REVIEW ARTICLE

Sports Med 2005; 35 (11): 967-989
0112-1642/05/0011-0967/$34.95/0

Possible Stimuli for Strength and Power Adaptation

Acute Mechanical Responses

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Abstract

A great deal of literature has investigated the effects of various resistance training programmes on strength and power changes. Surprisingly, however, our understanding of the stimuli that affect adaptation still remains relatively unexplained. It is thought that strength and power adaptation is mediated by mechanical stimuli, that is the kinematics and kinetics associated with resistance exercise (e.g. forces, contraction duration, power and work), and their interaction with other hormonal and metabolic factors. However, the effect of different combinations of kinematic and kinetic variables and their contribution to adaptation is unclear. The mechanical response to single repetitions has been investigated by a number of researchers; however, it seems problematic to extrapolate the findings of this type of research to the responses associated with a typical resistance training session. That is, resistance training is typified by multiple repetitions, sets and exercises, rest periods of varying durations and different movement techniques (e.g. controlled and explosive). Understanding the mechanical stimuli afforded by such loading schemes would intuitively lead to a better appreciation of how various mechanical stimuli affect adaptation. It will be evident throughout this article that very little research has adopted such an approach; hence our understanding in this area remains rudimentary at best. One should therefore remain cognizant of the limitations that exist in the interpretation of research in this field. We contend that strength and power research needs to adopt a set kinematic and kinetic analysis to improve our understanding of how to optimise strength and power.

Resistance training is thought a critical exercise stimulus for inducing changes in muscular strength and power. One key issue is which load, expressed as a percentage of one repetition maximum (% 1RM), best facilitates the development of maximal strength and power. Improvements in maximal strength are largely attributed to either an increase in muscle cross-sectional area (CSA) and/or improved neural coordination.[1,2] Training programmes designed to produce the greatest changes in muscle CSA (i.e. hypertrophy schemes) are often characterised by loads of approximately 70% 1RM,[3-5] whilst programmes designed to improve strength through enhanced neural coordination (i.e. neuronal schemes) are commonly typified by intensities of 85–100% 1RM.[5,6] However, recent research would suggest that such a perspective is somewhat simplistic given that lighter loads (<45% 1RM) have been found equally effective in improving strength and/or hypertrophy compared with heavy load training.[7-11]

In terms of power development, lighter loads (e.g. 45% 1RM) are thought important, based on optimising the mechanical power output of muscle during ballistic movements (e.g. bench-press throw).[12,13] The use of lighter training loads also enables greater velocities and accelerations to be achieved, which is thought to lead to the greater transfer of training effects for those athletic activities performed in such a manner. Despite this, many studies have found heavy load training (>70% 1RM) equally effective as light loads in enhancing various measures of muscular power.[10,14-17] It would seem from this literature that there is no consensus on what is the optimal training load for the development of maximal strength and power. With many studies in this area further characterised by different movements and contraction types, which training method maximises adaptation above any other is also a contentious issue. Such issues illustrate an apparent lack of understanding regarding the stimulus afforded by different training methods and the adaptive response of the body to such stimuli.

The kinematics and kinetics associated with resistance exercise (e.g. forces, contraction duration, power and work), has been proposed to be the most important stimuli for resistance training-induced adaptation to occur.[4] Many studies have investigated repetition kinematics and kinetics associated with different resistance exercises, loads and techniques,[12,18-22] and as such, much is known about the mechanical response to a single movement or repetition. However, to our knowledge no studies have systematically examined the same effects over multiple sets and/or exercises. Considering the inherent nature of a typical weight-training session (i.e. multiple repetitions, sets and exercises) such an analysis appears fundamental to improving our understanding of the kinematic and kinetic response to a single training session and thus, how acute mechanical stimuli contribute to strength and power development. The purpose of this article, therefore, is to discern how various resistance-training movements and loading schemes differ in terms of their mechanical responses. Where possible the influence of these factors will be differentiated in order to determine those mechanisms underpinning strength and power development. It is hoped such a treatise will enable better understanding of how to optimise the development of strength and/or power, and as a consequence improve strength and conditioning practice.

1. Mechanical Response to Resistance Exercise

There is no doubt that the mechanical stimuli associated with resistance training are necessary prerequisites for strength and power adaptation to occur. For example, it is thought that training loads need to be maximal or near maximal and of sufficiently long duration if strength and muscle CSA are to increase.[3,6] The distance over which force acts (work) may also be an important stimulus for changes in strength and muscle CSA to occur.[9,13] In order to improve muscular power, movements that produce high power output are the training methods of choice.[12,13,19] As the training load used often determines such responses, the prescription of load would appear to be the most important variable to consider for strength and power adaptation. However, the effect of load might be less important than the kinematics and kinetics associated with that load. That is, how a load is moved and/or the volume of load lifted will have a varied effect on the kinematic and kinetic response to movement, thereby changing the resultant adaptations. The following sections will discuss the kinematics and kinetics associated with different loads, contractions and techniques. In the first instance an analysis of the literature profiling a single repetition will be discussed and thereafter multiple repetition and set kinematics and kinetics will be addressed.

2. Single Repetition: Load Effects (Percentage of One Repetition Maximum)

2.1 Kinematics and Kinetics

The relationship between force and velocity is important for understanding movement, as all movement is a combination of these two qualities. A typical concentric force-velocity curve is shown in figure 1. According to this relationship, the ability of muscle to develop tension or force is greater at slower contraction velocities during shortening actions, as there is a greater time for these cross-bridges to generate tension.[23,24] The ability to produce greater forces at slower velocities is further related to changes in viscosity during movement. With an increase in shortening velocity there is greater fluid resistance in the sarcomere, requiring greater internal force to overcome and thereby resulting in lower total force production.[25]

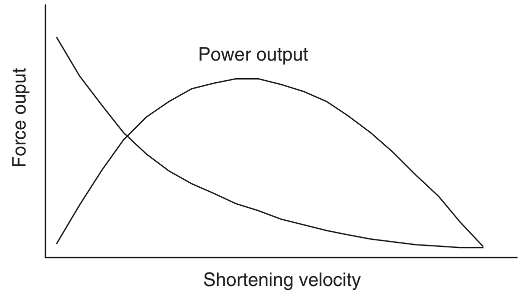

Fig. 1. Schematic representation of the force-power-velocity relationship of muscle.

A number of studies have examined the effect that load (% 1RM) has on force output, which clearly shows that force increases with an increase in load, as per the concentric force-velocity relationship (see table I). This is true for both mean and peak force output, irrespective of the exercise performed. For example, Newton et al.[19] examined the effect of bench-press throws, using concentric only and rebound techniques, at six different intensities (15%, 30%, 45%, 60%, 75% and 90% 1RM). With an increase in load, greater mean and peak forces were observed across both techniques. As expected, greater force outputs are associated with lower body exercises (~2700N) compared with upper-body exercises (~950N), across the various studies reviewed. This is likely to be a function of the larger muscle groups in the lower limbs and multiarticular nature of many leg exercises (e.g. squats). There appears to be a relationship (force-load relationship) between the load lifted and the amount of force generated, with an increase in load producing a concomitant increase in force output. It can be observed from table I that, on average, a 10% increase in load resulted in a 10% increase in force output.

Although greater forces are developed with heavier loads (force-load relationship), research in this area must still be interpreted with some caution. As expected, those individuals with greater 1RM

Table I. Effect of load (single repetitions) upon force output

Study	Subjects	Protocols	Results			
			load (minimum value)	value (N)	load (maximum value)	value (N)
Murphy et al.[22]	13 M (T)	CO (30%, 60%, 100% 1RM) and EO bench press (100%, 130%, 150% 1RM)	30% 1RM	~880	150% 1RM	~1200
Newton et al.[19]	17 M (T)	CO only and RB bench-press throws (15%, 30%, 45%, 60%, 75%, 90% 1RM)	15% 1RM (MF) 15% 1RM (PF)	~420–560 ~710–860	90% 1RM (MF) 90% 1RM (PF)	~900–1150 ~1100–1400
McBride et al.[26]	28 M (PL, OL, SP, CN)	CMJ (BW, 20kg, 40kg) and jump squats (30%, 60%, 90% 1RM)	BW (PF) [CN] BW (PF) [SP] BW (PF) [PL] BW (PF) [OL]	1741 1924 1854 2022	90% 1RM (PF) [CN] 90% 1RM (PF) [SP] 90% 1RM (PF) [PL] 90% 1RM (PF) [OL]	2687 3240 3478 3717
Cronin et al.[18]	27 M (UT)	CO and RB bench press and bench-press throws (30%, 40%, 50%, 60%, 70%, 80% 1RM)	30% 1RM (PF)	411–491	80% 1RM (PF)	820–915
Cronin and Crewther[27]	10 M (T)	Supine squats (30%, 60%, 90% 1RM)	30% 1RM (PF) 30% 1RM (MF)	970 (ECC) 943 (CON) 804 (ECC) 847 (CON)	90% 1RM (PF) 90% 1RM (MF)	2778 (ECC) 2214 (CON) 1962 (ECC) 1937 (CON)
Cronin et al.[28]	27 M (UT)	CO and RB bench press and bench-press throws (30%, 40%, 50%, 60%, 70%, 80% 1RM)	30% 1RM (MF)	~260	80% 1RM (MF)	~680

1RM = one repetition maximum; **BW** = bodyweight; **CMJ** = counter-movement jump; **CN** = controls; **CO** = concentric only; **CON** = concentric phase; **ECC** = eccentric phase; **EO** = eccentric only; **M** = males; **MF** = mean force; **OL** = Olympic lifters; **PF** = peak force; **PL** = power lifters; **RB** = rebound; **SP** = sprinters; **T** = trained; **UT** = untrained.

strength (e.g. Olympic/power lifters) use a greater absolute load and therefore produce greater forces at a given percentage of their 1RM.[26] With this in mind, age- and sex-related differences in strength become important when comparing data across studies. Differences in the measuring equipment (e.g. force platform and linear transducers) and modes of dynamometry (e.g. isoinertial and isotonic) used to determine force output also make comparisons difficult. The lifting technique employed is another important consideration. Some studies have employed techniques where the load or individual is projected in some manner (i.e. ballistic technique)[26,27] whilst others have used more traditional (i.e. non-projection) methods.[22] Research has also examined the mechanical response to different types of muscular contractions (e.g. concentric vs eccentric),[22] each with different force-velocity characteristics and another consideration when extrapolating data in this area. The influence of technique and contraction type upon load kinematics and kinetics will be addressed in sections 3–5.

Given that heavier loads are characterised by slower velocities (concentric force-velocity relationship), the use of such loads would also result in longer contraction durations during a single movement. This relationship is directly observable in table II where heavy loads have been shown to maximise contraction duration or the amount of time under tension (TUT), during a single repetition.[18,19,27] It can be observed that, on average, a 10% increase in load resulted in a 14% increase in TUT for the various exercises performed. These findings do not, however, reflect differences in training tempo as the assessments in these studies were generally performed with both maximal effort and intent. That is, the velocity of a given load is a function of not only load mass, but also the magnitude of effort employed to move that load. Thus, a load moved at submaximal intensity is likely to result in lower contractile velocities than movement produced with maximal intensity and, thereafter, increase TUT during that contraction. Similarly, the different lifting techniques used during assessment (e.g. traditional and ballistic) may also influence the velocity (and contraction duration) at which a given load may be moved.

With heavy loads producing greater forces and resulting in longer contraction periods than lighter loads, it may be speculated that the product of these variables (i.e. impulse) is also maximised under heavier loading conditions. Cronin and Crewther[27] examined three different loading intensities (30%, 60% and 90% 1RM), each performed explosively on a supine squat machine. An increase in load produced a concomitant increase in both TUT and force output for both the concentric and eccentric phases of each squatting movement. Accordingly, impulse production increased in a linear fashion with an increase in mass in the concentric (351, 863, 1816 N • sec, respectively) and eccentric (352, 773, 1239 N • sec, respectively) phases. The findings of Newton et al.[19] partially support these data. That is, an increase in both force output and TUT was observed with an increase in load (from 15% to 90% 1RM), during bench-press movements. Given that impulse is the product of force and time, it may be argued that this variable is a more appropriate measure of mechanical performance than either force output or TUT alone. Unfortunately, the assessment and/or practical significance of impulse are not well documented. To the knowledge of these authors, only one study[27] has examined such a variable.

The amount of work performed is another important mechanical variable. A number of studies[27,29-31] have assessed the amount of work performed with different exercises, reporting a concomitant increase in work with an increase in load. This is not surprising as the force component of the work formula (work = force × distance) is enhanced with heavier loads. On average, a 15% increase in work done was noted for a 10% increase in training load (see table II). Given that work is a function of force output, the amount of work performed during exercise is likely to be constrained by the same factors influencing force production, such as the muscle groups exercised, lifting technique employed and the 1RM strength of the population assessed. Also important is the distance of force application. It can be observed in table II that a range

Table II. Effect of load (single repetitions) upon time under tension, impulse and work

Study	Subjects	Protocols	Results			
			load (minimum value)	value	load (maximum value)	value
Time under tension						
Newton et al.[19]	17 M (T)	CO and RB bench-press throws (15%, 30%, 45%, 60%, 75%, 90% 1RM)	15% 1RM (CO) 15% 1RM (RB)	0.45 sec 0.33 sec	90% 1RM (CO) 90% 1RM (RB)	2.23 sec 1.54 sec
Cronin et al.[18]	27 M (UT)	CO and RB bench press and bench-press throws (30%, 40%, 50%, 60%, 70%, 80% 1RM)	30% 1RM	0.61–0.79 sec	80% 1RM	1.12–1.23 sec
Cronin and Crewther[27]	10 M (T)	Supine squats (30%, 60%, 90% 1RM)	30% 1RM 30% 1RM	0.44 sec (CON) 0.42 sec (ECC)	90% 1RM 90% 1RM	0.93 sec (CON) 0.64 sec (ECC)
Impulse						
Cronin and Crewther[27]	10 M (T)	Supine squats (30%, 60%, 90% 1RM)	30% 1RM 30% 1RM	351 N • sec (CON) 352 N • sec (ECC)	90% 1RM 90% 1RM	1816 N • sec (CON) 1239 N • sec (ECC)
Work						
Brown et al.[29]	15 M (T, ET, UT)	Leg press to failure (60%, 70%, 80% 1RM)	60% 1RM (T) 60% 1RM (ET) 60% 1RM (UT)	~718J ~506J ~522J	80% 1RM (T) 80% 1RM (ET) 80% 1RM (UT)	~911J ~691J ~728J
Craig and Kang[30]	4 M (T)	Half squats in 15 sec (75%, 90% 1RM)	75% 1RM	~570J	90% 1RM	~684J
Kang et al.[31]	3 M (T)	Squats and leg press to failure (3, 10, 25RM)	25RM (squat) 25RM (leg press)	395J 473J	3RM (squat) 3RM (leg press)	626J 841J
Cronin and Crewther[27]	10 M (T)	Supine squats (30%, 60%, 90% 1RM)	30% 1RM 30% 1RM	262J (CON) 239J (ECC)	90% 1RM 90% 1RM	576J (CON) 583J (ECC)

CO = concentric only; **CON** = concentric phase; **ECC** = eccentric phase; **ET** = endurance trained; **M** = males; **RB** = rebound; **RM** = repetition maximum; **T** = trained; **UT** = untrained.

of lower body exercises has been examined across research (e.g. full squat, half squat and supine squat). Thus, the amount of work performed in each study is not only a function of those factors influencing force output, but also the range of movement afforded by the different exercises and hence, the distance over which forces are applied.

A number of researchers have studied the effect that load (% 1RM) has on the power output of muscle (see table III). Where force output increases with load intensity (force-load relationship), power is the product of force and velocity; therefore, a certain combination of these variables will maximise the mechanical power output of muscle. A typical force-power-velocity curve is shown in figure 1. Earlier research indicated that maximal power output occurred at approximately 30% of maximum isometric strength and 30% of maximum shortening velocity.[32-35] However, more recent studies have reported that heavier loading intensities (e.g. 45–70% 1RM) may be superior in maximising the power output of muscle, irrespective of the exercise performed (see table III). This appears true for both mean and peak power output. In light of these recent findings a 'band width' approach for load intensity (e.g. 30–60% 1RM) is often prescribed to optimise the mechanical power output of muscle.[5] Similar to force output, greater power values have been reported in the performance of lower body exercises (~2000W) when compared with those of the upper body (~400W) [see table III]. This may again be attributed to the larger muscles of the lower limbs and multiarticular nature of many lower limb exercises.

Due to the force component of the power formula, differences in 1RM strength again require consideration when extrapolating data in this area. For instance, weight-trained individuals (e.g. Olympic/power lifters) are able to use greater absolute loads at a given percentage of their 1RM, resulting in greater power outputs compared with untrained individuals.[26] Other factors influencing strength (e.g. age and sex) and force production (e.g. lifting technique) should also be considered in this context. It has been reported that stronger subjects achieved peak power at a higher percentage of their 1RM compared with weaker subjects.[41] This finding would suggest that the ability to exert power output is transient and affected by changes in maximal strength. Baker,[21] however, found that the percentage 1RM that maximised power output was significantly lower in stronger professional (51%) compared with state rugby league players (55%), as well as for stronger subgroups within each group. It would seem as athletes become stronger they can produce greater power outputs with any absolute load, but the ability to produce power at a given percentage of their 1RM remains similar, as relative resistances increase proportionally to strength levels.

The lack of a standardised protocol for the collection and analysis of data presents a major difficulty when examining research in this area. That is, differences in data collection equipment and power calculations, inclusion or exclusion of bodyweight, calculation of load intensity, number of loads examined and instructions given, may lead to conflicting results. This would explain the wide range of loads often reported to optimise the power output of muscle. For example, studies that have not accounted for additional acceleration values when calculating power output, particularly when moving lighter loads (greater accelerations), may report power data that are artificially low. Furthermore, some studies[27] have calculated power by including the mass of the load alone, whereas others[37] have calculated power by including the mass of the load and the subject (i.e. system mass). The different variables used to denote power output (e.g. mean, peak, relative and instantaneous) and their practical significance further confound understanding in this area. These issues may further explain the wide range of values reported (~400W to ~4900W) across the studies reviewed (see table III). An in-depth examination of such issues is beyond the scope of this review, but may be sourced in other literature.[42,43] Given the lack of a standardised protocol for data collection/analysis and the reporting of power output, determining the load that maximises the

Table III. Effect of load (single repetitions) upon power output

Study	Subjects	Protocols	Results	
			load maximising power output	value (W)
Thomas et al.[36]	19 F (UT)	Leg press (34%, 40%, 45%, 50%, 56%, 60%, 64%, 68%, 78%, 84%, 89% 1RM)	56–78% 1RM (PP)	404
Newton et al.[19]	17 M (T)	CO and RB bench-press throws (15%, 30%, 45%, 60%, 75%, 90% 1RM)	30–45% 1RM (MP)	560–563
McBride et al.[26]	28 M (PL, OL, SP, CN)	CMJ (BW, 20kg, 40kg) and jump squats (30%, 60%, 90% 1RM)	BW (PP) [SP] 20KG (PP) [PL, OL, CN]	4906 3789–5386
Baker et al.[37]	32 M (T)	Jump squats (40, 60, 80, 100kg – system mass)	55–59% 1RM (MP) 47–63% 1RM[a]	1851
Baker[21]	49 M (T)	CO bench-press throws (40, 50, 60, 70, 80kg)	51% 1RM (MP) [NRL] 55% 1RM (MP) [SRL]	600 502
Baker et al.[20]	31 M (T)	CO bench-press throws (40, 50, 60, 70, 80kg)	55% 1RM (MP) 46–62% 1RM[a]	598
Cronin et al.[18]	27 M (UT)	CO and RB bench press and bench-press throws (30%, 40%, 50%, 60%, 70%, 80% 1RM)	50–70% 1RM (MP) 50–60% 1RM (PP)	~270–340 ~550–625
Izquierdo et al.[38]	47 M (UT) [MA, EL]	CO half squats (15%, 30%, 45%, 60%, 70% 1RM)	60% 1RM (PP) [MA] 70% 1RM (PP) [EL]	486 391
Izquierdo et al.[39]	70 M (WL, MDR, HBP, CYC, CN)	CO bench press (30%, 45%, 60%, 70%, 80%, 90%, 100% 1RM) CO half squats (30%, 45%, 60%, 70%, 80%, 90%, 100% 1RM)	30–45% 1RM (MP) 45–60% 1RM (MP)	200–391 385–755
Siegel et al.[40]	25 M (T)	Squats (30%, 40%, 50%, 60%, 70%, 80%, 90% 1RM)	50–70% 1RM (PP)	~950
Cronin and Crewther[27]	10 M (T)	Supine squats (30%, 60%, 90% 1RM)	60–90% 1RM (MP) 30–90% 1RM (MP) 60–90% 1RM (PP)	816–852 (ECC) 569–731 (CON) 1564–1406 (CON)

a Similarly effective to loads that maximised power output.

1RM = one repetition maximum; **BW** = bodyweight; **CN** = controls; **CO** = concentric only; **CON** = concentric phase; **CYC** = cyclists; **ECC** = eccentric phase; **EL** = elderly; **F** = females; **HBP** = handball players; **M** = males; **MA** = middle age; **MDR** = middle distance runners; **MP** = mean power; **NRL** = national rugby league; **OL** = Olympic lifters; **PL** = power lifters; **PP** = peak power; **RB** = rebound; **SP** = sprinters; **SRL** = state rugby league; **T** = trained; **UT** = untrained; **WL** = weight lifters.

mechanical power output of muscle remains difficult.

The manner in which a given exercise is performed (i.e. free weights vs fixed machines) is also an important consideration. Compared with fixed machines, free-weight lifting offers many advantages such as a greater degree of freedom and greater training variation. Free weights also allow the better transfer of effects to functional performance where most machines are limited by their design (e.g. matching strength curves, movement in a single plane and single joint action). It may be speculated that such differences would result in disparate kinematics and kinetics when performing the same movement and exercise, either with free weights or a fixed machine. Although this article is based on more traditional weight-lifting practices, the authors do recognise the wider use of Olympic-style lifts (e.g. snatch, and clean and jerk) within strength and conditioning practice. Due to the multiarticular nature of Olympics lifts and the greater amount of muscle mass used, on average, power outputs during Olympic-style lifts are much greater than those developed during more traditional lifts.[44] Still, the technical nature of these lifts means that they require some degree of specialised training, as well as the use of more expensive laboratory equipment (e.g. force platform) in order to accurately quantify the kinematic and kinetic response to such movements. An analysis of the mechanical response to Olympic lifting is provided in other literature.[44]

2.2 Implications for Strength and Power Development

Strength adaptation is largely attributed to changes in neural function (motor unit recruitment, firing frequency, synchronisation and reflex activity) and muscle morphology (muscle CSA).[1,45] The mechanism for these adaptations may be explained by the 'stimulus-tension' theory, that is, the intensity (% 1RM) and the duration of muscular tension (i.e. forces) are responsible for neural and morphological adaptation.[46] Heavy loads would seem fundamental to strength development, as high forces are associated with maximal motor unit recruitment according to the 'size principle', with these units also firing at higher frequencies.[4,47] High force development may also act to inhibit the force-feedback (Golgi tendon organs) reflex mechanisms and/or improve the synchronisation of motor unit firing.[1,48,49] In terms of muscle growth, the development of high forces is also thought important for the remodelling of muscle tissue (protein synthesis and degradation).[50,51] The application of high forces stimulates receptor and membrane sensitivities, and growth factors in the muscle, thereby triggering an increase in protein turnover and leading to the accretion of muscle protein.[52,53] High load forces, particularly when the muscle is actively stretched, may further mediate muscle tissue growth by inducing greater tissue damage (greater damage = greater tissue regeneration). More detailed information regarding the mechanisms for strength development can be examined in other sources.[4,48,54-56] Given the relative importance of high forces for adaptation, the use of heavy training loads would appear to provide the superior stimulus for maximal strength development.

It may be that force alone does not adequately account for changes in strength and hypertrophy, but rather the distance over which that force acts or work.[9,13] The benefits of work are partially supported by the greater strength gains found with high volume programmes (greater volume = greater work) compared with low volume programmes.[57-61] In performing a greater amount of work the active muscles are likely to undergo greater mechanical stress (e.g. forces, contraction duration and stretch) leading to greater muscular adaptation. An increase in mechanical work also produces greater hormonal and metabolic responses,[62-65] which are other factors important for muscular adaptation (muscle growth) to occur.[25,66] If the amount of work done was an important stimulus for inducing changes in maximal strength, then the prescription of heavy training loads would again appear the superior training option (greater forces = greater work). Examination of work done as a training stimulus is, however, limited to dynamic weight-training movements, as the performance of static or isometric contractions do not result in limb movement and thus, no mechanical work is performed.

TUT is another factor thought important for strength and hypertrophic adaptation.[2,6] In theory, the longer a muscle is subjected to a given training stimulus the greater the potential for adaptation to occur. Given the longer contraction durations associated with heavier loads, the prescription of such loading intensities would again seem better suited to produce the greatest changes in maximal strength. More advanced training methods used within practice (e.g. super slow training and pause training) partially support such a notion. That is, such methods are adopted in order to increase the duration in which muscle is under tension, leading to greater morphological adaptation than that achieved with more traditional weight-training methods. However, it is unlikely that TUT alone is the critical stimulus for adaptation to occur. Endurance training, for example, is typically characterised by high volume training (high total repetitions = high TUT) and is not thought to result in substantial hypertrophy and/or strength gains.[5,67] This may be attributed to the lighter loads (lower forces) utilised with endurance training, which further underscores the importance of heavier training loads for improving maximal strength.

Given the relative importance of high forces and TUT to maximal strength development, it may be speculated that impulse production is the critical stimulus for adaptation. Unfortunately, such a contention has not been investigated. Our understanding of strength adaptation may benefit from research differentiating between impulse as opposed to force and TUT and mapping adaptation thereafter. In terms of explosive or powerful activities, impulse production would also seem to be of some importance for training adaptation to occur. For instance, Schmidtbleicher[45] defined power as the ability of the neuromuscular system to produce the greatest impulse in a given time period. Therefore, the development of high forces in a short period of time or greater forces in the same period of time may prove to be an effective training stimulus for those activities that require the specific generation of forces in such a manner (e.g. sprint running and long jumping). Weight-training techniques that maximise force and/or minimise the time over which the force is applied and their subsequent effect upon performance, are other possible areas for investigation.

It may be speculated that light training loads would provide the superior stimulus for the development of muscular power. The use of lighter loads allows greater contractile velocities to be achieved (load-velocity relationship) and, therefore, would seem ideal for maximising athletic performance, given that training-induced adaptation is likely to occur at or near the velocity at which one trains.[47] The coordination of force application into functional movement or inter-muscular coordination is another benefit afforded by light-load/high-velocity training.[68] The specific training effects associated with light-load/high-velocity training may be attributed to changes in motor control, involving factors such as reflex inhibition (Golgi tendon organs) and facilitation (muscle spindles), coactivation of the antagonists and synergistic involvement during movement.[47,69] Performing explosive movements with lighter training loads may further benefit power adaptation, through the preferential recruitment of the high-threshold motor units and the muscle fibres they innervate.[70,71] Again, an in-depth review of such mechanisms is beyond the scope of this review, but may be viewed in other sources.[47,72]

It has been suggested that training loads that maximise mechanical power output would also optimise power performance.[12,19,73] In theory, such loads optimise the contribution of force and velocity, thereby potentially benefiting a wider range of performance measures, compared with either light-load (high-velocity) or heavy-load (high-force) training. Whilst the prescription of load based upon maximising mechanical power output appears an attractive strategy for power development, what may be critical is the ability to exert force at speeds specific to a sporting or athletic movement. That is, the load that produces optimal power output for a given sporting movement or activity. Although power performance is often associated with high movement velocities (e.g. sprinting, jumping and throwing) other activities such as Olympic weightlifting also have a power component. Similarly, as kicking a ball, throwing a shot put, and tackling an opponent involve different masses and hence force-velocity characteristics, moving one load (i.e. load that maximises mechanical power output) for all activities may not maximise adaptation. With this in mind, it would seem appropriate to train power at similar velocities for optimal sport-specific adaptation.

3. Single Repetition: Contraction Type

3.1 Kinematics and Kinetics

It is well known that eccentric muscle actions enable greater forces to be developed in active muscles, compared with concentric-only muscle actions.[23,66,74] Where greater forces are generated with heavier loads (slower contraction velocities) during shortening, an increase in load velocity during lengthening results in greater force generation (force = mass × acceleration), until the load is no longer under muscular control (see figure 2). During eccentric muscle actions it is thought that there is greater contribution from the elastic components of the musculo-tendinous unit, increasing the potential for force generation.[23,74] As a consequence, eccentric muscle actions are able to generate greater maximal tension (force) or produce similar tension with less motor units recruited compared with concentric-only muscle actions. Eccentric actions are also associated with lower ‘metabolic’ costs than concentric actions.[75,76] On the basis of these benefits,

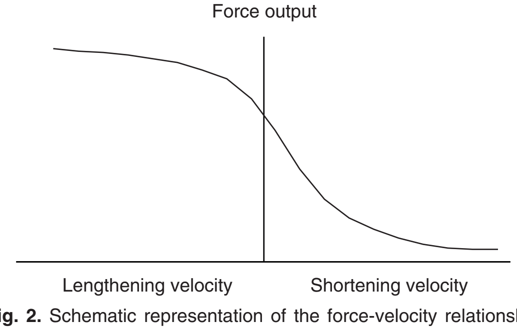

Fig. 2. Schematic representation of the force-velocity relationship of muscle during shortening and lengthening contractions.

eccentric-only actions are often thought to provide greater ‘mechanical efficiency’ than concentric-only actions.[25]

As a result of the greater mechanical efficiency afforded by eccentric contractions, supra-maximal loads (>100% concentric 1RM) may be employed, facilitating the development of high-load forces. A study by Murphy et al.[22] examined the effect of concentric- and eccentric-only contractions, utilising bench-press movements. Loads of 30%, 60% and 100% concentric 1RM were used in the concentric conditions, with loads of 100%, 130% and 150% concentric 1RM used in the eccentric conditions. As expected, force output increased with an increase in mass in the concentric conditions and further, with the heavier masses in the eccentric conditions. Although no differences in force output were found between the three eccentric movements, such data support the use of supra-maximal eccentric loading as a means to increase force production. Other studies have also investigated the mechanical response to eccentric movements;[19,27] however, given that only submaximal loads were employed, little is still known about the kinematics and kinetics associated with supra-maximal loading conditions. Given the wider use of heavy eccentric loading within practice, it is recommended that research investigate the mechanical response to such training methods.

3.2 Implications for Strength and Power Development

As resistance training is generally performed with both eccentric and concentric muscle actions, the combined effect of these contractions is likely to contribute to the training response. As mentioned previously, heavy eccentric loading is often used within practice allowing ‘supramaximal’ loads to be utilised and high forces to be developed for greater strength and/or hypertrophic gains (stimulus-tension theory). In the development of high muscular forces, heavy eccentric loading affords other potential training benefits. For example, it has been speculated that the larger high-threshold motor units may be preferentially recruited under supramaximal loading conditions,[47] which would seem ideal for maximal strength and power development. If these units contributed to a greater proportion of hypertrophy than the low-threshold motor units,[56,77] their selective recruitment through such actions may further augment morphological adaptation. Another benefit of loading in this manner is the higher incidence of microscopic muscle injury,[78,79] providing an ideal stimulus for morphological adaptation to occur according to the protein degradation-synthesis response of muscle.

The potential benefits afforded by eccentric loading are not without some controversy. Concentric-only training, for example, has been found equally effective in stimulating strength and hypertrophy changes compared with eccentric-only training.[76,80-82] This may be explained by the fact that many of these studies employed sub-maximal training loads (<100% concentric 1RM) and thus, the benefits of eccentric training may not be fully realised, or the greater metabolic costs associated with concentric-only actions.[75,76] Concentric-only contractions have also been shown to elicit greater hormonal responses (e.g. growth hormone), compared with eccentric-only contractions using the same absolute load.[83] Whether or not eccentric actions provide the superior training stimulus to concentric actions with the same relative load, remains a topic of debate. Eccentric muscle actions are also characterised by reduced motor unit activation compared with concentric actions,[25,47] which would suggest that less muscle fibres are recruited and trained. Still, there may be greater relative tension produced by each individual muscle fibre with less motor units activated per movement. Such issues limit our understanding of eccentrics and the prescription of such exercise.

One of the main limitations of employing eccentric- or concentric-only loading for power development is the lack of specificity (e.g. contraction type and velocity). It is known that resistance training-induced performance gains, related to concentric- or eccentric-only actions, are likely to result in contraction-specific adaptation.[84,85] In contrast, most athletic activities are characterised by a combination of both eccentric and concentric actions (stretch shortening cycle [SSC]) during movement. The functional importance of the SSC will be addressed in the next section. Still, it may be speculated that training in such a manner would benefit power development in those activities requiring high levels of contraction-specific strength. For example, activities that involve landing under high loading conditions (e.g. gymnastics) are likely to require a certain amount of lengthening or eccentric strength for successful performance. Eccentric strength may also benefit those sporting activities characterised by high limb velocities and requiring limb direction to be changed at speed (e.g. sprinting). Certainly those sports characterised by predominantly single muscle contractions, such as swimming and cycling, would no doubt benefit from some type of training in this manner.

4. Single Repetition: Rebound versus Non-Rebound

4.1 Kinematics and Kinetics

The SSC is a common pattern of muscle activation that occurs when an eccentric action precedes a concentric muscle action.[25] Cronin et al.[18] examined the effect of concentric-only and rebound bench-press movements (throw and non-throw) across a range of loads (30%, 40%, 50%, 60%, 70%, 80% 1RM). The rebound bench press resulted in greater force (peak 14.1%) and power (mean 11.7%) output on average across all loads, compared with the non-rebound conditions. Other research has reported similar findings,[19,28,41] thereby demonstrating the potentiating effect of rebound. These effects may be attributed to the enhanced kinematics associated with rebound movement. For example, greater accelerations (peak 38.5%) and velocities (mean 12.4%) were reported across all loads, comparing rebound and concentric-only actions, whether or not the load was held or thrown (see table IV). The augmentation from SSC muscle action is typically attributed to a number of factors including: the storage and re-utilisation of elastic energy in the series elastic component of the musculo-tendinous unit;[86,87] spinal reflexes;[88] and long latency re-

Table IV. Effect of technique (single repetitions) on peak and mean velocities, peak accelerations, peak and mean force, peak and mean power, and duration of concentric contraction during bench-press movements at different loading intensities (30–80% 1RM)[18,28]

% 1RM	PV (m/sec)	MV (m/sec)	PA (m/sec^2)	PF (N)	MF (N)	PP (W)	MP (W)	DOCC (sec)
Concentric-only bench press								
30	1.49	0.82	5.87	414.1	257.9	467.4	211.5	0.629
40	1.35	0.73	4.63	505.9	339.5	532.0	250.0	0.683
50	1.16	0.64	3.78	583.8	429.2	552.1	271.7	0.761
60	1.01	0.55	2.96	660.9	509.4	549.3	280.8	0.818
70	0.86	0.36	2.43	766.4	588.8	542.4	266.8	0.964
80	0.68	0.33	1.93	826.3	677.8	478.2	222.0	1.125
Rebound bench press								
30	1.52	0.91	8.54	491.8	262.1	463.2	237.0	0.614
40	1.37	0.83	7.11	596.1	340.5	536.3	283.1	0.642
50	1.21	0.75	6.33	692.7	427.2	557.9	312.8	0.739
60	0.99	0.62	4.97	786.4	513.4	550.6	315.4	0.803
70	0.83	0.53	4.12	876.6	599.1	542.3	316.3	0.945
80	0.65	0.39	3.19	906.5	679.0	468.9	261.3	1.238
Concentric-only bench-press throw								
30	1.63	0.87	5.74	411.1	258.2	522.0	223.5	0.792
40	1.45	0.77	4.73	505.2	340.3	575.0	263.3	0.816
50	1.27	0.68	3.76	589.2	430.6	621.0	290.7	0.826
60	1.05	0.57	2.85	657.3	508.8	609.3	290.9	0.883
70	0.89	0.47	2.45	772.8	594.8	580.0	280.9	0.953
80	0.72	0.36	2.06	820.5	677.8	527.5	232.2	1.213
Rebound bench-press throw								
30	1.68	0.98	8.51	488.8	261.6	531.8	252.3	0.782
40	1.48	0.87	7.34	593.5	341.2	590.6	296.5	0.779
50	1.30	0.78	6.67	714.3	424.7	626.4	325.5	0.793
60	1.08	0.66	5.01	777.3	511.4	609.4	336.6	0.844
70	0.88	0.53	4.33	866.1	594.8	681.7	326.7	0.944
80	0.69	0.39	3.25	914.1	678.7	499.3	271.7	1.180

1RM = one repetition maximum; **DOCC** = duration of concentric contraction; **MF** = mean force; **MP** = mean power; **MV** = mean velocity; **PA** = peak acceleration; **PF** = peak force; **PP** = peak power; **PV** = peak velocity.

sponses[89] that increase muscle stimulation, allowing the muscle to reach maximum activation prior to the concentric muscle action.[90]

As a result of the enhanced kinematics, it is not surprising that the concentric phase of SSC movements generally result in shorter contraction durations than non-rebound movements, regardless of the technique employed.[18,19,28] To our knowledge, no research has specifically examined work done or impulse production when comparing rebound and non-rebound conditions. Despite this, it may be speculated that with an increase in force production (with a given load) that greater work would also result when utilising the SSC. An increase in force output with rebound further suggests that SSC movements elicit greater impulse production. However, given that studies in this area have indicated a reduction in contraction duration with rebound,[18,19,28] the combined effect of force output (increase) and TUT (decrease) upon the impulse produced remains highly speculative. The assessment of work and impulse under different loading conditions is an area for further investigation, which may help understand the nature of the acute mechanical stimulus and its contribution to strength and power adaptation.

Whilst the potentiating effects of rebound to the concentric muscle action are well recognised, such effects may be limited to the initial period of the concentric movement. Cronin et al.[18,28] reported that the use of rebound did not enhance peak velocities over that found in non-rebound bench presses. Newton et al.[19] reported similar findings and attributed this to the recovery of stored elastic energy. That is, elastic and reflex potentiation only enhance the initial phase of the concentric movement and that peak velocities occur later where the effects of the SSC have diminished.[19] An interaction between the potentiating effects of the SSC and the load utilised is also evident within research in this area (see table IV). For example, greater changes in peak forces were observed when moving a load of 30% 1RM (18–19% SSC enhancement) than that achieved with a load of 80% 1RM (10–11% SSC enhancement). This would suggest that the potentiating effect of rebound decreases when heavier masses are lifted. The mechanisms for this are likely to involve a slower rate of eccentric muscle action, longer duration eccentric muscle action and slower coupling times when utilising heavier loads.[18,19]

4.2 Implications for Strength and Power Development

The SSC has been shown to augment a variety of kinematic and kinetic variables across a spectrum of loads. As most training programmes are performed with rebound, it may be assumed that changes in maximal strength are, in some capacity, related to the potentiating effects of both the elastic (i.e. tendon and epimysium) and active components (i.e. cross-bridges) of muscle. Quantifying the exact contribution of the SSC to changes in muscular performance, however, remains difficult. Realising that pre-stretching the muscle enhances the concentric muscle action, eliminating the influence of the SSC may intuitively elicit greater contribution from the contractile machinery. If changes in strength and hypertrophy were largely attributed to adaptations within the contractile elements, concentric-only training would provide an attractive training option for greater contractile development. Weight-training techniques such as rest-pause or super slow training would be preferred in such circumstances as the potentiating effects of the eccentric phase are reduced, thereby potentially stressing the contractile element of the muscle for greater strength and hypertrophic gain. Since pre-stretch shortens the duration of the concentric phase, eliminating the eccentric contribution will also result in greater TUT and provide additional stimulus for adaptation.

Unlike strength, the utilisation of the SSC appears an important consideration for power adaptation. Given that pre-stretch is an inherent aspect of many athletic activities (e.g. running, jumping and throwing) the use of rebound during training would seem fundamental to improving performance in those activities characterised by such actions. First, SSC movements enable greater power outputs to be developed for greater power adaptation. Second, the velocity and acceleration profile of rebound movement more closely simulate those occurring during sporting performance and everyday activities (e.g. high velocities and longer periods of accelerations) compared with non-rebound movement. Explosive power performance is also thought to respond to training in which athletes perform SSC movements with high stretch forces, improving both the tolerance to, and utilisation of, high stretch loads.[6,69] It may be argued that plyometrics (e.g. depth jumps and bounding) are often prescribed for power development on the basis of these benefits, with such movements typically performed in an explosive manner and coupled with eccentric-concentric muscle actions.

5. Single Repetition: Traditional versus Ballistic

5.1 Kinematics and Kinetics

The term 'ballistic' refers to techniques in which the load (e.g. the bar and/or oneself) is projected or released at the end of the concentric phase. Various studies have reported enhanced kinematic and kinetic responses to exercise utilising ballistic movements.[12,18,28,91] For example, Newton et al.[12] reported a significant increase in power output with a ballistic technique (mean 70%, peak 67%), when comparing traditional and bench-press throw movements. Although ballistic movement appears to enhance the power output of muscle, the effect of such a technique upon force output is less clear. In their study, Newton et al.[12] also reported a significant increase in force output (mean only); however, the enhancement of force output (35%) was much smaller than the power enhancement observed with the ballistic movement. Similar findings were reported by Cronin et al.[18] That is, an increase in power output (mean 5.8%, peak 9.1%) on average was found across all loads when comparing traditional and ballistic bench-press movements; however, no changes in force output were reported between these movements. These findings suggest that force output is less influenced by the performance of ballistic movements.

Similar to rebound, the potentiation afforded by ballistic techniques may be attributed to altered load kinematics. A bench-press throw (45% 1RM) for example, allowed the bar to be accelerated for 96% of the throw movement as opposed to 60% for a traditional movement,[12] thereby having a significant effect upon load velocities (i.e. mean 27%, peak 36%) and related kinetics thereafter. As a result of this enhancement, it is not surprising that ballistic movements also reduce the contraction duration for the concentric phase of movement.[12] Despite this, other studies have reported longer durations for the concentric phase, utilising ballistic movements.[18,28] Disparate findings may be explained by the measurement of work, as muscle activation will only be achieved up to the point of release, despite the load being thrown a greater distance. Some studies[12,27] have accounted for this and reported 'muscular work' whilst others have examined 'system work'[18,28] and accordingly, variability in the amount of time taken to perform the concentric phase of movement. This is certainly an important consideration when examining all mechanical responses given their dependence upon load displacement. Again, we may only speculate as to the effect of ballistics movements upon other variables such as work and impulse.

5.2 Implications for Strength and Power Development

If ballistic techniques contributed to greater force development, then training in this manner may provide a more effective stimulus for maximal strength. Ballistic techniques may further contribute to the training stimulus in developing high eccentric forces when 'catching' and lowering the load. Previously, it was thought that heavier loads (>60–70% 1RM) were necessary for strength and hypertrophic adaptation given the greater forces associated with heavier loads. However, such beliefs were based on techniques that did not involve the projection of the load. Ballistic techniques may enhance the mechanical response to resistance exercise (e.g. greater force production) and in doing so provide an alternative strategy for maximal strength with the use of lighter (<45% 1RM) training loads.[7,9,11] It should, however, be realised that the benefits afforded by such techniques may decrease as load increases, due to the inability to project the bar or oneself at heavier loads. The use of ballistic-type movements may be further limited by the shorter contraction durations, over the concentric phase of movement. Whether or not ballistic techniques provide the superior stimulus for maximal strength adaptation, compared with traditional techniques, remains unknown.

Ballistic techniques would appear to offer an ideal stimulus for power development given that such movements elicit greater power outputs for a given load. Training in this manner would also develop a velocity profile more closely resembling that occurring during most athletic activities (i.e. high velocities) and overcome one of the main limitations of using traditional techniques, where a large portion of the movement is spent decelerating the load. That is, most athletic activities are characterised by longer periods of acceleration; therefore, training in this manner would provide potentially greater transfer of training effects (sports specificity) for optimal adaptation and successful performance thereafter. It may be further speculated that the acceleration profile associated with ballistic techniques increases the 'loading' period of muscle, for greater adaptation. In fact, many of the specific neural responses associated with ballistic training (e.g. high firing rates, antagonist coactivation, inhibition of agonists and preferential motor unit recruitment),[47,70,71] would seem ideal for improving power performance. Accordingly, exercise choice and the lifting technique employed are important considerations in the effective prescription of resistance exercise for improving power performance.

Various issues surround the effective use of such a training strategy with strength and conditioning practice. Given that the load or individual is released during ballistic training, the likelihood for injury may increase due to the excessive loading placed upon the muscular and skeletal systems during the ‘catch’ and ‘throw’ phases. Given the high load forces developed, particularly in the catching phase, training in this manner may not be appropriate for untrained or novice trainers and likely to be limited to more advanced weight lifters with an established strength base. A further issue may be the availability of appropriate equipment and/or machines (e.g. Smith machine) within practice, to allow such movements to be performed correctly and in a safe manner. Although ballistic movements would appear to offer a great deal of benefit for improving power performance, whether or not ballistic training produces the optimal stimulus for power adaptation has not yet been determined. Further research is therefore needed to determine the efficacy of such a training method as a stimulus for power adaptation.

6. Multiple Repetitions and Sets

6.1 Kinematics and Kinetics

Given that resistance exercise usually involves multiple sets and exercises, the kinematic and kinetic response to a single repetition may have little practical significance in terms of understanding the stimulus imposed by a typical training session. For example, Cronin and Crewther[27] found that a single repetition at 90% 1RM produced superior forces (mean and peak) during both the eccentric and concentric phases than either 30% or 60% 1RM. However, when examining set responses (equated by volume) greater eccentric and concentric forces (totals) were observed in the 30% 1RM condition. Combined values for TUT and power output were also greater in the 30% 1RM condition (see table V). Similar results have been found for total work done. Where research has reported an increase in work with mass during single repetitions,[27,29-31] these same studies reported greater total work in the lightest loading conditions examined. This is due to differences in training volume where the performance of high total repetitions with a lighter load accounts for the greater forces (and work) associated with heavier loads. Therefore, set responses to resistance exercise would appear to be influenced by both the intensity of the load (%1RM) and the volume of load lifted (repetitions performed). The impulse produced over multiple repetitions appears less clear. Although no differences were found when comparing total eccentric impulse, the 90% 1RM condition resulted in greater total concentric impulse.[27] Still, few data are available to adequately characterise the mechanical response to multiple repetitions of resistance exercise.

Examining research in this area must also be done with some caution. For example, the total amount of work performed in the assessment of the lower body differed considerably between studies, from ~6000 to ~33000J (see table V). This may be due to several factors such as differences in exercise technique, as well as the protocols used in the various studies (e.g. repetitions to failure, repetitions in 15 seconds, equated by volume). The training status or 1RM strength of the population assessed is another important consideration. Stronger individuals not only use greater absolute loads compared with weaker individuals, but may also perform a greater number of repetitions at any given load (% 1RM). Brown et al.[29] for instance, found that weight-trained males not only used a heavier load at 70% 1RM, but also performed more repetitions to failure at this load, compared with untrained males (22 vs 14 repetitions, respectively). The ability of experienced weight lifters to train at a greater relative intensity may be explained by the ‘trained’ status of these individuals in combination with other factors, such as familiarity with the testing procedures and

Table V. Effect of load (multiple repetitions) on total work, total forces, total time under tension, total power and total impulse

Study	Subjects	Protocols	Results			
			load (minimum value)	value	load (maximum value)	value
Total work						
Brown et al.[29]	15 M (T, ET, UT)	Leg press to failure (60%, 70%, 80% 1RM)	80% 1RM (T) 80% 1RM (ET) 80% 1RM (UT)	9844J 7053J 4951J	60% 1RM (T) 60% 1RM (ET) 60% 1RM (UT)	33 208J 22 074J 19 330J
Craig and Kang[30]	4 M (T)	Half squats in 15 sec (75%, 90% 1RM)	90% 1RM	~3500J	75% 1RM	~6200J
Kang et al.[31]	3 M (T)	Squats and leg press to failure (3%, 10%, 25RM)	3RM (squat) 3RM (leg press)	1878J 2524J	25RM (squat) 25RM (leg press)	9875J 11 831J
Cronin and Crewther[27]	10 M (T)	Supine squats equated by volume (6 × 30%, 3 × 60%, 2 × 90% 1RM)	90% 1RM 90% 1RM	1168J (ECC) 1153J (CON)	30% 1RM 30% 1RM	1433J (ECC) 1510J (CON)
Total forces, total time, total power and total impulse						
Cronin and Crewther[27]	10 M (T)	Supine squats equated by volume (6 × 30%, 3 × 60%, 2 × 90% 1RM)	90% 1RM	ECC		ECC
				1.29 sec 3925N 1704W	30% 1RM	2.67 sec 4829N 3233W
					30%, 60%, 90% 1RM[a]	2116–2535 N • sec
				CON		CON
			90% 1RM	1.87 sec 3876N 1139W	30% 1RM	2.53 sec 5084N 3626W
			30% 1RM	2111 N • sec	90% 1RM	3632 N • sec

a No differences between loads.

1RM = one repetition maximum; **CON** = concentric phase; **ECC** = eccentric phase; **ET** = endurance trained; **M** = males; **T** = trained; **UT** = untrained.

greater tolerance to muscular fatigue. The small number of subjects employed in some of these studies (four or less)[30,31] also makes comparisons problematic. Given these issues, making broad conclusions based on such findings is somewhat limited.

Manipulating weight-training technique is common within practice to overload the muscular system.[2] For example, a reduction of lifting tempo may reduce the contribution of the SSC during rebound movements and elicit greater contractile contribution. A slow eccentric phase compared with the concentric phase may also serve to exhaust eccentric strength and promote specific training-induced gains. However, to our knowledge, only one study has examined the kinematic and kinetic response to different techniques, over multiple repetitions. Keogh et al.[92] examined the mechanical response of seven techniques (isokinetics, eccentrics, functional isometrics, super slow motion, rest pause, breakdowns and maximal power training) using a bench-press movement. Each movement was performed over approximately six repetitions. Understandably, many of these techniques produced specific responses. For example, maximal power training (30% 1RM) maximised power output per repetition, whilst super slow motion training (55% 1RM) maximised total contraction duration. However, extrapolating this information is limited with few variables assessed and with data (except duration) reported for the first, middle and last repetitions alone.[92] Examination of different weight-training techniques, as performed in practice, would also provide greater understanding in this area.

Given the importance of force and TUT to maximal strength adaptation, it is interesting to note that no studies have reported the cumulative effect of these variables over the course of different loading schemes. Research has, in the examination of endocrine responses to resistance exercise, reported total work between hypertrophy and neuronal loading schemes.[63-65,93] On average, greater total work was observed in the hypertrophy schemes, when comparing data between male (60 000J vs 50 000J) and female (32 000J vs 25 000J) populations, respectively. The difference in work may be explained by the greater training volume (i.e. sets × repetitions × load) in those schemes designed to induce hypertrophy. Whilst these data provide some understanding as to the mechanical stress afforded by different schemes and the stimulus for adaptation (e.g. high total work = muscle growth), the assessment of work alone does not adequately reflect the mechanical stimulus imposed by a single training session. It may be argued that the stimulus afforded by a bout of exercise be determined by simply multiplying repetition responses by the number of repetitions performed. However, such an analysis does not provide sufficient understanding as to the kinematic and kinetic response across exercise, as some programmes (e.g. hypertrophy) are associated with a fatigue component.[94] Furthermore, many advanced weight-training methods involve the manipulation of the various training variables or complex combinations, with a given training programme (e.g. super sets, giant sets, pre-exhaust sets and drop sets). Thus, an in-depth analysis of load kinematics and kinetics across exercise is needed to characterise the actual dynamics of these and other training sessions.

6.2 Implications for Strength and Power Development

The limitations to our discussion about the practical applications of the kinematics and kinetics of a single repetition are obvious. Strength and power adaptation necessitate the use of loading schemes characterised by multiple repetitions, sets and exercises, varied intensities (% 1RM), rest periods and training volumes.[5,95,96] It is the specific configuration of these variables that determines the mechanical response to a weight-training session and thereafter, long-term adaptation. Neuronal schemes are often characterised by heavy loads (e.g. 85–100% 1RM) with few repetitions per set (e.g. 1–6) and long rest periods (e.g. 3–5 minutes). Hypertrophy schemes are commonly characterised by lower intensities (e.g. 75% 1RM), more repetitions (e.g. 8–12) and shorter rest periods (e.g. 1 minute). Hypertrophy training is further typified by high training volume, more so than neuronal training. Based on the above protocols, it may be speculated that near maximal forces are necessary to induce maximal strength through neural mediated adaptation.[2,45] Conversely, total force production (and total work) would appear of greater importance for morphological adaptation to occur. The amount of TUT would also seem important for muscle growth given the high number of repetitions performed and with movement during hypertrophy training deliberately controlled and often performed to muscular fatigue.[5,96] The loading parameters associated with hypertrophy training (i.e. high total work, shorter rest periods) would also appear necessary for inducing greater hormonal and metabolic activity, which are important factors for muscle growth to occur.[76,96,97]

Although heavy loads appear necessary for inducing strength changes, many studies have found light load (<45% 1RM) training equally effective in increasing muscle CSA and strength compared with heavier load training methods.[7-11] Therefore, it would seem that the use of heavier loads for hypertrophy and strength development is not as important as originally thought. From the data presented, heavy training loads no doubt maximise the mechanical response to resistance exercise (i.e. force output, TUT, work and impulse) when single repetitions are compared and are the basis for their prescription (see tables I, II and IV). However, when examining set responses, superior kinematics and kinetics (i.e. total forces, total TUT, total work and total power) have been reported using lighter loads when the methodologies have equated by volume. Under these conditions, the magnitude of the load was less important than the volume of load lifted in determining the mechanical response to resistance exercise. With only limited scientific data available, determining the mechanical response to a typical weight-training session, as performed in practice, is difficult; however, such findings may help explain the efficacy of lighter load training for strength and hypertrophy development. That is, a light load lifted ballistically and repeatedly for a high number of repetitions may enhance the mechanical response to resistance exercise and produce those stimuli (e.g. high total forces, greater TUT and high total work) necessary for strength and hypertrophy adaptation to occur.

Confounding understanding in this area is the fact that few studies have equated different training interventions by volume. As such, any reported findings may simply reflect differences in volume rather than the specific kinematic and kinetic characteristics associated with a particular scheme. Unfortunately, the great majority of research has not employed such an approach[7,8,10,15,98-101] and as a result many of the conclusions and practical applications about strength and power training are fundamentally flawed. Research that has adopted such an approach (equal volume training) have reported similar changes in strength and muscle CSA across a range of loading schemes (e.g. 6–8RM vs 15–20RM vs 30–40RM).[102-104] These findings again challenge the prescription of heavy training loads as the only means for maximal strength adaptation. It is important to note that interpreting research in this area is further inhibited by the fact that many weight-training studies have employed untrained subjects.[7,15,17,80,98,100,102-104] Compared with trained individuals, subjects with little or no previous training experience are likely to respond to any type of weight-training protocol, particularly during the initial stages of training. These issues further confound understanding in this area regarding the optimal stimulus for strength and power development.

A common training method for power development involves the use of lighter loads (e.g. 45% 1RM) where movements are performed in an explosive and/or ballistic manner.[12,13] Training in this manner is further typified by relatively low volume and moderate rest periods (e.g. 2–3 minutes) to maintain the 'quality' of performance (e.g. high power output). However, the rationale for the prescription of load based upon maximising mechanical power output could be questioned in terms of the power demands of a particular activity, as previously mentioned. An additional benefit of using lighter loads exists in the fact that such intensities would allow greater velocities to be achieved, thereby potentially resulting in the greater transfer of effects (i.e. velocity specificity) to functional performance.

However, some studies have indicated that velocity-specific training effects may only be realised after a base level of strength and power is developed.[14,73,105] It is also important to recognise the fact that the internal conduction velocity of muscle may be independent of external movement velocity; therefore, it may be that the 'intention' to move a load at high velocity is of greater importance than actual movement velocities achieved.[70,106] Again, the load utilised may be less important for high-velocity power adaptation to occur, particularly if movements are performed with both maximal effort and intent.

The effective prescription of load for muscular power is also hindered by conflicting findings, with light and heavy load training found equally effective in enhancing various measures of power.[10,14-17] These findings may be partially explained by the ambiguous nature of power performance and those issues surrounding velocity-specific training effects. In fact, reviews in this area have indicated the success of various training methods (e.g. maximal strength, plyometrics, isometrics, explosive power, and combined plyometrics and weights) in facilitating improvement in power and/or functional performance.[7,107,108] With this in mind, it may be of greater importance in determining the training method that maximises power above any other. Various authors cite the importance of combining weight training, plyometric training and sport-specific training for optimal power performance.[69,109,110] Research supports such a notion having found combined (light and heavy loads) training protocols superior to either method alone in improving various measures of power.[8,15,16] Unfortunately, our understanding of this method (mechanical stimuli) and its contribution to power development, as with other training strategies, is again limited by the lack of kinematic and kinetic data.

7. Conclusions

Given the importance of these mechanical stimuli, it is disconcerting to note the paucity of literature that has investigated how these factors and their interaction, might affect the development of strength and power. It would seem that our understanding of the kinematic and kinetic responses to various weight-training methods is in its infancy; therefore, a true understanding of the adaptations elicited by various resistance training protocols are for the most part not well understood. It is suggested that research examine the mechanical response to resistance exercise as performed within practice (i.e. multiple repetitions, sets and exercises) in order to develop a better understanding as to the mechanical stimuli afforded by different weight-training programmes. Equating between specific parameters (e.g. TUT, force and power) may also enable a better understanding of the importance of such variables in the development of strength and power. Until research examines these responses within such a framework, much of the research will not contribute to our understanding of how various schemes optimise strength and power development.

Acknowledgements

The authors would like to thank the Health Research Council of New Zealand for their support during the preparation of this manuscript. No sources of funding were used to assist in the preparation of this review. The authors have no conflicts of interest that are directly relevant to the content of this review.

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