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MUSCLE HYPERTROPHY: A NARRATIVE REVIEW ON TRAINING

PRINCIPLES FOR INCREASING MUSCLE MASS

Louis P Howe, MSc., BSc, Dr Paul Read, Dr Mark Waldron

ABSTRACT

Developing muscle cross sectional area has the potential to enhance performance for many athletes. As emerging evidence challenges traditional beliefs regarding the prescription of hypertrophy focused training programs, this review provides an overview of the current literature relating, specifically, to programming variables. Evidence-based recommendations are provided for the design of effective resistance training programs, with the goal of increasing an athlete’s skeletal muscle mass.
INTRODUCTION

Within a strength and conditioning coach’s practice, the development of physical qualities that result in improvements in athletic performance are arguably at the heart of the role. One such physical quality is maximal force development as it relates to the constraints of each specific sport skill (86). Although neurological factors primarily contribute to the development of force, structural adaptations following long-term strength training may also influence force generation capacity (19), though the role of muscle hypertrophy is likely to be exaggerated for increasing maximal strength (50). Nonetheless, increases in muscle mass are typically desirable in instances where athletes are required to produce large forces against their external environment. Indeed, cross-sectional area of the limbs has been associated with both horizontal and vertical power production in elite athletes (94). This concept provides the rationale for developing the skeletal muscular system, prior to neural factors, as part of a ‘phase potentiation periodisation model’ (86). Therefore, increases in muscle mass can, in many circumstances, support athletic development to a point.

Alongside performance considerations, increasing muscle mass may also be required following injury occurrence. During the rehabilitation process, muscle atrophy is a key concern, secondary to unloading (40). In cases where muscle atrophy is heightened due to immobilisation, the rehabilitation time has been suggested to be extended (8). Therefore, recovery of lean muscle tissue may be a significant objective that should be achieved in order to restore the athlete to full function following injury.

Three proposed primary mechanisms are responsible for training adaptations, including: mechanical tension, metabolic stress and muscle damage (66). Mechanical
tension refers to the loading of muscle and is proposed to disrupt skeletal muscle structures, compromising the integrity of individual muscle fibres and leading to cellular responses via stimulation of the mTOR pathway (38). Local metabolic stress involves the accumulation of metabolic by-products, such as blood lactate (B[La]) and hydrogen ions ([H⁻]), caused by a cumulative demand on fast glycolysis (32, 90). It is thought that this metabolic perturbation has the potential to stimulate anabolism through mechanisms associated with increased local release of myokines, greater reactive oxygen species production, cell swelling and acute hormonal responses (67). Lastly, muscle damage is theorised to lead to hypertrophic responses (37), whereby the inflammatory response and upregulation of muscle protein synthesis to exercise induced muscle damage results in greater muscle size. For the interested reader seeking further understanding of each mechanism and the underlying physiological adaptations, please refer to Schoenfeld (66).

Traditional beliefs of the most effective strategies for the development of lean muscle tissue have recently been challenged (17). This article reviews the current body of literature related to training considerations for increasing muscle hypertrophy in young healthy adults. Where appropriate, this review will indicate the training status of the subjects used for each investigation. As such, this will allow coaches to adequately interpret the discussion in order to suitably apply the findings in their own strength and conditioning practice. In particular, this article discusses the following foundational factors that should influence a coach’s decision-making when designing resistance training programs for increasing muscle size:

- Training volume
• Load
• Training frequency
• Training to momentary muscular failure
• Exercise variation
• Contraction type
• Exercise order
• Repetition tempo
• Inter-set recovery

Evidence-based recommendations will be provided for the design of effective resistance training programs, with the goal of increasing an athlete’s skeletal muscle mass.

This article does not describe, with any detail, the physiological mechanisms for increasing in muscle mass, nor does it examine the evidence relating to specific training techniques aimed at increasing muscle hypertrophy. Likewise, while a variety of nutritional and lifestyle factors can be manipulated to augment the effects of hypertrophy training (63), these will not be discussed herein.

**TRAINING VOLUME**

Resistance training volume, described as the amount of work completed for any given unit of time, is a key variable for consideration in the pursuit of muscle hypertrophy. Much like increases in maximal strength (44), muscle hypertrophy is enhanced following high-volume longitudinal programs, particularly when multiple sets of exercise are utilised, rather than single set routines (45). This evidence has been used to support the current American College of Sports Medicine (ACSM)
recommendations, which suggest prescribing multiple sets for advanced lifters in order to increase muscle hypertrophy (4). Acutely, significant increases in muscle protein synthesis have been observed following high volume training in comparison to low volume sessions (14), thus reinforcing this recommendation.

Although acute responses are not linearly accompanied by long-term increases in lean muscle mass (53), numerous longitudinal studies have demonstrated that high volume training facilitates muscle hypertrophy (20, 58, 59, 62). Using ultrasound to measure elbow flexor and extensor muscle thickness, Radaelli et al. (59) showed that five sets of exercises per training session resulted in significantly greater upper arm development when compared to one and three set routines, across a six-month training period. This increase in muscle mass was accompanied by significantly superior gains in five repetition maximum (RM) loads for the bench press and lat pull down following the high volume intervention (59).

While findings of higher volumes leading to superior gains in muscle growth are not consistent throughout the literature (11, 51), a recent meta-analysis identified a dose-response relationship between training volume and muscle hypertrophy (73). For example, high weekly volumes (>10 total sets per body part, per week) were associated with greater increases in muscle mass than lower volumes (< 5 sets, per body part, per week), with an effect size of 0.241 (73). Schoenfeld et al. (73) concluded that higher volume training produces greater gains in muscle mass than lower volume training.
The mechanisms underlying the relationship between high training volume and increased muscle mass are potentially linked to the prolonged metabolic stress (34). A greater number of total sets per body part increases the total duration placed on the relevant energy systems and variety of muscle fibres during training. However, if prolonged metabolic stress is responsible for increases in muscle hypertrophy following high volume routines, then coaches should carefully manage the types of exercises that comprise their program, particularly if high-load exercises are included. For example, utilisation of drop sets has the potential to heighten the accumulation of metabolic by-products by placing greater demand on the fast glycolytic energy systems (33). If a high number of sets of this type of training were to be prescribed across sessions in order to increase volume, then an athlete may be taken beyond their recovery threshold, resulting in a blunting of the hypertrophy response (28).

It is important to emphasise that the relationship between volume and muscle growth is unlikely to be linear. That is; continual increases in training volume would inevitably lead to a plateau in the development of muscle mass. This concept is supported by the recent findings of Amirthalingham et al (3). In their investigation, no significant difference in muscle hypertrophy was found between subjects who performed either 5 sets of 10 repetitions or 10 sets of 10 repetitions over a six-week period (3). Coaches should appreciate each individual athlete’s recovery capacity when prescribing training programs, with excessive volumes leading to extended overreaching or, perhaps overtraining syndrome (83). The net effect of this would be a reduction in the capacity for anabolic processes due to a heightened catabolic status and increased protein metabolism (46). In this sense, the relationship between volume and hypertrophy training is suggested to follow an inverted-U curve (71). As each
individual possesses their own capacity to recover from a given amount of work, strength and conditioning coaches should use appropriate testing and monitoring tools to identify thresholds which maximize increases in muscle mass, while maintaining the athlete’s health.

LOAD
The manipulation of load during resistance training, which is typically presented as the percentage of maximal load that can be used for any given movement, has been proposed as a vital factor in maximising muscle hypertrophy (66). This is likely to relate directly to the mechanism of ‘mechanical tension’, as increased load results in an intensification of tension on the musculotendinous unit. However, loads exceeding 85 % 1RM, while maximising mechanical tension, fail to provide adequate stress to the fast glycolytic system due to reduced time under tension (60). Therefore, as a compromise in emphasising both mechanical tension and metabolic stress simultaneously, moderate loads (70-85 % 1RM) are traditionally recommended (4).

It has been suggested that high-load training (>65 % 1RM) leads to superior gains in muscle mass due to the recruitment and fatigue of higher threshold motor units (43, 57). This outcome might be desirable among athletes, as hypertrophy of fast-twitch fibres is known to be much greater than slow-twitch muscle fibres (1, 89) and fast-twitch fibres demonstrate higher velocity contractions (97). Fry (29) showed that programs incorporating loads above 50 % 1RM led to greater fast-twitch fibre hypertrophy compared to slow-twitch fibres. Furthermore, during short duration isometric contractions with low-load (30-45 % 1RM), glycogen depletion is non-existent in type IIX fibres but rises significantly with increased resistance (91).
Although these findings suggest that type II fibres are stimulated to a greater degree when exposed to heavy loading, it has been suggested that low-load training also recruits fast-twitch muscle fibres, providing that the working set is continued close to volitional fatigue (15). When high-load training has been directly compared to low-load, Mitchell et al. (52) found no significant difference in fibre-type specific hypertrophy. However, this study has been suggested to be underpowered (57), consequently lacking the sensitivity required to establish a difference in fibre type hypertrophy between loading strategies. As this investigation did establish a non-significant difference in type I hypertrophy between high- and low-load training (17 vs. 30%, respectively) (52), it may be that the lack of statistical power prevented the identification of differences. Mitchell et al. (52) used a sample size of 12 participants per group, which would achieve a poor statistical power of 0.17, based on our own post-hoc analysis, assuming an alpha level of 0.05 and an effect size 0.3 ($d$). It is important for coaches to note that this investigation demonstrated very little difference between high- and low-load training for type II fibre hypertrophy (16 vs. 18%, respectively) (52). Further evidence is required to establish whether load determines fibre-type hypertrophy. Of course, coaches shouldn’t underestimate the importance of recruiting a wide range of motor units through the prescription of high and low loads. Indeed, in the development of muscle cross sectional area, which is determined by the increase in myofibrillar proteins and thus muscle fibre diameter, a reliance upon the hypertrophy of type I fibres also exists. Exercises that activate a greater proportion of type I fibres would, therefore, be of equal use in maximising hypertrophic adaptation.
When considering whole muscle hypertrophy, a meta-analysis by Schoenfeld et al. (76) showed high-load training (> 65 % 1RM) to be no more effective than low-load training (<60 % 1RM) for increasing skeletal muscle mass. However, there was a non-significant trend in favour of high-load training (p = 0.076), which might be due to the low number of studies investigating the effects of training load on muscle hypertrophy. The use of low-load training strategies is supported by reports that training at 30 % 1RM resulted in greater acute muscle protein synthesis relative to high-load training (90 % 1RM), providing low load training is continued to failure (15). Additionally, Mitchell et al. (52) showed that a low-load training (30 % 1RM) regime resulted in similar increases in whole muscle cross-sectional area when compared to high-load training (80 % 1RM) over a 10-week period. Furthermore, using a moderate loading scheme (8-12RM) or a variety of training loads (2-4RM, 8-12 RM and 20-30RM) across a training week has been shown to result in similar increases in muscle mass following an eight-week intervention (72).

Therefore, when coaches are prescribing a training stimulus for muscle hypertrophy, high- or low-loads may be selected. Traditionally, loads > 65 % 1RM have been prescribed for hypertrophy programs, which might not be necessary. This information might also be useful for injury rehabilitation, where low-load training can be an effective method to increase muscle mass without the augmented forces associated with high-load training, leading to reduced joint loads.

While low-load training might be equally as effective for muscle hypertrophy, coaches should not overlook the superior strength adaptations that high-load training provides in comparison to low-load training (10, 65, 55, 68). These differences are
explained by the principle of training specificity, whereby the all-out efforts required
during high-load training produces maximal force, whereas low-load training requires
only low-to-moderate forces in a fatigued state (18). As such, high-load training that
results in the accumulation of considerable training volume may allow for increased
muscle strength alongside substantial increases in muscle mass. Such adaptations
have been defined as functional hypertrophy, where increases in muscle mass and
maximal strength occur simultaneously (64).

**TRAINING FREQUENCY**

Training frequency is defined as the number of training sessions per unit of time.
From the perspective of increasing an athlete’s muscle mass, training frequency
relates directly to training volume. During a single training session, the capacity to
recover from the work performed is limited. Therefore, for high levels of training
volume to be achieved, multiple sessions are likely to be required. As training volume
is a key factor in muscle growth (73), optimising training frequency will allow for
volume to be maximized without excessive fatigue being incurred.

In establishing the optimal training frequency for muscle hypertrophy, Wernborn et
al. (95) showed that two-to-three training sessions per week was optimal. This is
supported by a recent meta-analysis, identifying that two weekly training sessions for
the same muscle group led to significantly greater increases in muscle mass compared
to one or three sessions per week (74). These findings are in contrast to the traditional
practices of some bodybuilders, who are reported to train a single muscle group once
per week (36). However, it should be noted that both Schoenfeld et al. (74) and
Wernborn et al. (95) included both untrained and trained subjects in their analysis, potentially impacting the application for athletic populations.

For the majority of resistance-trained athletes, it is inevitable that the training volume per session and training frequency are inversely related, such that an increase in training frequency leads to a reduction in volume per session. In the case of a high frequency training program, where a muscle group is trained on multiple occasions, the training volume for each session should be lower in order to prevent excessive weekly training volumes. High training frequency should be periodized strategically so that adequate recovery is provided between sessions. Indeed, training the same muscle group before protein synthesis has returned to homeostasis may impair the muscle hypertrophy process (49); thus, 48 to 72 hours’ rest between training sessions for the same muscle group may be required in order to optimise the training response (74).

Although this general recommendation is likely to be appropriate for many athletes, it has been recently suggested that higher training frequencies may be more beneficial for trained individuals in stimulating greater muscle hypertrophy (23). As trained individuals adapt to resistance training in the long-term by reducing the muscle protein synthesis response (22), distributing training volume across a higher frequency has the potential to increase the total time spent in a positive protein balance by an athlete (23). Such approach would require a large reduction in training volume per session in order to avoid the accumulation of excessive fatigue. Dankel et al. (23) suggests strategies of high training frequency may be less than optimal for untrained individuals, as the subsequent bouts of resistance training would likely
interfere with the increase protein synthesis response for the preceding training
session. While this hypothesis is supported mechanistically, at present little evidence
exists to confirm this theoretical model and future investigations are required.

TRAINING TO MOMENTARY MUSCULAR FAILURE

Training to momentary muscular failure results in the inability to produce the
necessary force to lift a load through the concentric phase (66). When training to
failure, it is hypothesised that maximal motor unit recruitment is achieved resulting in
the fatigue of a greater number of muscle fibres (16, 98), in turn leading to a greater
hypertrophic response. Performing repeated muscle contractions of a fixed load (i.e. a
set) to failure is associated with progressive increases in both the perception of effort
(5) and muscle activation levels (obtained from surface EMG) (87). These findings
infer an increase in the recruitment of high-threshold motor units (87). In support of
this, Burd et al. (14) reported no differences in muscle adaptation in low- or high-load
training strategies, providing that each set was completed to failure. However, it is
difficult to come to such conclusions where training volume is not equated.

Goto et al. (34) investigated the effects of training to failure on muscle hypertrophy in
a twelve-week study, where participants were volume-matched and assigned to either
a group that trained to failure or a group that incorporated an intra-set rest preventing
failure from occurring. With volume equated, the “no-rest” group using repetition
maximums achieved significantly greater muscle hypertrophy in the quadriceps, along
with higher levels of maximal strength (34). This is similar to the findings of Schott
(78), who also identified training to failure induced superior hypertrophy adaptations
compared to finishing a set prior to failure.
Although these findings indicate the positive effects of training to failure, caution should be taken with routinely prescribing this approach. Sundstrup et al. (87) reported that complete concentric failure was not required in order to achieve full muscle activation using EMG analysis, with a plateau occurring during the final 3-5 repetitions with a 15 RM load. This is an important consideration, as routinely performing resistance training to failure may produce symptoms of overtraining, and subsequent threats to the anabolic status of athletes (39). As many of the studies evaluating the benefits of training to failure are of relatively short duration, the long-term implications are yet to be elucidated. Such findings have been identified in training programs for maximal strength (25). Therefore, it is recommended that practitioners strategically expose their athletes to training that induces failure to prevent the occurrence of overtraining.

EXERCISE VARIATION

Traditionally, bodybuilders tend to subscribe to the notion that broad exercise variation is required in order to maximize muscle hypertrophy (36). A proposed rationale is that muscles such as the pectoralis major (47) and trapezius (7) perform different movements of the same joint segment via the functional subdivisions of each muscle (6). As such, manipulating exercises has the potential to target large sections of the muscle. For example, in the case of the pectoralis major, utilising a 15° decline during the bench press results in greater EMG activity of the sternal fibres relative to the clavicular fibres (47). Therefore, in order to overload specific portions of different muscles, a wider variety of exercises is essential to recruit and fatigue all muscle subdivisions.
The above concept may be extended to muscles that possess numerous fibres orientated at a variety of angles between the origin and insertion. For example, both the long head and short head of the biceps brachii musculature are architecturally classified as fusiform (31); the biceps brachii is not functionally compartmentalised like the pectoralis major muscle. By manipulating shoulder and elbow positioning, the biceps brachii demonstrates a region-specific muscle activation strategy during supination (12). Furthermore, during elbow flexion, the biceps brachii does not uniformly shorten, suggesting that separate muscle fascicles contract concentrically at varying rates thus manipulating the range in the work produced for each muscle fibre (31).

Non-uniform muscle fibre recruitment has also been shown to occur in the hamstrings musculature, with EMG activity varying between the lower and upper fibres, depending on whether the hamstrings were required to flex the knee or extend the hip against resistance (69). This finding was supported by the work of Mendez-Villanueva et al. (54), who used functional magnetic resonance imaging to demonstrate regional differences in muscle activation of each head of the hamstrings during a variety of posterior chain exercises. Likewise, during resisted elbow extensions, multi-joint and single joint exercises have been shown to elicit regional differences in muscle activation. For example, single-joint elbow extension exercise has been shown to increase activation of the distal portion of the triceps brachii (92). Chronic adaptations to these exercises led to greater increases in cross-sectional area in the distal region of the muscle after a 12-week overloaded intervention program (92). Similarly, Wakahara et al. (93) showed that a multi-joint elbow extension
exercise (dumbbell bench press) increased muscle activation levels of the middle and proximal region of the triceps brachii, leading to greater growth in these areas. This suggests that in order to maximize hypertrophic adaptation, it is necessary to stress the muscle across its different portions (proximal-distal) using a variety of exercises.

Fonseca et al. (26) showed that changing exercises within a 12-week period was more effective for increasing muscle strength and hypertrophy compared to solely manipulations in training load. Within this investigation, hypertrophy of the vastus medialis and rectus femoris was more for subjects who varied exercises over three-week cycles, compared to subjects who used the same exercise throughout (26). This evidence supports the concept of utilizing numerous exercises in order to fully exploit adaptations of muscle hypertrophy.

One potential mechanism for the regional differences in hypertrophy may be the compartmentalisation of skeletal muscle (6). Within the neuromuscular system, sections of the muscle are innervated by specific motor units that are responsible for orchestrating the contraction of their respective fibres (6). Indeed, even fusiform muscle fibres terminate intrafascicularly (31, 96), meaning that there is potential for various neuromuscular compartments to exist within a given muscle. As fibre-type distribution inside muscles is also region specific (47, 84), intramuscular differences are likely to exist relative to function. Therefore, resistance training targeting preferential hypertrophy of fast-twitch fibres with strategies such as eccentric-only training, may also lead to non-uniform hypertrophy (discussed in the following section). It is likely that each muscle contains multiple neuromuscular compartments that can be selectively overloaded through varying exercise selection.
CONTRACTION TYPE

Eccentric muscle contractions increase the amount of mechanical stress on the musculotendinous units (7). While EMG amplitude is lower during eccentric contractions, fast-twitch fibres are preferentially recruited over their slow-twitch counterparts, leading to greater tension per muscle fibre and a bias toward type II fibre damage (79). The greater muscle damage incurred promotes an adaptive response in the fast-twitch fibres, which possess greater potential for growth (1).

Traditional methods to determine loads during a program typically use the concentric strength of the athlete (i.e. percentage of 1 RM). However, because eccentric strength can be as much as 45 % greater than concentric strength (41), it is likely that eccentric training is rarely exploited to its full potential. Since, submaximal eccentric training does not acutely raise muscle protein synthesis when compared to concentric training, the downstream effects on muscle hypertrophy are likely to be limited if traditional approaches to quantify load are used (21). However, when eccentric training is performed with maximal resistance, muscle protein synthesis is significantly greater than load-matched concentric training (56). When eccentric training is applied over a number of weeks, muscle hypertrophy adaptations are shown to be superior to that of concentric training (61). Therefore, supra-maximal eccentric training is likely to induce greater hypertrophic adaptations, assuming that the necessary recovery is provided. However, this is not consistent within the literature, with some studies identifying no difference between modes of contraction (28). This is potentially due to difficulties in matching volume-load between conditions, with eccentric training requiring higher loads.
In a recent meta-analysis, Schoenfeld et al. (77) identified a non-significant trend that eccentric-only training induced greater hypertrophic adaptations than concentric-only concentric training for inducing hypertrophic gains (p=0.076). Mean effect sizes for muscle growth following eccentric-only and concentric-only training were 1.02 and 0.77 respectively, with an effect size difference of 0.27. The authors propose that due to many of the studies included for analysis matching the total repetitions performed and not total work, the higher amount of work completed was likely to be a major influence on these findings (77).

A further consideration with eccentric training is the identification of region-specific hypertrophy. Franchi et al. (27) showed that although muscle hypertrophy of the vastus lateralis was equal between concentric and eccentric training, mid portion hypertrophy was higher in the concentric group, whereas the eccentric group experienced greater growth in the distal division. This may be due to the change in muscle architecture, secondary to the activation of altered molecular responses, following a concentric or eccentric-only training intervention (27). Eccentric-only resistance training leads to increases in fascicle length, while concentric-only training promotes greater pennation angles, indicating a higher number of sarcomere’s in parallel (27). This has the potential to alter the force-velocity relationship of any given muscle, with an increased fascicle length (sarcomere’s in series) resulting in superior shortening velocities (19). Conversely, a muscle with a larger pennation angles has the capacity to create higher levels of force due to an increased number of sarcomeres in parallel (19).
EXERCISE ORDER

It is generally recommended that multi-joint exercises, relying on work being produced by large muscle groups, should be performed in the initial stages of a training session (2). As more repetitions can be completed with any given load earlier in the training session (82), greater long-term accumulation of training volumes will occur in response to exercises that are performed during these periods (81). While this is dependent upon the design of the training session, it is, therefore, possible that using multi-joint exercises at the start of a training session will result greater hypertrophic adaptations in larger muscle groups.

Although this provides one reason to include multi-joint exercises earlier in the training session, little evidence exists to support this hypothesis. This is mostly due to limited amount of studies investigating the relationship between chronic structural adaptations and exercise order (81). Of the research that does exist, Simão et al. (80) and Spineti et al. (85) both showed that ordering training sessions such that single-joint elbow extension and flexion exercises were performed before the bench press and lat pull-down, resulted in increased triceps muscle volume when compared to the reverse order (effect size = 2.07 and 1.08 vs. 0.75 and 0.40). It should be noted that no difference was seen for the biceps musculature between conditions in either investigation (80, 85). However, neither study attempted to establish whether structural changes occurred in the pectoralis major and latissimus dorsi muscles, limiting the scope of their conclusions. It is likely that muscles trained and fatigued in the early stages of a training session will accumulate higher training volumes and therefore, adapt to a greater extent. As such, practitioners should prioritize exercises
for completion in the initial stages of the training session, based on the individual
needs of the athlete (81).

One issue with performing single-joint exercises prior to multi-joint exercises is that
the pre-fatigued muscle may alter the muscle activation patterns during the multi-joint
exercise. In both the lower extremity (9) and upper extremity (30), pre-fatiguing a
muscle with a single-joint exercise has been shown to decrease the recruitment of the
muscle during a multi-joint exercise. This occurs alongside an increased recruitment
of the synergistic muscles during the compound movement (30). However, activating
a muscle with a single-joint exercise but not to the point of fatigue may increase its
activation in the subsequent multi-joint exercise (42). Therefore, coaches may order
exercises to strategically manipulate the recruitment patterns of prime movers during
exercises in order to alter muscle activation patterns.

**REPETITION TEMPO**

Explosive strength training demonstrates a clear advantage over slow concentric
training for strength development (13). This is likely to be due to the higher forces
that are required to increase acceleration during the concentric phase of an
appropriately loaded lift. However, when attempting to develop muscle mass, this
relationship is not evident (70). This potentially occurs due to the reduced lifting
speed requiring less force, prolonging the duration of the set leading to increased
metabolic stress. When loads are lifted with the intention of achieving a high velocity,
the forces will be higher, increasing the tension of the muscle. In such instances
where the repetition duration increases, loading must be reduced due to the time
component placing increased demands on the involved energy systems (88).
Therefore, manipulating repetition tempo is just another example of the inverse-relationship between volume and load.

The available evidence shows equivocal differences between short and long repetition tempos for muscle hypertrophy development. Tanimoto and Ishii (88) determined that as long as subjects trained to failure, there was no significant difference in quadriceps hypertrophy following high-load normal tempo training (1-second concentric: 1-second eccentric: 1-second relaxation) when compared to a low-load, slow training group (3-seconds concentric: 3-seconds eccentric: 1-second relaxation). Furthermore, a recent meta-analysis showed no significant difference in muscle growth when comparing regimes consisting of 0.5-seconds to 8-seconds for completion of the concentric phase of a lift (70). Thus, manipulating repetition tempo between blocks of training provides coaches with another strategy that may provide a novel form of overload through increasing training volume (via long repetition duration) or load (via short repetition durations).

**INTER-SET RECOVERY**

Much like repetition duration, coaches may also change inter-set recovery periods to alter the balance of the training volume-load relationship. With short duration recovery periods (< 30-seconds), training volume may be increased as training density rises. However, if insufficient recovery is provided to fully replenish the anaerobic energy stores (34), the load must be reduced. Likewise, with higher inter-set recovery periods, greater loads may be used for each set at the expense of maintaining high training density, coupled with additional rest time (24).
Research investigating inter-set recovery periods suggests that short rest intervals (≤ 60-seconds) potentially compromises volume load due to drastic reductions in the load used, when compared to longer recoveries (3-minutes) (75). This is supported by Buresh et al. (17), who showed greater increases in quadriceps cross-sectional area when utilising longer (2.5 minutes), compared to shorter (60 seconds) inter-set recoveries. However, caution should be applied when interpreting these results, as in each of these studies volume was equated. Such control may remove the benefits of utilising short recoveries, as training density cannot be increased. Whether shorter rest periods permit tolerable increases in training volume has not yet been studied. Therefore, further evidence is required in order to make clearer recommendations regarding the manipulation of inter-set rest periods for increasing muscle hypertrophy (35).

CONCLUSION

Certain aspects of traditional hypertrophy training have been recently challenged. A more detailed understanding of key programming variables is therefore required to maximize training effectiveness. Using the training principles outlined in this review, coaches can design and deliver evidence-based hypertrophy training that has the potential to increase athletic performance or expedite recovery from injury.

The current body of evidence suggests that there is no ideal load prescription to maximize muscle hypertrophy. In fact, from a loading perspective, there appears to be very few constraints, providing that the intensity of effort is high. However, an important variable that must be considered is training volume. High training volumes are necessary for maximising muscle growth. This may be accomplished through a
variety of approaches; one being increased training frequency. The current literature indicates between 2-3 training sessions per muscle group per week are most effective, although there may be potential for superior gains in muscle hypertrophy with the prescription of higher frequencies (>3) in trained individuals.

Exercise variation is also important to access all ‘functional compartments’ of individual muscles. This may be accomplished by including variations of basic exercises that place stress on specific muscle divisions. By incorporating a variety of exercises for a single muscle in the training program of an athlete, the hypertrophic response has the potential to be enhanced. Such adaptations may also be obtained with varying the type of contraction, as concentric-only and eccentric-only loading strategies have been shown to provide hypertrophic adaptations in different sections of a muscle. Furthermore, it seems that eccentric-only training has the potential to increase muscle mass beyond that of concentric-only training through the increase in total work performed.

Finally, exercise order, repetition tempo and inter-set recovery periods may all be manipulated at the program level in order to present the athlete with a novel stimulus. These variables should be considered in relation to the individual athlete goals and the desired outcome.
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