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REVIEW ARTICLE

Is There a Minimum Intensity Threshold for Resistance Training-Induced Hypertrophic Adaptations?

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Abstract In humans, regimented resistance training has been shown to promote substantial increases in skeletal muscle mass. With respect to traditional resistance training methods, the prevailing opinion is that an intensity of greater than ~60 % of 1 repetition maximum (RM) is necessary to elicit significant increases in muscular size. It has been surmised that this is the minimum threshold required to activate the complete spectrum of fiber types, particularly those associated with the largest motor units. There is emerging evidence, however, that low-intensity resistance training performed with blood flow restriction (BFR) can promote marked increases in muscle hypertrophy, in many cases equal to that of traditional high-intensity exercise. The anabolic effects of such occlusion-based training have been attributed to increased levels of metabolic stress that mediate hypertrophy at least in part by enhancing recruitment of high-threshold motor units. Recently, several researchers have put forth the theory that low-intensity exercise (≤50 % 1RM) performed without BFR can promote increases in muscle size equal, or perhaps even superior, to that at higher intensities, provided training is carried out to volitional muscular failure. Proponents of the theory postulate that fatiguing contractions at light loads is simply a milder form of BFR and thus ultimately results in maximal muscle fiber recruitment. Current research indicates that low-load exercise can indeed promote increases in muscle growth in untrained subjects, and that these gains may be functionally, metabolically, and/or aesthetically meaningful. However, whether hypertrophic adaptations can equal that achieved with higher intensity resistance exercise (≤60 % 1RM) remains to be determined. Furthermore, it is not clear as to what, if any, hypertrophic effects are seen with low-intensity exercise in well-trained subjects as experimental studies on the topic in this population are lacking. Practical implications of these findings are discussed.

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1 Introduction

Muscle tissue displays a high level of plasticity, allowing it to readily adapt to both acute and chronic imposed demands [1]. Studies have clearly demonstrated that when subjected to functional overload, muscle tissue responds by increasing its cross-sectional area (CSA). Animal models using passive stretch, synergist ablation (surgical removal of one muscle to cause increased overload of the synergists), and neuromuscular electrical stimulation produce hypertrophic increases of as much as 100 % [2]. In humans, regimented resistance training has been shown to promote marked increases in skeletal muscle mass [3, 4]. Although hypertrophy occurs in all fiber types, fast-twitch (FT) fibers display an approximately 50 % greater capacity for growth compared with their slow-twitch (ST) counterparts [2, 5]. That said, there is a high degree of inter-individual variability with respect to the extent of hypertrophic adaptation across the full spectrum of fiber types [5].

Three primary factors have been proposed to mediate hypertrophic adaptations pursuant to resistance training: mechanical tension, metabolic stress, and muscle damage [3]. A number of researchers have surmised that tension is the primary driving force in this process [6, 7]. However, assuming that a given level of mechanical tension is

achieved, both metabolic stress and tissue damage may become increasingly important factors in optimizing a hypertrophic response [8, 9]. Studies to date are inconclusive as to whether one particular parameter predominates with respect to activating the cellular and molecular mechanisms responsible for regulating muscle growth [2].

With respect to traditional resistance training methods, the prevailing opinion is that a concentric intensity of greater than ~60 % of 1 repetition maximum (RM) is necessary to elicit significant increases in muscle size [10–12]. It has been surmised that this is the minimum threshold required to activate the complete spectrum of fiber types, particularly those associated with the largest motor units (MUs) [13]. There is emerging evidence, however, that low-intensity resistance training performed with blood flow restriction (BRF) can promote significant increases in muscle hypertrophy, in many cases equal to that of traditional high-intensity exercise [14]. Restriction of blood flow is achieved by wrapping an elastic implement (such as knee or elbow wraps) at the proximal portion of a limb so that circulation is occluded to working muscles during performance of resistance exercise. The anabolic effects of such occlusion-based training have been attributed to increased levels of metabolic stress, i.e., a buildup of metabolites pursuant to glycolytic energy production. It is theorized that metabolic stress mediates hypertrophy at least in part by enhancing recruitment of high-threshold MUs [15], but other mechanisms are also believed to play a role in the process including cell swelling, elevated hormonal levels, and increased production of reactive oxygen species [16, 17].

Recently, several researchers have put forth the theory that low-intensity exercise (≤50 % 1RM) performed without BFR can promote increases in muscle size equal, or perhaps even superior, to that at higher intensities, provided training is carried out to volitional muscular failure [4, 18]. Proponents of the theory postulate that fatiguing contractions at light loads is simply a milder form of BFR and thus ultimately results in maximal muscle fiber recruitment [19]. It has been surmised that as long as progressive overload is employed, even the most serious lifters can realize significant increases in muscle hypertrophy from such low-intensity training [19]. The purpose of this review therefore is to evaluate the literature on the topic in an attempt to determine the minimum intensity required for optimal hypertrophic adaptations. Evidence-based recommendations are then made to help guide program design when devising hypertrophy-oriented routines.

To carry out this review, English-language literature searches of the PubMed, EBSCO, and Google Scholar databases were conducted for all time periods up to December 2012. Combinations of the following keywords were used as search terms: 'skeletal muscle'; 'hypertrophy'; 'muscle growth'; 'cross sectional area'; 'intensity'; 'loading'; 'low load'; 'repetition range'; 'resistance training'; and 'resistance exercise'. The reference lists of articles retrieved in the search were then screened for any additional articles that had relevance to the topic.

2 Theoretical Basis for Lower Intensity Hypertrophic Adaptations

Maximal muscle hypertrophy is predicated on recruiting as many MUs as possible in the target muscles and achieving high firing rates in these MUs for a sufficient length of time [11]. The mechanisms by which mechanical forces lead to muscular adaptations are still not fully understood. Current theory proposes that the process is regulated by a phenomenon called mechanotransduction whereby sarcolemmal-bound mechanosensors, such as integrins and focal adhesions, convert mechanical energy into chemical signals that mediate intracellular anabolic and catabolic pathways, ultimately leading to a shift in muscle protein balance that favors synthesis over degradation [20]. A summation of anabolic signals of an adequate magnitude is required to generate sustained responses that lead to muscle protein accretion [21].

Many signaling pathways have been identified as playing a part in the regulation of muscle mass, with certain pathways acting in a permissive role and others providing direct mediation of cellular processes that influence messenger RNA translation and hypertrophy [22]. Signaling pathways that have been identified include phosphatidylinositol 3-kinase-protein kinase B-mammalian target of rapamycin, mitogen-activated protein kinase (MAPK), and various calcium (Ca^{2+})-dependent pathways, amongst others. Although these pathways may overlap at key regulatory steps, evidence suggests that they are interactive rather than redundant [23]. For example, although Akt and MAPK/extracellular signal-related kinase (ERK) both have been shown to stimulate mammalian target of rapamycin to a similar extent, the combined effects of both lead to an even greater stimulation compared with either pathway alone [24]. A complete discussion of these signaling pathways and their functions is beyond the scope of this article. For further information, interested readers are referred to recent reviews by Bassel-Duby and Olson, [25], Miyazaki and Esser [26], and Glass [27].

Claims for a hypertrophic effect of low-intensity resistance exercise are based on the premise that recruitment of the full spectrum of MUs is achieved at virtually any intensity, provided training is carried out to the point of concentric muscular failure [18]. It remains questionable, however, whether this belief holds true in practice. There is

evidence that fatiguing contractions result in a corresponding increase in electromyography (EMG) activity, presumably resulting from an increased contribution of high-threshold MUs recruited to maintain force output [28], but it is not clear what level of intensity is required to initiate activation of these high-threshold MUs. Furthermore, beyond a certain intensity level, the resistive exercise would become more reliant on aerobic metabolism and thus could be continued for extended periods of time in the upper levels of steady state. This shift in energy system contribution would conceivably result in a competitive interaction between anabolic and catabolic signaling pathways that leads to adaptations associated more with endurance than strength [29].

Studies corroborating the supposition that low-intensity training to failure equates to a milder form of BFR are lacking. Wernbom et al. [4] demonstrated that peak EMG activity was similar between three sets of low-intensity (30 % 1RM) unilateral knee extensions performed with and without BFR to muscular failure. Mean values were not reported thereby prohibiting analysis of the effects on muscle recruitment over the course of the entire range of sets. Further research is necessary to better determine the relationship between muscle recruitment and low-intensity exercise with and without BRF.

There is evidence that muscle recruitment is indeed greater in high-intensity exercise compared with low-intensity blood flow-restricted exercise. Employing a model that examined inorganic phosphate splitting via ^{31}P-magnetic resonance spectroscopy, Suga et al. [30] displayed that FT fiber recruitment occurred in only 31 % of subjects who performed BFR training at 20 % 1RM compared with 70 % of those who trained at 65 % 1RM. This finding is consistent with other research showing that exercise performed at high intensities produces substantially greater EMG activity compared with BFR exercise at 20 % 1RM, indicating an attenuated recruitment at the lower training intensity [31, 32]. Follow-up work by Suga et al. [33] showed that splitting of P_i peaks at 30 % 1RM approached those of higher intensity exercise, but nevertheless did not reach levels indicative of equal muscle fiber recruitment. Only when blood flow-restricted exercise was carried out at an intensity of 40 % 1RM did P_i peaks equate to, and actually exceed, those associated with traditional high-intensity training. Lending further support to these findings, Cook et al. [34] recently demonstrated that EMG amplitude of the vastus lateralis, vastus medialis, and rectus femoris during knee extension exercise to failure was significantly greater at a high intensity (70 % 1RM) than at a low intensity (20 % 1RM) both with and without BFR. The aforementioned studies are limited to the use of the knee extension; further research is needed using a variety of single- and multi-joint movements with varying percentages of 1RM performed to failure to provide a better understanding of the subject.

3 Acute Responses to Varying Resistance Exercise Intensities

Several animal studies have evaluated the effects of different intensities on acute signaling responses. Using an in situ model, Martineau et al. [35] subjected rat plantaris muscles to peak concentric, eccentric, and isometric actions via electrical stimulation. Results showed tension-dependent phosphorylation of c-Jun N-terminal kinase (JNK) and ERK, with higher mechanical tension resulting in progressively greater phosphorylation. This suggests that peak tension is a better predictor of MAPK phosphorylation than either time-under-tension or rate of tension development. Interestingly, follow-up work by the same laboratory found a linear relationship between time under tension and signaling of JNK, whereas rate of tension change showed no effect, highlighting the importance of time under tension in anabolic signaling [36]. Taken together, these findings point to the importance of overall training volume for maximizing the acute molecular responses related to skeletal muscle hypertrophy irrespective of training intensity.

In an attempt to qualify the acute effects of resistance training intensity in humans, Kumar et al. [37] investigated the acute exercise responses at 20–90 % 1 RM in healthy young and old men. The protocol was designed so that volume of training was approximately equal between training intensities. Thus, at 20 % intensity, participants performed three sets of 27 repetitions; at 40 % intensity, three sets of 14 repetitions were performed; at 60 % intensity, training consisted of three sets of nine repetitions; at 75 % intensity, three sets of eight repetitions were performed; and at 90 % intensity, six sets of three repetitions were performed. Increases in myofibrillar muscle protein synthesis (MPS) were minimal after exercise at 20 % and 40 % 1RM but values significantly and markedly increased at 60 % 1RM, plateauing thereafter. Similarly, phosphorylation of p70S6K was maximized at intensities of 60–90 % 1RM, peaking just prior to the maximal rise in MPS. These results held true in both younger and older subjects, suggesting that the stimulatory effect on MPS reaches a maximum at ~60–75 % 1RM of isotonic exercise. The authors did not state whether low-load training was carried out to muscular failure, but based on the study design this does not appear to be the case. This is an important limitation as research indicates the hypertrophic response to low-load training is predicated on lifting to the point of voluntary muscular failure [38–40].

Burd et al. [39] sought to determine whether resistance exercise intensity had a differential effect on MPS and

anabolic signaling. A quasi within-subject design was used where 15 young, recreationally active men performed four sets of unilateral knee extensions at 30 % and 90 % 1RM to volitional muscular failure. A third condition involved performing the exercise at 30 % 1RM with external work (repetitions × load) matched to the 90 % condition. At 4-h post-exercise, measures of MPS were elevated at all conditions studied, but levels in the 30 % work-matched condition were approximately half that of the other two conditions. Interestingly, myofibrillar MPS remained elevated at 24-h post-exercise only in the 30 % to failure condition. Phosphorylation of p70S6K was significantly increased at 4 h only in the 30 % to failure condition, and this elevation was correlated with the degree of stimulation of myofibrillar MPS. These findings suggest that low-intensity exercise performed to volitional fatigue induces greater acute muscular responses compared with high-intensity exercise. The fact that volume was substantially greater in the 30 % condition versus the 90 % condition confounds the ability to isolate the impact of intensity on the variables studied.

Although these studies provide relevant clues as to the anabolic effects of various intensities of exercise, their findings are not necessarily predictive of long-term changes in lean body mass. Evaluation of measures of MPS following an acute bout of resistance exercise do not always occur in parallel with chronic upregulation of causative myogenic signals [41] and may not reflect hypertrophic responses experienced pursuant to regimented resistance training carried out over a period of weeks or months [42]. Moreover, the acute responses of subjects with minimal training experience, in particular, must be viewed with caution as results may be primarily a function of the unfamiliarity of exercise and thus not applicable to the response of well-trained individuals [2, 43]. Given these inherent limitations, any attempt to extrapolate findings from such data to hypertrophic adaptations is speculative, at best.

4 Chronic Adaptations to Varying Resistance Exercise Intensities

A number of studies have attempted to directly evaluate long-term hypertrophic adaptations along the strength-endurance intensity continuum. Findings between these studies are inconsistent and discrepant. Table 1 summarizes the relevant research to date.

Campos et al. [44] was the first to investigate the topic in a well-controlled experimental fashion. Thirty-two untrained men (mean ± SD: age 22.5 ± 5.8 years) were randomly assigned to one of three lower body training protocols: a low-repetition group ($n = 9$) that performed 3–5 RM for four sets of each exercise with 3-min rest intervals between sets; an intermediate repetition group ($n = 11$) that performed 9–11 RM for three sets with 2-min rest intervals; or a high-repetition group ($n = 7$) that performed 20–28 RM for two sets with 1-min rest intervals. A control group ($n = 5$) performed no resistance exercise. The exercise regimen consisted of the leg press, squat, and knee extension with total volume load approximately equal between groups. Training was carried out 2 days a week for the first 4 weeks and 3 days a week for the final 4 weeks. Resistance was progressively increased throughout the training period to maintain repetition ranges and all sets were performed to momentary concentric muscular failure. Muscle biopsy was used to assess changes in fiber CSA of the vastus lateralis. After 8 weeks, both the high and intermediate repetition groups displayed significant increases of 12.5 %, 19.5 %, and 26 % in CSA for type I, IIA, and IIX fibers, respectively. Increases in muscle fiber CSA for the high-repetition group did not reach statistical significance for any of the fiber types, indicating that lower intensity exercise is substandard for promoting increases in hypertrophy.

Employing the same basic training program as Campos et al. [44], Leger et al. [45] divided 25 healthy men into either a low- or high-repetition group; an intermediate group was not included as part of the study design. Subjects were older than in the Campos et al. [44] study (age 36 ± 4.9 years) and had not participated in a resistance training program for at least 1 year. Muscle volume was assessed by computed tomography (CT). After 8 weeks, an approximately 10 % increase in quadriceps CSA was noted in both groups with no significant differences found between training protocols. Follow-up work by this laboratory [46], in a similar population demographic, also reported 10 % increases in quadriceps hypertrophy with no significant differences between groups using the same training protocol. The researchers attributed the discrepancy between their results and that of Campos et al. [44] to the detrained status of the somewhat older subjects, theorizing that any type of resistance training in this population would promote a sufficient overload stimulus to elicit increases in muscle growth.

Tanimoto and Ishii [40] evaluated the muscular response of low-intensity exercise performed with slow movement and tonic force generation to a traditional higher intensity routine in 24 untrained men. Subjects were randomly assigned to perform repetitions of the leg extension at either 50 % RM with a 6-s cadence (3 s for both concentric and eccentric actions) and no relaxing phase between repetitions (LST; $n = 8$) or 80 % RM at a tempo of 1 s for both concentric and eccentric actions with 1-s relaxation between repetitions (HN; $n = 8$). Both of these groups performed approximately eight repetitions per set until

Table 1 Summary of long-term studies evaluating the effects of training intensity on muscle hypertrophy

Study	Subjects	Design	Volume equated	Train to failure	Measurement	Findings
Campos et al. [44]	32 untrained young men (5 served as non-exercising controls)	Random assignment to either low intensity (3–5 RM), intermediate intensity (9–11 RM) for 3 sets with 2-min rest intervals, or high-intensity (20–28 RM) exercise. Exercise consisted of 2–4 sets of squat, leg press, and leg extension, performed 3 days a week for 8 weeks	Yes	Yes	Muscle biopsy	Significant increases in CSA for high-intensity exercise; no significant increase in CSA for low-intensity exercise
Leger et al. [45]	24 untrained middle-aged men	Random assignment to either low intensity (3–5 RM) or a high intensity (20–28 RM) exercise. Exercise consisted of 2–4 sets of squat, leg press, and leg extension, performed 3 days a week for 8 weeks	Yes	Yes	CT	No differences in CSA between low- and high-intensity exercise
Lamon et al. [46]	25 untrained middle-aged men	Random assignment to either low-intensity (3–5 RM) or high-intensity (20–28 RM) exercise. Exercise consisted of 2–4 sets of squat, leg press, and leg extension, performed 3 days a week for 8 weeks	Yes	Yes	CT	No differences in CSA between low- and high-intensity exercise
Tanimoto and Ishii [40]	24 untrained young men	Random assignment to either 50 % RM with a 6-s tempo and no relaxing phase between repetitions, 80 % RM with a 2-s tempo and 1-s relaxation between repetitions, or 50 % RM with a 2-s tempo and 1-s relaxation between repetitions. Exercise consisted of 3 sets of knee extensions, performed 3 days a week for 12 weeks	No	Yes	MRI	No differences in CSA between low- and high-intensity exercise
Tanimoto et al. [47]	36 untrained young men (12 served as non-exercising controls)	Random assignment to either 55–60 % RM with a 6-s tempo and no relaxing phase between repetitions or 80–90 % RM with a 2-s tempo and 1-s relaxation between repetitions. Exercise consisted of 3 sets of squat, chest press, lat pulldown, abdominal bend, and back extension, performed 2 days a week for 13 weeks	No	Yes	B-mode ultrasound	No differences in CSA between low- and high-intensity exercise
Holm et al. [48]	11 untrained young men	Random, counterbalanced performance of 10 sets of unilateral leg extensions, training one leg at 70 % 1RM and the contralateral leg at 15.5 % 1RM, performed 3 days a week for 12 weeks	Yes	No	MRI	Significantly greater increases in CSA in high-intensity versus low-intensity exercise
Mitchell et al. [50]	18 untrained young men	Randomized assignment to perform 2 of 3 unilateral leg extension protocols: 3 sets at 30 % RM; 3 at 80 % RM; or 1 set at 80 % RM. Training was carried out 3 days per week for 10 weeks	No	Yes	MRI, muscle biopsy	No differences in CSA between low- and high-intensity exercise
Schuenke et al. [51]	34 untrained young women	Randomized assignment to either moderate intensity (80–85 % RM) at a tempo of 1–2 s, a low intensity ($\sim$40–60 % RM) at a tempo of 1–2 s, or slow speed ($\sim$40–60 % RM) at a tempo of 10 s concentric and 4 s eccentric. Exercise consisted of 3 sets of squat, leg press, and leg extension, performed 2–3 days a week for 6 weeks	No	Yes	Muscle biopsy	Significant increases in CSA for high-intensity exercise; no significant increase in CSA for low-intensity exercise
Ogasawara et al. [52]	9 untrained young men	Non-randomized crossover design to perform 4 sets of bench press exercise at 75 % 1RM. Training was carried out 3 days a week for 6 weeks. After a 12-month washout period, the same protocol was performed at 30 % 1RM	No	Yes	MRI	No differences in CSA between low- and high-intensity exercise

RM repetition maximum, *CSA* cross-sectional area, *CT* computed tomography, *MRI* magnetic resonance imaging

failure and the intensity was progressively adjusted based on performance in the previous session. A third group (LN; $n = 8$) performed low-intensity exercise (50 % RM) using the normal tempo employed in the high-intensity protocol and thus did not work to volitional failure. Training was carried out 3 days a week for 12 weeks. At the end of the study period, muscle CSA as determined by magnetic resonance imaging (MRI) increased significantly in both the LST and HN groups (5.4 $\pm$ 3.7 % vs. 4.3 $\pm$ 2.1 %, respectively), with no significant differences noted between the groups. The LN group did not significantly increase muscle mass. These results again emphasize the

importance of training to muscular failure for eliciting a hypertrophic response during low-load training.

This study design was subsequently replicated by the same laboratory [47] using a total-body resistance training program consisting of three sets of the squat, chest press, lat pull-down, abdominal bend, and back extension. Intensity was slightly higher for both groups (55–60 % in the LST group and 80–90 % in the HN group), as necessitated by the multi-joint nature of the exercises. Again, significant increases in muscle size were detected in both the LST and HN groups (mean ± SD: 6.8 ± 3.4 % vs. 9.1 ± 4.2 %, respectively), with no significant differences noted between groups. While these findings are intriguing, they are confounded by the altered repetition cadence, thereby making it impossible to draw relevant conclusions as to traditional intensity recommendations. Moreover, although results did not reach statistical significance in the total-body protocol, high-intensity exercise produced an approximately 34 % greater absolute increase in hypertrophy. Thus, it seems likely that the small sample size resulted in a type II error.

Holm et al. [48] studied the effects of light-load resistance exercise in 11 sedentary young men. A within-subject design was employed whereby subjects performed ten sets of unilateral leg extensions, training one leg at 70 % 1RM and the contralateral leg at 15.5 % 1RM in a randomized, counterbalanced fashion. Training was carried out 3 days a week for a total of 12 weeks. Muscle CSA of the quadriceps as determined by MRI was greater by threefold in the high-intensity leg compared with the leg that performed low-intensity exercise. It should be noted that the low-intensity exercise involved performing one repetition every 5 s for 3 min, calling into question the extent of fatigue experienced during exercise performance, and thus obscuring the ability to extrapolate conclusions to low-load training to failure. Interestingly, a subsequent study using the same protocol in healthy, young men showed a significant 18 % increase in satellite cell number associated with the low-load protocol after 12 weeks of training, indicating that low-intensity exercise has a favorable effect on early-stage myogenesis [49].

In a follow-up to their previously mentioned, acute training study [39], Stuart Phillips' laboratory employed a quasi within-subject design to test the hypothesis that these results would translate into long-term gains in muscle hypertrophy [50]. Eighteen untrained men (mean ± SD: age 21 ± 1 years) were randomly assigned to perform two of three different resistance training protocols involving unilateral knee extension exercise for each leg to momentary concentric muscular failure as follows: three sets of low-intensity exercise at 30 % RM; three sets of high-intensity exercise at 80 % RM; and one set of high-intensity exercise at 80 % RM. Training was carried out 3 days per week for 10 weeks. Muscular adaptations of the vastus lateralis was assessed by MRI and muscle biopsy. At the end of the study period, both the low- and multi-set high-intensity groups realized significant increases in muscle volume (mean ± SD: 6.8 ± 1.8 % vs. 7.2 ± 1.9 %, respectively), with no differences found between the groups. The single-set high-intensity group also showed significant increases in hypertrophy, although the gains were less than half that of the other two groups (mean ± SD: 3.2 ± 0.8 %). Interestingly, fiber analysis by muscle biopsy showed that the low-intensity group displayed greater hypertrophy of type I fibers while the high-intensity group displayed greater hypertrophy of type II fibers, suggesting a fiber type-specific adaptive response along the strength-endurance continuum. The study was limited by the sole use of the leg extension exercise, which is not representative of training routines normally employed in a hypertrophy-oriented program.

A recent study by Schuenke et al. [51] investigated both the effects of intensity as well as tempo on muscle hypertrophy. Thirty-four untrained women were randomly divided into one of three groups: A traditional strength (TS) group that performed sets of 6–10 RM at a cadence of 1–2 s on the concentric and eccentric portion of the repetition; a traditional muscular endurance (TE) group that performed 20–30 repetitions at the same speed as TS; and a slow-speed (SS) group that performed 6–10 repetitions at a tempo of 10 s on concentric action and 4 s on the eccentric action. Both TE and SS trained at an intensity of ~40–60 % 1RM while TS trained at ~80–85 % 1RM. The longer duration of cadence in the SS routine is associated with a reduced momentum and a greater consistency in average force (vs. peak force) over a complete repetition compared with training with TE. Training consisted of three sets of the leg press, squat, and knee extension to momentary muscular failure with ~2-min rest intervals afforded between sets. Training was carried out 2 days a week for the first week and 3 days a week for the remaining 5 weeks. Muscle biopsy was used to assess CSA of the vastus lateralis. After 6 weeks, significant increases were noted in TS for types I, IIA, and IIX fiber areas (mean ± SD: 26.6 ± 22.7 %, 32.9 ± 20.4 %, and 41.1 ± 32.7 % respectively), whereas no significant differences were seen in TE. Interestingly, SS displayed significant increases in both types IIA IIX CSA, although these changes were less than half that of that experienced by TS. It remains conceivable that hypertrophy might manifest more gradually in lower intensity exercise and, if so, would therefore not have been evident in this study given its short duration.

Most recently, Ogasawara et al. [52] found similar increases in CSA of the pectoralis major and triceps brachii in subjects performing free-weight bench press exercise at

75 % 1RM versus 30 % 1RM to concentric muscle failure. The study employed a within-subject design whereby nine previously untrained subjects performed the higher intensity exercise for the initial 6 weeks of the study and then, after a 12-month washout period of detraining, performed 6 weeks of the low-load exercise in a non-randomized fashion. Although intriguing, these findings must be viewed with caution as 'muscle memory' via neural mechanisms and/or satellite cell accretion may have influenced results [5, 53, 54].

The mixed and conflicting results between these studies are hard to justify and likely a function of the varied study designs and methods of assessment. One issue of note is the use of different techniques for measuring muscular adaptations including biopsy, MRI, ultrasound, and/or CT. Each of these techniques has various inherent strengths and weaknesses, causing difficulties when attempting to reconcile research findings [2].

The use of different exercise protocols serves to further confound results. Some of the studies involved only a few sets of single-joint exercise while others employed multi-set routines consisting of combinations of single- and multi-joint exercises more representative of traditional hypertrophy training practices. In addition, some studies equated volume between training conditions while other studies did not. These confounding issues hinder the ability to draw relevant comparisons between studies.

Another major limitation of the current body of literature is a lack of statistical power because of small sample sizes. Studies to date have generally involved fewer than ~30 exercising subjects with ≤12 subjects per group studied. This substantially raises the possibility of a type II error, whereby significant differences cannot be determined when in fact they do exist. Greater statistical power could be achieved by pooled analysis of data; however, the disparate methods employed in existing studies to date make such a meta-analysis problematic.

Finally, and importantly, all studies to date have been carried out in untrained or minimally trained subjects. It is well established that highly trained individuals respond differently than those who lack training experience [55]. A 'ceiling effect' makes it progressively more difficult for trained individuals to increase muscular gains, thereby necessitating more demanding resistance training protocols to elicit a hypertrophic response. Moreover, there is emerging evidence that consistent resistance exercise can alter anabolic intracellular signaling in rodents [56] and humans [57], indicating an attenuated hypertrophic response. As such, current findings cannot necessarily be generalized to a well trained population. Future research should therefore focus on the hypertrophic effects of training intensity in those with at least 1 year or more of regular, consistent resistance training experience.

5 Conclusions

Although it is evident that a minimum intensity threshold exists to promote increases in muscle mass, the precise level of intensity needed to achieve hypertrophic adaptations has yet to be elucidated. Based on current research, it does appear that low-load exercise can indeed promote increases in muscle growth in untrained subjects, and that these gains may be functionally, metabolically, and/or aesthetically meaningful. However, whether hypertrophic adaptations can equal that achieved with higher intensity resistance exercise (≤60 % 1RM) remains dubious. Furthermore, it is not clear as to what, if any, hypertrophic effects are seen with low-intensity exercise in well-trained subjects, as experimental studies on the topic in this population are lacking.

The preponderance of evidence indicates that blood flow-restricted resistance exercise at intensity levels ≤20 % 1RM does not result in recruitment of the full spectrum of MUs, making it highly unlikely that non-occluded resistance exercise at similar intensities would achieve comparable muscle activation to high-intensity exercise. Recruitment of FT fibers with blood flow-restricted resistance exercise at 30 % has been shown to approach, but not equal, that of high-intensity exercise [33]. Given these findings, it would appear that intensities above 30 % are needed for complete muscle fiber recruitment. It therefore stands to reason that if traditional resistance exercise ≤30 % 1RM does in fact promote muscular gains equal to that of high-intensity exercise, as has been found in a limited number of studies [45, 46, 50], the differences in protein accretion seemingly would have to be made up by a greater degree of hypertrophy in type I and perhaps type IIA fibers. It is conceivable that other factors attributed to metabolic stress (e.g., cell swelling, autocrine/paracrine factors, and systemic hormonal elevations) may allow for such enhanced adaptations. This appears to be the case with BFR, as marked hypertrophy is routinely seen at intensities ≤30 % 1RM [14], presumably mediated by a heightened metabolic build-up [16, 58]. Whether similar effects are realized in low-load training without BFR remains to be elucidated. Moreover, some exercises may lend themselves well to promoting BFR and thus heightening metabolic stress at lower loads (those with consistent torques) while others may not (those with torque curves that considerably drop off during the lift). Further research is needed to investigate these issues.

Another consideration that needs to be taken into account is the necessity to train to fatigue during low-intensity training. It has been hypothesized that persistently training to volitional muscular failure increases the potential for overtraining and psychological burnout [59]. Indeed, Izquierdo, et al. [60] found that training to failure

caused reductions in resting insulin-like growth factor-1 levels and a blunting of resting testosterone levels over a 16-week protocol, suggesting that subjects may have been over-trained by the end of the study. The negative effects of overtraining generally take time to manifest and thus likely would not have been evident in the current studies on training intensity given their relatively short duration ($\leq$12 weeks). In practice, however, this would necessitate the implementation of more frequent unloading periods over the course of a periodic training program compared with higher intensity exercise. It is not clear how such alterations might affect long-term hypertrophic gains.

Research seems to suggest that a moderate repetition range (6–12 RM) using a controlled lifting cadence may be optimal for maximizing gains in muscle hypertrophy [7, 61, 62], although evidence is far from conclusive on the subject. This so-called 'hypertrophy range' may conceivably provide an optimal combination of mechanical tension, metabolic stress, and muscle damage, thereby generating a sustained anabolic response that maximizes muscle protein accretion [3]. Regardless of the existence of an ideal hypertrophy range, however, a strong case can be made for incorporating the use of a variety of training intensities into a hypertrophy-oriented program. Low-repetition resistance training (1–5 RM) enhances neuromuscular adaptations necessary for the development of maximal strength [61]. These adaptations allow the use of heavier loads, and thereby greater mechanical tension, at a given moderate intensity. Conversely, higher repetition training (15+ RM) can help to attenuate the exercise-induced rise in blood lactate [63], delaying the onset of fatigue and thus leading to a greater inroading of fibers during hypertrophy-type training. This varied approach would seem to be of particular importance for those with considerable training experience, as a greater degree of overload is necessary for continued adaptation in these individuals.

It is also conceivable that people may respond differently to exercise intensity based on individual muscle morphology. There is clear evidence that men and women exhibit large variations in their response to the same resistance training protocol, with some subjects displaying little to no muscular gains and others showing profound increases in muscle mass [64, 65]. These variances may be due, at least in part, to differences in muscle fiber-type distribution. Studies show a large genetic variability between individuals in the percentage of FT versus ST fibers for a given muscle [66], and these disparities can have implications in the response to exercise [67]. This raises the possibility that adaptations to low- and high-training intensities may be specific to the fiber-type profile of the target muscle. For example, there is evidence that the predominantly ST soleus muscle is much less responsive to traditional resistance exercise compared with primarily FT muscles such as the vastus lateralis and the biceps brachii [68]. Would the soleus respond better to a high-repetition protocol given its high percentage of ST fibers? Although this concept is intriguing in theory, a fiber-type exercise prescription based on training intensity has not been confirmed through research and thus remains speculative. Moreover, given the inter-individual variability of fiber-type composition, it would be difficult if not impossible to non-invasively determine fiber-type ratios of each muscle, thus making application impractical for the vast majority of people.

In conclusion, there is evidence that low-load training can increase muscle mass in untrained subjects. Therefore, low-load training to failure appears to be an effective strategy to increase muscle mass during early-stage training. This may have particular relevance in populations such as the elderly and individuals who may not be able to perform resistance exercise at higher intensities. It remains questionable, however, as to whether the extent of hypertrophy in low-load training is comparable to what can be achieved through heavy resistance exercise. Based on recruitment data, it would appear that intensities above 30 % RM are needed to optimize type II fiber activation in the absence of active BFR. Moreover, research evaluating the effects of such training in promoting hypertrophic benefits in experienced lifters is lacking at this time. Future research should seek to clarify the extent of hypertrophic effects along the intensity continuum using realistic training programs, as well as elucidating these effects in individuals with considerable training experience.

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