

Strength and hypertrophy adaptations between low- versus high-load resistance training:

A systematic review and meta-analysis

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Abstract

2 The purpose of this paper was to conduct a systematic review of the current body of literature
3 and a meta-analysis to compare changes in strength and hypertrophy between low- versus high-
4 load resistance training protocols. Searches of PubMed/MEDLINE, Cochrane Library and
5 Scopus were conducted for studies that met the following criteria: 1) an experimental trial
6 involving both low- ($\leq 60\%$ 1 RM) and high- ($>60\%$ 1 RM) load training; 2) with all sets in the
7 training protocols being performed to momentary muscular failure; 3) at least one method of
8 estimating changes in muscle mass and/or dynamic, isometric or isokinetic strength was used; 4)
9 the training protocol lasted for a minimum of 6 weeks; 5) the study involved participants with no
10 known medical conditions or injuries impairing training capacity. A total of 21 studies were
11 ultimately included for analysis. **Gains in 1RM strength were significantly greater in favor of
12 high- versus low-load training**, while no significant differences were found for isometric strength
13 between conditions. **Changes in measures of muscle hypertrophy were similar between
14 conditions. The findings indicate that maximal strength benefits are obtained from the use of
15 heavy loads while muscle hypertrophy can be equally achieved across a spectrum of loading
16 ranges.**

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18 **KEYWORDS:** heavy loading; light loading; muscle mass; muscle strength; repetition maximum
19 continuum

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Introduction

23 Current resistance training (RT) guidelines profess that loads in excess of 70% 1
24 repetition maximum (RM) are required to maximize adaptations in muscular strength and
25 hypertrophy (2). Similarly, the so-called "RM continuum" purports that gains in muscular
26 strength are optimal with loads of 1-5 RM and hypertrophic gains are best achieved with loads of
27 6-12 RM (5). These recommendations are predicated on the belief that heavy loads are necessary
28 to recruit the highest threshold motor units (MU) responsible for promoting maximal muscular
29 adaptations.

30 It remains debatable as to whether lighter load training is capable of recruiting the entire
31 MU pool during a given set of repetitions. Prevailing research indicates that muscle fiber
32 recruitment follows the size principle, which dictates that the smallest MUs are recruited first
33 during a given movement with successively larger MUs engaged as force production

34 requirements increase (21). Although this would seem to support the need for heavy loads to
35 maximize muscular adaptations, some researchers have alternatively postulated that training with
36 intensities as low as 30% 1 RM will ultimately result in complete MU recruitment provided sets
37 are carried out to momentary muscular failure (8, 10).

38 Surface electromyography (sEMG) studies consistently show lower mean electrical
39 amplitudes when training at low (<50% 1 RM) versus high (>70% 1 RM) intensities of load,
40 even when sets are carried out to muscular failure (24, 41). Conversely, others have
41 demonstrated comparable peak EMG amplitudes between high- and low-load, and moderate- and
42 high-load training, and such discrepant findings may result from differing methods of analysis
43 through the time-course of a set to failure (18, 40). It should be noted that sEMG amplitude is not
44 only a function of recruitment but also includes factors such as rate coding (firing frequency),
45 synchronization (simultaneous discharge of MUs), propagation velocity (speed at which an
46 action potential travels along the membrane of a muscle fiber) and intracellular action potentials
47 (6, 12). These factors, in turn, can be influenced by exercise-induced fatigue, thus potentially
48 confounding the ability to draw inferences as to the effects of loading intensity from EMG
49 findings. Moreover, it has been posited that MUs may momentarily de-recruit and re-recruit (MU
50 “cycling”) throughout a light-load set of repetitions to maintain force output (16), thereby
51 altering the magnitude of sEMG amplitude. Importantly, the level of sEMG amplitude does not
52 necessarily correlate with long-term exercise-induced increases in strength and hypertrophy, and
53 thus conclusions must be tempered in the context of these limitations.

54 Ultimately, determination of causality on the topic requires longitudinal studies that
55 directly investigate the effects of RT using low versus high loads. A meta-analysis of such trials
56 by Schoenfeld et al. (43) concluded that both high- and low-load training produced significant

57 increases in both muscle strength and hypertrophy, but noted that statistical probability favored
58 the heavier load conditions for both outcomes. At the time of that search (December 2013), only
59 9 studies met inclusion criteria, limiting statistical power of the analysis. Subsequently, there
60 have been a number of additional studies published on the topic (4, 14, 15, 32), providing a
61 greater ability to draw practical inferences and carry out subanalysis of potential covariates.
62 Therefore, the purpose of this paper was to conduct a systematic review of the current body of
63 literature and a meta-analysis to compare changes in strength and hypertrophy between low-
64 versus high-load resistance training protocols.

65 **Methods**

66 *Inclusion Criteria*

67 Our analysis was confined to studies published in English-language peer-reviewed
68 journals that met the following criteria: 1) an experimental trial involving both low- ($\leq 60\%$ 1
69 RM) and high- ($>60\%$ 1 RM) load training; 2) with all sets in the training protocols being
70 performed to momentary muscular failure; 3) at least one method of estimating changes in
71 muscle mass and/or dynamic, isometric or isokinetic strength was used; 4) the training protocol
72 lasted for a minimum of 6 weeks; 5) the study involved participants with no known medical
73 conditions or injuries impairing training capacity. As some studies reported loading as the
74 number of repetitions, rather than a percentage of 1 RM, all repetitions up to 15 RM were
75 considered as high-load, while repetitions >15 RM were considered as low-load.

77 *Search Strategy*

78 The systematic literature search of English-language journals was conducted in
79 accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses

80 (PRISMA) guidelines (30). Searches of PubMed/MEDLINE, Cochrane Library and Scopus were
81 conducted from inception of indexing to March, 2017. The following syntax was used to carry
82 out the search: muscle hypertrophy AND muscle strength AND (skeletal muscle OR resistance
83 training OR cross-sectional area OR growth OR training intensity OR training load OR high load
84 OR low load OR muscle fibers OR loading OR muscle thickness OR bodybuilding OR fitness).
85 The reference lists of articles retrieved in the search were subsequently perused for any
86 additional articles that had potential applicability to the topic as outlined by Greenhalgh and
87 Peacock (19). Forward citation tracking of the studies meeting the inclusion criteria was
88 performed in Google Scholar. To reduce the potential for selection bias, each of these studies
89 were independently perused by two of the investigators (BJS and JG), and a mutual decision was
90 made as to whether or not they met basic inclusion criteria. Any inter-reviewer disagreements
91 were settled by consensus and/or consultation with the third investigator (DO).

92

93 Of the studies initially reviewed, 49 were determined to be potentially relevant to the
94 topic based on information contained in the abstracts. Full text of these articles were then
95 screened and 24 were regarded as suitable for inclusion based on the criteria outlined. Attempts
96 were made to contact the authors of a given study in the case that relevant data were missing.
97 Three studies (27, 53, 54) had to be omitted from analysis due to lack of adequate data hence
98 leaving 21 studies for analysis. Figure 1 shows a flow chart of the literature search. Table 1
99 summarizes the studies included for analysis.

100

*****Insert Figure 1 About Here*****

101

*****Insert Table 1 About Here*****

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103 *Coding of Studies*

104 Studies were read and individually coded by two of the investigators (BJS and JG) for the
105 following variables: (a) authors, title and year of publication; (b) participant information such as
106 sample size, gender, age, and training status. For age, the following classification was used:
107 participants aged 18-39 years are classified as young adults, participants aged 40-64 years are
108 classified as middle-aged adults and participants aged ≥ 65 years are classified as older adults.
109 Training status was categorized as in Schoenfeld et al. (43); (c) description of the training
110 intervention, including duration, the intensity of load, weekly training frequency, resistance
111 training exercises, and where reported, the tempo and rest interval length; (d) methods used for
112 the assessment of hypertrophy. Methods of measurement were classified as direct (magnetic
113 resonance imaging [MRI], computerized tomography [CT] and ultrasound), indirect (skinfolds,
114 dual energy X-ray absorptiometry [DEXA] and air displacement plethysmography [BOD-POD])
115 and in vitro (i.e. biopsy); (e) test(s) used for assessing strength outcomes (isokinetic knee
116 extension and/or flexion, maximal voluntary contraction and/or maximal dynamic strength [i.e. 1
117 RM]); (f) region/muscle of body measured (upper, lower, or both); (g) pre and post-intervention
118 mean \pm standard deviation (SD) values related to hypertrophy and strength outcomes; (h)
119 reported adverse effects and adherence to the training program. Coding files were crosschecked
120 between the authors, with discussion and agreement required for any observed differences. To
121 prevent the potential for coder drift, we randomly selected 30% of the studies for recoding as
122 outlined by Cooper et al. (11). Per case agreement was determined by dividing the number of
123 variables coded the same by the total number of variables. Acceptance required a mean
124 agreement of 90%.

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126 *Methodological quality*

127 The quality of each study was independently assessed by 2 of the authors (JG and BJS),
128 and agreement was mutually determined for any observed discrepancies. Study quality was
129 evaluated by use of the 11-point Physiotherapy Evidence Database (PEDro) scale, which has
130 been shown to be a valid measure of the methodologic quality of randomized trials (13) and
131 displays acceptable inter-rater reliability (33). Given that the assessors are rarely blinded, and
132 that is impossible to blind the participants and investigators, in supervised exercise interventions,
133 we elected to remove items 5, 6, and 7 from the scale, which are specific to blinding. With the
134 removal of these items, the maximum result on the modified PEDro 8-point scale was 7 (i.e. the
135 first item is not included in the total score). The qualitative methodology ratings were adjusted
136 similar to that used in previous exercise-related systematic reviews (26) as follows: 6-7 =
137 “excellent”; 5 = “good”; 4 = “moderate”; and, 0 to 3 = “poor”.

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139 *Calculation of Effect Size*

140 For each hypertrophy outcome, an effect size (ES) was calculated as the pretest-posttest
141 change, divided by the pooled pretest SD (31). A percentage change from pretest to posttest was
142 also calculated. An adjustment for small sample bias was applied to each ES (31). The variance
143 around each ES was calculated using the sample size in each study and mean ES across all
144 studies (7).

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146 *Statistical Analyses*

147 A random effects model was employed using robust variance meta-regression for
148 multilevel data structures, with adjustments for small samples (20, 49). Study was used as the

149 clustering variable to account for correlated effects within studies. Observations were weighted
150 by the inverse of the sampling variance. Model parameters were estimated by the method of
151 restricted maximum likelihood (REML) (48). Separate meta-regressions were performed on ESs
152 for 1-RM, isometric strength, isokinetic strength, body composition, direct assessments of
153 muscle size, and muscle fiber size via biopsy. Load classification (high or low) was included as a
154 moderator in all regression models. To assess the practical significance of the outcomes, the
155 equivalent percent change was calculated for each meta-regression outcome. To allow generation
156 of a forest plot, mean differences in effect sizes were calculated for each study to give a study-
157 level ES, and a meta-regression was performed on those ESs. To explore whether an interaction
158 existed between training load and upper or lower body muscle groups, separate regressions were
159 performed on training load and its interaction with body half (upper or lower) if sufficient data
160 was available.

161 In order to identify the presence of highly influential studies which might bias the
162 analysis, a sensitivity analysis was carried out for each model by removing one study at a time,
163 and then examining the training load predictor. Studies were identified as influential if removal
164 resulted in a change of the predictor going from significant or a trend ($P \leq 0.10$) to non-
165 significant ($P > 0.10$), or vice versa, or if removal caused a large change in the magnitude of the
166 coefficient.

167 All analyses were performed using package metafor in R version 3.3.2 (The R
168 Foundation for Statistical Computing, Vienna, Austria). Effects were considered significant at P
169 ≤ 0.05 , and trends were declared at $0.05 < P \leq 0.10$. Data are reported as $\bar{x} \pm$ standard error of
170 the means (SEM) and 95% CIs.

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172 **Results**

173 Results of all outcomes are presented in Table 2. The mean rating of study quality as
174 assessed by the PEDro scale was 5.6, indicating the pool of studies to be of good to excellent
175 quality; no study in the analysis was deemed to be of poor quality.

176 *****Insert Table 2 About Here*****

177 *1-RM*

178 The final analysis comprised 84 ESs from 14 studies. The mean ES across all studies was
179 1.50 ± 0.23 (CI: 1.01, 1.99). The mean percent change was $31.6 \pm 4.5\%$ (CI: 22.0, 41.2). There
180 was a significant difference in mean ES between high and low loads ($\Delta = -0.37 \pm 0.10$; CI: -0.59,
181 -0.16; $P = 0.003$), with high load resulting in a greater mean ES and percentage gain (Table 2).
182 Study level analysis revealed an effect size that significantly favored high loads (ES = $0.58 \pm$
183 0.16 ; CI: 0.28, 0.89; $P = 0.002$; Figure 2). There was no interaction between training load and the
184 half of the body trained ($P = 0.69$). Sensitivity analyses did not reveal any influential studies.

185 *****Insert Figure 2 About Here*****

186 *Isometric Strength*

187 The final analysis comprised 23 ESs from 8 studies. The mean ES across all studies was
188 0.60 ± 0.19 (CI: 0.15, 1.05). The mean percent change was $21.5 \pm 5.3\%$ (CI: 8.9, 34.2). There
189 was no significant difference in mean ES between high and low loads ($\Delta = -0.09 \pm 0.10$; CI: -
190 $0.34, 0.17$; $P = 0.43$; Table 2). Study level analysis showed no significant impact of load (ES =
191 0.16 ± 0.11 ; CI: -0.10, 0.41; $P = 0.19$; Figure 3). There was insufficient data to examine the
192 interaction between training load and the half of the body trained. Sensitivity analysis revealed
193 one influential study. Removal of the study by Van Roie et al. (51) changed the magnitude of the

194 non-significant difference between high and low loads ($\Delta = -0.24 \pm 0.13$; CI: -0.57, 0.08; P =
195 0.11).

196 *****Insert Figure 3 About Here*****

197 *Isokinetic Strength*

198 There were 41 isokinetic strength ESs from 4 studies. There was an insufficient number
199 of studies to model the impact of loading on isokinetic strength.

200 *Lean Body Mass*

201 There were 14 body composition ESs from 5 studies. There was an insufficient number
202 of studies to model the impact of loading on lean mass changes.

203 *Muscle Hypertrophy*

204 The final analysis comprised 41 ESs from 10 studies. The mean ES across all studies was
205 0.47 ± 0.08 (CI: 0.28, 0.65). The mean percent change was $7.6 \pm 1.2\%$ (CI: 4.9, 10.4). There was
206 a trend towards a difference in mean ES between high and low loads ($\Delta = -0.11 \pm 0.06$; CI = -
207 0.24, 0.03; P = 0.10), with high load being slightly greater than low loads (Table 2). However,
208 study level analysis showed no impact of load (ES = 0.03 ± 0.05 ; CI: -0.08, 0.14; P = 0.56;
209 Figure 4). There was no interaction between training load and the half of the body trained (P =
210 0.46). Sensitivity analyses revealed five influential studies (Table 3). Removal of each of the
211 three most influential studies (37, 47, 51) resulted in non-significant P-Values (P = 0.22 – 0.46)
212 along with decreases in the ES difference between high and low loads ($\Delta = -0.06 - -0.09$).

213 *****Insert Figure 4 About Here*****

214 *Muscle Fiber Size*

215 There were 23 muscle fiber size ESs from 4 muscle biopsy studies. There was an
216 insufficient number of studies to model the impact of loading on muscle fiber size.

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Discussion

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The present meta-analysis encompassed a total of 21 studies – more than double that of the previous meta-analysis on the topic (43). This fairly large body of research provided ample statistical power to draw inferences as to the effects of loading on muscle hypertrophy and isotonic and isometric strength, although data remain insufficient for assessing changes in measures isokinetic strength, and muscle fiber and lean body mass. The analysis produced several interesting revelations.

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The outcomes for strength were somewhat conflicting depending on the modality of testing. Heavy loading showed a clear advantage for gains in 1 RM strength, with probability estimates indicating an almost certain likelihood of differences compared to low-load training ($P = 0.003$) (23). The superiority of heavy loading for maximal isotonic strength is consistent with the principle of specificity, which dictates that the more closely a training program replicates the requirements of a given outcome, the greater the transfer of the training to that outcome (5). Considering the essence of 1 RM testing is to lift maximal loads, it logically follows that training closer to one's RM would have the greatest transfer to this outcome. Nevertheless, both heavy and light loads showed large effects for 1 RM increases (1.69 and 1.32, respectively), translating into mean percentage gains of 35.4% and 28.0%, respectively. Our findings therefore indicate that while heavy loads are required to achieve maximal gains in isotonic strength, lighter loads promote substantial increases in this outcome as well. It should be noted that our findings on the topic are primarily based on untrained subjects as only 3 studies investigated isotonic strength changes between conditions in those with resistance training experience. A subanalysis of training status showed that the direction of the interaction was even larger in trained subjects, suggesting that heavier loading may become increasingly more important for maximal gains in

240 isotonic strength as one garners training experience. However, the paucity of data on the topic
241 limits the ability to draw definitive conclusions.

242 With respect to isometric strength, both high and low loads produced similar gains, with
243 minimal differences displayed in mean percentage changes (22.6% versus 20.5%, respectively).
244 At face value this implies that when training specificity is offset by testing on a neutral
245 instrument, increases in force production can be equally achieved regardless of loading zone.
246 However, sensitivity analysis showed that removal of Van Roie et al. (51) substantially altered
247 the magnitude of the difference between conditions, with the 95% confidence interval (-0.08,
248 0.57) showing an overt advantage to heavier loading. The relatively low number of studies on the
249 topic limited statistical power to draw firm inferences, but examination of the revised confidence
250 interval (-0.57, 0.08) indicates a likely benefit in favor of heavier loading, albeit of a relatively
251 small magnitude (23).

252 There was an insufficient number of studies to quantify a magnitude of effect on
253 isokinetic strength in high- versus load-low training. Of the 3 studies that investigated changes in
254 this outcome measure, Aagaard et al. (1) found that only those training with high-loads were able
255 to increase isokinetic strength in a cohort of elite young soccer players. Conversely, Van Roie et
256 al. (51) and Hisaeda et al. (22) reported no significant differences between conditions in
257 untrained community-dwelling elderly adults and young women, respectively. Whether physical
258 activity levels and/or factors specific to these diverse populations contributed to the
259 discrepancies remains to be determined.

260 Data from direct measures of muscle size indicate similar hypertrophic changes between
261 high- and low-load conditions. Although differences in mean ES ($p = 0.10$) suggests a likely
262 probability favoring heavier load training (23), study level analysis as illustrated in Figure 4

263 showed no impact of load ($P = 0.56$) and the mean percentage gains were comparable between
264 high- and low-load conditions (8.3% versus 7.0%, respectively). Moreover, sensitivity analysis
265 revealed a number of studies unduly influenced results, and the removal of the most influential
266 studies markedly reduced the probability of a difference in mean ES ($P = 0.22 - 0.46$). The
267 findings therefore indicate that both heavy and light loads can be equally effective in promoting
268 muscle growth provided training is carried out with a high level of effort. Intriguingly, emerging
269 research shows a potential fiber type-specific effect of loading zones, with heavier loads showing
270 greater increases in type II muscle fiber cross sectional area and lighter loads showing greater
271 increases in type I muscle fiber growth (34, 35, 52). If true, this implies a potential benefit to
272 training across a spectrum of repetitions when to goal is maximize hypertrophic adaptations.
273 That said, not all studies have found such an effect (32) and further research is therefore needed
274 to draw relevant practical inferences.

275 While not all studies reported attendance during the training programs, those that did
276 report a high level of adherence (i.e. >87% of total training sessions). It has been suggested that
277 low load training might result in greater discomfort compared with high load training (17).
278 However, the findings would suggest that the both types of training were equally effective
279 regarding adherence to the training protocols. Furthermore, it would seem that training with both
280 high- and low-load might be equally safe, as only two out of the 21 included studies (25, 43)
281 reported mild adverse effects (i.e. minor tendonitis and two minor injuries [one in each group],
282 respectively).

283 It should be noted that several studies included in the analysis had potential confounding
284 variables that may have impacted results. In the study by Fink et al. (14), interset rest intervals
285 for the low-load condition were 30 seconds while the high-load condition rested 3 minutes. In the

286 study by Popov et al. (37), the low-load group performed repetitions without relaxation while
287 those in the high-load group paused during the isometric portions of the lift. Repetition durations
288 in both studies by Tanimoto et al. (46, 47) were different between conditions, with the low-load
289 condition lifting at a tempo of 3s-0s-3s (concentric-isometric-eccentric) versus a 1s-1s-1s tempo
290 in the high-load condition. The extent and direction to which these factors may have influenced
291 hypertrophic adaptations is not clear.

292 **Practical Applications**

293 The findings of this meta-analysis can provide specific guidance regarding the
294 prescription of training loads to promote increased muscular hypertrophy and strength. With
295 respect to the development of muscular strength, one must consider the needs of the individual
296 first and foremost. For those who participate in strength sports, particularly where maximal loads
297 are required in specific lifts, then training with high loads on the evaluated lifts is advantageous
298 (principle of specificity). Training with low-loads to failure requires exercise volume (work) and
299 time in excess of high-load training, suggesting high-load training may be more efficient.
300 Recently Mattocks et al. (28) demonstrated this principle finding comparable improvements in
301 muscular strength in those who completed only regular one RMs against a higher volume
302 hypertrophy program, albeit in untrained participants.

303 Given the robust increases from low-load training on measures of isotonic and isometric
304 maximal strength, and the similar changes in muscle hypertrophy when compared to heavy
305 loading, there is significant flexibility in the loading ranges that can be prescribed to promote
306 muscular strength and mass. Emerging evidence indicating fiber type-specific adaptations from
307 training with high- versus low-loads suggests a potential benefit to training across a spectrum of

308 loading zones when maximizing muscle hypertrophy is the primary goal. This hypothesis
309 warrants further study.

310 It should be noted that all included studies in this analysis used momentary muscular
311 failure as the point of set termination. Consequently, application of these findings to RT
312 programming must consider the contribution of concentric failure to the observed findings.
313 While training to failure may not result in superior adaptations than non-failure RT despite
314 increased training volume (39), comparable results cannot reasonably be assumed for sub-
315 maximal, non-failure training based on the present analysis. This highlights the need for further
316 research on the role of effort, fatigue and failure in the relationship between training loads and
317 changes in muscular strength and hypertrophy.

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ACCEPTED

Table 1. Overview of studies meeting inclusion criteria

Study	Participants characteristics	Comparison groups (sets x repetition [rest interval duration#])	Tempo (concentric-isometric-eccentric)	Volume equated?	Duration of intervention; weekly training frequency	Resistance training exercise(s)	Hypertrophy/strength measurement	Findings
Aagaard et al. (1)	Young untrained men (n = 22)	High load - 4 x 8 RM Low load - 4 x 16 RM* Low load - 4 x 24 RM Non-exercising control group*	Not reported	No	12 weeks; 3x	Knee extension	Isokinetic knee extension Isokinetic knee flexion	Significant pre- to post-intervention increases in strength only in the high load group.
Anderson et al. (3)	Young untrained men (n = 43)	High load - 3 x 6-8 RM Low load - 2 x 30-40 RM Low load - 1 x 100-150 RM	Not reported	Yes	9 weeks; 3x	Bench press	1 RM bench press	Significant pre- to post-intervention increases in strength in all groups. Significantly greater increases in strength in the high load vs. low load groups.
Au et al. (4)	Young trained men (n = 46)	High load - 3 x 8-12 RM [1 min] Low load - 3 x 20-25 RM [1 min] Non-exercising control group*	Not reported	No	12 weeks; 4x	Seated row, bench press, front plank, machine-guided shoulder press, bicep curls, triceps extension, wide grip pull downs, inclined leg press, cable hamstring curl, machine-guided knee extension	BOD-POD 1 RM bench press 1 RM leg press	Significant pre- to post-intervention increases in lean body mass, upper and lower body strength in both exercising groups, with significant between-group differences only in 1 RM bench press strength for high vs low load group.
Campos et al. (9)	Young untrained men (n = 32)	High load - 4 x 3-5 RM [3 min] High load - 3 x 9-11 RM [2 min] Low load - 2 x 20-28 RM [1 min] Non-exercising control group*	Not reported	Yes	8 weeks; 2-3x	Squat, leg press, knee extension	Biopsy 1 RM squat 1 RM leg press 1 RM knee extension	Significant pre- to post-intervention increases in CSA only for the high load groups. Significantly greater increases in muscle strength in the high load vs. low load group.
Fink et al. (15)	Young untrained men (n = 21)	High load - 3 x 8-12 RM [90 sec]	1-0-2 for all groups	No	8 weeks; 3x	Unilateral biceps preacher curl	MRI MVC	Significant pre- to post-intervention increases in CSA in all groups, with

		Low load - 3 x 30-40 RM [90 sec] Mixed high and low load group – 4 weeks of 3 x 8-12 RM and 4 weeks of 3 x 30-40 RM [90 sec]*						no significant between-group differences. Significantly greater increases in muscle strength in the high load vs. low load group.
Fink et al. (14)	Young untrained men (n = 20)	High load - 3 x 8 RM [3 min] Low load - 3 x 20 RM [30 sec]	1-0-2 for both groups	No	8 weeks; 3x	Barbell curl, preacher curl, hammer curl, close grip bench press, french press, dumbbell extension	MRI MVC	Significant pre- to post-intervention increases in CSA in both groups, with no significant between-group differences. Significantly greater increases in muscle strength in the high load vs. low load group.
Fisher et al. (17)	Young untrained men (n = 7)	High load - 3 x 80% MVT [2 min] Low load - 3 x 50% MVT [2 min]	2-1-3 for both groups	No	6 weeks; 1x	Knee extension	MVT	Significant pre- to post-intervention increases in strength for both groups, with no significant between-group differences.
Hisaeda et al. (22)	Young untrained woman (n = 11)	High load - 8-9 x 5 RM ['sufficient'] Low load - 5-6 x 15 RM [90 sec]	Fast as possible	Yes	8 weeks; 3x	Knee extension	MRI MVC	Significant pre- to post-intervention increases in CSA and strength for both groups, with no significant between-group differences.
Kerr et al. (25)	Untrained middle-aged woman (n = 46)	High load - 3 x 8 RM [2-3 min] Low load - 3 x 20 RM [2-3 min]	Not reported	No	1 year; 3x	Hip extension, hip flexion, hip abduction, hip adduction, leg press, wrist curl, reverse wrist curl, wrist pronation/supination, biceps curl, triceps press-down	1 RM hip extension 1 RM hip flexion 1 RM hip abduction 1 RM hip adduction 1 RM leg press 1 RM wrist curl	Significant pre- to post-intervention increases in strength for both groups, with no significant between-group differences.

							1 RM reverse wrist curl 1 RM wrist pronation/supination 1 RM biceps curl 1 RM triceps press-down	
Mitchell et al. (29)	Young untrained men (n = 18)	High load - 3 x 80% RM High load - 1 x 80 % 1 RM* Low load - 3 x 30% 1 RM	Not reported	No	10 weeks; 3x	Unilateral knee extension	MRI Biopsy 1 RM knee extension MVC	Significant pre- to post-intervention increases in CSA for all groups, with no significant between-group differences. Significant pre- to post-intervention increases in strength for all groups, with significantly greater increases in 1 RM muscle strength in the high load vs. low load group.
Morton et al. (32)	Young trained men (n = 49)	High load - 3 x 8-12 RM [1 min] Low load - 3 x 20-25 RM [1 min]	Not reported	No	12 weeks; 4x	Seated row, bench press, front plank, machine-guided shoulder press, bicep curls, triceps extension, wide grip pull downs, inclined leg press, cable hamstring curl, machine-guided knee extension	DEXA Biopsy 1 RM bench press 1 RM leg press 1 RM shoulder press 1 RM knee extension	Significant pre- to post-intervention increases in CSA and lean body mass for all groups, with no significant between-group differences. Significant pre- to post-intervention increases in strength for all groups, with significantly greater increases in 1 RM bench press strength in the high load vs. low load group.

Ogasawara et al. (36)	Young untrained men (n = 9)	High load - 3 x 75% 1 RM [3 min] Low load - 4 x 30% 1 RM [3 min]	1-0-1 for both groups	No	6 weeks; 3x	Bench press	MRI 1 RM bench press MVC	Significant pre- to post-intervention increases in CSA for all groups, with no significant between-group differences. Significant pre- to post-intervention increases in strength for all groups, with significantly greater increases in strength in the high load vs. low load group.
Popov et al. (37)	Young untrained men (n = 18)	High load - 3 and 7 x 80% MVC [10 min] Low load - 1 and 4 x 50% MVC [10 min]	Not reported	No	8 weeks; 3x	Leg press	MRI MVC	Significant pre- to post-intervention increases in CSA and strength for all groups, with no significant between-group differences.
Rana et al. (38)	Young untrained females (n = 34)	High load - 3 x 6-10 RM High load low velocity - 3 x 6-10 RM* Low load - 3 x 20-30 RM Non-exercising control group*	1-0-2 for high and low load groups. 10-0-4 for the high load low velocity group	No	6 weeks; 2-3x	Leg press, back squat (smith machine) and knee extension	BOD-POD 1 RM squat 1 RM leg press 1 RM knee extension	Significant pre- to post-intervention increases in lean body mass for all groups, with no significant between-group differences. Significant pre- to post-intervention increases in strength for all groups, with significantly greater increases in 1 RM leg press in the high load vs. low load group.
Schoenfeld et al. (42)	Young trained men (n = 18)	High load - 3 x 8-12 RM Low load - 3 x 25-35 RM	1-0-2 for both groups	No	8 weeks; 3x	Bench press, barbell military press, wide grip pulldowns, seated cable row, barbell back squat, machine leg press, and machine knee extension	Ultrasound 1 RM bench press 1 RM squat	Significant pre- to post-intervention increases in muscle thickness in both groups, with no significant between-group differences. Significantly greater increases in 1 RM squat strength in the high load vs. low load group.
Schuenke et al. (44) \$	Young untrained females (n = 34)	High load - 3 x 6-10 RM High load low velocity - 3 x 6-10 RM*	1-0-2 for high and low load groups. 10-0-4 for	No	6 weeks; 2-3x	Leg press, back squat (smith machine) and knee extension	Skinfolds Biopsy	No significant pre- to post-intervention differences in lean body mass. Significant pre- to post-intervention

		Low load - 3 x 20-30 RM Non-exercising control group*	the high load low velocity group					increases in CSA only in the high load group
Stone & Coulter (45)	Young untrained females (n = 50)	High load - 3 x 6-8 RM [2-3 min] Low load - 2 x 15-20 RM [2-3 min] Low load - 1 x 30-40 RM [2-3 min]	Not reported	Yes	9 weeks; 3x	Bench press, triceps push-down, arm curl, lat pulldown, squat	1 RM bench press 1 RM squat	Significant pre- to post-intervention increases in strength in all groups, with no significant between-group differences.
Tanimoto & Ishii (46)	Young untrained men (n = 24)	High load - 3 x 80% 1 RM [1 min] Low load low velocity - 3 x 50% 1 RM [1 min]* Low load - 3 x 50% 1 RM [1 min]	1-1-1 for the high and low load groups 3-0-3 for the low load low velocity group	No	12 weeks; 3x	Knee extension	MRI 1 RM knee extension MVC	Significant pre- to post-intervention increases in CSA and MVC strength only in the high load group. Significant pre- to post-intervention increases in 1 RM knee extension strength in all groups, with no significant between-group differences.
Tanimoto et al. (47)	Young untrained men (n = 36)	High load - 3 x 80% 1 RM [1 min] Low load - 3 x 55-60% 1 RM [1 min] Non-exercising control group*	1-1-1 for the high load group 3-0-3 for the low load group	No	13 weeks; 2x	Chest press, lat pulldown, abdominal bend, and back extension, squat	Ultrasound DEXA 1 RM squat 1 RM chest press 1 RM lat pulldown 1 RM abdominal bend 1 RM back extension	Significant pre- to post-intervention increases in muscle thickness, lean body mass and strength in both groups, with no significant between-group differences.

Van Roie et al. (50)	Young untrained men (n = 21) and woman (n = 15)	High load - 1 x 10-12 RM Low load - 1 x 60 RM + 10-20 RM Low load - 1 x 10-12 with 40% 1 RM*	1-0-2 for both groups	No	9 weeks; 3x	Knee extension	1 RM knee extensions MVC Isokinetic knee extension	Significant pre- to post-intervention increases in 1 RM strength in all groups. Significantly greater increases in 1 RM strength in the high load vs. low load groups. Significant pre- to post-intervention increases in MVC only for the high load group. Significant pre- to post-intervention increases in isokinetic strength only for the low load group.
Van Roie et al. (51)	Untrained older men (n = 26) and woman (n = 30)	High load - 2 x 10-15 RM [2 min] Low load - 1 x 80-100 RM Low load - 1 x 60 RM + 10-20 RM	2-0-3 for all groups	No	12 weeks; 3x	Leg press and knee extension	CT 1 RM knee extension 1 RM leg press MVC Isokinetic knee extension	Significant pre- to post-intervention increases in CSA for all groups, with no significant between-group differences. Significantly greater increases in 1 RM strength in the high and low load+ vs. low load group. Significant pre- to post-intervention increases in MVC strength for all groups, with no significant between-group differences. Significant pre- to post-intervention increases in isokinetic strength only for the high load group.

= not all studies reported rest interval duration; * = the group was not included in the meta-analysis; \$ = the same data as in the Rana et al. (38) study; RM = repetition maximal; BOD-POD = air displacement plethysmography; DEXA = dual energy X-ray absorptiometry; MRI = magnetic resonance imaging; MVC = maximal voluntary contraction; MVT = maximal voluntary torque; CT = computed tomography; CSA = cross-sectional area

Table 2. Impact of training load on strength and hypertrophy

Outcome	Load	ES	95% CI	P Value for Difference	Equivalent percentage gain (%)
1-RM	High	1.69 ±	1.25, 2.14	0.003	35.3 ± 4.3
	Low	0.23 1.32 ± 0.23	0.87, 1.76		28.0 ± 4.8
Isometric Strength	High	0.64 ±	0.06, 1.22	0.43	22.6 ± 6.3
	Low	0.24 0.55 ± 0.18	0.10, 1.00		20.5 ± 5.7
Isokinetic Strength			Insufficient Studies for Analysis		
Lean Body Mass			Insufficient Studies for Analysis		
Muscle Hypertrophy	High	0.53 ±	0.30, 0.76	0.10	8.3 ± 1.5
	Low	0.10 0.42 ± 0.08	0.23, 0.60		7.0 ± 1.2

RM = repetition maximal; ES = effect size; CI = confidence interval

Table 3. Sensitivity analyses for hypertrophy

Study Removed	Δ ES Between High & Low Loads	95% CI	P Value for Difference
None	-0.11 ± 0.06	-0.24, 0.03	0.10
Fink et al. (15)	-0.13 ± 0.05	-0.25, 0.00	0.04
Hisaeda et al. (22)	-0.11 ± 0.06	-0.25, 0.03	0.11
Popov et al. (37)	-0.08 ± 0.06	-0.23, 0.07	0.26
Tanimoto et al. (47)	-0.06 ± 0.08	-0.25, 0.12	0.46
Van Roie et al. (51)	-0.09 ± 0.07	-0.25, 0.07	0.22
ES = effect size; CI = confidence interval			

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Figure Captions

Figure 1: Flow diagram of search process

Figure 2: Forest plot of studies comparing changes in 1RM strength in high- versus low-load training. The data shown are mean \pm 95% CI; the size of the plotted squares reflect the statistical weight of each study. Abbreviations: ES (effect size)

Figure 3: Forest plot of studies comparing changes in isometric strength in high- versus low-load training. The data shown are mean \pm 95% CI; the size of the plotted squares reflect the statistical weight of each study. Abbreviations: ES (effect size)

Figure 4: Forest plot of studies comparing changes in muscle hypertrophy in high- versus low-load training. The data shown are mean \pm 95% CI; the size of the plotted squares reflect the statistical weight of each study. Abbreviations: ES (effect size)

ACCEPTED

Figure 1







