European Journal of Sport Science
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tejs20

Muscular adaptations in low- versus high-load resistance training: A meta-analysis

Brad J. Schoenfeld[a], Jacob M. Wilson[b], Ryan P. Lowery[b] & James W. Krieger[c]

[a] Department of Health Sciences, CUNY Lehman College, Bronx, NY, USA

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

[c] Weightology LLC, Redmond, WA, USA

Published online: 20 Dec 2014.

European Journal of Sport Science, 2014
http://dx.doi.org/10.1080/17461391.2014.989922

Routledge
Taylor & Francis Group

REVIEW ARTICLE

Muscular adaptations in low- versus high-load resistance training: A meta-analysis

BRAD J. SCHOENFELD[1], JACOB M. WILSON[2], RYAN P. LOWERY[2], & JAMES W. KRIEGER[3]

[1]*Department of Health Sciences, CUNY Lehman College, Bronx, NY, USA,* [2]*Department of Health Sciences and Human Performance, University of Tampa, Tampa, FL, USA,* [3]*Weightology LLC, Redmond, WA, USA*

Abstract

There has been much debate as to optimal loading strategies for maximising the adaptive response to resistance exercise. The purpose of this paper therefore was to conduct a meta-analysis of randomised controlled trials to compare the effects of low-load (≤60% 1 repetition maximum [RM]) versus high-load (≥65% 1 RM) training in enhancing post-exercise muscular adaptations. The strength analysis comprised 251 subjects and 32 effect sizes (ESs), nested within 20 treatment groups and 9 studies. The hypertrophy analysis comprised 191 subjects and 34 ESs, nested with 17 treatment groups and 8 studies. There was a trend for strength outcomes to be greater with high loads compared to low loads (difference = 1.07 ± 0.60; CI: −0.18, 2.32; p = 0.09). The mean ES for low loads was 1.23 ± 0.43 (CI: 0.32, 2.13). The mean ES for high loads was 2.30 ± 0.43 (CI: 1.41, 3.19). There was a trend for hypertrophy outcomes to be greater with high loads compared to low loads (difference = 0.43 ± 0.24; CI: −0.05, 0.92; p = 0.076). The mean ES for low loads was 0.39 ± 0.17 (CI: 0.05, 0.73). The mean ES for high loads was 0.82 ± 0.17 (CI: 0.49, 1.16). In conclusion, training with loads ≤50% 1 RM was found to promote substantial increases in muscle strength and hypertrophy in untrained individuals, but a trend was noted for superiority of heavy loading with respect to these outcome measures with null findings likely attributed to a relatively small number of studies on the topic.

Keywords: *Muscle recruitment, low-load exercise, light weights*

It has been well established that regimented resistance exercise can promote marked increases in muscle strength and hypertrophy, with improvements in these outcome measures seen irrespective of age and gender (Ivey et al., 2000; Kosek, Kim, Petrella, Cross, & Bamman, 2006). Exercise-induced muscular adaptations are at least in part attributed to a phenomenon called mechanotransduction, whereby sarcolemmal-bound mechanosensors, such as integrins and focal adhesions, convert mechanical energy into chemical signals that mediate myocellular anabolic and catabolic pathways (Zou et al., 2011). When subjected to mechanical overload, the signalling cascade upregulates anabolic processes in a manner that results in a net increase in muscle protein synthesis, thereby leading to an enlargement of fibres (Glass, 2005). The extent of hypertrophy has been shown to vary by fibre type, with fast-twitch (FT) fibres displaying an approximately 50% greater capacity for growth in comparison to their slow-twitch (ST) counterparts (Adams & Bamman, 2012; Kosek et al., 2006). It should be noted, however, that a high degree of inter-individual variability exists in this regard, with some individuals displaying substantially greater ST hypertrophy than others (Kosek et al., 2006).

Proper manipulation of programme variables is considered essential to optimise post-exercise muscular adaptations (Kraemer & Ratamess, 2004). One such variable is the amount of load lifted, generally quantified as a percentage of 1 repetition maximum (RM). Studies show that alterations to the training load have a significant effect on acute post-exercise metabolic, hormonal and neural responses – factors that have been postulated to mediate enhancements in muscle strength and hypertrophy (Kraemer & Ratamess, 2004). Accordingly, there has been much debate as to optimal loading strategies for maximising the adaptive response to resistance exercise. Some have hypothesised that a load of at least

Correspondence: B. J. Schoenfeld, Department of Health Sciences, CUNY Lehman College, 250 Bedford Park Blvd West, APEX Building, Bronx, NY 10468, USA. E-mail: brad@workout911.com

65% 1 RM is necessary to elicit favourable increases in hypertrophy, with even higher loads needed to maximise strength gains (Kraemer & Ratamess, 2004; Kraemer et al., 2002; McDonagh & Davies, 1984). This belief is predicated on the premise that heavier loading is required to achieve full recruitment of the higher threshold motor units and that optimal improvements in strength and hypertrophy can only be accomplished through complete motor unit activation (Kraemer & Ratamess, 2004).

The assertion that heavy weights are necessary for optimising the post-exercise muscular response has recently been challenged, however, with some researchers claiming that very low loads can promote adaptations similar to high-load training (Burd, Mitchell, Churchward-Venne, & Phillips, 2012). It has been surmised that as long as intensity of effort is maximal, even experienced lifters can realise significant increases in muscle hypertrophy from training with low loads (Burd, Moore, Mitchell, & Phillips, 2012). Proponents claim that complete high-threshold motor unit recruitment can be achieved with low-load training provided repetitions are carried out to momentary muscular failure. But although research clearly shows FT fibres are indeed recruited during low-load training, there is evidence that recruitment does not equal what is achieved from the use of heavier loads (Akima & Saito, 2013; Cook, Murphy, & Labarbera, 2013). Recent work from our lab supports these findings, with both mean and peak electromyographic values showing markedly and significantly higher activation during performance of the leg press at 75% 1 RM versus 30% 1 RM (Schoenfeld, Contreras, Willardson, Fontana, & Tiryaki-Sonmez, 2014). Despite this evidence, training to failure at 30% 1 RM has been found to produce a similar acute muscle protein synthetic response to a 90% 1 RM protocol 4-h post-exercise, with myofibrillar muscle protein synthesis remaining elevated only in the 30% to failure condition at the 24-h mark (Burd et al., 2010). Moreover, 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 muscle protein synthesis (MPS). These findings suggest that low-load exercise when performed to muscular failure results in greater acute adaptive responses compared to training with heavy loads. The study did not report muscle protein breakdown, and results were limited by an inability to localise MPS based on fibre type. Results were also confounded by a greater total volume of weight lifted in the low-load condition. Moreover and importantly, the evaluation of MPS following an acute bout of resistance exercise does not always occur in parallel with chronic upregulation of causative myogenic signals (Coffey, Shield, et al., 2006a) and may not reflect experienced hypertrophic responses subsequent to regimented resistance training carried out over a period of weeks or months (Mitchell, Churchward-Venne, Parise, et al., 2014; Timmons, 2011). This is a complex area of research, however, and interested readers are referred to the recent review by Mitchell, Churchward-Venne, Cameron-Smith, and Phillips (2014) for an in-depth discussion of the topic.

A number of longitudinal studies have been carried out that compare muscular adaptations in low- versus high-load training programs. Results of these studies have been conflicting. One issue with the current body of research on the topic is that studies have employed small sample sizes. Thus, it is possible that null findings may be attributable to a Type II error as a result of the studies being underpowered. In addition, various methodological issues between protocols confound results, making it difficult to draw definitive conclusions. Thus, by increasing statistical power and controlling for confounding variables, a meta-analysis may help to provide clarity on the topic. The purpose of this paper therefore was to conduct a meta-analysis to compare muscular adaptations between low- and high-load resistance training programmes.

Methodology

Inclusion criteria

Only randomised controlled trials or randomised crossover trials involving both low- and high-load training were considered for inclusion. High-load training was defined here as lifting weights ≥65% 1 RM; low-load training was defined as lifting loads ≤60% 1 RM. Resistance training protocols had to span at least 6 weeks and directly measure dynamic muscle strength and/or hypertrophy as a primary outcome variable. In addition, the training protocols had to be carried out to momentary muscular failure – the inability to complete another concentric repetition while maintaining proper form.

Search strategy

To carry out this review, English-language literature searches of the PubMed, EBSCO and Google Scholar databases were conducted from January 1980 to December 2013. Combinations of the following keywords were used as search terms: "skeletal muscle"; "hypertrophy"; "growth"; "cross-sectional area"; "intensity"; "strength"; "loading"; "low load"; "light load"; "resistance training" and "resistance exercise". Consistent with methods outlined by Greenhalgh and Peacock (2005), the reference lists of articles retrieved in the search were then screened for any additional articles that had relevance to the topic. Abstracts from conferences, reviews and unpublished dissertations/theses were excluded from analysis.

A total of 846 studies were evaluated based on search criteria. To reduce the potential for selection bias, each of these studies was independently perused by two of the investigators (B. J. S. and R. P. L.), and a mutual decision was made as to whether or not they met basic inclusion criteria. Any inter-reviewer disagreements were settled by consensus and/or consultation with the third investigator. A total of 13 studies were identified that investigated low- versus high-load training in accordance with the criteria outlined (see Figure 1). Three studies (Leger et al., 2006; Weiss, Coney, & Clark, 1999, 2000) had to be omitted from analysis due to lack of adequate data thereby leaving 10 studies for analysis. Figure 1 shows a flowchart of the literature search. Table I summarises the studies included for analysis.

Coding of studies

Studies were read and individually coded by two of the investigators (B. J. S. and R. P. L.) for the following variables: descriptive information of subjects by group including gender, body mass index, training status (trained subjects were defined as those with at least one year resistance training experience), age and stratified subject age (classified as either young [18–29 years], middle-aged [30–49 years] or elderly [50+ years]); whether the study was a parallel or within-subject design; the number of subjects in each group; duration of the study; exercise volume (single set, multi-set or both); whether volume was equated between groups; rest interval between sets (short rest of less than 2 minutes vs. long rest of 2 minutes or more); type of hypertrophy measurement (magnetic resonance imaging, computerised tomography, ultrasound, biopsy, etc.) and region/muscle of body measured (upper, lower or both) and strength measure(s) employed for testing (free weights or isokinetic/isometric dynamometry). Coding was cross-checked between coders, and any discrepancies were resolved by mutual consensus. To assess potential coder drift, 30% of the studies were randomly selected for recoding as described by Cooper, Hedges, and Valentine (2009). Per case agreement was determined by dividing the number of variables coded the

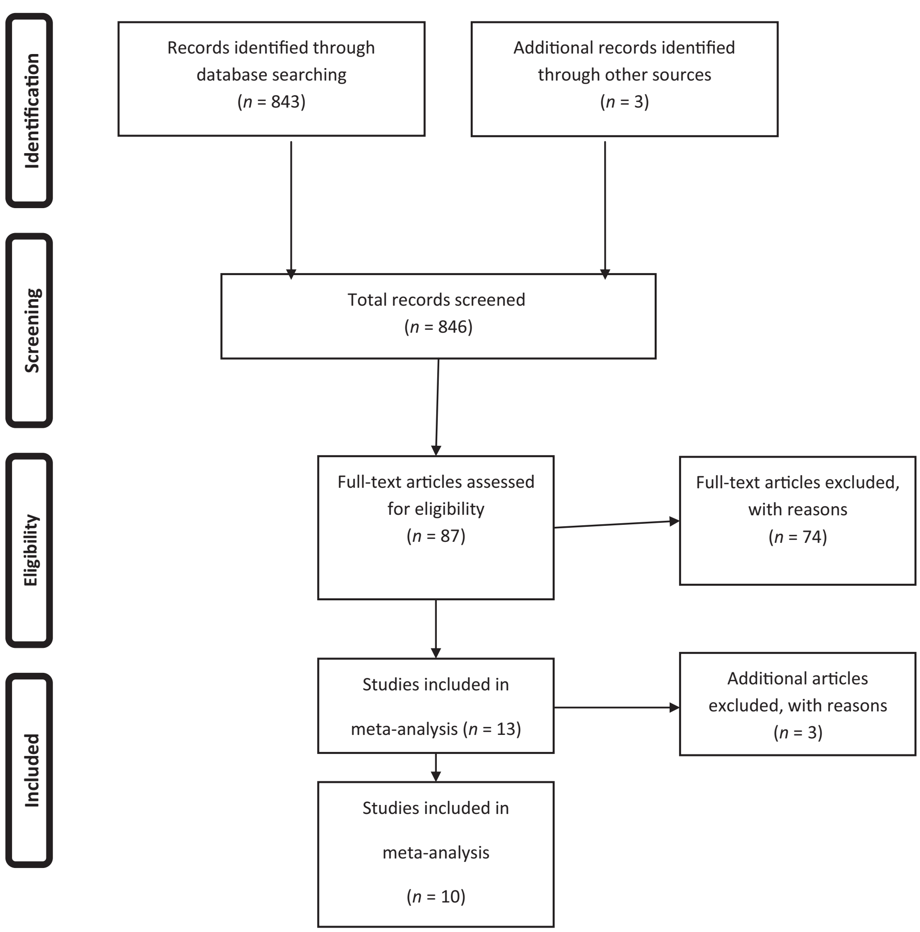

Figure 1. Flow diagram of the literature search.

Table I. Overview of studies meeting inclusion criteria

Study	Subjects	Design	Volume equated?	Hypertrophy measurement	Findings
Anderson and Kearney (1982)	Forty-three untrained young men	Random assignment to either three sets of high-intensity (6–8 RM), two sets of medium intensity (30–40 RM) or one set of low intensity (100–150 RM). Exercise consisted of the bench press performed 3 days a week for 9 weeks. Tempo was consistent between conditions	Yes	N/A	Significantly greater increases in strength for the high- vs. medium- and low-intensity groups
Campos et al. (2002)	Thirty-two untrained young men (five served as non-exercising controls)	Random assignment to either high-intensity (3–5 RM), intermediate-intensity (9–11 RM) or low-intensity (20–28 RM) exercises. Exercise consisted of 2–4 sets of squat, leg press and leg extension, performed 3 days a week for 8 weeks. Tempo was consistent between conditions	Yes	Muscle biopsy	Significant increases in CSA for high-intensity exercise; no significant increase in CSA for low-intensity exercise. Significantly greater increases in muscle strength for high vs. low intensity
Mitchell et al. (2012)	Eighteen untrained young men	Randomly assignment to perform two of three unilateral leg extension protocols: three sets at 30% RM, three at 80% RM and one set at 80% RM. Tempo was consistent between conditions. Training was carried out 3 days per week for 10 weeks	No	MRI, muscle biopsy	No differences in CSA between low- and high-intensity exercise. Significantly greater strength gains in high vs. low load
Ogasawara, Loenneke, Thiebaud, and Abe(2013)	Nine untrained young men	Non-randomised crossover design to perform four sets of bench press exercise at 75% 1 RM. Training was carried out 3 days a week for 6 weeks. Tempo was consistent between conditions. After a 12-month washout period, the same protocol was performed at 30% 1 RM	No	MRI	No differences in CSA between low- and high-intensity exercise. Significantly greater increases in strength favouring high vs. low load
Popov et al. (2006)	Eighteen untrained young men	Random assignment to either high intensity (80% of MVC) or low intensity (50% MVC) without relaxation. Exercise consisted of leg press exercise performed 3 days a week for 8 weeks. Tempo was consistent between conditions	No	MRI	No differences in CSA or strength between groups
Schuenke et al. (2012)	Thirty-four untrained young women	Randomised assignment to either moderate intensity (80–85% RM) at a tempo of 1–2 seconds, a low intensity (~40–60% RM) at a tempo of 1–2 seconds or slow speed (~40–60% RM) at a tempo of 10 seconds concentric and 4 seconds eccentric. Exercise consisted of three sets of squat, leg press and leg extension, performed 2–3 days a week for 6 weeks	No	Muscle biopsy	Significant increases in CSA for high-intensity exercise; no significant increase in CSA for low-intensity exercise
Stone and Coulter (1994)	Fifty untrained young women	Three sets of 6–8 RM, two sets of 15–20 RM and one set of 30–40 RM. A combination of free weight and machine exercises were performed for the upper and lower body. Tempo was consistent between conditions. Training was carried out 3 days a week for 9 weeks	Yes	N/A	No differences in strength between groups

Table I. (Continued)

Study	Subjects	Design	Volume equated?	Hypertrophy measurement	Findings
Tanimoto and Ishii (2006)	Twenty-four untrained young men	Random assignment to either 50% RM with a 6 second tempo and no relaxing phase between repetitions, 80% RM with a 2 second tempo and 1 second relaxation between repetitions or 50% RM with a 2 second tempo and 1 second relaxation between repetitions. Exercise consisted of three sets of knee extensions, performed 3 days a week for 12 weeks.	No	MRI	No differences in CSA or strength between low- and high-intensity exercise
Tanimoto et al. (2008)	Thirty-six untrained young men (12 served as non-exercising controls)	Random assignment to either ~55% RM with a 6-second tempo and no relaxing phase between repetitions or 80–90% RM with a 2-second tempo and 1-second relaxation between repetitions. Exercise consisted of three sets of squat, chest press, lat pulldown, abdominal bend and back extension, performed 2 days a week for 13 weeks	No	B-mode ultrasound	No differences in CSA or strength between low- and high-intensity exercise
Van Roie, Delecluse, Coudyzer, Boonen,and Bautmans (2013)	Fifty-six untrained elderly adults	Random assignment to perform leg press and leg extension training at either high load (2 × 10–15 repetitions at 80% 1 RM), low load (1 × 80–100 repetitions at 20% 1 RM) or low load + (1 × 60 repetitions at 20% 1 RM, followed by 1 × 10–20 repetitions at 40% 1 RM) for 12 weeks. Tempo was consistent between conditions	No	CT	No differences in muscle volume between groups. Greater increases in strength for high- and low+- vs. low-load conditions

RM, repetition maximum; CSA, cross-sectional area; CT, computerised tomography; MRI, magnetic resonance imaging; MVC, maximal voluntary contraction.

same by the total number of variables. Acceptance required a mean agreement of 0.90.

Calculation of effect size

For each 1-RM strength or hypertrophy outcome, an effect size (ES) was calculated as the pretest–posttest change, divided by the pretest standard deviation (SD; Morris & DeShon, 2002). The sampling variance for each ES was estimated according to Morris and DeShon (2002). Calculation of the sampling variance required an estimate of the population ES and the pretest–posttest correlation for each individual ES. The population ES was estimated by calculating the mean ES across all studies and treatment groups (Morris & DeShon, 2002). The pretest–posttest correlation was calculated using the following formula (Morris & DeShon, 2002):

$$r = \frac{\left(s_1^2 + s_2^2 - s_D^2\right)}{\left(2 s_1 s_2\right)}$$

where s_1 and s_2 are the SD for the pre- and posttest means, respectively, and s_D is the SD of the difference scores. s_D was estimated using the following formula (Technical guide: Data analysis and interpretation [online]):

$$s_D = \sqrt{\left(\left(\frac{s_1^2}{n}\right) + \left(\frac{s_2^2}{n}\right)\right)}$$

Statistical analyses

Meta-analyses were performed using hierarchical linear mixed models, modelling the variation between studies as a random effect, the variation between treatment and control groups as a random effect nested within studies and the low- versus high-load comparison as a fixed effect (Hox & de Leeuw, 2003). The within-group variances were assumed known. Observations were weighted by the inverse of the sampling variance (Morris & DeShon, 2002). Model parameters were estimated by the method of restricted maximum likelihood (Thompson & Sharp, 1999). Denominator degree of freedom for statistical tests and CIs was calculated according to Berkey, Hoaglin, Mosteller, and Colditz (1995). Separate analyses were performed for strength and hypertrophy. Due to sample size limitations, no subgroup analyses were performed. All analyses were performed using SAS Enterprise Guide Version 4.2 (Cary, NC, USA). Effects were considered significant at $p \leq 0.05$, and trends were declared at $0.05 < p \leq 0.10$. Data are reported as means (±SEs) and 95% CIs.

Results

Study characteristics

The strength analysis comprised 251 subjects and 32 ESs, nested within 20 treatment groups and 9 studies. The weighted mean strength ES across all studies and groups was 1.75 ± 0.34 (CI: 0.96, 2.55). The hypertrophy analysis comprised 191 subjects and 34 ESs, nested with 17 treatment groups and 8 studies. The weighted mean hypertrophy ES across all studies and groups was 0.61 ± 0.12 (CI: 0.33, 0.89).

Strength model

The mean muscle strength ES difference between high- and low-load groups for each individual study, along with the overall weighted mean difference across all studies, is shown in Figure 2. No significant differences between groups were seen, but there was a trend for strength outcomes to be greater with high loads compared to low loads (difference = 1.07 ± 0.60; CI: −0.18, 2.32; $p = 0.09$). The mean ES for low loads was 1.23 ± 0.43 (CI: 0.32, 2.13). The mean ES for high loads was 2.30 ± 0.43 (CI: 1.41, 3.19).

Hypertrophy model

The mean muscle hypertrophy ES difference between high- and low-load groups for each individual study, along with the overall weighted mean difference across all studies, is shown in Figure 3. No significant differences between groups were seen, but there was a trend for hypertrophy outcomes to be greater with high loads compared to low loads (difference = 0.43 ± 0.24; CI: −0.05, 0.92; $p = 0.076$). The mean ES for low loads was 0.39 ± 0.17 (CI: 0.05, 0.73). The mean ES for high loads was 0.82 ± 0.17 (CI: 0.49, 1.16).

Discussion

This is the first meta-analysis to investigate muscular adaptations in low- versus high-load training. The study produced several important and novel

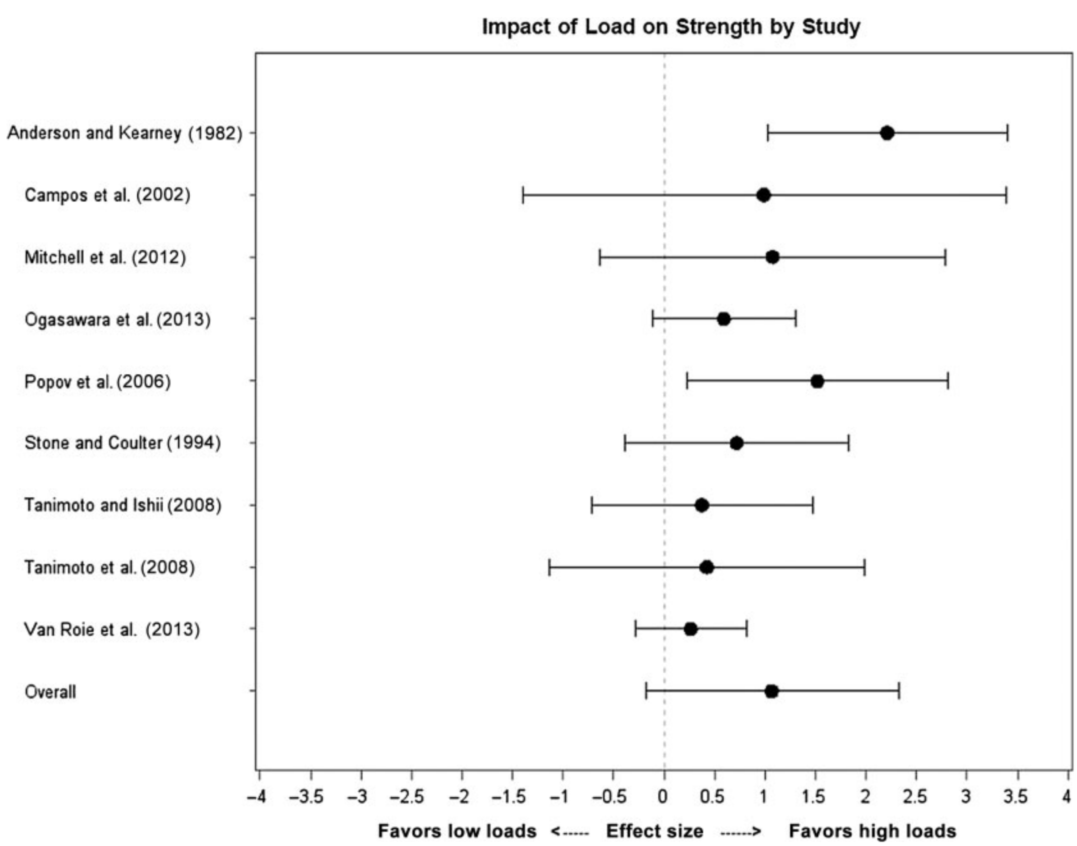

Figure 2. Forest plot of the impact of load on strength by study.

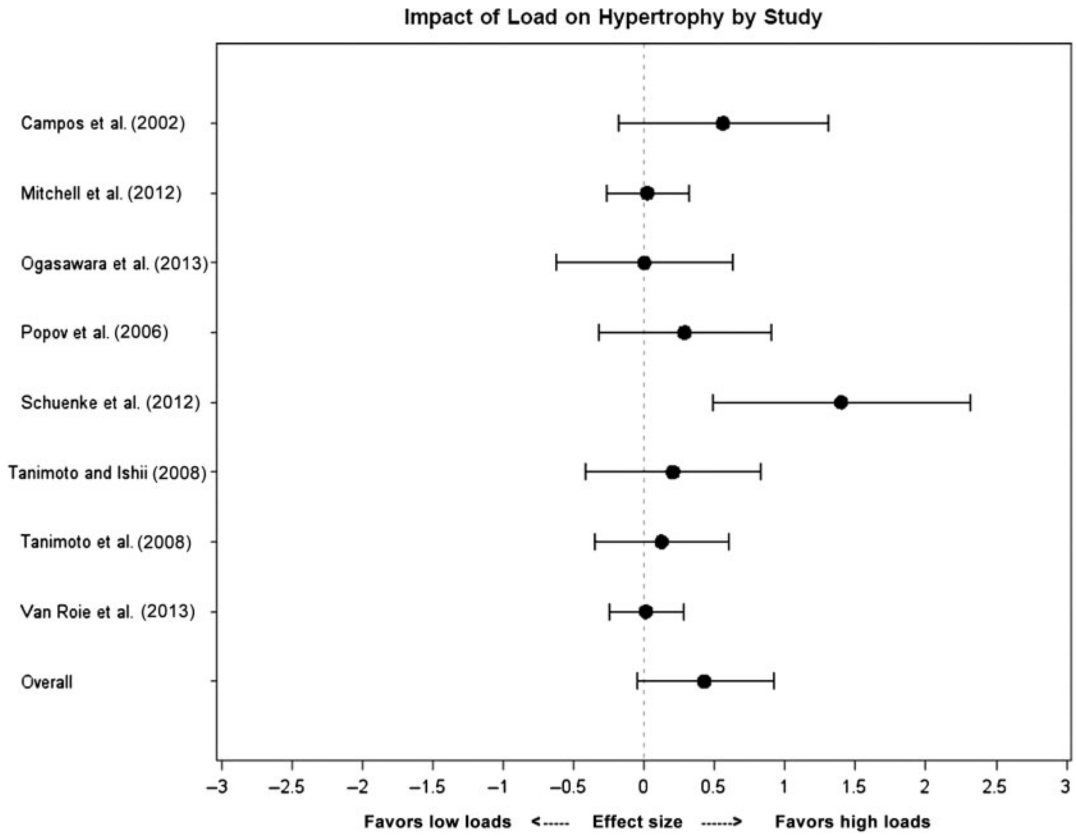

Figure 3. Forest plot of the impact of load on hypertrophy by study.

findings. With respect to muscle hypertrophy, we found no significant differences in ES between high- versus low-load training protocols. To an extent, these results run contrary to established guidelines for hypertrophy training, which state that loads greater than ~65% 1 RM are needed to maximise the hypertrophic response (Kraemer & Ratamess, 2004; Kraemer et al., 2002; McDonagh & Davies, 1984). The current study provides compelling evidence that substantial muscle growth can in fact be achieved training with loads ≤60% 1 RM, with gains approaching those using higher percentages of 1 RM. It should be noted, however, that there was a trend for greater growth when using heavy loads as compared to light loads ($p = 0.076$). This is reflected in the mean ES data, where high-load training showed a strong effect for hypertrophy (0.82 ± 0.17) while low-load training showed only a moderate effect (0.39 ± 0.17). These data suggest that those seeking to maximise hypertrophy might benefit from the use of heavier loads.

With respect to increases in muscular strength, no significant differences in ES were seen between high- and low-load training protocols. Consistent with the concept of a "strength-endurance continuum," it is generally believed that adaptations associated with light-load protocols are specific to enhancing muscular endurance and that any improvements in the ability to exert maximal force are minimal (Campos et al., 2002). On the surface, results of the present study would seem to refute these assertions as pooled analysis of results showed that significant increases in strength are possible when low-load training is carried out to muscular failure. However, closer scrutiny of data indicates that these findings must be interpreted with caution. Although both high- and low-load training showed a strong effect for increases in strength, the magnitude of the difference in means for ES was large between the two protocols (2.30 ± 0.43 versus 1.23 ± 0.43, respectively), and the p-value for the difference showed a trend for significance in favour of high-load training ($p = 0.09$). In addition, the 95% CI differential favoured high-load training (CI: −0.18–2.32). Moreover, as seen in Figure 2, all nine studies investigating the topic favoured high-load training, and six of these studies showed a moderate to strong difference in magnitude of effect. Taken in combination, it can be inferred that the relative paucity of studies on the topic limited statistical power and thus obscured our ability to detect significant differences. While it is evident that low-load training can promote robust increases in muscular strength, the body of research would seem to suggest that the use of heavier loads might be required for maximum effect.

It is not clear from our analysis whether hypertrophy in low- versus high-load training manifested in a fibre-type specific manner. As previously mentioned, there is evidence that muscle fibre recruitment is suboptimal when training with low loads (Akima & Saito, 2013; Cook et al., 2013). Recent work from our lab found that heavy-load training produced significantly greater mean and peak muscle activation of thigh musculature compared to low-load training (by 35% and 22%, respectively) during performance of the leg press (Schoenfeld et al., 2014). On the other hand, the duration of the light-load set was three- to four-fold higher compared to the heavy-load set, indicating that fibres activated during light-load training received considerably greater time-under-load (TUL) versus that achieved during heavy loading. Given that Type I fibres have a higher threshold for fatigability, the greater TUL during low-load training would conceivably maximise their stimulation and thus promote a greater hypertrophic response. This hypothesis is consistent with the findings of Mitchell et al. (2012), who compared knee extension training at 80% of 1-RM versus 30% of 1-RM over 10 weeks. Although similar increases between groups were reported in whole muscle hypertrophy of the quadriceps as assessed by magnetic resonance imaging, tissue analysis from muscle biopsy revealed an increased Type I fibre area in the low-load condition (~23% versus ~16% in low versus high load, respectively), whereas the high-load condition favoured greater Type II fibre area (~15% versus ~12% in high versus low load, respectively). Other studies that have investigated the topic have failed to show a fibre-type-specific response across the strength-endurance continuum (Campos et al., 2002; Schuenke et al., 2012). The reason for discrepancies between studies is not clear. Further research is needed to provide clarity on whether differences do in fact exist between loading strategies with respect to fibre-type hypertrophy and, if so, quantify the magnitude of these differences.

An important consideration to take into account when generalising results of this meta-analysis is that all of the included studies employed untrained or recreationally trained subjects. There is evidence that regular performance of resistance training can modulate the hypertrophic response to loading (Schoenfeld, 2013). As an individual gains lifting experience, a "ceiling effect" makes it progressively more difficult to increase muscle mass, perhaps mediated by an altered anabolic intracellular signalling cascade (Coffey, Zhong, et al., 2006; Ogasawara, Kobayashi, et al., 2013). In support of this point, untrained subjects have been shown to increase muscle mass from cardiovascular exercise – a modality that is not sufficient to induce hypertrophy in a well-trained population (Konopka & Harber, 2014). Thus, more demanding resistance training protocols may be needed to elicit a hypertrophic response in those who regularly lift weights, perhaps including the use of heavier loads. Similarly, while loads ≤60% 1 RM can promote significant strength increases, some researchers have put forth the notion that greater loading is required as an individual attains a more advanced training status to realise further improvements (Kraemer & Ratamess, 2004). This hypothesis is based on the fact that early-phase strength-related adaptations are characterised by enhancements in motor learning and coordination and that heavier loads are therefore necessary to maximise strength-related outcomes once an individual acquires these basic motor skills. A ceiling effect might have implications with respect to strength gains as well. Future research should seek to investigate the response to different loading strategies in those with at least one year of consistent resistance training experience.

A limitation of current research on high versus low loading is the relatively brief duration of the training protocols. The longest study spanned 13 weeks and several were as short as 6 weeks. Although these time frames are certainly long enough to realise significant increases in muscular strength and hypertrophy, it remains to be determined whether results would diverge over longer training periods. This conundrum should be addressed in future research. It should also be noted that the studies included for analysis had inherent differences in manipulation of variables, such as exercise selection, rest intervals and frequency. Thus, pooling of data may not necessarily reflect these discrepancies and their potential impact on results. Although no statistically significant differences were noted between conditions, the variability in the response to training and the observed trend for a positive effect of heavy-load training warrants further research with larger sample sizes.

Practical applications

This meta-analysis provides compelling evidence that training with loads ≤60% 1 RM can promote substantial increases in muscle strength and hypertrophy in untrained individuals. However, a strong trend was noted for superiority of heavy loading with respect to these outcome measures, with null findings likely attributed to the relatively small number of studies meeting inclusion criteria. It may well be that a combination of heavy and light loading is best for maximising muscular adaptations associated with resistance training, conceivably by promoting optimal hypertrophy of both Type I and Type II muscle fibres. Our findings also have important implications for the elderly and those suffering from musculoskeletal conditions, such as osteoarthritis, who clearly can enhance muscular adaptations by training with lighter loads that are more easily tolerated. Given the dearth of data on experienced lifters, future research should focus on elucidating the response of well-trained populations to low- versus high-load protocols.

References

Adams, G., & Bamman, M. M. (2012). Characterization and regulation of mechanical loading-induced compensatory muscle hypertrophy. *Comprehensive Physiology*, 2829–2970.

Akima, H., & Saito, A. (2013). Activation of quadriceps femoris including vastus intermedius during fatiguing dynamic knee extensions. *European Journal of Applied Physiology*, *113*, 2829–2840. doi:10.1007/s00421-013-2721-9

Anderson, T., & Kearney, J. T. (1982). Effects of three resistance training programs on muscular strength and absolute and relative endurance. *Research Quarterly for Exercise and Sport*, *53*(1), 1–7. doi:10.1080/02701367.1982.10605218

Berkey, C. S., Hoaglin, D. C., Mosteller, F., & Colditz, G. A. (1995). A random-effects regression model for meta-analysis. *Statistics in Medicine*, *14*, 395–411. doi:10.1002/sim.4780140406

Burd, N. A., Mitchell, C. J., Churchward-Venne, T. A., & Phillips, S. M. (2012). Bigger weights may not beget bigger muscles: Evidence from acute muscle protein synthetic responses after resistance exercise. *Applied Physiology, Nutrition, and Metabolism*, *37*, 551–554. doi:10.1139/h2012-022

Burd, N. A., Moore, D. R., Mitchell, C. J., & Phillips, S. M. (2012). Big claims for big weights but with little evidence. *European Journal of Applied Physiology*, *113*, 267–268. doi:10.1007/s00421-012-2527-1

Burd, N. A., West, D. W., Staples, A. W., Atherton, P. J., Baker, J. M., Moore, D. R., … Phillips, S. M. (2010). Low-load high volume resistance exercise stimulates muscle protein synthesis more than high-load low volume resistance exercise in young men. *PLoS One*, *5*, e12033. doi:10.1371/journal.pone.0012033

Campos, G. E. R., Luecke, T. J., Wendeln, H. K., Toma, K., Hagerman, F. C., Murray, T. F., … Staron, R. S. (2002). Muscular adaptations in response to three different resistance-training regimens: Specificity of repetition maximum training zones. *European Journal of Applied Physiology*, *88*(1–2), 50–60. Retrieved from http://www.hubmed.org/display.cgi?uids=12436270

Coffey, V. G., Shield, A., Canny, B. J., Carey, K. A., Cameron-Smith, D., & Hawley, J. A. (2006). Interaction of contractile activity and training history on mRNA abundance in skeletal muscle from trained athletes. *American Journal of Physiology: Endocrinology and Metabolism*, *290*, E849–E855. doi:10.1152/ajpendo.00299.2005

Coffey, V. G., Zhong, Z., Shield, A., Canny, B. J., Chibalin, A. V., Zierath, J. R., & Hawley, J. A. (2006). Early signaling responses to divergent exercise stimuli in skeletal muscle from well-trained humans. *FASEB Journal: Official Publication of the Federation of American Societies for Experimental Biology*, *20*, 190–192. doi:10.1096/fj.05-4809fje

Cook, S. B., Murphy, B. G., & Labarbera, K. E. (2013). Neuromuscular function after a bout of low-load blood flow-restricted exercise. *Medicine & Science in Sports & Exercise*, *45* (1), 67–74. doi:10.1249/MSS.0b013e31826c6fa8

Cooper, H., Hedges, L., & Valentine, J. (2009). *The handbook of research synthesis and meta-analysis* (2nd ed.). New York, NY Russell Sage Foundation.

Glass, D. J. (2005). Skeletal muscle hypertrophy and atrophy signaling pathways. *International Journal of Biochemistry & Cell Biology*, *37*, 1974–1984. doi:10.1016/j.biocel.2005.04.018

Greenhalgh, T., & Peacock, R. (2005). Effectiveness and efficiency of search methods in systematic reviews of complex evidence: Audit of primary sources. *British Medical Journal*, *331*, 1064–1065. doi:10.1136/bmj.38636.593461.68

Hox, J. J., & de Leeuw, E. D. (2003). Multilevel models for meta-analysis. In S. P. Reise & N. Duan (Eds.), *Multilevel modeling: Methodological advances, issues, and applications* (pp. 90–111). Mahwah, NJ: Lawrence Erlbaum.

Ivey, F. M., Roth, S. M., Ferrell, R. E., Tracy, B. L., Lemmer, J. T., Hurlbut, D. E., … Hurley, B. F. (2000). Effects of age, gender, and myostatin genotype on the hypertrophic response to heavy resistance strength training. *Journals of Gerontology. Series A, Biological Sciences and Medical Sciences*, *55*, M641–M648.

Konopka, A. R., & Harber, M. P. (2014). Skeletal muscle hypertrophy after aerobic exercise training. *Exercise and Sport Sciences Reviews*, *42*(2), 53–61. doi:10.1249/JES.0000000000000007

Kosek, D. J., Kim, J. S., Petrella, J. K., Cross, J. M., & Bamman, M. M. (2006). Efficacy of 3 days/wk resistance training on myofiber hypertrophy and myogenic mechanisms in young vs. older adults. *Journal of Applied Physiology*, *101*, 531–544. doi:10.1152/japplphysiol.01474.2005

Kraemer, W. J., Adams, K., Cafarelli, E., Dudley, G. A., Dooly, C., Feigenbaum, M. S., … Triplett-McBride, T. (2002). American college of sports medicine position stand. progression models in resistance training for healthy adults. *Medicine & Science in Sports & Exercise*, *34*, 364–380. Retrieved from http://www.hubmed.org/display.cgi?uids=11828249

Kraemer, W. J., & Ratamess, N. A. (2004). Fundamentals of resistance training: Progression and exercise prescription. *Medicine & Science in Sports & Exercise*, *36*, 674–688. doi:10.1249/01.MSS.0000121945.36635.61

Leger, B., Cartoni, R., Praz, M., Lamon, S., Deriaz, O., Crettenand, A., … Russell, A. P. (2006). Akt signalling through GSK-3beta, mTOR and Foxo1 is involved in human skeletal muscle hypertrophy and atrophy. *Journal of Physiology*, *576*, 923–933. doi:10.1113/jphysiol.2006.116715

McDonagh, M. J. N., & Davies, C. T. M. (1984). Adaptive response of mammalian skeletal muscle to exercise with high loads. *European Journal of Applied Physiology and Occupational Physiology*, *52*, 139–155. doi:10.1007/BF00433384

Mitchell, C. J., Churchward-Venne, T. A., Cameron-Smith, D., & Phillips, S. M. (2014). What is the relationship between the acute muscle protein synthetic response and changes in muscle mass? *Journal of Applied Physiology*. Advance online publication. doi:10.1152/japplphysiol.00609.2014

Mitchell, C. J., Churchward-Venne, T. A., Parise, G., Bellamy, L., Baker, S. K., Smith, K., … Phillips, S. M. (2014). Acute post-exercise myofibrillar protein synthesis is not correlated with resistance training-induced muscle hypertrophy in young men. *PLoS One*, *9*, e89431. doi:10.1371/journal.pone.0089431

Mitchell, C. J., Churchward-Venne, T. A., West, D. D., Burd, N. A., Breen, L., Baker, S. K., & Phillips, S. M. (2012). Resistance exercise load does not determine training-mediated hypertrophic gains in young men. *Journal of Applied Physiology*, *113*(1), 71–77. doi:10.1152/japplphysiol.00307.2012

Morris, S. B., & DeShon, R. P. (2002). Combining effect size estimates in meta-analysis with repeated measures and independent-groups designs. *Psychological Methods*, *7*(1), 105–125. doi:10.1037/1082-989X.7.1.105

Ogasawara, R., Kobayashi, K., Tsutaki, A., Lee, K., Abe, T., Fujita, S., … Ishii, N. (2013). mTOR signaling response to resistance exercise is altered by chronic resistance training and detraining in skeletal muscle. *Journal of Applied Physiology*, *114*, 834–940. doi:10.1152/japplphysiol.01161.2012

Ogasawara, R., Loenneke, J. P., Thiebaud, R. S., & Abe, T. (2013). Low-load bench press training to fatigue results in muscle hypertrophy similar to high-load bench press training. *International Journal of Clinical Medicine*, *4*, 114–121.

Popov, D. V., Tsvirkun, D. V., Netreba, A. I., Tarasova, O. S., Prostova, A. B., Larina, I. M., … Vinogradova, O. L. (2006). Hormonal adaptation determines the increase in muscle mass and strength during low-intensity strength training without relaxation. *Fiziologiia Cheloveka*, *32*(5), 121–127.

Schoenfeld, B. J. (2013). Is there a minimum intensity threshold for resistance training-induced hypertrophic adaptations? *Sports Medicine*, *43*, 1279–1288. doi:10.1007/s40279-013-0088-z

Schoenfeld, B. J., Contreras, B., Willardson, J. M., Fontana, F., & Tiryaki-Sonmez, G. (2014). Muscle activation during low- versus high-load resistance training in well-trained men. *European Journal of Applied Physiology*, *114*, 2491–2497. doi:10.1007/s00421-014-2976-9

Schuenke, M. D., Herman, J. R., Gliders, R. M., Hagerman, F. C., Hikida, R. S., Rana, S. R., … Staron, R. S. (2012). Early-phase muscular adaptations in response to slow-speed versus traditional resistance-training regimens. *European Journal of Applied Physiology*, *112*, 3585–3595. doi:10.1007/s00421-012-2339-3

Stone, M. H., & Coulter, S. P. (1994). Strength/endurance effects from three resistance training protocols with women. *Journal of Strength and Conditioning Research*, *8*, 231–234.

Tanimoto, M., & Ishii, N. (2006). Effects of low-intensity resistance exercise with slow movement and tonic force generation on muscular function in young men. *Journal of Applied Physiology*, *100*, 1150–1157. doi:10.1152/japplphysiol.00741.2005

Tanimoto, M., Sanada, K., Yamamoto, K., Kawano, H., Gando, Y., Tabata, I., … Miyachi, M. (2008). Effects of whole-body low-intensity resistance training with slow movement and tonic force generation on muscular size and strength in young men. *Journal of Strength and Conditioning Research/National Strength & Conditioning Association*, *22*, 1926–1938. doi:10.1519/JSC.0b013e318185f2b0

Technical guide: Data analysis and interpretation. Retrieved from http://nces.ed.gov/programs/coe/guide/g3c.asp

Thompson, S. G., & Sharp, S. J. (1999). Explaining heterogeneity in meta-analysis: A comparison of methods. *Statistics in Medicine*, *18*, 2693–2708. doi:10.1002/(SICI)1097-0258(19991030)18:20<2693::AID-SIM235>3.0.CO;2-V

Timmons, J. A. (2011). Variability in training-induced skeletal muscle adaptation. *Journal of Applied Physiology (Bethesda, Md.: 1985)*, *110*, 846–853. doi:10.1152/japplphysiol.00934.2010

Van Roie, E., Delecluse, C., Coudyzer, W., Boonen, S., & Bautmans, I. (2013). Strength training at high versus low external resistance in older adults: Effects on muscle volume, muscle strength, and force-velocity characteristics. *Experimental Gerontology*, *48*, 1351–1361. doi:10.1016/j.exger.2013.08.010

Weiss, L. W., Coney, H. D., & Clark, F. C. (1999). Differential functional adaptations to short-term low-, moderate- and high-repetition weight training. *Journal of Strength and Conditioning Research*, *13*, 236–241.

Weiss, L. W., Coney, H. D., & Clark, F. C. (2000). Gross measures of exercise-induced muscular hypertrophy. *Journal of Orthopaedic and Sports Physical Therapy*, *30*(3), 143–148. doi:10.2519/jospt.2000.30.3.143

Zou, K., Meador, B. M., Johnson, B., Huntsman, H. D., Mahmassani, Z., Valero, M. C., … Boppart, M. D. (2011). The alpha(7)beta(1)-integrin increases muscle hypertrophy following multiple bouts of eccentric exercise. *Journal of Applied Physiology*, *111*, 1134–1141. doi:10.1152/japplphysiol.00081.2011