strength) presented high reproducibility, reducing bias.

In summary, this study has identified that although HV-RT promoted greater hypertrophy than LV-RT, both RT protocols promoted similar gains in W’ and MIVC. Moreover, only the muscle strength remained a predictor of W’. Taken together, these results suggest that the RT-induced increase in W’ is not dependent on muscle mass

gains but is, at least in part, dependent on muscle strength gains. Thus, if the focus is to increase the W', the lower volume of RT is sufficient.

Disclosure interest statement

The authors declare no conflicts of interest.

References

1. **Huebner M, Meltzer DE, Perperoglou A. Age-associated Performance Decline and Sex Differences in Olympic Weightlifting. Medicine and science in sports and exercise. 2019;51(11):2302-8. doi: 10.1249/MSS.0000000000002037**
2. **Bondarev D, Laakkonen EK, Finni T, Kokko K, Kujala UM, Aukee P, et al. Physical performance in relation to menopause status and physical activity. Menopause. 2018;25(12):1432-41. doi: 10.1097/GME.0000000000001137**
3. **El Khoudary SR, Greendale G, Crawford SL, Avis NE, Brooks MM, Thurston RC, et al. The menopause transition and women's health at midlife: a progress report from the Study of Women's Health Across the Nation (SWAN). Menopause. 2019;26(10):1213-27. doi: 10.1097/GME.0000000000001424**
4. **Collins BC, Laakkonen EK, Lowe DA. Aging of the musculoskeletal system: How the loss of estrogen impacts muscle strength. Bone. 2019;123:137-44. doi: 10.1016/j.bone.2019.03.033**
5. **Phillips SK, Rook KM, Siddle NC, Bruce SA, Woledge RC. Muscle weakness in women occurs at an earlier age than in men, but strength is preserved by hormone replacement therapy. Clin Sci (Lond). 1993;84(1):95-8. doi: 10.1042/cs0840095**
6. **Greendale GA, Sternfeld B, Huang M, Han W, Karvonen-Gutierrez C, Ruppert K, et al. Changes in body composition and weight during the menopause transition. JCI insight. 2019;4(5)doi: 10.1172/jci.insight.124865**
7. **Hunter SK. The Relevance of Sex Differences in Performance Fatigability. Medicine and science in sports and exercise. 2016;48(11):2247-56. doi: 10.1249/MSS.0000000000000928**
8. **Kent-Braun JA, Fitts RH, Christie A. Skeletal muscle fatigue. Comprehensive Physiology. 2012;2(2):997-1044. doi: 10.1002/cphy.c110029**
9. **Yoon T, Doyel R, Widule C, Hunter SK. Sex differences with aging in the fatigability of dynamic contractions. Experimental gerontology. 2015;70:1-10. doi: 10.1016/j.exger.2015.07.001**
10. **Nyberg M, Seidelin K, Andersen TR, Overby NN, Hellsten Y, Bangsbo J. Biomarkers of vascular function in premenopausal and recent postmenopausal women of similar age: effect of exercise training. American journal of physiology Regulatory, integrative and comparative physiology. 2014;306(7):R510-7. doi: 10.1152/ajpregu.00539.2013**
11. **Parker BA, Smithmyer SL, Pelberg JA, Mishkin AD, Proctor DN. Sex-specific influence of aging on exercising leg blood flow. J Appl Physiol (1985). 2008;104(3):655-64. doi: 10.1152/japplphysiol.01150.2007**
12. **Sundberg CW, Prost RW, Fitts RH, Hunter SK. Bioenergetic basis for the increased fatigability with ageing. The Journal of physiology. 2019;597(19):4943-57. doi: 10.1113/JP277803**
13. **Kordi M, Menzies C, Parker Simpson L. Relationship between power-duration parameters and mechanical and anthropometric properties of the thigh in elite cyclists. European journal of applied physiology. 2018;118(3):637-45. doi: 10.1007/s00421-018-3807-1**

14. Byrd MT, Wallace BJ, Clasey JL, Bergstrom HC. Contributions of Lower Body Strength Parameters to Critical Power and Anaerobic Work Capacity. Journal of strength and conditioning research. 2018doi: 10.1519/JSC.0000000000002555
15. Byrd MT, Switalla JR, Eastman JE, Wallace BJ, Clasey JL, Bergstrom HC. Contributions of Body-Composition Characteristics to Critical Power and Anaerobic Work Capacity. International journal of sports physiology and performance. 2018;13(2):189-93. doi: 10.1123/ijspp.2016-0810
16. Miura A, Endo M, Sato H, Barstow TJ, Fukuba Y. Relationship between the curvature constant parameter of the power-duration curve and muscle cross-sectional area of the thigh for cycle ergometry in humans. European journal of applied physiology. 2002;87(3):238-44. doi: 10.1007/s00421-002-0623-3
17. Abdalla LHP, Denadai BS, Bassan NM, Greco CC. Exercise tolerance during muscle contractions below and above the critical torque in different muscle groups. Applied physiology, nutrition, and metabolism = Physiologie appliquee, nutrition et metabolisme. 2018;43(2):174-9. doi: 10.1139/apnm-2017-0381
18. Burnley M. Estimation of critical torque using intermittent isometric maximal voluntary contractions of the quadriceps in humans. J Appl Physiol (1985). 2009;106(3):975-83. doi: 10.1152/japplphysiol.91474.2008
19. Poole DC, Burnley M, Vanhatalo A, Rossiter HB, Jones AM. Critical Power: An Important Fatigue Threshold in Exercise Physiology. Medicine and science in sports and exercise. 2016;48(11):2320-34. doi: 10.1249/MSS.0000000000000939
20. Burnley M, Vanhatalo A, Jones AM. Distinct profiles of neuromuscular fatigue during muscle contractions below and above the critical torque in humans. J Appl Physiol (1985). 2012;113(2):215-23. doi: 10.1152/japplphysiol.00022.2012
21. Iepsen UW, Jorgensen KJ, Ringbaek T, Hansen H, Skrubbeltrang C, Lange P. A Systematic Review of Resistance Training Versus Endurance Training in COPD. Journal of cardiopulmonary rehabilitation and prevention. 2015;35(3):163-72. doi: 10.1097/HCR.0000000000000105
22. Giuliano C, Karahalios A, Neil C, Allen J, Levinger I. The effects of resistance training on muscle strength, quality of life and aerobic capacity in patients with chronic heart failure - A meta-analysis. International journal of cardiology. 2017;227:413-23. doi: 10.1016/j.ijcard.2016.11.023
23. Denadai BS, Greco CC. Resistance training and exercise tolerance during high-intensity exercise: moving beyond just running economy and muscle strength. J Appl Physiol (1985). 2018;124(2):526-8. doi: 10.1152/japplphysiol.00800.2017
24. Berg OK, Kwon OS, Hureau TJ, Clifton HL, Thurston T, Le Fur Y, et al. Maximal strength training increases muscle force generating capacity and the anaerobic ATP synthesis flux without altering the cost of contraction in elderly. Experimental gerontology. 2018;111:154-61. doi: 10.1016/j.exger.2018.07.013
25. Edge J, Hill-Haas S, Goodman C, Bishop D. Effects of resistance training on H+ regulation, buffer capacity, and repeated sprints. Medicine and science in sports and exercise. 2006;38(11):2004-11. doi: 10.1249/01.mss.0000233793.31659.a3
26. de Menezes Bassan N, Denadai BS, de Lima LCR, Carita RAC, Abdalla LHP, Greco CC. Effects of resistance training on impulse above end-test torque and muscle fatigue. Experimental physiology. 2019;104(7):1115-25. doi: 10.1113/EP087204
27. Dankel SJ, Kang M, Abe T, Loenneke JP. Resistance training induced changes in strength and specific force at the fiber and whole muscle level: a meta-analysis. European journal of applied physiology. 2019;119(1):265-78. doi: 10.1007/s00421-018-4022-9
28. Bishop D, Jenkins DG. The influence of resistance training on the critical power function & time to fatigue at critical power. Australian journal of science and medicine in sport. 1996;28(4):101-5. doi:
29. Sawyer BJ, Stokes DG, Womack CJ, Morton RH, Weltman A, Gaesser GA. Strength training increases endurance time to exhaustion during high-intensity exercise despite no change in critical power. Journal of strength and conditioning research. 2014;28(3):601-9. doi: 10.1519/JSC.0b013e31829e113b

30. Garber CE, Blissmer B, Deschenes MR, Franklin BA, Lamonte MJ, Lee IM, et al. American College of Sports Medicine position stand. Quantity and quality of exercise for developing and maintaining cardiorespiratory, musculoskeletal, and neuromotor fitness in apparently healthy adults: guidance for prescribing exercise. Medicine and science in sports and exercise. 2011;43(7):1334-59. doi: 10.1249/MSS.0b013e318213fefb
31. Dankel SJ, Counts BR, Barnett BE, Buckner SL, Abe T, Loenneke JP. Muscle adaptations following 21 consecutive days of strength test familiarization compared with traditional training. Muscle & nerve. 2017;56(2):307-14. doi: 10.1002/mus.25488
32. Schoenfeld BJ, Contreras B, Krieger J, Grgic J, Delcastillo K, Belliard R, et al. Resistance Training Volume Enhances Muscle Hypertrophy but Not Strength in Trained Men. Medicine and science in sports and exercise. 2019;51(1):94-103. doi: 10.1249/MSS.0000000000001764
33. Schoenfeld BJ, Ogborn D, Krieger JW. Dose-response relationship between weekly resistance training volume and increases in muscle mass: A systematic review and meta-analysis. Journal of sports sciences. 2017;35(11):1073-82. doi: 10.1080/02640414.2016.1210197
34. Peterson MD, Sen A, Gordon PM. Influence of resistance exercise on lean body mass in aging adults: a meta-analysis. Medicine and science in sports and exercise. 2011;43(2):249-58. doi: 10.1249/MSS.0b013e3181eb6265
35. Borde R, Hortobagyi T, Granacher U. Dose-Response Relationships of Resistance Training in Healthy Old Adults: A Systematic Review and Meta-Analysis. Sports Med. 2015;45(12):1693-720. doi: 10.1007/s40279-015-0385-9
36. ACSM. American College of Sports Medicine position stand. Progression models in resistance training for healthy adults. Medicine and science in sports and exercise. 2009;41(3):687-708. doi: 10.1249/MSS.0b013e3181915670
37. Nunes PR, Barcelos LC, Oliveira AA, Furlanetto Junior R, Martins FM, Orsatti CL, et al. Effect of resistance training on muscular strength and indicators of abdominal adiposity, metabolic risk, and inflammation in postmenopausal women: controlled and randomized clinical trial of efficacy of training volume. Age (Dordr). 2016;38(2):40. doi: 10.1007/s11357-016-9901-6
38. Nunes PRP, Barcelos LC, Oliveira AA, Furlanetto R, Jr., Martins FM, Resende E, et al. Muscular Strength Adaptations and Hormonal Responses After Two Different Multiple-Set Protocols of Resistance Training in Postmenopausal Women. Journal of strength and conditioning research. 2019;33(5):1276-85. doi: 10.1519/JSC.0000000000001788
39. Maden-Wilkinson TM, Degens H, Jones DA, McPhee JS. Comparison of MRI and DXA to measure muscle size and age-related atrophy in thigh muscles. Journal of musculoskeletal & neuronal interactions. 2013;13(3):320-8. doi:
40. Milioni F, de Poli RAB, Saunders B, Gualano B, da Rocha AL, Sanchez Ramos da Silva A, et al. Effect of beta-alanine supplementation during high-intensity interval training on repeated sprint ability performance and neuromuscular fatigue. J Appl Physiol (1985). 2019;127(6):1599-610. doi: 10.1152/japplphysiol.00321.2019
41. Bland JM, Altman DG. Calculating correlation coefficients with repeated observations: Part 2--Correlation between subjects. BMJ. 1995;310(6980):633. doi: 10.1136/bmj.310.6980.633
42. Clark IE, Vanhatalo A, Thompson C, Wylie LJ, Bailey SJ, Kirby BS, et al. Changes in the power-duration relationship following prolonged exercise: estimation using conventional and all-out protocols and relationship with muscle glycogen. American journal of physiology Regulatory, integrative and comparative physiology. 2019;317(1):R59-R67. doi: 10.1152/ajpregu.00031.2019
43. Broxterman RM, Craig JC, Smith JR, Wilcox SL, Jia C, Warren S, et al. Influence of blood flow occlusion on the development of peripheral and central fatigue during small muscle mass handgrip exercise. The Journal of physiology. 2015;593(17):4043-54. doi: 10.1113/JP270424

44. Zarzissi S, Zghal F, Bouzid MA, Hureau TJ, Sahli S, Ben Hassen H, et al. Centrally-mediated regulation of peripheral fatigue during knee extensor exercise and consequences on the force-duration relationship in older men. European journal of sport science. 2019:1-9. doi: 10.1080/17461391.2019.1655099

45. Hureau TJ, Broxterman RM, Weavil JC. The mechanistic basis of the power-time relationship: potential role of the group III/IV muscle afferents. The Journal of physiology. 2016;594(24):7165-6. doi: 10.1113/JP273333

Table 1: Baseline Characteristics.

Variables	CTRL	LV-RT	HV-RT	P group
Age (years)	59.80 ± 9.43	58.53 ± 8.03	59.31 ± 8.37	0.921
Time of menopause (years)	10.13 ±8.14	12.6 ± 9.88	9.06 ± 6.76	0.488
Body mass (kg)	61.21 ± 17.98	67.65 ± 13.78	67.75 ± 13.37	0.951
Height (m)	1.60 ± 0.04	1.59 ± 0.06	1.59 ±0.05	0.897
BMI (Kg/m²)	27.10 ± 6.63	26.76 ± 4.76	26.60 ± 4.98	0.968
Body fat (kg)	30.01 ± 11.89	28.99 ± 9.28	28.87 ± 8.78	0.942
ASMI (Kg/m²)	6.78 ± 1.31	6.78 ± 0.84	6.72 ± 1.09	0.988
Medication intake				
Antihyperglycemic (n)	1	0	2	-
Antihypertensive (n)	4	3	4	-
Antiasmatic (n)	0	0	0	-
Anti-inflammatory (n)	0	0	0	-
Antiallergic (n)	0	0	0	-
Antidepressives (n)	4	0	4	-
Antianxiolytics (n)	1	1	1	-
Antihypercholesterolemia (n)	5	2	3	-
Antiulcers (n)	0	1	0	-
Calcium (n)	1	2	1	-
Analgesics (n)	0	0	0	-
Estrogen therapy (n)	0	0	0	-
Thyroxin therapy (n)	3	1	3	-

Continuous data are presented as mean and standard deviation. BMI = Body mass index; ASMI = appendicular skeletal muscle index; CTRL= control group; LV= Lower volume resistance training; HV-RT = Higher volume resistance training.

Table 2: Body composition and muscular performances of PW at baseline and after 12 weeks of intervention.

Variables	CTRL		LV-RT		HV-RT		P group	P moment	P interaction
	Pre	Post	Pre	Post	Pre	Post			
TLBM (kg)	4.6 ± 1.0	4.6 ± 1.1	4.6 ± 0.7	4.8 ± 0.8*	4.4 ± 0.8	4.8 ± 1.0*‡	0.955	<0.001	<0.001
W′ (N.m.s)	3912. 2 ± 1841.2	3821.8 ± 1869.2	4209.8 ± 1237.9	5727.3 ± 1913.7*	3643.4 ± 1479.2	4496.3 ± 1783.9*	0.179	<0.001	0.001
CT (N.m)	49.3 ± 14.0	51.9 ± 17.2	53.6 ± 20.5	59.7 ± 20.7	52.0 ± 19.8	53.2 ± 17.0	0.668	0.016	0.283
MIVC (N.m)	114.3 ± 40.3	115.8 ± 36.4	118.1 ± 38.2	137.9 ± 40.4*	110.4 ± 27.7	117.0 ± 29.6*	0.225	<0.001	0.001

Continuous data are presented as mean and standard deviation. CTRL = control group; LV-RT = Lower volume resistance training; HV-RT = Higher volume resistance training; TBLM = Thigh lean body mass; W′ = Impulse above the critical torque; CT = Critical torque; MIVC = Maximal isometric voluntary contraction; * = different to control group; ‡ = different to Lower volume group.

Table 3. Association of the changes in muscle strength and TLBM with the change in W′ utilizing the within-subject model

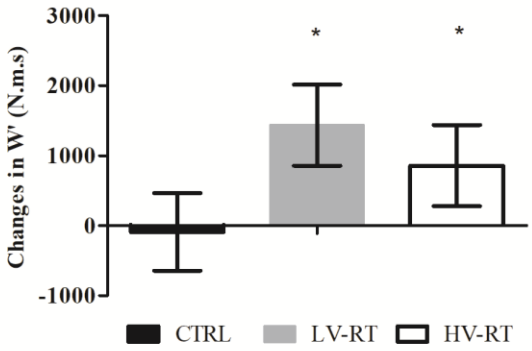
	B	**CI 95%**	**R^2**	**P**	**Observed power**
Model 1					
Muscle strength (N.m)	67.4	40.8 – 93.9	0.52	**<0.001**	**0.99**
TLBM (Kg)	2251.0	863.6 – 3638.5	0.31	**0.003**	**0.89**
Model 2					
Muscle strength (N.m)	57.6	23.2 – 92.0	0.33	**0.002**	**0.91**
TLBM (Kg)	671.0	-0.823.2 – 2165.2	0.03	0.363	0.145

Model 1= raw analysis; Model 2= Muscle strength adjusted by TLBM and TLBM adjusted by muscle strength

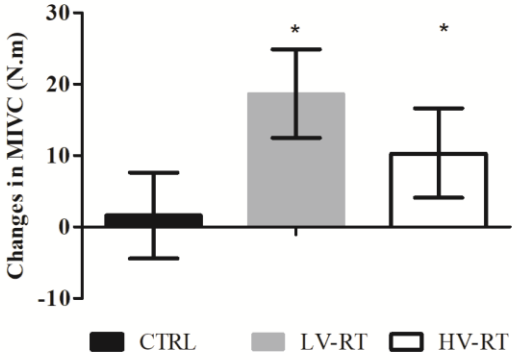
Figure 1. Panel A, B and C shows the delta adjusted by pre values of W′, MIVC and TLBM, respectively. * indicates $p < 0.05$ when compared with the control and # indicates $p < 0.05$ when compared with lower-volume resistance training.

Supplementary. Figure. Hyperbolic shape of torque-time relationship. The dashed line indicates the CT. All points above the line form the area under the curve, indicating W′. Mean ± SD of each contraction.

A



B



C