1. Title page

Title: Influence of resistance training load on measures of skeletal muscle hypertrophy and improvements in maximal strength and neuromuscular task performance: a systematic review and meta-analysis.

Running title: Influence of load on resistance training adaptations.

Authors: Martin C. Refalo [1], D. Lee Hamilton [2], D. Robert Paval [3], Iain J. Gallagher [3], Simon A. Feros [1], & Jackson J. Fyfe [2].

Affiliations:

1. Deakin University, Geelong, Australia, Centre for Sport Research (CSR), School of Exercise and Nutrition Sciences.
2. Deakin University, Geelong, Australia, Institute for Physical Activity and Nutrition (IPAN), School of Exercise and Nutrition Sciences.
3. University of Stirling, FK9 4LA, UK, Faculty of Health Sciences and Sport.

Corresponding author:

Jackson J. Fyfe, PhD

Institute for Physical Activity and Nutrition (IPAN), School of Exercise and Nutrition Sciences

Deakin University, Geelong, Australia.

Email: jackson.fyfe@deakin.edu.au

ORCiD: 0000-0002-9541-2336

2. Abstract

This systematic review and meta-analysis determined resistance training (RT) load effects on various muscle hypertrophy, strength, and neuromuscular performance task [e.g., countermovement jump (CMJ)] outcomes. Relevent studies comparing higher-load [>60% 1-repetition maximum (RM) or <15-RM] and lower-load (≤60% 1-RM or ≥ 15-RM) RT were identified, with 45 studies (from 4713 total) included in the meta-analysis. Higher- and lower-load RT induced similar muscle hypertrophy at the whole-body (lean/fat-free mass; [ES (95% CI) = 0.05 (-0.20 to 0.29), *P* = 0.70]), whole-muscle [ES = 0.06 (-0.11 to 0.24), *P* = 0.47], and muscle fibre [ES = 0.29 (-0.09 to 0.66), *P* = 0.13] levels. Higher-load RT further improved 1-RM [ES = 0.34 (0.15 to 0.52), *P* = 0.0003] and isometric [ES = 0.41 (0.07 to 0.76), *P* = 0.02] strength. The superiority of higher-load RT on 1-RM strength was greater in younger [ES = 0.34 (0.12 to 0.55), *P* = 0.002] versus older [ES = 0.20 (-0.00 to 0.41), *P* = 0.05] participants. Higher- and lower-load RT therefore induce similar muscle hypertrophy (at multiple physiological levels), while higher-load RT elicits superior 1-RM and isometric strength. The influence of RT loads on neuromuscular task performance is however unclear.

Key words: strength; muscle hypertrophy; resistance training; load; systematic review.

3. Introduction

Resistance training (RT) is the only non-pharmacological intervention known to improve strength and induce skeletal muscle hypertrophy [1]. While the manipulation of various RT parameters (e.g., volume [2], intensity [3], frequency [4], and rest periods [5]) can influence RT outcomes, both the volume [defined as either volume load (sets * repetitions * load) or set volume (number of sets completed irrespective of repetitions and load)] and intensity of RT seem to have the greatest influence on muscle hypertrophy and strength development [6]. Defining RT intensity is contentious [7, 8] and may describe either the loads lifted (which define absolute and relative intensity), or the degree of effort applied, during a set [6]. Previous studies exploring the influence of RT loads on physiological adaptations have shown comparable muscle hypertrophy across a wide spectrum of loads [3, 9], and greater dynamic, but not isometric, strength gains with higher- versus lower loads [3]. For example, a meta-analysis by Schoenfeld and colleagues [3] found muscle hypertrophy and isometric strength development was similar with higher-load (>60% 1-RM or ≤15-RM) versus lower-load (≤60% 1-RM or >15-RM) RT, while higher-load RT promoted greater dynamic 1-RM strength gain. Lopez and collegues [9] also noted superior dynamic 1-RM strength gain for both high-load (≤8-RM) and moderate-load (9-15-RM) RT versus low-load RT (>15-RM), and no influence of RT load on muscle hypertrophy.

Current meta-analytic evidence [3, 9] therefore highlights the versatility of RT loads for promoting muscle hypertrophy and the superiority of higher RT loads for improving dynamic 1-RM strength. There are, however, a number of methodological considerations when interpreting the role of RT load in promoting muscle hypertrophy and maximal strength development. Assessing muscle hypertrophy with RT is particularly complex, due not only to ambiguity in its definition as a biological construct, but also given the many tools available to assess indices of muscle hypertrophy at multiple physiological levels (e.g., whole-body versus whole-muscle or muscle fibre-specific measures), with variability in aspects of validity, reliability, and specificity between measures [10]. Such complexities are highlighted by the divergent magnitudes of muscle hypertrophy observed at different physiological levels after the same RT intervention [e.g., greater changes in muscle fibre versus whole-muscle vastus lateralis CSA (cross-sectional area)] [11-13], and that certain measures [e.g., whole-body measures such as DXA (dual x-ray absorptiometry)] are less sensitive for detecting RT-induced muscle hypertrophy versus other gold-standard measures of whole-muscle size [e.g., MRI (magnetic resonance imaging) or CT (computed tomography)] [14]. For these reasons, the measures used to assess muscle hypertrophy can strongly influence conclusions on the influence of RT parameters, including load, on these outcomes. While some meta-analyses examining the influence of RT load on physiological adaptations analysed different muscle hypertrophy outcomes (i.e., lean body mass, whole-muscle CSA, and muscle fibre CSA) seperately [3], others combined various indices of muscle hypertrophy into a single outcome [9]. The latter approach is likely problematic [15], as it precludes insight into the influence of RT load on muscle hypertrophy outcomes known to respond divergently to RT interventions. An updated analysis of the influence of RT loads on various indices of muscle hypertrophy seperately is therefore warranted to ensure conclusions are specific to the measures of muscle hypertrophy used in individual studies.

In addition to muscle hypertrophy outcomes, various methodological considerations apply when determining the influence of RT load on maximal strength. Strength may be assessed using multiple methods, including dynamic strength [typically the one-repetition maximum (1-RM)], isometric strength, or isokinetic strength. Because strength is a highly task-specific phenomenon [16], improvements in strength with RT depend on various elements of specificity (e.g., movement pattern, range of motion, lifting velocity, and intensity/load specificity). Because of these factors, the magnitude of strength gain with RT is largest when the measures used to assess strength mimic the RT intervention itself. This concept is highlighted by observations that higher-load RT elicits superior strength gains versus lower-load RT when strength is assessed during measures that mimic higher-load RT (i.e., dynamic 1-RM strength) [3, 9], but not when assessed using measures non-specific to either loading condition (i.e., isometric strength) [3, 17]. It is therefore recommended that studies comparing strength outcomes between multiple RT conditions (e.g., higher- versus lower-load RT) assess multiple strength measures to avoid potentially biased outcomes due to task specificity [18]. Only one [3] of the three [3, 9] meta-analyses performed to date analysed the effects of RT load on multiple strength outcomes (i.e., both dynamic 1-RM and isometric strength, while the meta-analysis of isokinetic strength outcomes was not possible due to insufficient data [3]), with one combining multiple strength assessments into a single outcome [19], and the other only assessing dynamic 1-RM strength [9]. Determining the influence of RT load on multiple strength outcomes is therefore necessary to determine whether advantages of higher-load RT for dynamic 1-RM strength gain are likely mediated by task specificity, or whether these benefits transfer to strength gain during non-specific measures (i.e., isometric or isokinetic strength).

To control for factors independent of RT load *per se* that might influence physiological adaptation to RT, such as intensity-of-effort (commonly defined as the proximity to which a set is taken to momentary muscular failure [20]), previous meta-analyses [3, 9] have only included studies whereby higher- and lower-load RT sets were performed to muscular failure. While this approach theoretically ensures the degree of muscle activation – and therefore presumably the stimuli for muscle hypertrophy – is similar for higher- and lower-load RT, there are also limitations with this approach. In particular, while intensity-of-effort is considered an important determinant of muscle hypertrophy with RT, it appears less important for strength development [6]. Excluding studies that compared higher- versus lower-load RT performed at sub-maximal intensities-of-effort therefore precludes insight into the influence of RT load on physiological adaptations (particularly strength outcomes) independent of the proximity to which RT is performed to muscular failure. Such insights are of high practical importance, as consistently performing RT to muscular failure is not feasible for many individuals due to differences in motivation and tolerances to exertion and discomfort [21]. In addition, perceptions of discomfort may limit an individuals' ability to reach true muscular failure, particularly with lighter RT loads [15] invalidating the assumption that higher- and lower-load RT performed to muscular failure involves near-equivalent muscle activation. Further work is therefore required to elucidate the influence of load on physiological adaptations to RT involving various intensities-of-effort, and to determine whether intensity-of-effort may have independently influenced these adaptations.

Previous systematic reviews and meta-analyses investigating the influence of RT load have focused on strength and muscle hypertrophy outcomes [3, 9, 19], but the influence of RT load on changes in sport-specific (e.g., jumping, sprinting and change of direction) or neuromuscular [e.g., countermovement jump (CMJ) and isometric mid-thigh pull (IMTP)] performance tasks has not been investigated. Maximal strength contributes to improvements in sport-specific performance tasks such as jumping, sprinting and change of direction [22, 23], and improved strength enhances mechanical power and rates of force development, both of which are key components of athletic performance [22]. It is therefore possible that because strength relates to performance in sport-specific and neuromuscular performance tasks, performance in these tasks will be further improved with RT that optimises strength development [22, 23]. It is unclear, however, whether RT load influences changes in performance during sport-specific tasks or in tests related to neuromuscular performance (e.g., CMJ or IMTP).

Various other methodological factors may also influence the role of RT load in physiological adaptations to RT and therefore contribute to heterogeneity between studies. For example, the dose-response relationship between RT volume, which can be modified independently of RT load *per se*, and muscle hypertrophy (up to an undertermined threshold) [2] may influence comparisons of muscle hypertrophy following high- versus low-load RT interventions not equated for total volume. Other methodological factors, including the age [24] and training experience [25] of participants, may also moderate the influence of RT load on physiological adaptations and should be considered when interpreting the available evidence. This systematic review and meta-analysis therefore aimed to further elucidate the role of RT load in developing various indices of maximal strength (i.e., dynamic 1-RM, isometric, and isokinetic strength), muscle hypertrophy (i.e., lean body/fat-free mass, and both whole-muscle and muscle fibre CSA), and sport-specific or neuromuscular task performance. We also aimed to explore the influence of additional methodological factors (i.e., participant age, training status, and RT intensity-of-effort) that may influence the role of RT load in physiological adaptation to RT.

4. Methods

4.1 Criteria for study selection

4.1.1 Population

Studies of participants of any age, sex, and training history were included. Studies of participants with chronic diseases (e.g., heart disease, type 2 diabetes, cancer, and hypertension) were excluded.

4.1.2 Resistance training intervention

Studies that incorporated resistance training of at least six weeks in duration (which was considered an acceptable duration for substantial changes in both strength and muscle hypertrophy to occur, and was consistent with previous meta-analyses [3, 9, 19]), and included at least one group that performed higher-load RT (>60% 1-RM or <15-RM) and at least one other group that performed lower-load RT (≤60% 1-RM or ≥ 15-RM), were included. Studies incorporating additional modalities that may influence the role of RT load in physiological adaptation (e.g., blood flow restriction or hypoxia) were excluded. In the case of a study that included more than one group undertaking either higher- or lower-load RT, and applied additional factors (e.g., blood flow restriction or a deliberately slow tempo) to some of the groups that may differentially influence adaptation to RT, these additional group(s) were excluded from the analysis (see Table 1).

4.1.3 Assessment of strength, muscle hypertrophy, and sport-specific or neuromuscular task performance

Studies that included a measure of either maximal strength (dynamic 1-RM or ≤5-RM strength, isometric [maximal voluntary isometric contraction (MVIC)] strength, or isokinetic strength) and/or muscle hypertrophy (muscle thickness, whole-limb or muscle CSA or volume, muscle fibre CSA (fCSA), or lean body/fat free mass via dual x-ray absorptiometry

(DXA) or bioelectrical impedance analysis (BIA)) and/or sport-specific (e.g., jumping, sprinting, or changing-of-direction) or neuromuscular (e.g., CMJ or IMTP) task performance were included.

4.2 Search strategy and study identification

The literature search followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines [26]. Literature searches of the PubMed, SCOPUS and SPORTDiscus databases were conducted in August 2020 using the following search terms for each individual database:

1. "resistance training" OR "resistance exercise" OR "strength training"
2. "high load" OR "high-load" OR "low load" OR "low-load" OR "high intensity" OR "high-intensity" OR "low intensity" OR "low-intensity"
3. strength OR "maximal strength" OR "isometric strength" or "isokinetic strength" OR "maximal force" OR MVC OR MVIC OR 1RM OR 1-RM OR "1 RM" OR "one repetition maximum" or "one-repetition maximum" OR sprint* OR "vertical jump" OR "countermovement jump" OR CMJ OR "isometric mid-thigh pull" OR "isometric mid thigh pull" OR "isometric midthigh pull" OR IMTP
4. "muscle hypertrophy" OR "muscle size" OR "muscle growth" OR "muscle mass" OR "muscle thickness" OR "cross-sectional area"

An overview of the article identification process is shown in Figure 1. Conference abstracts, review articles, commentaries, or duplicated data in publications were excluded from the analysis. The article identification process was completed independently by two authors (MR and JF) with any disagreement resolved by mutual discussion.

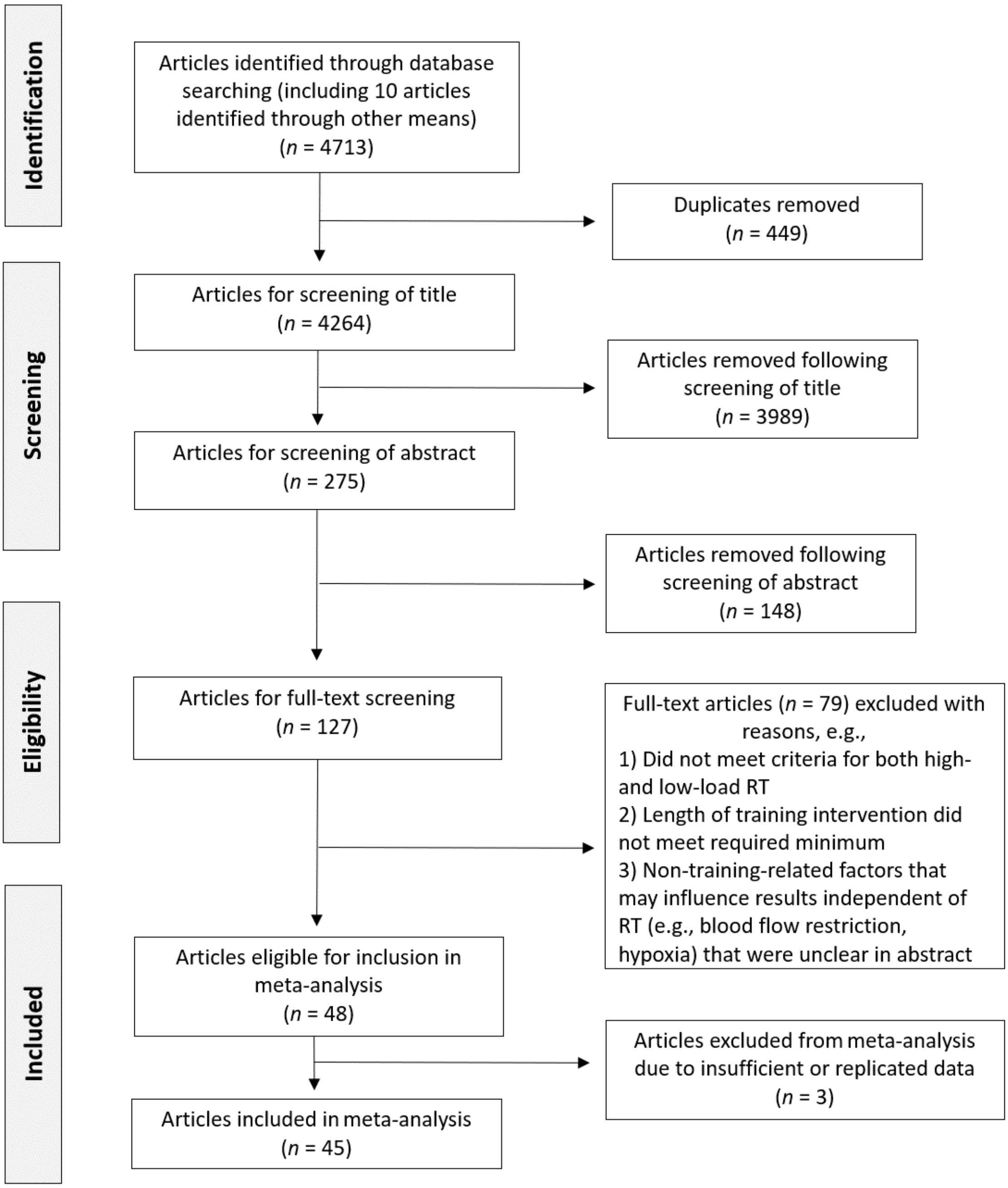

Figure 1. PRISMA flow chart of systematic literature search and article selection process.

4.3 Data extraction

Relevant characteristics of each study were extracted into an Excel spreadsheet (Supplementary File A). Where study outcomes were presented in figures instead of numerical data, data was extracted using an online tool (WebPlotDigitizer, San Francisco, California, USA). Study characteristics included the age (<60 years for younger, ≥60 years for older), sex, and training status (trained or untrained as pertains to RT) of participants, details of the RT intervention including the number of sets, repetitions and loads used, duration of the intervention, training frequency per week, muscle groups trained, and raw data from pre- and post-intervention for all relevant outcome measures. A summary of the characteristics of each included study and sub-group included in the meta-analysis is presented in Table 1.

4.4 Methodological quality assessment

Evaluation of methodological study quality was conducted using the tool for the assessment of study quality and reporting in exercise (TESTEX) scale [27] and is shown in Table 2. The TESTEX scale is an exercise science-specific scale, designed for use by exercise specialists, to assess the quality and reporting of exercise training trials. The scale contains 12 criteria that can either be scored a 'one' or not scored at all; 1, eligibility; 2, randomisation; 3, allocation concealment; 4, groups similar at baseline; 5, assessor blinding; 6, outcome measures assessed in 85% of patients (3 possible points); 7, intention-to-treat; 8, between-group statistical comparisons (2 possible points); 9, point-estimates of all measures included; 10, activity monitoring in control groups; 11, relative exercise intensity remained constant; 12, exercise parameters recorded. As items 5 and 6 each have three sub-criteria (with two of the sub-criteria for item 5 scored as yes/no and therefore not scored numerically), and item 8 has two sub-criteria, the a best possible total score is 15 points.

4.5 Calculation of effect size and statistical analysis

Within the studies, the average value of the means and average standard deviation for each outcome measure at both pre- and post-intervention were calculated for both high-load and low-load groups. For the analysis of muscle hypertrophy outcomes, studies that assessed changes in whole-muscle size (i.e., muscle thickness, muscle cross-sectional area, or muscle volume using ultrasound, MRI, or CT) were combined, while studies assessing muscle fCSA (via muscle biopsy) or lean body/fat free mass (via DXA, BIA, or BodPod) were analysed seperately. The average standard deviation was calculated using the formula proposed in the Cochrane Handbook for Systematic Reviews [28]. After calculating the average mean and the average standard deviation pre- and post-intervention for each study, we determined the mean change (post minus pre) and the standard deviation change [29] for the high-load and low-load groups. These values were used in RevMan5 (Review Manager (RevMan), V.5.4; Cochrane Collaboration) with a Random-Effects model to calculate the standardised mean difference (SMD) between treatments (high-load versus low-load). Effect size (ES) values were interpreted according to Cohen [30], whereby values of 0.2 to 0.49 indicate small, 0.50 to 0.79 indicate medium, and ≥0.80 indicate large, effects. Heterogeneity was assessed using the I^2 statistic and/or the standard deviation (SD) derived from the study-estimate random effect (represented as Tau^2).

Table 1. Summary of the characteristics of all included studies.

Abbreviations: 1-RM, one-repetition maximum; BB, barbell; BB, biceps brachii; CSA, cross-sectional area; CT, computerised tomography; DXA, dual x-ray absorptiometry; fCSA, fibre cross-sectional area; GM, gluteus maximus; LBM, lean body mass; MRI, magnetic resonance imaging; MVIC, maximum voluntary isometric contraction; PM, pectoralis major; QF, quadriceps femoris; RF, rectus femoris; Reps, repetitions; RM, repetition maximum; TB, triceps brachii; VL, vastus lateralis; VM, vastus medialis; ‡ = group excluded from the meta-analysis; ↑ = increased; = ↓ decreased, = ↔ no change or difference.

Study	**Participants**	**Age (mean ± SD)**	**RT intervention**	**Intervention duration (sessions/week)**	**Interventions equated for total volume**	**RT performed to volitional failure**	**Outcome measures**	**Key findings**
Aagaard et al. 1994 [31]	Younger male elite soccer players (*n*=24)	23 ± 3.4 y	High-load: 4 * 8-RM	12 weeks (3 /week)	No	Yes	Isokinetic strength (knee extension/flexion)	↑ Isokinetic strength for the high-load group only.
			Low-load: 4 * 24-RM					
			Loaded kicking movements‡					

			Control group (no exercise)‡					
Anderson & Kearney 1982 [32]	Younger untrained males (*n*=43)	20.7 ± 1.8 y	High-load: 3 * 6–8-RM Low load: 3 * 30–40-RM Low load: 1 * 100–150-RM	9 weeks (3/week)	No	Yes	1-RM strength (bench press)	↑ 1-RM strength for both groups, with greater ↑ in 1-RM strength for the high-load vs. low-load groups.
Au et al. 2017 [33]	Younger trained males (*n*=46)	23 ± 2.3 y	High-load: 3 * 8–12 reps (75-90% 1-RM) Low-load: 3 * 20–25 reps (30-50% 1-RM) Control group (maintained physical activity)‡	12 weeks (4/week)	No	Yes	1-RM strength (bench press and leg press) Lean body mass (BodPod)	↑ 1-RM strength for both groups, with greater ↑ in 1-RM bench press strength for the high-load group. ↑ LBM for both groups, with no between-group differences.

Beneka et al. 2005 [34]	Older males and females (*n*=64)	68.8 ± 4.2 y	High-load 1: 3 * 4–6 reps (90% 1-RM) High-load 2: 3 * 8–10 reps (70% 1-RM) Low-load: 3 * 12–14 reps (50% 1-RM) Control group (no exercise)‡	16 weeks (3/week)	No	No	Isokinetic strength (knee extension)	↑ Isokinetic strength at all velocities other than $180°·s^{-1}$ for all groups, with greater ↑ in the high-load group for 60, 90 and $120°·s^{-1}$.
Bezerra et al. 2019 [35]	Older untrained males (*n*=18)	63.4 ± 6.1 y	High-load: 3 * 5-RM Low-load: 1 * 15-RM	12 weeks (2/week)	No	Yes (only for seated row)	5-RM strength (seated row)	↑ 5-RM strength for both groups, with no between group differences.
Campos et al. 2002 [36]	Younger untrained males (*n*=32)	22.5 ± 5.8 y	High-load 1: 4 * 3-5-RM	8 weeks (2-3/week)	Yes	Yes	1-RM strength (squat, leg press, knee extension)	↑ 1-RM strength for all groups, with greater ↑ in the high-load groups.

			High-load 2: 3 * 9-11RM Low-load: 2 * 20–28-RM Control group (no exercise)‡				Muscle fCSA (biopsy; VL)	↑ VL fCSA for the high-load groups only.
De Vos et al. 2005 [37]	Older untrained males (*n*=100)	68.5 ± 5.7 y	High-load: 3 * 8 reps (80% 1-RM) Low-load 1: 3 * 8 reps (20% 1-RM) Low-load 2: 3 * 8 reps (50% 1-RM) Control group (no exercise)‡	8-12 weeks (2/week)	Yes	No	1-RM strength (leg press, chest press, knee extension, seated row, leg curl)	↑ Total 1-RM strength for all groups, with greater ↑ in the high-load group.

Fatouros et al. 2006 [38]	Older untrained males (*n*=50)	70.4 ± 3.8 y	High-load: 3 * 10 reps (80% 1-RM) Low-load 1: 3 * 10 reps (40% 1-RM) Low-load 2: 3 * 10 reps (60% 1-RM) Control group (no exercise)‡	24 weeks (3/week)	Yes	No	1-RM strength (leg press, chest press)	↑ 1-RM strength for all groups, with greater ↑ in the high-load group.
Fink et al. 2016 [39]	Younger male gymnastics athletes (*n*=21)	23.3 ± 2.7 y	High-load: 3 sets at 80% 1-RM Low-load: 3 sets at 30% 1-RM Mixed load: – alternated protocols every 2 weeks‡	8 weeks (3/week)	No	Yes	MVIC strength (elbow flexors) Muscle CSA (MRI; elbow flexors)	↑ MVIC strength for the high-load group only. ↑ Elbow flexor CSA for all groups, with no between-group differences.

Franco et al. 2019 [40]	Younger untrained females (*n*=32)	23.7 ± 3.9 y	High-load: 3 * 8–10-RM Low-load: 3 * 30–35-RM	9 weeks (2/week)	No	Yes	1-RM strength (leg extension) Fat and bone free lean mass (DXA)	↑ 1-RM strength for both groups, with no between-group differences. ↑ Fat-free/lean mass for both groups, with greater ↑ in the low-load group.
Harris et al. 2004 [41]	Older untrained males and females (*n*=61)	71.2 ± 5.1 y	High-load 1: 4 * 6-RM High-load 2: 3 * 9-RM Low-load: 2 * 15-RM Control group (no exercise)‡	18 weeks (2/week)	No	Yes	1-RM strength (knee extension, leg press, leg curl, biceps curl, triceps extension, lat pull-down, shoulder press, bench press)	↑ Total 1-RM strength in all groups, with no between-group differences.
Hisaeda et al. 1996 [42]	Younger untrained females (*n*=11)	20.1 ± 1.6 y	High-load: 8–9 sets of 4–5-RM	8 weeks (3/week)	Yes	N/A	Isokinetic strength (knee extension)	↑ Isokinetic strength for both groups, with no between-group differences.

			Low-load: 5–6 sets of 15–20-RM				Muscle CSA (MRI; QF, RF, VL, VM, VI)	↑ Thigh (VL, VM, RF) CSA for both groups, with no between-group differences.
Holm et al. 2008 [43]	Younger untrained males (*n*=11)	24.7 ± 1.1 y	High-load: 10 * 8 reps (70% 1-RM) Low-load: 10 * 36 reps (15.5% 1-RM)	12 weeks (3/week)	Yes	No	1-RM strength (knee extension) MVIC strength (knee extension) Isokinetic strength (knee extension) Muscle CSA (MRI; QF)	↑ 1-RM strength for both groups, greater increases in the high-load group. ↑ MVIC and isokinetic strength for the high-load group only. ↑ VL CSA for both groups, greater ↑ in the high-load group.
Hortobagyi et al. 2001 [44]	Older untrained males (*n*=37)	72 ± 4.7 y	High-load: 5 * 4–6 reps (80% 1-RM) Low-load: 5 * 8–12 reps (40% 1-RM)	10 weeks (3/week)	No	No	1-RM strength (leg press) MVIC strength (knee extension)	↑ 1-RM and MVIC strength for both groups, with no between-group differences. ↑ Concentric and eccentric isokinetic strength only with both conditions combined,

			Control group (no exercise)‡				Isokinetic strength (knee extension)	with no between-group differences.
Ikezoe et al. 2017 [45]	Younger untrained males (*n*=15)	23.1 ± 2.6 y	High-load: 3 * 8 reps (80% 1-RM) Low-load: 12 * 8 reps (30% 1-RM)	8 weeks (3/week)	No	No	1-RM strength (knee extension) MVIC strength (knee extension) Muscle thickness (ultrasound; RF)	↑ 1-RM and MVIC strength for both groups, with no between-group differences. ↑ RF thickness for both groups, with no between-group differences.
Jenkins et al. 2017 [46]	Younger untrained males (*n*=26)	23.1 ± 4.7 y	High-load: 3 sets at 80% 1-RM Low-load: 3 sets at 30% 1-RM	6 weeks (3/week)	No	Yes	1-RM strength (knee extension) MVIC strength (knee extension) Muscle thickness	↑ 1-RM and MVIC strength for both groups, with greater ↑ in the high-load group. ↑ Muscle thickness (VL, VM, RF) for both groups, with no between-group differences.

							(ultrasound; VL, VM, RF)	
Jessee et al. 2018 [47]	Younger untrained males and females (*n*=40)	21 ± 2 y	High-load: 4 sets at 70% 1-RM Low-load 1: 4 sets at 15% 1-RM Low-load 2: 4 sets at 15% 1-RM (40% arterial occlusion pressure)‡ Low-load 3: 4 sets at 15% 1-RM (80% arterial occlusion pressure)‡	8 weeks (2/week)	No	Yes	1-RM strength (knee extension) MVIC strength (knee extension) Isokinetic strength (knee extension) Muscle thickness (ultrasound; anterior and lateral thigh at 30%, 40%, 50%, and 60% femur length)	↑ 1-RM strength for the high-load group only. ↑ MVIC and isokinetic (at 180°·s^{-1} but not 60°·s^{-1}) strength for both groups, with no between-group differences. ↑ Thigh muscle thickness for both groups, with no between-group differences.
Jones et al. 2001 [48]	Younger trained males (*n*=26)	20.6 ± 1.4 y	High-load: 4 * 3–10 reps (70–90% 1-RM)	10 weeks (2/week)	No	No	1-RM strength (squat)	↑1-RM strength for both groups, with greater increases in the high-load group.

			Low-load: 4 * 5–15 reps (40–60% 1-RM)				Jump performance (set angle jump, squat jump, depth jump)	↑ Peak force for both groups in 50% 1-RM squat jump and set angle jump only. ↑ Peak power for both groups in 30% 1-RM and 50% 1-RM squat jump only. ↑ Peak velocity for both groups in depth jump only. No between-group differences.
Kalapotharakos et al. 2004 [49]	Older untrained males (*n*=33)	64.9 ± 4.2 y	High-load: 3 * 8 reps (80% 1-RM) Low-load: 3 * 15 reps (60% 1-RM) Control group (no exercise)‡	12 weeks (3/week)	No	No	1-RM strength (knee extension, knee flexion, elbow extension, elbow flexion, lat-pulldown, chest press) Isokinetic strength (knee extension/flexion) Muscle CSA	↑ 1-RM strength for both groups, with greater ↑ in the high-load group. ↑ Isokinetic strength for both groups at 60 and 180°·s^{-1}, with greater ↑ in the high-load group. ↑ Midthigh CSA for both groups, with greater ↑ in the high-load group.

							(CT; mid-thigh)	
Kerr et al. 1996 [50]	Postmenopausal females (*n*=56)	57.1 ± 4.2 y	High load: 3 * 8-RM Low load: 3 * 20-RM	52 weeks (2/week)	No	No	1-RM strength (wrist curl, reverse wrist curl, wrist pronation/supination, biceps curl, triceps pushdown, hip extension, hip flexion, hip abduction, hip adduction, leg press)	↑ 1-RM strength for both groups, with no between-group differences.
Lasevicius et al. 2018 [51]	Younger untrained males (*n*=30)	24.5 ± 2.4 y	High-load 1: 3 sets at 80% 1-RM High-load 2: 3 sets at 60% 1-RM Low-load 1: 3 sets at 20% 1-RM	12 weeks (2/week)	Yes	Yes	1-RM strength (leg press, elbow flexion) Muscle thickness (ultrasound; elbow flexors, VL)	↑ 1-RM strength for all groups, with greater ↑ in the high-load 1 (80% 1-RM) group. ↑ Elbow flexor and VL thickness for all groups, with greater ↑ in the high-load 1 (80% 1-RM) group.

			Low-load 2: 3 sets at 40% 1-RM					
Lasevicius et al. 2019 [52]	Younger untrained males (*n*=25)	19–34 y (overall mean ± SD not provided)	High-load 1: 3 sets at 80% 1-RM (2 min) Low-load 1: 3 sets at 30% 1-RM (2 min) High-load 2: 3+ sets at 80% 1-RM (2 min)‡ Low-load 2: 3+ sets at 30% 1-RM (2 min)‡	8 weeks (2/week)	Yes	Yes Yes No No	1-RM strength (knee extension) Muscle CSA (MRI; QF)	↑ 1-RM strength for all groups, with greater ↑ in the high-load groups. ↑ QF muscle CSA for both high loads groups and low-load to failure, with no-between group differences. ↔ In outcome measures for low load not to failure.
Lim et al. 2019 [53]	Younger untrained males (*n*=21)	Mean ages 23–24 y per group	High-load: 3 sets at 80% 1-RM Low-load 1: 3 sets at 30% 1-RM	10 weeks (3/week)	No	Yes	1-RM strength (leg extension) Isokinetic	↔ In 1-RM strength for either group. ↑ Isokinetic strength for low-

		(overall mean ± SD not provided)	(volume-matched to high-load) Low-load 2: 3 sets at 30% 1-RM				strength (knee extension) Muscle fCSA (biopsy; VL)	load 2 at 240°·s^{-1}, ↔ observed in the other groups. ↑ Type I muscle fibre CSA for high-load and low-load 2, with ↔ observed in low-load 1. ↑ Type II muscle fibre CSA were found in all groups. No between-group differences.
Mitchell et al. 2012 [17]	Younger untrained males (*n*=18)	21 ± 0.8 y	High-load 1: 3 sets at 80% 1-RM	10 weeks (3/week)	No	No	1-RM strength (knee extension)	↑ MVIC and 1-RM strength for all groups, with greater ↑ in 1-RM strength in the high load groups.
			High-load 2: 1 set at 80% 1-RM‡			Yes	MVIC strength (knee extensors)	↑ QF CSA and VL fCSA for all groups, with no between-group differences.
			Low-load: 3 sets at 30% 1-RM to the point of fatigue			No	Muscle CSA (MRI, QF)	
							Muscle fCSA (biopsy; VL)	

Morton et al. 2016 [54]	Younger trained males (*n*=49)	23 ± 1 y	High-load: 3 * 8–12 reps (75–90% 1-RM) (1 min) Low-load: 3 * 20–25 reps (30–50% 1-RM) (1 min)	12 weeks (4/week)	No	Yes	1-RM strength (bench press, leg press, shoulder press, knee extension) Lean body mass (DXA) Muscle fCSA (biopsy; VL)	↑ 1-RM strength for both groups, with no between-group differences. ↑ LBM and VL fCSA for both groups, with no between-group differences.
Moss et al. 1997 [55]	Younger trained males (*n*=30)	23.2 ± 3.2 y	High-load: 3–5 * 2 at 90% 1-RM Low-load 1: 3–5 * 10 at 15% 1-RM Low-load 2: 3–5 * 7 at 35% 1-RM	9 weeks (3/week)	No	No	1-RM strength (elbow flexion) Muscle CSA (CT; elbow flexors)	↑ 1-RM strength for all groups, with a greater ↑in the high-load group. ↑ Elbow flexor CSA for the low-load (2) group only.
Nobrega et al. 2018 [56]	Younger untrained males (*n*=27)	23 ± 3.6 y	High-load 1: 3 sets at 80% 1-RM (2 min)	12 weeks (2/week)	No	Yes	1-RM strength (knee extension)	↑ 1-RM strength for all groups, with no between-group differences.

			High-load 2: 3 sets at 80% 1-RM (2 min)			No	Muscle CSA (ultrasound; VL)	↑ VL muscle CSA for all groups, with no between-group differences.
			Low-load 1: 3 sets at 30% 1-RM (2 min)			Yes		
			Low-load 2: 3 sets at 30% 1-RM (2 min)			No		
Ogasawara et al. 2013 [57]	Younger untrained males (*n*=9)	25 ± 3 y	High-load: 3 * 75% 1-RM (3 min)	6 weeks (3/week)	No	No	1-RM strength (bench press)	↑ 1-RM and MVIC strength for both groups, with greater ↑ in the high-load group.
			Low-load: 4 * 30% 1-RM (3 min)				MVIC strength (elbow extensors)	↑ TB and PM CSA for both groups, with no between-group differences.
							Muscle CSA	

							(MRI; PM and TB)	
Popov et al. 2006 [58]	Younger untrained males (*n*=18)	21 ± 2 y	High-load: 3 and 7 * 80% MVC (10 min) Low-load: 3 and 4 * 50% MVC (10 min)	8 weeks (3/week)	No	No	MVIC strength (knee extensors) Muscle CSA (MRI; QF and GM)	↑ MVIC strength for both groups, with no between-group differences. ↑ QF and GM CSA for both groups, with no between-group differences.
Rana et al. 2008 [59]	Younger untrained females (*n*=26)	21.1 ± 2.7 y	High load 1 (TS): 3 * 6–10 RM (80–85% 1-RM) High load 2 (SS): 3 * 6–10 RM (80–85% 1-RM) at intentionally slow velocity‡ Low load (TE): 3 * 20–30 RM (40–60% 1-RM) Control group (no exercise)‡	6 weeks (2-3/week)	No	Yes	1-RM strength (squat, leg press, knee extension) Lean body mass (BodPod) Vertical jump height	↑ 1-RM strength for all groups. Greater ↑ in 1-RM leg press and knee extension strength in the high-load, normal velocity group vs. other groups. ↑ LBM for all groups, with no between-group differences. ↔ in vertical jump height.

Ribeiro et al. 2020 [60]	Older untrained females (*n*=27)	71.5 ± 5.3 y	High-load: 3 * 10-RM Low-load: 3 * 15-RM	8 weeks (3/week)	No	Yes	1-RM strength (chest press, knee extension, preacher curl) Fat-free mass (DXA)	↑ 1-RM strength and fat-free mass for both groups, with no between-group differences.
Richardson et al. 2019 [61]	Older untrained males and females (*n*=40)	66.5 ± 5.3 y	High-load (once-weekly): 3 * 7 (80% 1-RM) High-load 2 (twice-weekly): 3 * 7 (80% 1-RM) Low-load 1 (once-weekly): 3 * 14 (40% 1-RM) Low-load 2 (twice-weekly): 3 * 14 (40% 1-RM) Control (usual activities)‡	10 weeks (1-2/week)	No	Yes	1-RM strength (leg press, calf raise, leg extension, leg curl, seated row, chest press, tricep extension, bicep curl) Lean body mass (bioelectrical impedance analysis)	↑ 1-RM strength for all groups, with greater ↑ in the high-load 2 group. ↔ in LBM for any of the groups.

Schoenfeld et al. 2015 [62]	Younger untrained males (*n*=24)	23.3 (range 18-33) y	High-load: 3 * 8–12-RM Low-load: 3 * 25–35-RM	8 weeks (3/week)	No	Yes	1-RM strength (squat and bench press) Muscle thickness (ultrasound; elbow flexors and extensors, QF)	↑ 1-RM bench press strength for the high-load group only. ↑ 1-RM squat strength for both groups, with a greater ↑ in the high-load group. ↑ Upper arm and QF thickness for both groups, with no between-group differences.
Schoenfeld et al. 2020 [63]	Younger untrained males (*n*=26)	22.5 y (SD not provided)	High-load: 4 * 6–10-RM Low-load: 4 * 20–30-RM	8 weeks (2/week)	No	Yes	MVIC strength (plantar flexors) Muscle thickness (ultrasound; medial and lateral gastrocnemius, soleus)	↑ Isometric strength and muscle thickness for both groups, with no between-group differences.
Schuenke et al. 2012 [64]	Younger untrained females (*n*=34)	21.1 ± 2.7 y	High load 1 (TS): 3 * 6–10 RM (80–85% 1-RM)	6 weeks (2-3/week)	No	Yes	Muscle fCSA (biopsy; VL)	↑ Mean fCSA only for the TS group, with no between-group differences.

			High load 2 (SS): 3 * 6–10 RM (80–85% 1-RM) at intentionally slow velocity‡ Low load (TE): 3 * 20–30 RM (40–60% 1-RM) Control group (no exercise)‡				Fat-free mass (skinfolds)	↔ in fat-free mass for neither group.
Seynnes et al. 2004 [65]	Older untrained males (*n*=14)	82 ± 2.6 y	High-load: 3 * 8 reps (80% 1-RM) Low-load: 3 * 8 reps (40% 1-RM) Control (placebo) group: 3 * 8 reps (unloaded)‡	10 weeks (3/week)	Yes	No	1-RM strength (knee extension)	↑ 1-RM strength for both groups, with a greater ↑ in the high-load group.
Stefanaki et al. 2019 [66]	Younger females not engaging in	29.7 ± 4.7 y	High-load: 1 * 80% of 1-RM	6 weeks (2/week)	No	Yes	1-RM strength (knee extension	↑ 1-RM strength for all groups, with no between-group differences.

	more than 2 hours of RT/wk (*n*=13)		Low-load: 1 * 30% 1-RM				and elbow flexion) Muscle thickness (untrasound; VL and BB)	↑ BB and VL muscle thickness for all groups, with no between-group differences.
Stone & Coulter 1994 [67]	Younger untrained females (*n*=50)	23.1 ± 3.5 y	High-load (3 * 6–8-RM) Low-load 1 (3 * 15–20-RM) Low-load 2 (3 * 30–40-RM)	9 weeks (3/week)	No	Unclear	1-RM strength (squat, bench press)	↑ 1-RM strength for all groups, with no between-group differences.
Taaffe et al. 1996 [68]	Older untrained females (*n*=25)	67.3 ± 0.4 y	High-load: 3 x 7 reps (80% 1-RM) Low-load: 3 x 14 reps (40% 1-RM) Control (no exercise)‡	52 weeks (3/week)	No	No	1-RM strength (leg press, knee extension, knee flexion) Muscle fCSA (biopsy; VL)	↑ 1-RM strength for both groups, with no between-group differences. ↑ Type I fCSA for both groups but ↔ in type II fCSA, with no between-group differences. ↔ in thigh LBM in both groups.

							Lean body mass (DXA)	
Tanimoto & Ishii 2006 [69]	Younger untrained males (*n*=24)	19.4 ± 0.6 y	High-load: 3 * 80% 1-RM (normal tempo) Low-load 1: 3 * 50% 1-RM (slow tempo)‡ Low-load 2: 3 * 50% 1-RM (normal tempo)	12 sessions (3/week)	No	Yes	1-RM (knee extension) MVIC strength (knee extensors) Isokinetic strength (knee extensors) Muscle CSA (MRI; QF)	↑ 1-RM strength for all groups, with no between-group differences. ↑ MVIC strength for the high-load group only. ↔ in isokinetic strength at 90, 200 and 300°·s^{-1} in the low-load (slow) group. ↑ in high-load group at 90°·s^{-1} but not 200 and 300°·s^{-1}. ↑ in low-load group at 90 and 200°·s^{-1} but not at 300°·s^{-1}. No between-group differences. ↑ QF CSA for the high-load group only.
Tanimoto et al. 2008 [70]	Younger untrained males (*n*=24)	19.3 ± 0.6 y	High-load: 3 x 80–90% 1-RM (normal tempo)	13 weeks (2/week)	No	Yes	1-RM strength (squat, chest press, lat pull-down, ab bend, back extension, knee	↑ 1-RM strength for both groups, with no between-group differences. ↑ Chest, upper arm, abdomen, subscapula and thigh thickness for both groups, with no

			Low-load: 3 * 55–60% 1-RM (slow tempo) Control group (no exercise)‡				extension) Muscle thickness (ultrasound; chest, anterior and posterior upper arm, abdomen, subscapula, anterior and posterior thigh) Lean body mass (DXA)	between-group differences. ↑ LBM for both groups, with no between-group differences.
Van Roie et al. 2013a [71]	Younger untrained males and females (*n*=36)	21.8 ± 2.1 y	High-load: 1 * 8–12 reps (80% 1RM) Low-load 1: 60 repetitions at 20-25% 1-RM, followed by 1 * 10–12 reps (40% 1-RM)	9 weeks (3/week)	No	Yes Yes	1-RM strength (knee extension) MVIC strength (knee extensors)	↑ 1-RM strength for both groups, with a greater ↑ in the high-load group. ↑ MVIC strength for the high-load group only. ↑ Isokinetic strength for the low-load group only.

			Low-load 2: 1 * 10–12 reps (40% 1-RM) ‡			No	Isokinetic strength (knee extension)	
Van Roie et al. 2013b [72]	Older untrained males and females (*n*=56)	67.9 ± 5.1 y	High-load: 2 * 10–15 reps (80% 1-RM) Low-load 1: 1 * 80–100 reps (20% 1-RM) Low-load 2: 1 * 60 reps (20% 1-RM) + 1 x 10–20 reps (40% 1-RM)	12 weeks (3/week)	No	Yes	1-RM strength (leg press, knee extension) MVIC strength (knee extensors) Isokinetic strength (knee extension) Muscle CSA (CT; thigh)	Greater ↑ in 1-RM strength in the high-load and low-load (2) group vs. low-load (1) group. ↑ MVIC strength for all groups, with no between-group differences. ↑ Isokinetic strength for the high-load group only. ↑ Thigh muscle CSA for all groups, with no between-group differences.
Vargas et al. 2019 [73]	Younger trained males (*n*=20)	27.6 ± 6.7 y	High-load: 3 * 6–8 RM Low-load: 3 * 20–25 RM	8 weeks (4/week)	No	Yes	Lean body mass (DXA)	↑ LBM for the high-load group only.

			Control group (continue with usual exercise habits)‡					
Wallerstein et al. 2012 [74]	Older untrained males (*n*=30)	64.3 ± 4 y	High-load: 2–4 * 4–10 reps (70–90% 1-RM) Low-load: 2–4 * 4–7 reps (30–50% 1-RM) Control group (no exercise)‡	16 weeks (2/week)	Yes	No	1-RM strength (chest press, leg press) Muscle CSA (MRI, QF)	↑ 1-RM strength for both groups, with no between-group differences. ↑ QF CSA for both groups, with no between-group differences.

Table 2. Methodological quality for each included study assessed using the (TESTEX) scale.

	TESTEX scale item																	
Study	**1**	**2**	**3**	**4**	**5a**	**5b**	**5c**	**6a**	**6b**	**6c**	**7**	**8a**	**8b**	**9**	**10**	**11**	**12**	**Total score**
Aagaard et al. (1994)	1	0	0	1	No	No	0	0	0	0	0	0	0	1	0	1	1	**5**
Anderson & Kearney (1982)	1	1	0	1	No	No	0	0	0	0	0	1	1	1	0	1	1	**8**
Au et al. (2017)	1	0	0	1	No	No	0	1	0	1	0	1	1	1	0	1	1	**9**
Beneka et al. (2005)	1	0	0	1	No	No	0	0	0	0	0	1	1	1	0	0	1	**6**
Bezarra et al. (2019)	1	1	0	1	No	No	0	1	1	1	0	1	1	1	0	1	1	**11**
Campos et al. (2002)	1	0	0	1	No	No	0	0	0	0	0	1	1	1	0	1	1	**7**
De Vos et al. (2005)	1	0	0	1	No	No	0	1	1	1	0	1	1	1	0	1	1	**10**
Fatouros et al. (2006)	1	0	0	1	No	No	0	1	0	1	0	1	1	1	0	1	1	**9**
Fink et al. (2016)	1	1	0	1	No	No	0	0	0	0	0	1	0	1	0	1	1	**7**
Franco et al. (2019)	1	1	0	1	No	No	0	0	0	0	0	1	1	1	0	1	1	**8**
Harris et al. (2004)	1	1	1	1	No	No	0	1	1	1	0	1	0	1	0	1	1	**11**
Hisaeda et al. (1996)	1	1	0	1	No	No	0	0	0	0	0	1	1	1	0	1	1	**8**
Holm et al. (2008)	1	1	0	1	No	No	0	1	0	1	0	1	1	1	0	1	1	**10**

Hortobagyi et al. (2001)	1	1	0	1	No	No	0	1	1	1	0	1	1	1	0	1	1	**11**
Ikezoe et al. (2017)	1	0	0	1	No	No	0	0	1	0	0	1	1	1	0	1	1	**8**
Jenkins et al. (2017)	1	1	0	0	No	No	0	1	1	1	0	1	1	1	0	1	1	**10**
Jessee et al. (2018)	1	1	0	0	No	No	0	1	1	1	0	1	1	0	0	0	1	**8**
Jones et al. (2001)	0	1	0	1	No	No	0	0	0	0	0	1	1	1	0	0	1	**6**
Kalapotharakos et al. (2004)	1	1	1	1	No	No	0	1	0	1	0	1	1	1	0	0	1	**10**
Kerr et al. (1996)	1	1	0	1	No	No	0	0	1	1	0	1	1	1	0	1	1	**10**
Lasevicius et al. (2018)	0	1	0	1	No	No	0	0	0	0	0	1	1	1	0	1	1	**7**
Lasevicius et al. (2019)	1	1	0	1	No	No	0	0	0	0	0	1	1	1	0	1	1	**8**
Lim et al. (2019)	1	1	0	1	No	No	0	0	0	0	0	1	1	1	0	1	1	**8**
Mitchell et al. (2012)	1	1	0	1	No	No	0	0	0	0	0	0	1	1	0	0	0	**5**
Morton et al. (2016)	1	1	0	1	No	No	0	1	1	1	0	1	1	1	0	1	1	**11**
Moss et al. (1997)	0	1	1	1	No	No	0	0	0	0	0	1	1	1	0	1	1	**8**
Nobrega et al. (2018)	1	1	1	1	No	No	0	1	0	1	0	1	1	1	0	0	1	**10**
Ogasawara et al. (2013)	1	0	0	1	No	No	0	1	0	1	0	1	1	1	0	1	1	**9**
Popov et al. (2006)	0	0	0	1	No	No	0	0	0	0	0	1	1	1	0	0	0	**4**

Rana et al. (2008)	1	0	0	1	No	No	0	1	0	0	0	1	1	1	0	0	0	**6**
Riberio et al. (2020)	1	1	0	1	No	No	1	1	0	1	0	0	0	1	0	1	1	**9**
Richardson et al. (2019)	1	1	0	1	No	No	0	0	1	0	0	1	1	1	0	1	1	**9**
Schoenfeld et al. (2015)	1	1	0	1	No	No	0	1	1	1	0	1	1	1	0	1	1	**11**
Schoenfeld et al. (2020)	1	1	0	1	No	No	1	1	1	1	0	1	1	1	0	1	1	**12**
Schuenke et al. (2012)	1	1	0	1	No	No	0	0	0	0	0	1	1	1	0	1	1	**8**
Seynnes et al. (2004)	1	1	1	1	No	No	0	1	1	1	0	1	1	1	0	1	1	**12**
Stefanaki et al. (2019)	1	1	0	1	No	No	0	1	0	1	0	1	1	1	0	0	1	**9**
Stone & Coulter (1994)	0	0	0	1	No	No	0	1	0	1	0	1	1	1	0	1	1	**8**
Taaffe et al. (1996)	1	1	0	1	No	No	0	0	0	1	0	1	1	1	0	1	1	**9**
Tanimoto & Ishii (2006)	1	1	0	1	No	No	0	0	0	0	0	1	1	1	0	1	1	**8**
Tanimoto et al. (2008)	1	1	0	1	No	No	0	0	0	0	0	1	1	1	0	1	1	**8**
Van Roie et al. (2013a)	1	1	0	1	No	No	0	0	0	0	0	1	1	1	0	1	1	**8**
Van Roie et al. (2013b)	1	1	0	1	No	No	0	1	0	1	0	1	1	1	0	1	1	**10**
Vargas et al. (2019)	1	1	0	1	No	No	0	0	0	0	0	1	1	1	0	1	1	**8**
Wallerstein et al. (2012)	1	1	0	1	No	No	0	0	0	0	0	1	1	1	0	1	1	**8**

260

5. Results

5.1 Search results

Three of the 48 studies eligible for inclusion after full-text screening were excluded as either the raw pre/post intervention data could not be extracted/could not be provided by the authors [21, 75] or included data previously published in another included study [76]. Additionally, one study [47] was excluded from the analyses of whole-muscle size, isometric (MVIC) strength, and isokinetic strength, and one study [68] was excluded from the analyses of lean body mass and muscle fCSA analysis [68], as the raw pre/post intervention data could not be extracted and could not be provided by the authors for these measures. Thus, 45 studies were included in the meta-analysis. Only two studies [48, 59] included measures of sport-specific or neuromuscular task performance, and the findings of these studies are therefore summarised qualitatively.

5.2 Methodological quality assessment

The methodological quality of included studies was assessed using the TESTEX scale [27]. Study quality scores ranged from 4 to 12 (out of a possible 15), with mean and median scores of 9 and 8, respectively (Table 2). Based on the range of study quality scores, we defined low, medium and high quality scores as between 4-7 (n = 9), between 8-10 (n = 29), and ≥11 (n = 7), respectively, which ensured an approximately even distribution of studies across subgroups.

We then performed subgroup analyses to examine whether study quality may have contributed to the heterogeneity observed for the 1-RM, isometric, and isokinetic strength analyses. For the 1-RM strength analysis, no heterogeneity ($I^2 = 0\%$) was observed in the high-quality group (n=6), while both the moderate- ($I^2 = 64\%$) and low-quality ($I^2 = 43\%$)

subgroups showed high degrees of heterogeneity (Supplementary Figure 1). There was, however, no difference in outcomes between methodological quality subgroups (*P* = 0.36).

Study quality appeared to influence heterogeneity in the isometric strength analysis (Supplementary Figure 2), with an inverse relationship between study quality and heterogeneity (I^2 values of 0%, 31%, and 68% for high-, moderate-, and low-quality studies, respectively). There was, however, no difference in outcomes between methodological quality subgroups (*P* = 0.14). Study quality did not explain heterogeneity in the isokinetic strength meta-analysis (Supplementary Figure 3), with I^2 values of 0% and 47% for moderate- and low-quality studies, respectively, while only a single high-quality study was included. There was no difference in outcomes between methodological quality subgroups (*P* = 0.96). While low heterogeneity (I^2 = 0-10%) was observed in the analyses for whole-muscle size, muscle fibre CSA, and lean body/fat-free mass, subgroup analyses (Supplementary Figures 4-6) nevertheless confirmed there was no influence of study quality on heterogeneity or outcomes.

5.3 Meta-analysis results

Dynamic 1-RM strength

A total of 36 studies measured dynamic 1-RM strength in one or more of the following exercises: bench press, chest press, overhead press, seated row, lat pulldown, forearm flexion, elbow extension, elbow flexion, leg press, squat, knee extension, knee flexion, back extension, and abdominal bend. Twenty [17, 32, 33, 36-38, 43, 46-49, 51, 52, 55, 57, 59, 61, 62, 65, 71] out of the 36 studies found greater improvements in 1-RM strength with high-load compared to low-load RT, while equivalent improvements between both loading conditions were noted in 15 studies [40, 41, 44, 45, 50, 54, 56, 60, 66-70, 72, 74]. One study [35] measured dynamic 5-RM strength (for the seated row exercise) and found equivalent improvements between high-load and low-load RT.

Meta-analytic outcomes for dynamic 1-RM strength are shown in Figure 2 and included 537 and 650 ES values from 36 studies for high-load and low-load RT, respectively. There was an advantage for high-load RT versus low-load RT on dynamic 1-RM strength (ES = 0.34, 95% CI: 0.15 to 0.52; $P = 0.0003$). Moderate heterogeneity amongst studies was observed ($Tau^2 = 0.17$, $I^2 = 55\%$, $P = 0.0001$).

Sub-group analyses for dynamic 1-RM strength outcomes revealed an advantage for high-load versus low-load RT in untrained (ES = 0.37, 95% CI: 0.15 to 0.59; $P = 0.0009$) but not trained (ES = 0.21, 95% CI: -0.14 to 0.55; $P = 0.24$) participants (Figure 2). There was also a larger advantage for high-load versus low-load RT in younger (ES = 0.41, 95% CI: 0.14 to 0.68; $P = 0.003$) versus older (ES = 0.20, 95% CI: 0.00 to 0.40; $P = 0.05$) participants (Supplementary Figure 7). However, there were no statistically significant differences between dynamic 1-RM strength outcomes for studies in untrained versus trained participants ($P = 0.59$) or in younger versus older participants ($P = 0.23$).

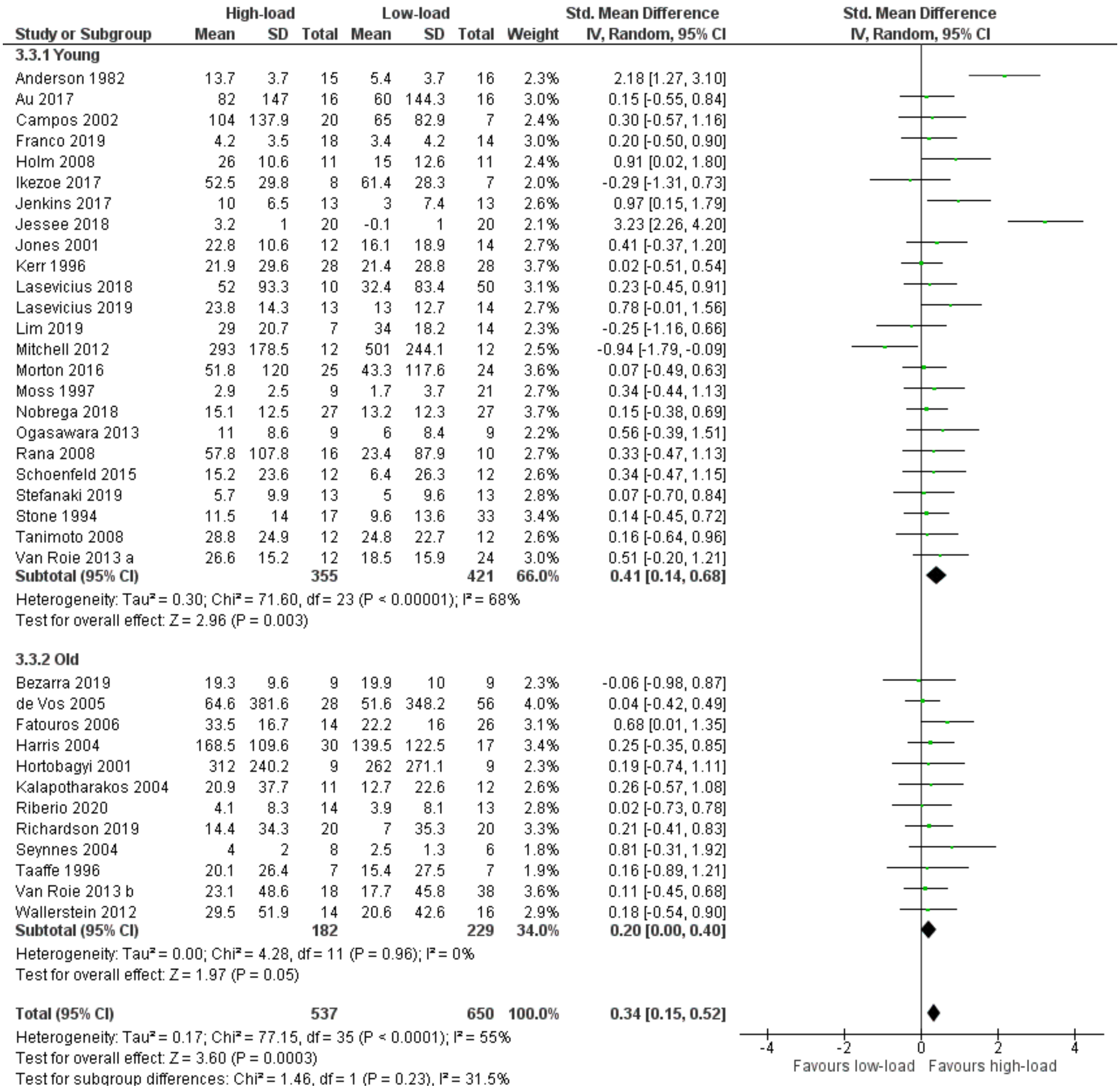

Figure 2. Influence of high-load vs. low-load RT on dynamic 1-RM strength development with subgroup analyses based on studies in younger (<60 years) versus older (≥60 years) participants. Point estimates and error bars signify the standardised mean difference between high-load and low-load groups and 95% confidence interval (CI) values, respectively.

Isometric [maximum voluntary isometric contraction (MVIC)] strength

A total of 15 studies measured isometric (MVIC) strength, with eight of these studies [17, 31, 39, 43, 46, 57, 69, 71] showing an advantage of high-load RT, and no studies suggesting an advantage of low-load RT. The remaining seven studies [42, 44, 45, 47, 58, 63, 72] found equivalent improvements between loading conditions.

Meta-analytic outcomes for isometric (MVIC) strength are shown in Figure 3 and included 136 and 166 ES values from 14 studies for high-load and low-load RT, respectively. Overall there was an advantage for high-load RT versus low-load RT on isometric (MVIC) strength (ES = 0.41, 95% CI: 0.07 to 0.76; $P = 0.02$). Moderate heterogeneity amongst studies was observed ($Tau^2 = 0.20$, $I^2 = 49\%$, $P = 0.02$).

Sub-group analyses (Figure 3) showed an advantage for high-load RT versus low-load RT on isometric (MVIC) strength in younger participants (ES = 0.53, 95% CI: 0.13 to 0.92; $P = 0.009$), while only two studies used older participants.

There was also an advantage for high-load RT versus low-load RT on isometric (MVIC) strength in untrained participants (ES = 0.42, 95% CI: 0.04 to 0.80; $P = 0.03$), but not for participants whose training status was unclear (ES = 0.40, 95% CI: -0.78 to 1.58; $P = 0.51$; Supplementary Figure 8). No included studies measured isometric (MVIC) strength in trained participants.

However, there were no statistically significant differences in isometric (MVIC) strength outcomes for untrained versus trained participants ($P = 0.97$) or younger versus older participants ($P = 0.06$).

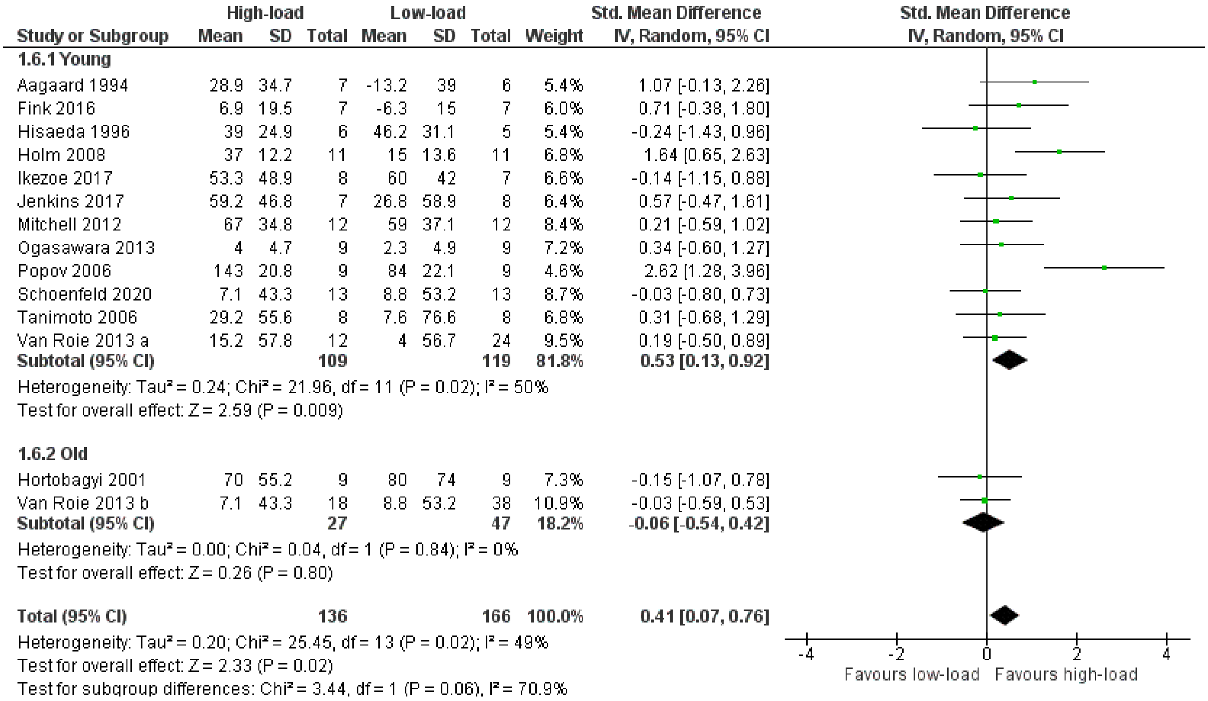

Figure 3. Influence of high-load vs. low-load RT on isometric (MVIC) strength development with subgroup analyses based on studies in younger (<60 years) versus older (≥60 years) participants. Point estimates and error bars signify the standardised mean difference between high-load and low-load groups and 95% confidence interval (CI) values, respectively.

Isokinetic strength

A total of 11 studies investigated the effects of high-load and low-load RT on isokinetic strength and showed inconsistent results. Five [31, 34, 43, 49, 72] of the 11 studies demonstrated greater increases in isokinetic strength with high-load compared to low-load RT, four studies [42, 44, 47, 69] found equivalent increases for both loading conditions, and two studies [53, 71] showed an advantage to low-load RT.

Meta-analytic outcomes for isokinetic strength are shown in Figure 4 and included 121 and 143 ES values from ten studies for high-load and low-load RT, respectively. Overall there was no difference between high-load and low-load RT for isokinetic strength (ES = 0.19, 95% CI: -0.10 to 0.49; *P* = 0.20). Low heterogeneity between studies was observed (Tau^2 = 0.05, I^2 = 23%, *P* = 0.24).

Sub-group analyses (Figure 4) revealed no difference between high-load RT versus low-load RT in younger participants (ES = 0.25, 95% CI: -0.34 to 0.83; *P* = 0.41) or older participants (ES = 0.16, 95% CI: -0.18 to 0.50; *P* = 0.35).

There was also no difference between high-load RT versus low-load RT on isokinetic strength on isokinetic strength in untrained participants (ES = 0.19, 95% CI: -0.17 to 0.56; *P* = 0.29), while the training status of participants was unclear in one study [31] (Supplementary Figure 9). No included studies that measured isokinetic strength used trained participants.

There were no statistically significant differences between isokinetic strength outcomes for untrained versus trained (*P* = 0.93) or younger versus older participants (*P* = 0.81).

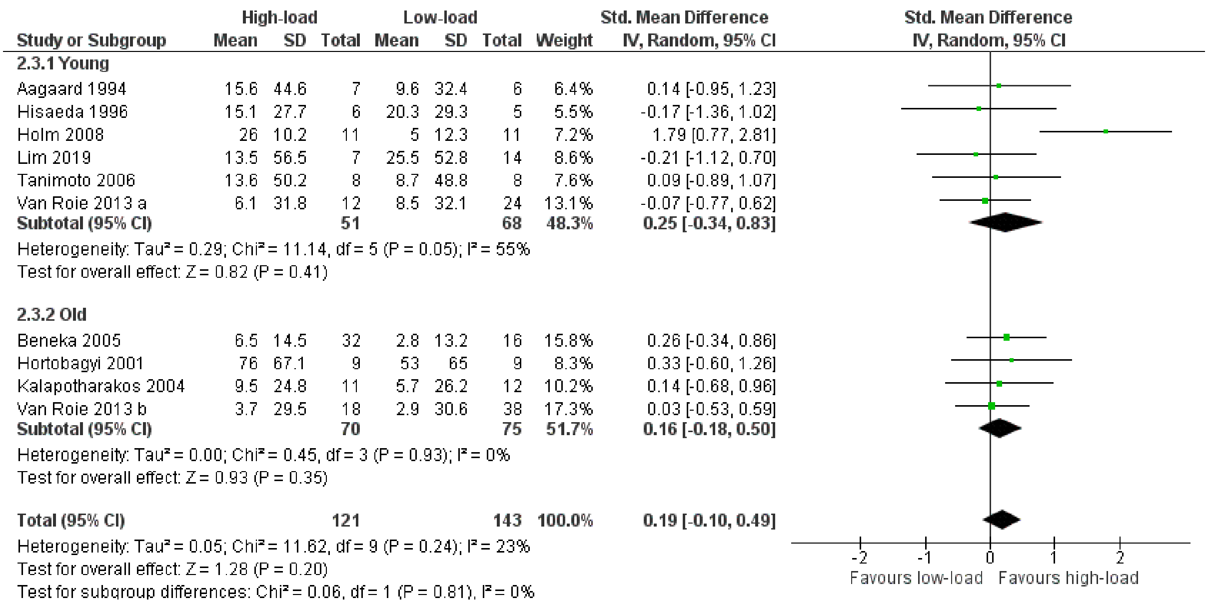

Figure 4. Influence of high-load vs. low-load RT on isokinetic strength development with subgroup analyses based on studies in younger (<60 years) versus older (≥60 years)

participants. Point estimates and error bars signify the standardised mean difference between high-load and low-load groups and 95% confidence interval (CI) values, respectively.

Whole-muscle size

A total of eight studies measured muscle thickness via ultrasound at multiple measurement sites including the upper thigh, lower arm, upper arm and chest. Seven [45-47, 62, 63, 66, 70] of the eight studies identified equivalent increases in muscle thickness between high-load and low-load RT, and one study [51] found greater improvements for high-load RT.

Similar findings to studies measuring muscle thickness were noted in the 13 studies that measured whole-muscle CSA via magnetic resonance imaging (MRI) [17, 39, 42, 43, 52, 57, 58, 69, 74], computerised tomography (CT) scan [49, 55, 72], or ultrasound [56]. This is perhaps not surprising, as muscle thickness (measured by ultrasound) correlates well with muscle CSA as measured by CT or MRI [77]. Of the 13 studies, nine [17, 39, 42, 52, 56-58, 72, 74] identified a similar increase in whole-muscle CSA between high-load and low-load RT groups, three [43, 49, 69] demonstrated an advantage to high-load RT, and only one [55] found greater improvements in the low-load condition.

Meta-analytic outcomes for whole-muscle size are shown in Figure 5 and included 229 and 304 ES values from 20 studies for high-load and low-load RT, respectively. Overall there was no difference between high-load and low-load RT for changes in whole-muscle size (ES = 0.06, 95% CI: -0.11 to 0.24, $P = 0.47$). Low heterogeneity amongst studies was observed ($Tau^2 = 0$, $I^2 = 0\%$, $P = 1.00$).

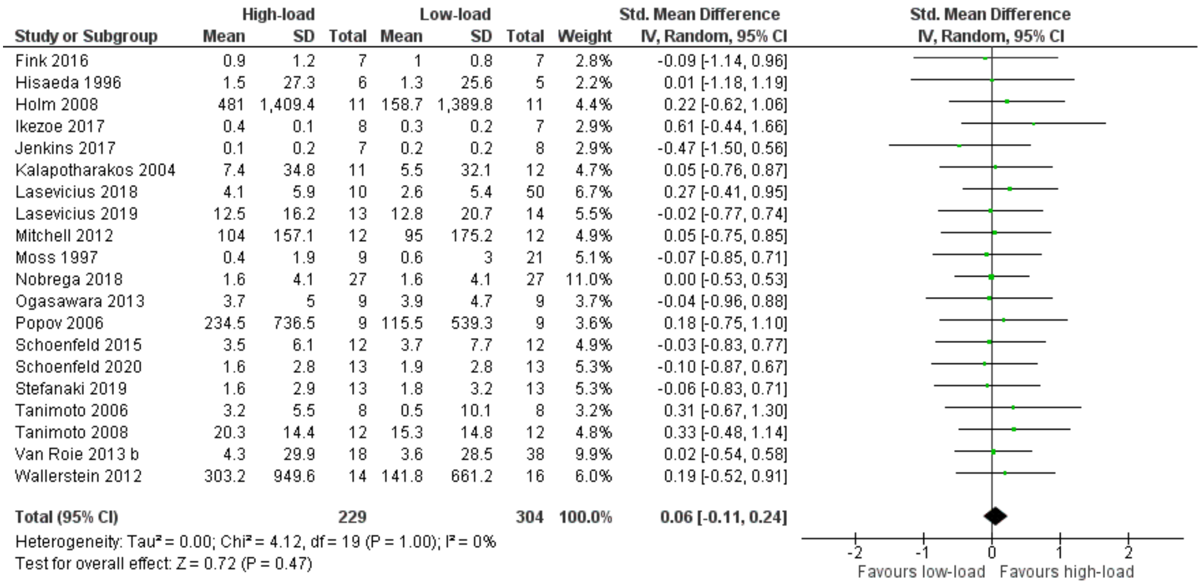

Figure 5. Influence of high-load vs. low-load RT on whole-muscle size. Point estimates and error bars signify the standardised mean difference between high-load and low-load groups and 95% confidence interval (CI) values, respectively.

Muscle fibre cross-sectional area (fCSA)

A total of six studies measured muscle fCSA via muscle biopsy. Four of the six studies [17, 53, 54, 68] demonstrated equivalent improvements in muscle fCSA amongst both loading conditions and two studies [36, 64] revealed greater improvements for high-load RT.

Meta-analytic outcomes for muscle fibre cross-sectional area (fCSA) are shown in Figure 6 and included 73 and 65 ES values from five studies for high-load and low-load RT, respectively. There was no difference between high-load and low-load RT on changes in muscle fCSA (ES = 0.29, 95% CI: -0.09 to 0.66, $P = 0.13$). Low heterogeneity amongst studies was observed ($Tau^2 = 0.02$, $I^2 = 10\%$, $P = 0.35$).

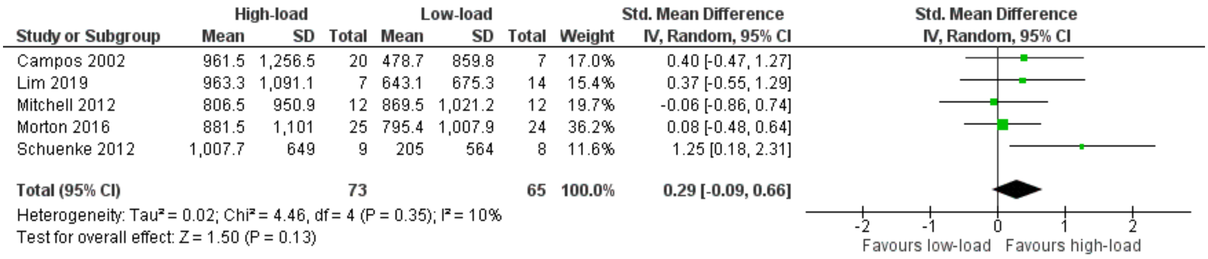

Figure 6. Influence of high-load vs. low-load RT on muscle fibre cross-sectional area (fCSA). Point estimates and error bars signify the standardised mean difference between high-load and low-load groups and 95% confidence interval (CI) values, respectively.

Lean body mass (LBM) or fat-free mass

A total of ten studies used either DXA [40, 54, 60, 68, 70, 73], BodPod [33, 59], bioelectrical impedance analysis [61] or skinfolds [64] to measure changes in lean body mass (LBM) or fat-free mass. Six [33, 54, 59, 60, 64, 70] of the ten studies found no differences between loading conditions, one study [73] demonstrated an advantage for high-load RT, while another [40] showed the opposite effect. Two studies [61, 68] found no change in LBM from pre- to post-training in both loading conditions.

Meta-analytic outcomes for LBM/fat-free mass are shown in Figure 7 and included 140 and 127 ES values from nine studies for high-load and low-load RT, respectively. There was no difference between high-load and low-load RT on changes in LBM or fat-free mass (ES = 0.05, 95% CI: -0.20 to 0.29, $P = 0.70$). Low heterogeneity amongst studies was observed ($Tau^2 = 0$, $I^2 = 0\%$, $P = 0.76$).

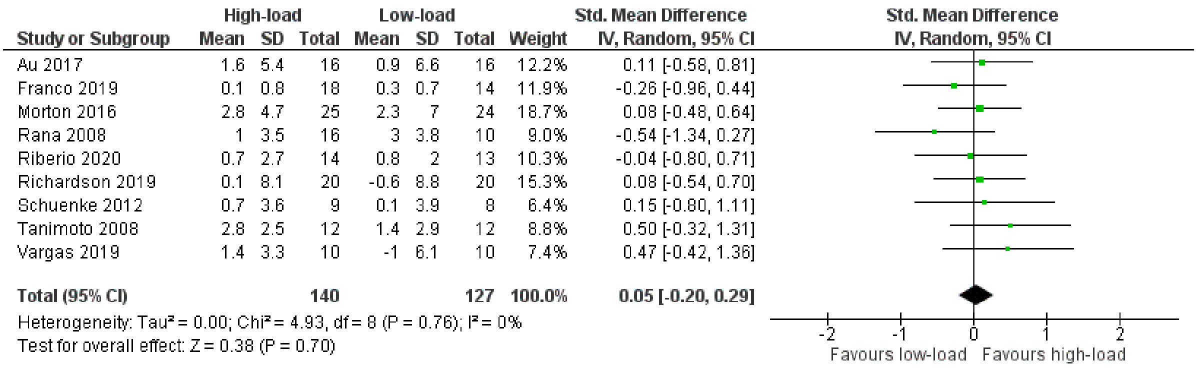

Figure 7. Influence of high-load vs. low-load RT on lean body mass (LBM) or fat-free mass. Point estimates and error bars signify the standardised mean difference between high-load and low-load groups and 95% confidence interval (CI) values, respectively.

Sport-specific or neuromuscular task performance

Given the limited availability of data, it was not possible to conduct a meta-analysis evaluating the influence of training load on sport-specific or neuromuscular task performance. Of the two studies included that measured sport-specific or neuromuscular task performance [48, 59], one study [48] used several jump tests (i.e., set angle jump, depth jump, weighted squat jump) and the other study [59] used a maximal jump height test. No change in jump height in response to high-load and low-load RT from pre- to post-training was observed in one study [59], whilst the other [48] found equivalent improvements in jump task performance between both loading conditions.

6. Discussion

The findings of this systematic review and meta-analysis provide further comprehensive evidence that higher- and lower-load RT are similarly effective for improving multiple indices of muscle hypertrophy (i.e., changes in whole-body lean/fat-free mass and in both whole-muscle and muscle fibre-specific CSA), and extend previous findings by demonstrating higher-load RT is advantageous for improving both dynamic 1-RM and isometric (MVIC) strength, but not for isokinetic strength. Due to limited available evidence, it remains unclear whether the superiority of higher-load RT for dynamic 1-RM and isometric strength development translates to greater improvements in sport-specific and neuromuscular task performance.

Influence of RT load on strength development

The superior improvements in dynamic (1-RM) and isometric strength, but not isokinetic strength, with higher-load RT are in partial agreement with previous findings [3, 9]. Both Schoenfeld and colleagues [3] and Lopez et al. [9] found superior improvements in dynamic 1-RM strength with higher- versus lower-load RT (with the latter also showing an advantage of moderate-load RT), while Schoenfeld et al. [3] found equivalent isometric strength gains between loading conditions. In the present study, sub-group analyses showed an advantage of higher-load RT for improving dynamic (1-RM) strength in untrained, but not in trained, participants (consistent with others [9]), and a greater advantage for higher-load RT in younger versus older participants. While the present data therefore consolidate the superior influence of higher-load RT on dynamic 1-RM strength, it is possible a wider spectrum of RT loads may positively influence aspects of strength in older and/or resistance-trained individuals. The present findings of greater improvements in isometric strength with higher-load RT, and no clear influence of RT load for isokinetic strength development, provide novel insights from previous studies [3, 9]. The present findings therefore provide a more comprehensive overview and advance the current understanding of the effects of RT load and moderating influence of participant characteristics on various strength outcomes.

The analysis of changes in multiple measures of strength with higher- versus lower-load RT allows insight into the potential mechanisms by which RT loading conditions may influence strength development. Similar to previous work [3], we found variability in the magnitude of advantage of higher-load RT across different strength outcomes. Specifically, there was a similar advantage of higher-load RT for improving both dynamic 1-RM strength and isometric strength (ES = 0.34 and 0.41, respectively), with no difference between loading conditions for isokinetic strength development (ES = 0.19). Previous observations of greater dynamic 1-RM, but similar isometric, strength development with higher-load RT [3, 17] may be attributed to the task-specificity of strength development (related to load/intensity specificity in particular) that favours higher-load RT interventions in dynamic 1-RM assessments [78, 79]. Given strength improvements with RT are most specific to the exercises performed during RT [78, 79], and the exercises during which dynamic 1-RM strength is assessed are typically incorporated into the RT intervention, we anticipated a greater advantage for higher-load RT for improving dynamic 1-RM strength versus isometric strength. In contrast, our finding that higher-load RT is similarly advantageous for improving both dynamic 1-RM and isometric strength suggests the superiority of higher-load RT may instead be mediated by non-task-specific neuromuscular adaptations. For example, the load-dependent effects of RT on improvements in neural drive [46], which may stimulate greater neural adaptations (e.g., improved agonist activation, motor unit synchronization, motor unit firing rates, and reduced antagonist co-activation) that underpin strength gain with RT [80], may at least partially explain the similar advantage of higher-load RT for both dynamic 1-RM and isometric strength gain. Each of the strength outcomes included in the present meta-analysis require maximal neuromuscular activation, which is further improved with higher- versus lower-load RT [46]. It therefore remains possible that despite less task-specificity between the RT exercises in the included studies and isometric strength assessments, the greater neural adaptations likely elicited by higher- versus lower-load RT may have contributed to the superiority of higher load RT for both isometric and dynamic 1-RM strength. In addition, the observation that muscle hypertrophy was similar between RT loading conditions also adds weight to the notion that the superiority of higher-load RT for dynamic 1-RM and isometric strength gain was attributed to non-hypertrophic (i.e., neural) mechanisms.

A number of methodological factors must be considered when interpreting the evidence for the influence of RT load on strength development. In particular, variation in the RT protocols used by individual studies was a likely contributor to the heterogeneity observed. While our analysis broadly classified the RT protocols used by included studies as either higher or lower load, there was considerable variation within the definitions of higher- and lower-load RT, both in terms of load and training volume. Indeed, higher-load RT protocols varied from examples including 8-9 sets at 4-5-RM [42] and 1 set at 80% 1-RM [66], while lower-load RT protocols varied from examples including 3 sets of 12-14 (50% 1-RM) [34] to 1 x 100-150-RM [32]. Such differences in the magnitude of divergence between higher-load and lower-load RT conditions would undoubtedly influence the magnitude of effects favouring either loading condition on outcome measures. In addition, variability in both the duration (ranging from 6 to 52 weeks) and weekly frequency (ranging from 1 to 4 times per week) of the RT interventions, as well as the muscle group specificity (e.g., upper- vs. lower-body) of the exercises used in the RT intervention may all influence strength development with RT and therefore contribute to the observed heterogeneity.

Taken together, the synergistic effects of greater improvements in neural drive and task specificity (albeit less so for isometric strength) may explain the greater improvements in dynamic 1-RM and isometric strength observed with higher-load RT. Similarly, the lack of a load-dependent influence on isokinetic strength is likely explained by similar mechanisms, since the task demands of isokinetic strength tests are not replicated in common RT interventions.

Influence of RT load on skeletal muscle hypertrophy

Consistent with previous findings [3, 9], we also observed that muscle hypertrophy responses were independent of RT load. This finding is in agreement with the notion that high (but not necessarily maximal) intensities-of-effort coupled with adequate RT volume, rather than RT load *per se*, are key stimuli for muscle hypertrophy [3, 6]. Together with previous evidence [3, 9], the findings therefore further highlight the versatility of RT loads that may be used to develop muscle hypertrophy.

Like the interpretation of the strength outcomes, a number of methodological factors must be considered when interpreting the influence of RT load on muscle hypertrophy. In particular, intensity-of-effort (proximity to muscular failure or the degree of internal focus/effort applied during a set) is a key stimulus for muscle hypertrophy due to its implications for motor unit recruitment and the exposure of active muscle fibres to mechanical tension [6]. Regardless of the RT load, maximal motor unit/muscle fibre recruitment can occur providing intensity-of-effort is high [6]. Whether or not RT sets are taken to (or close to) muscular failure may therefore influence study outcomes. However, there is evidence that training to muscular failure is not obligatory, and may even be detrimental, for muscle hypertrophy and strength outcomes [81, 82]. Notably, previous meta-analyses on this topic [3, 9, 19] excluded studies whereby both higher-load and lower-load RT was not performed to muscular failure, presumably to control for differences in intensity-of-effort across studies that may influence outcomes (e.g., muscle hypertrophy in particular). Since training to muscular failure (i.e., maximal intensities-of-effort) may be of greater importance to muscle hypertrophy than strength development [6], does not necessarily ensure equivalent muscle activation during higher- and lower-load RT due to greater difficulties in reaching true muscular failure with lighter RT loads [15], and may not always be feasible or sustainable in practice [15, 21], we chose to include all relevant studies independent of whether sets were performed to muscular failure or not. This approach resulted in a significantly larger number of included studies (45 studies in the present review vs. nine in Schoenfeld et al. [19], 21 in Schoenfeld et al. [3], and 28 in Lopez et al. [9]), and allowed qualitative insight into whether training to muscular failure influenced study outcomes independently of RT load. Of the studies included in the present meta-analysis, approximately 55% (24 of 45 studies) had participants in all groups perform RT to muscular failure. Despite between-study variability in whether RT was performed to muscular failure, the findings of similar muscle hypertrophy with higher- versus lower-load RT was highly consistent between studies, with low heterogeneity in study outcomes ($I^2 = 0\%$ for both whole-muscle hypertrophy and lean body/fat-free mass, and $I^2 = 10\%$ for muscle fibre-specific hypertrophy). It therefore appears the intensities-of-effort employed in the included studies were sufficiently high for both higher- and lower-load RT to expose muscle fibres to sufficient mechanical tension and stimulate muscle hypertrophy. These observations also provide further evidence that training to muscular failure is not obligatory for maximising muscle hypertrophy when RT is performed with either heavier or lighter loads.

From a practical perspective, it therefore may not be necessary for individuals to consistently apply near-maximal intensities-of-effort (particularly in trained individuals, who may be able to recruit higher-threshold motor units at greater proximities from muscular failure versus untrained individuals [83]) to induce additional muscle hypertrophy. Since higher intensities-of-effort during RT are associated with negative affective responses (particularly when lower loads are used) such as discomfort [21] in some individuals, consistently applying a high intensity-of-effort may exacerbate fatigue and potentially compromise adherence and long-term training outcomes.

The total volume of RT performed may also influence muscle hypertrophy outcomes and can be manipulated independently of RT load *per se*. There is indeed evidence for a dose response influence of RT on muscle hypertrophy, with higher weekly RT volumes leading to greater muscle growth [2]. It is therefore possible that whether or not high- and low-load RT protocols were matched for total volume performed may influence study outcomes. Twenty-six of the included studies that assessed muscle hypertrophy outcomes did not equate total RT volume between higher- and lower-load groups, which may advantage the higher-volume (i.e., lower-load) group from a muscle hypertrophy perspective. However, any potential advantage for lower-load RT was not evident in our findings, since 19 of the 26 studies in which higher- and lower-load RT was not volume-equated found no difference in muscle hypertrophy between loading conditions. These findings further highlight that sufficiently high intensities-of-effort may somewhat override the potential importance of total RT volume on muscle hypertrophy. While these findings suggest a limited role of RT volume in muscle hypertrophy, providing intensity-of-effort is sufficient, it is possible that RT volume may become more important for muscle hypertrophy as training experience increases – a notion supported by greater muscle hypertrophy observed with higher RT volumes in trained men [84].

A major limitation to the current understanding of the role of RT load (and by extension, any potential moderating influence of equating for RT volume) in muscle hypertrophy is the lack of evidence in participants with RT experience. Indeed, none of the 22 studies included in this review that measured changes in whole-muscle size (and 1 of the 6 studies that measured changes in muscle fibre size) were performed in trained participants. Future studies investigating the influence of RT load in physiological adaptation to RT should, where possible, incorporate participants with some degree of RT experience.

Influence of resistance training load on sport-specific or neuromuscular task performance

While there is evidence that RT is associated with improved sport-specific task performance (e.g., jumping, sprinting, and changing-of-direction) [22, 85], there is limited evidence for any RT load-dependent influence on improvements in these parameters. The two studies [48, 59] included in this review that measured sport-specific or neuromuscular task performance showed contrasting results, with one study [48] finding a similar improvement in various measures of jump performance (set angle jump, squat jump, depth jump) between loading conditions, and the other [59] showing no improvement in vertical jump performance for both conditions. The limited available evidence therefore makes clear interpretations difficult. Nevertheless, since higher-load RT likely promotes greater neural adaptations [46] that underpin the superiority of higher-load RT for dynamic and isometric strength outcomes, and both neural adaptations and strength likely mediate improvements in sport-specific task performance [22], future studies may observe greater improvements in these measures with higher-load RT. It is also possible that optimising improvements in these measures may require other forms of power-specific training, such as complex/contrast or plyometric training, particularly when incorporating exercises that closely mimic the demands of sport-specific or neuromuscular performance tasks.

Limitations of current research and future directions

A number of limitations must be considered when interpreting the findings of the current systematic review and meta-analysis. The majority of included studies involved participants with minimal or no RT experience, making it difficult to elucidate any potential training experience-dependent effects on outcomes. Nonetheless, the limited number of studies conducted on participants with RT experience had similar findings to those in untrained participants, suggesting potential training status-dependent effects on outcomes may be limited. Further evidence in trained participants is nevertheless needed to more firmly draw this conclusion. Although we did not perform any sub-group anayses based on participant sex, only 14 of 45 total studies included female participants. While study outcomes appeared qualitatively similar between those studies including on male or female participants, future research is required to elucidate any potential sex-dependent moderating effects on the influence of RT load on outcomes. Another major limitation was the ages of the participants in the included studies, which was biased towards younger participants. We conducted sub-group analyses based on younger ($<$60 years) and older ($\geq$60 years) participants, and identified only 13 studies that included older participants, with only a single study [50] using participants aged between 30 and 60 years old. Future studies should therefore aim to include participants aged 30 and above to improve understanding of the potential moderating influence of age on responses to higher- versus lower-load RT.

The influence of other methodological differences on study outcomes, such as the rest periods used for the RT protocols, and individual factors such as tolerance to discomfort, must also be considered when interpreting the current findings. For example, the RT protocol used by Campos et al. [36] had between-set rest periods that varied between the higher-load (3 min) and lower- load (1 min) groups. It is possible this discrepancy in rest periods could influence the total RT volume accumulated by each group, and potentially advantage the group that accumulate a higher RT volume. Nevertheless, between-set rest periods may have limited influence on strength [5] and hypertrophy [86] responses to RT, although longer rest periods may be more important in trained individuals [86]. Furthermore, participants may be limited by their perception of effort and the degree of discomfort experienced, particularly during low-load conditions [15], leading to lowered intensities-of-effort and a diminished ability to maximise muscle hypertrophy. It is therefore possible that individuals undertaking a low-load RT intervention may volitionally terminate their sets due to discomfort as opposed to reaching true momentary muscular failure, which may influence comparions with higher-load conditions that may reach closer to muscular failure. Future studies comparing low-load and high-load conditions performed to muscular failure should therefore ensure participants can effectively gauge their intensity-of-effort and distinguish between momentary muscular failure and volitional termination of a set due to discomfort.

The majority of included studies did not equate total RT volume between low-load and high-load conditions, and a volume-dependent influence on outcomes was not evident. This may be due to most studies being conducted on untrained (or relatively untrained) participants that may require lower training volumes to stimulate physiological adaptations versus trained participants. It is therefore possible that equating for RT volume between higher- versus lower-load RT groups may be more important for future studies conducted in participants with RT experience.

Practical applications of key findings

The findings of this meta-analysis overall suggest higher RT loads (>60% 1-RM) promote greater dynamic and isometric strength gains compared to lighter RT loads (≤60% 1-RM), whereas a wider spectrum of loads may elicit muscle hypertrophy. Higher RT loads are therefore recommended for dynamic and isometric strength development, whereas for muscle hypertrophy, loads may be selected based on individual preferences and tolerance to discomfort experienced with high intensities-of-effort (which may be greater with lower RT loads). There are, however, additional practical considerations beyond load *per se* for maximising strength and muscle hypertrophy outcomes with RT. Firstly, task (or exercise) specificity has clear implications for strength development with RT and should be considered when designing RT programs. For this reason, exercises that are specific to the measure of strength used (and vice versa) should be integrated into a RT program focused on strength development to provide an accurate representation of the effectiveness of the intervention. Since motor learning forms a large component of strength development, it is possible that greater repetition practice opportunities may facilitate additional strength gains with RT, particularly in relatively untrained individuals or those learning new exercises or movement patterns. While lower-load RT is likely sub-optimal for long-term maximal strength development, it may facilitate the development of motor learning patterns during certain training phases that may provide the foundations for the subsequent implementation of higher-load RT. For this reason, lower-load RT involving larger repetition numbers, and/or higher training frequencies, may be used during certain training phases to facilitate greater repetition practice opportunities and associated motor learning. Ultimately, while higher-load RT is optimal for strength development, RT prescription should be tailored to the target strength outcome (e.g., 1-RM vs. 6-RM). It should also be considered that higher-load RT may require longer between-set rest intervals to limit excessive fatigue accumulation and maintain high levels of neural drive during subsequent exercises and sets.

In line with previous work [3], the present findings suggest various loads may be used to elicit muscle hypertrophy with RT, providing intensity-of-effort is sufficiently high (but not necessarily maximal). Performing RT with close proximity-to-failure may therefore be a strategy to maximise muscle hypertrophy independently of the load used. As in strength development, exercise selection is an important consideration when determining the suitability of performing RT close to muscular failure with higher or lower loads. In particular, exercises performed close to muscular failure should be selected to allow for safe execution and high levels of effort throughout a set, and to limit accumulation of excessive fatigue that may compromise intensity-of-effort in subsequent exercises and sets. Exercises where risk of injury is likely higher due to increased movement complexity and/or less stability (e.g., barbell squat versus leg press) may be less suitable for training close to muscular failure. In addition, since multi-joint exercises engage more muscle mass and thus involve higher neurological and aerobic demands [87] than single-joint exercises, training close to muscular failure with numerous multi-joint exercises per session may exacerbate fatigue and impair subsequent training quality. For this reason, high intensities-of-effort should be performed on a limited number of multi-joint exercises per session, with single-joint exercises performed closer to muscular failure to enhance the hypertrophic stimulus.

Compared with higher-load RT, lower-load RT induces greater metabolic stress within the active musculature due to prolonged anaerobic energy provision during longer duration sets. The metabolic stress elicited throughout lower-load, higher-repetition sets promotes higher levels of discomfort [15] that may impair the ability to reach high intensities-of-effort depending on individual tolerance to discomfort. It is therefore recommended that individuals select loads that allow them to reach a close proximity to muscular failure, and that individuals with less tolerance to discomfort prioritise higher versus lower loads.

7. Conclusion

The findings of this systematic review and meta-analysis suggest higher- and lower-load RT induce comparable skeletal muscle hypertrophy (assessed as either changes in lean body/fat-free mass, or in whole-muscle and muscle fibre-specific CSA), improvements in lean/fat-free mass, and isokinetic strength development, while higher-load RT is superior for improving both dynamic (1-RM) and isometric (MVIC) strength. The advantage of higher-load RT for improving dynamic (1-RM) strength was more evident in untrained and younger participants. Due to limited available evidence, the influence of RT load on sport-specific or neuromuscular task performance measures was unable to be determined. Higher-load RT is therefore recommended for improving dynamic and isometric strength, while elements of specificity including exercise/task and repetition range specificity should be considered when prescribing RT for maximising strength. Since a wide spectrum of RT loads may promote muscle hypertrophy, load selection may be informed by individual preferences, tolerance to levels of exertion and discomfort (which likely varies based on loading condition), and the suitability of a given exercise to a specific loading condition (e.g., complex exercises may be less suited to low-load RT performed close to failure). When aiming to maximise the muscle hypertrophic response from a given exercise, we advise selecting a load that a) does not limit safe exercise execution, b) allows for high levels of effort to be achieved within a given set, and c) limits the accumulation of excessive fatigue that may impair intensity-of-effort in subsequent exercises and sets, thereby maximising mechanical tension and the hypertrophic stimulus imparted on the active musculatature. The findings of this systematic review and meta-analysis therefore suggest higher-load RT is superior for improving both dynamic (1-RM) and isometric strength (but not isokinetic strength) compared with lower-load RT, and muscle hypertrophy occurs independently of RT load and regardless of whether intensity-of-effort is maximal. A lack of studies in both trained and older participants was a clear limitation of the available literature and should be addressed in future studies. There is also limited evidence on the influence of RT load for improving sport-specific (i.e., jumping, sprinting, and changing-of-direction) or neuromuscular (e.g., CMJ and IMTP) performance tasks.

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9. Declarations

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Ethics approval

Not applicable.

Consent to participate

Not applicable.

Consent for publication

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Availability of data and material

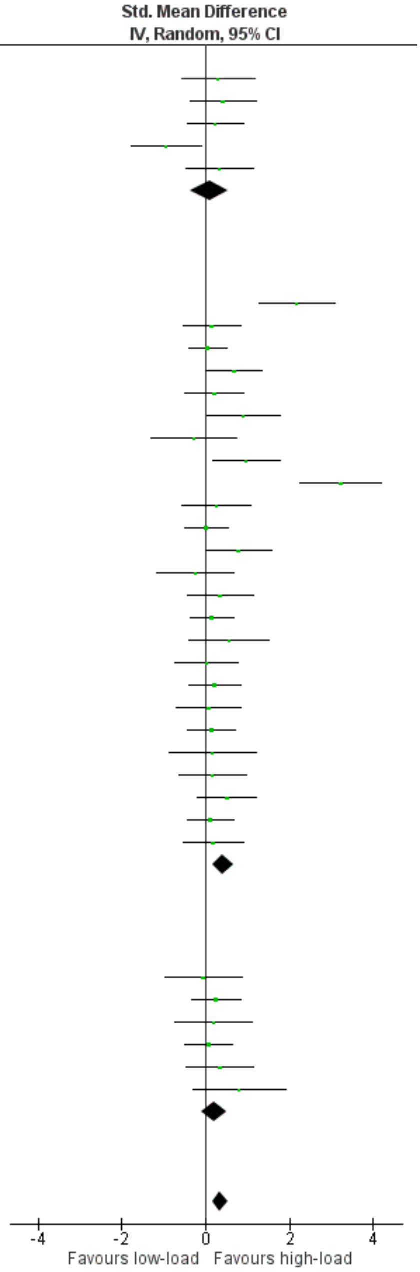
The data sets generated and analysed for this article are available in supplementary information (Supplementary File A).

Author contributions

Article conceptualisation: MCR, DLH, SAF, and JJF; literature search: MCR and JJF; data analysis: DRP and IJG; drafted manuscript: MCR and JJF; critically revised manuscript: all authors.

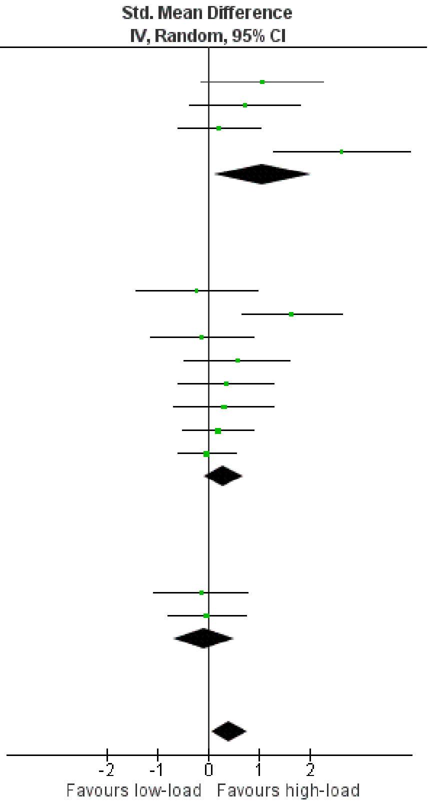
10. Supplementary Information (SI)

Study or Subgroup	High-load Mean	High-load SD	High-load Total	Low-load Mean	Low-load SD	Low-load Total	Weight	Std. Mean Difference IV, Random, 95% CI
3.4.1 Low-quality								
Campos 2002	104	137.9	20	65	82.9	7	2.4%	0.30 [-0.57, 1.16]
Jones 2001	22.8	10.6	12	16.1	18.9	14	2.7%	0.41 [-0.37, 1.20]
Lasevicius 2018	52	93.3	10	32.4	83.4	50	3.1%	0.23 [-0.45, 0.91]
Mitchell 2012	293	178.5	12	501	244.1	12	2.5%	-0.94 [-1.79, -0.09]
Rana 2008	57.8	107.8	16	23.4	87.9	10	2.7%	0.33 [-0.47, 1.13]
Subtotal (95% CI)			**70**			**93**	**13.4%**	**0.08 [-0.38, 0.55]**
Heterogeneity: Tau² = 0.12; Chi² = 7.01, df = 4 (P = 0.14); I² = 43%								
Test for overall effect: Z = 0.35 (P = 0.72)								
3.4.2 Moderate-quality								
Anderson 1982	13.7	3.7	15	5.4	3.7	16	2.3%	2.18 [1.27, 3.10]
Au 2017	82	147	16	60	144.3	16	3.0%	0.15 [-0.55, 0.84]
de Vos 2005	64.6	381.6	28	51.6	348.2	56	4.0%	0.04 [-0.42, 0.49]
Fatouros 2006	33.5	16.7	14	22.2	16	26	3.1%	0.68 [0.01, 1.35]
Franco 2019	4.2	3.5	18	3.4	4.2	14	3.0%	0.20 [-0.50, 0.90]
Holm 2008	26	10.6	11	15	12.6	11	2.4%	0.91 [0.02, 1.80]
Ikezoe 2017	52.5	29.8	8	61.4	28.3	7	2.0%	-0.29 [-1.31, 0.73]
Jenkins 2017	10	6.5	13	3	7.4	13	2.6%	0.97 [0.15, 1.79]
Jessee 2018	3.2	1	20	-0.1	1	20	2.1%	3.23 [2.26, 4.20]
Kalapotharakos 2004	20.9	37.7	11	12.7	22.6	12	2.6%	0.26 [-0.57, 1.08]
Kerr 1996	21.9	29.6	28	21.4	28.8	28	3.7%	0.02 [-0.51, 0.54]
Lasevicius 2019	23.8	14.3	13	13	12.7	14	2.7%	0.78 [-0.01, 1.56]
Lim 2019	29	20.7	7	34	18.2	14	2.3%	-0.25 [-1.16, 0.66]
Moss 1997	2.9	2.5	9	1.7	3.7	21	2.7%	0.34 [-0.44, 1.13]
Nobrega 2018	15.1	12.5	27	13.2	12.3	27	3.7%	0.15 [-0.38, 0.69]
Ogasawara 2013	11	8.6	9	6	8.4	9	2.2%	0.56 [-0.39, 1.51]
Riberio 2020	4.1	8.3	14	3.9	8.1	13	2.8%	0.02 [-0.73, 0.78]
Richardson 2019	14.4	34.3	20	7	35.3	20	3.3%	0.21 [-0.41, 0.83]
Stefanaki 2019	5.7	9.9	13	5	9.6	13	2.8%	0.07 [-0.70, 0.84]
Stone 1994	11.5	14	17	9.6	13.6	33	3.4%	0.14 [-0.45, 0.72]
Taaffe 1996	20.1	26.4	7	15.4	27.5	7	1.9%	0.16 [-0.89, 1.21]
Tanimoto 2008	28.8	24.9	12	24.8	22.7	12	2.6%	0.16 [-0.64, 0.96]
Van Roie 2013 a	26.6	15.2	12	18.5	15.9	24	3.0%	0.51 [-0.20, 1.21]
Van Roie 2013 b	23.1	48.6	18	17.7	45.8	38	3.6%	0.11 [-0.45, 0.68]
Wallerstein 2012	29.5	51.9	14	20.6	42.6	16	2.9%	0.18 [-0.54, 0.90]
Subtotal (95% CI)			**374**			**480**	**70.7%**	**0.42 [0.18, 0.66]**
Heterogeneity: Tau² = 0.23; Chi² = 66.42, df = 24 (P < 0.00001); I² = 64%								
Test for overall effect: Z = 3.39 (P = 0.0007)								
3.4.3 High-quality								
Bezarra 2019	19.3	9.6	9	19.9	10	9	2.3%	-0.06 [-0.98, 0.87]
Harris 2004	168.5	109.6	30	139.5	122.5	17	3.4%	0.25 [-0.35, 0.85]
Hortobagyi 2001	312	240.2	9	262	271.1	9	2.3%	0.19 [-0.74, 1.11]
Morton 2016	51.8	120	25	43.3	117.6	24	3.6%	0.07 [-0.49, 0.63]
Schoenfeld 2015	15.2	23.6	12	6.4	26.3	12	2.6%	0.34 [-0.47, 1.15]
Seynnes 2004	4	2	8	2.5	1.3	6	1.8%	0.81 [-0.31, 1.92]
Subtotal (95% CI)			**93**			**77**	**15.9%**	**0.21 [-0.10, 0.52]**
Heterogeneity: Tau² = 0.00; Chi² = 1.78, df = 5 (P = 0.88); I² = 0%								
Test for overall effect: Z = 1.35 (P = 0.18)								
Total (95% CI)			**537**			**650**	**100.0%**	**0.34 [0.15, 0.52]**
Heterogeneity: Tau² = 0.17; Chi² = 77.15, df = 35 (P < 0.0001); I² = 55%								
Test for overall effect: Z = 3.60 (P = 0.0003)								
Test for subgroup differences: Chi² = 2.06, df = 2 (P = 0.36), I² = 2.9%								



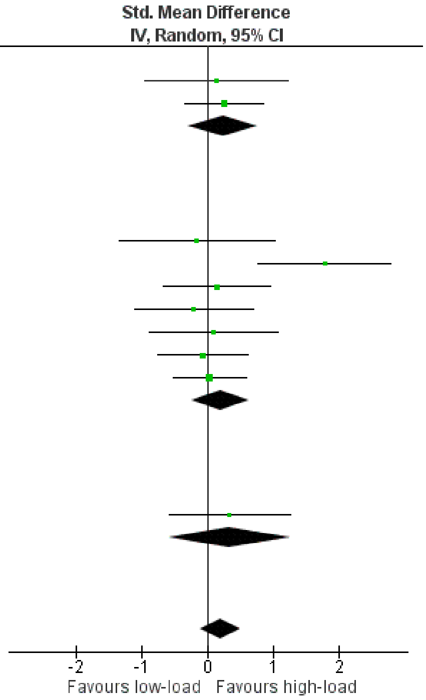
Supplementary Figure 1. Subgroup analysis of the influence of methodological quality on heterogeneity and outcomes for the influence of high-load vs. low-load RT on dynamic 1-RM strength development. Point estimates and error bars signify the standardised mean difference between high-load and low-load groups and 95% confidence interval (CI) values, respectively.

Study or Subgroup	High-load Mean	High-load SD	High-load Total	Low-load Mean	Low-load SD	Low-load Total	Weight	Std. Mean Difference IV, Random, 95% CI
1.7.1 Low-quality								
Aagaard 1994	28.9	34.7	7	-13.2	39	6	5.4%	1.07 [-0.13, 2.26]
Fink 2016	6.9	19.5	7	-6.3	15	7	6.0%	0.71 [-0.38, 1.80]
Mitchell 2012	67	34.8	12	59	37.1	12	8.4%	0.21 [-0.59, 1.02]
Popov 2006	143	20.8	9	84	22.1	9	4.6%	2.62 [1.28, 3.96]
Subtotal (95% CI)			**35**			**34**	**24.5%**	**1.06 [0.10, 2.02]**
Heterogeneity: Tau² = 0.64; Chi² = 9.30, df = 3 (P = 0.03); I² = 68%								
Test for overall effect: Z = 2.17 (P = 0.03)								
1.7.2 Moderate-quality								
Hisaeda 1996	39	24.9	6	46.2	31.1	5	5.4%	-0.24 [-1.43, 0.96]
Holm 2008	37	12.2	11	15	13.6	11	6.8%	1.64 [0.65, 2.63]
Ikezoe 2017	53.3	48.9	8	60	42	7	6.6%	-0.14 [-1.15, 0.88]
Jenkins 2017	59.2	46.8	7	26.8	58.9	8	6.4%	0.57 [-0.47, 1.61]
Ogasawara 2013	4	4.7	9	2.3	4.9	9	7.2%	0.34 [-0.60, 1.27]
Tanimoto 2006	29.2	55.6	8	7.6	76.6	8	6.8%	0.31 [-0.68, 1.29]
Van Roie 2013 a	15.2	57.8	12	4	56.7	24	9.5%	0.19 [-0.50, 0.89]
Van Roie 2013 b	7.1	43.3	18	8.8	53.2	38	10.9%	-0.03 [-0.59, 0.53]
Subtotal (95% CI)			**79**			**110**	**59.5%**	**0.30 [-0.08, 0.67]**
Heterogeneity: Tau² = 0.09; Chi² = 10.13, df = 7 (P = 0.18); I² = 31%								
Test for overall effect: Z = 1.54 (P = 0.12)								
1.7.3 High-quality								
Hortobagyi 2001	70	55.2	9	80	74	9	7.3%	-0.15 [-1.07, 0.78]
Schoenfeld 2020	7.1	43.3	13	8.8	53.2	13	8.7%	-0.03 [-0.80, 0.73]
Subtotal (95% CI)			**22**			**22**	**16.0%**	**-0.08 [-0.67, 0.51]**
Heterogeneity: Tau² = 0.00; Chi² = 0.03, df = 1 (P = 0.86); I² = 0%								
Test for overall effect: Z = 0.26 (P = 0.79)								
Total (95% CI)			**136**			**166**	**100.0%**	**0.41 [0.07, 0.76]**
Heterogeneity: Tau² = 0.20; Chi² = 25.45, df = 13 (P = 0.02); I² = 49%								
Test for overall effect: Z = 2.33 (P = 0.02)								
Test for subgroup differences: Chi² = 3.98, df = 2 (P = 0.14), I² = 49.7%								



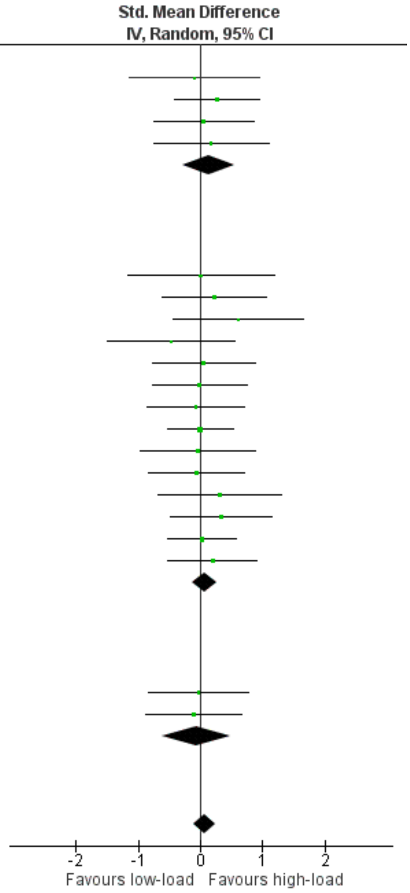
Supplementary Figure 2. Subgroup analysis of the influence of methodological quality on heterogeneity and outcomes for the influence of high-load vs. low-load RT on isometric (MVIC) strength development. Point estimates and error bars signify the standardised mean difference between high-load and low-load groups and 95% confidence interval (CI) values, respectively.

	High-load			Low-load				Std. Mean Difference
Study or Subgroup	Mean	SD	Total	Mean	SD	Total	Weight	IV, Random, 95% CI
2.4.1 Low-quality								
Aagaard 1994	15.6	44.6	7	9.6	32.4	6	6.4%	0.14 [-0.95, 1.23]
Beneka 2005	6.5	14.5	32	2.8	13.2	16	15.8%	0.26 [-0.34, 0.86]
Subtotal (95% CI)			**39**			**22**	**22.2%**	**0.23 [-0.30, 0.76]**
Heterogeneity: Tau² = 0.00; Chi² = 0.03, df = 1 (P = 0.85); I² = 0%								
Test for overall effect: Z = 0.86 (P = 0.39)								
2.4.2 Moderate-quality								
Hisaeda 1996	15.1	27.7	6	20.3	29.3	5	5.5%	-0.17 [-1.36, 1.02]
Holm 2008	26	10.2	11	5	12.3	11	7.2%	1.79 [0.77, 2.81]
Kalapotharakos 2004	9.5	24.8	11	5.7	26.2	12	10.2%	0.14 [-0.68, 0.96]
Lim 2019	13.5	56.5	7	25.5	52.8	14	8.6%	-0.21 [-1.12, 0.70]
Tanimoto 2006	13.6	50.2	8	8.7	48.8	8	7.6%	0.09 [-0.89, 1.07]
Van Roie 2013 a	6.1	31.8	12	8.5	32.1	24	13.1%	-0.07 [-0.77, 0.62]
Van Roie 2013 b	3.7	29.5	18	2.9	30.6	38	17.3%	0.03 [-0.53, 0.59]
Subtotal (95% CI)			**73**			**112**	**69.5%**	**0.19 [-0.25, 0.63]**
Heterogeneity: Tau² = 0.16; Chi² = 11.41, df = 6 (P = 0.08); I² = 47%								
Test for overall effect: Z = 0.84 (P = 0.40)								
2.4.3 High-quality								
Hortobagyi 2001	76	67.1	9	53	65	9	8.3%	0.33 [-0.60, 1.26]
Subtotal (95% CI)			**9**			**9**	**8.3%**	**0.33 [-0.60, 1.26]**
Heterogeneity: Not applicable								
Test for overall effect: Z = 0.70 (P = 0.49)								
Total (95% CI)			**121**			**143**	**100.0%**	**0.19 [-0.10, 0.49]**
Heterogeneity: Tau² = 0.05; Chi² = 11.62, df = 9 (P = 0.24); I² = 23%								
Test for overall effect: Z = 1.28 (P = 0.20)								
Test for subgroup differences: Chi² = 0.08, df = 2 (P = 0.96), I² = 0%								



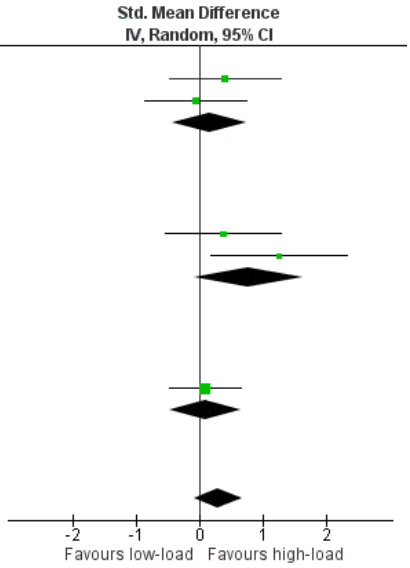
Supplementary Figure 3. Subgroup analysis of the influence of methodological quality on heterogeneity and outcomes for the influence of high-load vs. low-load RT on isokinetic 1-RM strength development. Point estimates and error bars signify the standardised mean difference between high-load and low-load groups and 95% confidence interval (CI) values, respectively.

Study or Subgroup	High-load Mean	High-load SD	High-load Total	Low-load Mean	Low-load SD	Low-load Total	Weight	Std. Mean Difference IV, Random, 95% CI
4.4.1 Low-quality								
Fink 2016	0.9	1.2	7	1	0.8	7	2.8%	-0.09 [-1.14, 0.96]
Lasevicius 2018	4.1	5.9	10	2.6	5.4	50	6.7%	0.27 [-0.41, 0.95]
Mitchell 2012	104	157.1	12	95	175.2	12	4.9%	0.05 [-0.75, 0.85]
Popov 2006	234.5	736.5	9	115.5	539.3	9	3.6%	0.18 [-0.75, 1.10]
Subtotal (95% CI)			**38**			**78**	**18.1%**	**0.14 [-0.28, 0.55]**
Heterogeneity: Tau² = 0.00; Chi² = 0.38, df = 3 (P = 0.94); I² = 0%								
Test for overall effect: Z = 0.64 (P = 0.52)								
4.4.2 Moderate-quality								
Hisaeda 1996	1.5	27.3	6	1.3	25.6	5	2.2%	0.01 [-1.18, 1.19]
Holm 2008	481	1,409.4	11	158.7	1,389.8	11	4.4%	0.22 [-0.62, 1.06]
Ikezoe 2017	0.4	0.1	8	0.3	0.2	7	2.9%	0.61 [-0.44, 1.66]
Jenkins 2017	0.1	0.2	7	0.2	0.2	8	2.9%	-0.47 [-1.50, 0.56]
Kalapotharakos 2004	7.4	34.8	11	5.5	32.1	12	4.7%	0.05 [-0.76, 0.87]
Lasevicius 2019	12.5	16.2	13	12.8	20.7	14	5.5%	-0.02 [-0.77, 0.74]
Moss 1997	0.4	1.9	9	0.6	3	21	5.1%	-0.07 [-0.85, 0.71]
Nobrega 2018	1.6	4.1	27	1.6	4.1	27	11.0%	0.00 [-0.53, 0.53]
Ogasawara 2013	3.7	5	9	3.9	4.7	9	3.7%	-0.04 [-0.96, 0.88]
Stefanaki 2019	1.6	2.9	13	1.8	3.2	13	5.3%	-0.06 [-0.83, 0.71]
Tanimoto 2006	3.2	5.5	8	0.5	10.1	8	3.2%	0.31 [-0.67, 1.30]
Tanimoto 2008	20.3	14.4	12	15.3	14.8	12	4.8%	0.33 [-0.48, 1.14]
Van Roie 2013 b	4.3	29.9	18	3.6	28.5	38	9.9%	0.02 [-0.54, 0.58]
Wallerstein 2012	303.2	949.6	14	141.8	661.2	16	6.0%	0.19 [-0.52, 0.91]
Subtotal (95% CI)			**166**			**201**	**71.7%**	**0.07 [-0.14, 0.27]**
Heterogeneity: Tau² = 0.00; Chi² = 3.40, df = 13 (P = 1.00); I² = 0%								
Test for overall effect: Z = 0.61 (P = 0.54)								
4.4.3 High-quality								
Schoenfeld 2015	3.5	6.1	12	3.7	7.7	12	4.9%	-0.03 [-0.83, 0.77]
Schoenfeld 2020	1.6	2.8	13	1.9	2.8	13	5.3%	-0.10 [-0.87, 0.67]
Subtotal (95% CI)			**25**			**25**	**10.2%**	**-0.07 [-0.62, 0.49]**
Heterogeneity: Tau² = 0.00; Chi² = 0.02, df = 1 (P = 0.89); I² = 0%								
Test for overall effect: Z = 0.24 (P = 0.81)								
Total (95% CI)			**229**			**304**	**100.0%**	**0.06 [-0.11, 0.24]**
Heterogeneity: Tau² = 0.00; Chi² = 4.12, df = 19 (P = 1.00); I² = 0%								
Test for overall effect: Z = 0.72 (P = 0.47)								
Test for subgroup differences: Chi² = 0.33, df = 2 (P = 0.85), I² = 0%								



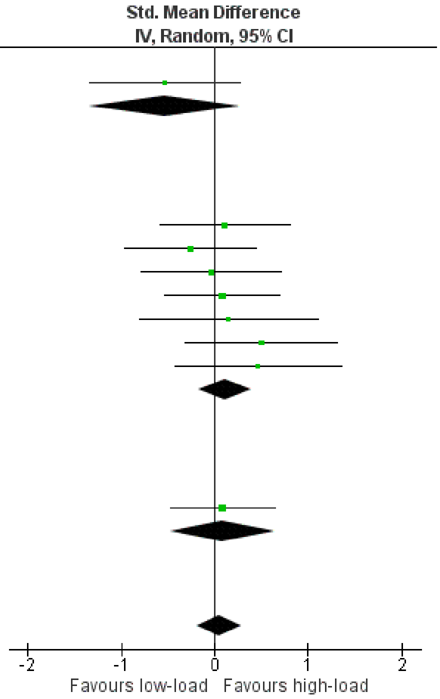
Supplementary Figure 4. Subgroup analysis of the influence of methodological quality on heterogeneity and outcomes for the influence of high-load vs. low-load RT on whole-muscle size. Point estimates and error bars signify the standardised mean difference between high-load and low-load groups and 95% confidence interval (CI) values, respectively.

Study or Subgroup	High-load Mean	High-load SD	High-load Total	Low-load Mean	Low-load SD	Low-load Total	Weight	Std. Mean Difference IV, Random, 95% CI
5.7.1 Low-quality								
Campos 2002	961.5	1,256.5	20	478.7	859.8	7	17.0%	0.40 [-0.47, 1.27]
Mitchell 2012	806.5	950.9	12	869.5	1,021.2	12	19.7%	-0.06 [-0.86, 0.74]
Subtotal (95% CI)			**32**			**19**	**36.7%**	**0.15 [-0.44, 0.74]**
Heterogeneity: Tau² = 0.00; Chi² = 0.58, df = 1 (P = 0.44); I² = 0%								
Test for overall effect: Z = 0.50 (P = 0.62)								
5.7.2 Moderate-quality								
Lim 2019	963.3	1,091.1	7	643.1	675.3	14	15.4%	0.37 [-0.55, 1.29]
Schuenke 2012	1,007.7	649	9	205	564	8	11.6%	1.25 [0.18, 2.31]
Subtotal (95% CI)			**16**			**22**	**27.1%**	**0.76 [-0.09, 1.62]**
Heterogeneity: Tau² = 0.13; Chi² = 1.50, df = 1 (P = 0.22); I² = 33%								
Test for overall effect: Z = 1.75 (P = 0.08)								
5.7.3 High-quality								
Morton 2016	881.5	1,101	25	795.4	1,007.9	24	36.2%	0.08 [-0.48, 0.64]
Subtotal (95% CI)			**25**			**24**	**36.2%**	**0.08 [-0.48, 0.64]**
Heterogeneity: Not applicable								
Test for overall effect: Z = 0.28 (P = 0.78)								
Total (95% CI)			**73**			**65**	**100.0%**	**0.29 [-0.09, 0.66]**
Heterogeneity: Tau² = 0.02; Chi² = 4.46, df = 4 (P = 0.35); I² = 10%								
Test for overall effect: Z = 1.50 (P = 0.13)								
Test for subgroup differences: Chi² = 1.85, df = 2 (P = 0.40), I² = 0%								



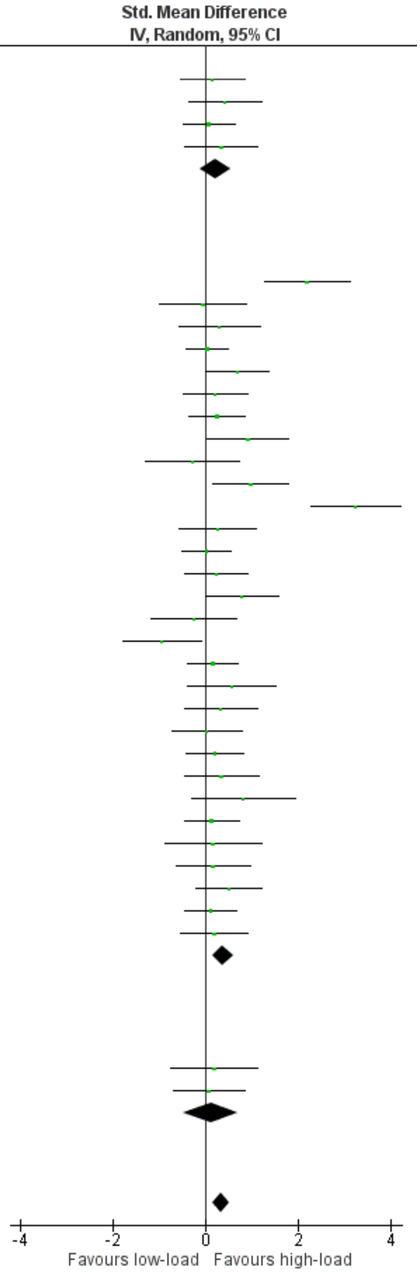
Supplementary Figure 5. Subgroup analysis of the influence of methodological quality on heterogeneity and outcomes for the influence of high-load vs. low-load RT on muscle fibre size. Point estimates and error bars signify the standardised mean difference between high-load and low-load groups and 95% confidence interval (CI) values, respectively.

	High-load			Low-load				Std. Mean Difference
Study or Subgroup	**Mean**	**SD**	**Total**	**Mean**	**SD**	**Total**	**Weight**	**IV, Random, 95% CI**
6.4.1 Low-quality								
Rana 2008	1	3.5	16	3	3.8	10	9.0%	-0.54 [-1.34, 0.27]
Subtotal (95% CI)			**16**			**10**	**9.0%**	**-0.54 [-1.34, 0.27]**
Heterogeneity: Not applicable								
Test for overall effect: Z = 1.30 (P = 0.19)								
6.4.2 Moderate-quality								
Au 2017	1.6	5.4	16	0.9	6.6	16	12.2%	0.11 [-0.58, 0.81]
Franco 2019	0.1	0.8	18	0.3	0.7	14	11.9%	-0.26 [-0.96, 0.44]
Riberio 2020	0.7	2.7	14	0.8	2	13	10.3%	-0.04 [-0.80, 0.71]
Richardson 2019	0.1	8.1	20	-0.6	8.8	20	15.3%	0.08 [-0.54, 0.70]
Schuenke 2012	0.7	3.6	9	0.1	3.9	8	6.4%	0.15 [-0.80, 1.11]
Tanimoto 2008	2.8	2.5	12	1.4	2.9	12	8.8%	0.50 [-0.32, 1.31]
Vargas 2019	1.4	3.3	10	-1	6.1	10	7.4%	0.47 [-0.42, 1.36]
Subtotal (95% CI)			**99**			**93**	**72.3%**	**0.11 [-0.17, 0.40]**
Heterogeneity: Tau² = 0.00; Chi² = 2.72, df = 6 (P = 0.84); I² = 0%								
Test for overall effect: Z = 0.76 (P = 0.45)								
6.4.3 High-quality								
Morton 2016	2.8	4.7	25	2.3	7	24	18.7%	0.08 [-0.48, 0.64]
Subtotal (95% CI)			**25**			**24**	**18.7%**	**0.08 [-0.48, 0.64]**
Heterogeneity: Not applicable								
Test for overall effect: Z = 0.29 (P = 0.77)								
Total (95% CI)			**140**			**127**	**100.0%**	**0.05 [-0.20, 0.29]**
Heterogeneity: Tau² = 0.00; Chi² = 4.93, df = 8 (P = 0.76); I² = 0%								
Test for overall effect: Z = 0.38 (P = 0.70)								
Test for subgroup differences: Chi² = 2.22, df = 2 (P = 0.33), I² = 9.7%								



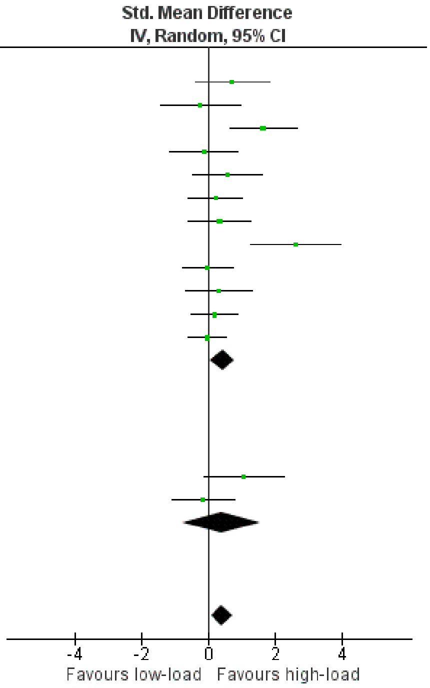
Supplementary Figure 6. Subgroup analysis of the influence of methodological quality on heterogeneity and outcomes for the influence of high-load vs. low-load RT on lean body mass/fat free mass. Point estimates and error bars signify the standardised mean difference between high-load and low-load groups and 95% confidence interval (CI) values, respectively.

Study or Subgroup	High-load Mean	High-load SD	High-load Total	Low-load Mean	Low-load SD	Low-load Total	Weight	Std. Mean Difference IV, Random, 95% CI
3.2.1 Trained								
Au 2017	82	147	16	60	144.3	16	3.0%	0.15 [-0.55, 0.84]
Jones 2001	22.8	10.6	12	16.1	18.9	14	2.7%	0.41 [-0.37, 1.20]
Morton 2016	51.8	120	25	43.3	117.6	24	3.6%	0.07 [-0.49, 0.63]
Moss 1997	2.9	2.5	9	1.7	3.7	21	2.7%	0.34 [-0.44, 1.13]
Subtotal (95% CI)			**62**			**75**	**12.0%**	**0.21 [-0.14, 0.55]**
Heterogeneity: Tau² = 0.00; Chi² = 0.64, df = 3 (P = 0.89); I² = 0%								
Test for overall effect: Z = 1.19 (P = 0.24)								
3.2.2 Untrained								
Anderson 1982	13.7	3.7	15	5.4	3.7	16	2.3%	2.18 [1.27, 3.10]
Bezarra 2019	19.3	9.6	9	19.9	10	9	2.3%	-0.06 [-0.98, 0.87]
Campos 2002	104	137.9	20	65	82.9	7	2.4%	0.30 [-0.57, 1.16]
de Vos 2005	64.6	381.6	28	51.6	348.2	56	4.0%	0.04 [-0.42, 0.49]
Fatouros 2006	33.5	16.7	14	22.2	16	26	3.1%	0.68 [0.01, 1.35]
Franco 2019	4.2	3.5	18	3.4	4.2	14	3.0%	0.20 [-0.50, 0.90]
Harris 2004	168.5	109.6	30	139.5	122.5	17	3.4%	0.25 [-0.35, 0.85]
Holm 2008	26	10.6	11	15	12.6	11	2.4%	0.91 [0.02, 1.80]
Ikezoe 2017	52.5	29.8	8	61.4	28.3	7	2.0%	-0.29 [-1.31, 0.73]
Jenkins 2017	10	6.5	13	3	7.4	13	2.6%	0.97 [0.15, 1.79]
Jessee 2018	3.2	1	20	-0.1	1	20	2.1%	3.23 [2.26, 4.20]
Kalapotharakos 2004	20.9	37.7	11	12.7	22.6	12	2.6%	0.26 [-0.57, 1.08]
Kerr 1996	21.9	29.6	28	21.4	28.8	28	3.7%	0.02 [-0.51, 0.54]
Lasevicius 2018	52	93.3	10	32.4	83.4	50	3.1%	0.23 [-0.45, 0.91]
Lasevicius 2019	23.8	14.3	13	13	12.7	14	2.7%	0.78 [-0.01, 1.56]
Lim 2019	29	20.7	7	34	18.2	14	2.3%	-0.25 [-1.16, 0.66]
Mitchell 2012	293	178.5	12	501	244.1	12	2.5%	-0.94 [-1.79, -0.09]
Nobrega 2018	15.1	12.5	27	13.2	12.3	27	3.7%	0.15 [-0.38, 0.69]
Ogasawara 2013	11	8.6	9	6	8.4	9	2.2%	0.56 [-0.39, 1.51]
Rana 2008	57.8	107.8	16	23.4	87.9	10	2.7%	0.33 [-0.47, 1.13]
Riberio 2020	4.1	8.3	14	3.9	8.1	13	2.8%	0.02 [-0.73, 0.78]
Richardson 2019	14.4	34.3	20	7	35.3	20	3.3%	0.21 [-0.41, 0.83]
Schoenfeld 2015	15.2	23.6	12	6.4	26.3	12	2.6%	0.34 [-0.47, 1.15]
Seynnes 2004	4	2	8	2.5	1.3	6	1.8%	0.81 [-0.31, 1.92]
Stone 1994	11.5	14	17	9.6	13.6	33	3.4%	0.14 [-0.45, 0.72]
Taaffe 1996	20.1	26.4	7	15.4	27.5	7	1.9%	0.16 [-0.89, 1.21]
Tanimoto 2008	28.8	24.9	12	24.8	22.7	12	2.6%	0.16 [-0.64, 0.96]
Van Roie 2013 a	26.6	15.2	12	18.5	15.9	24	3.0%	0.51 [-0.20, 1.21]
Van Roie 2013 b	23.1	48.6	18	17.7	45.8	38	3.6%	0.11 [-0.45, 0.68]
Wallerstein 2012	29.5	51.9	14	20.6	42.6	16	2.9%	0.18 [-0.54, 0.90]
Subtotal (95% CI)			**453**			**553**	**83.0%**	**0.37 [0.15, 0.59]**
Heterogeneity: Tau² = 0.22; Chi² = 75.78, df = 29 (P < 0.00001); I² = 62%								
Test for overall effect: Z = 3.32 (P = 0.0009)								
3.2.3 Unknown training status								
Hortobagyi 2001	312	240.2	9	262	271.1	9	2.3%	0.19 [-0.74, 1.11]
Stefanaki 2019	5.7	9.9	13	5	9.6	13	2.8%	0.07 [-0.70, 0.84]
Subtotal (95% CI)			**22**			**22**	**5.0%**	**0.12 [-0.47, 0.71]**
Heterogeneity: Tau² = 0.00; Chi² = 0.04, df = 1 (P = 0.85); I² = 0%								
Test for overall effect: Z = 0.39 (P = 0.70)								
Total (95% CI)			**537**			**650**	**100.0%**	**0.34 [0.15, 0.52]**
Heterogeneity: Tau² = 0.17; Chi² = 77.15, df = 35 (P < 0.0001); I² = 55%								
Test for overall effect: Z = 3.60 (P = 0.0003)								
Test for subgroup differences: Chi² = 1.06, df = 2 (P = 0.59), I² = 0%								



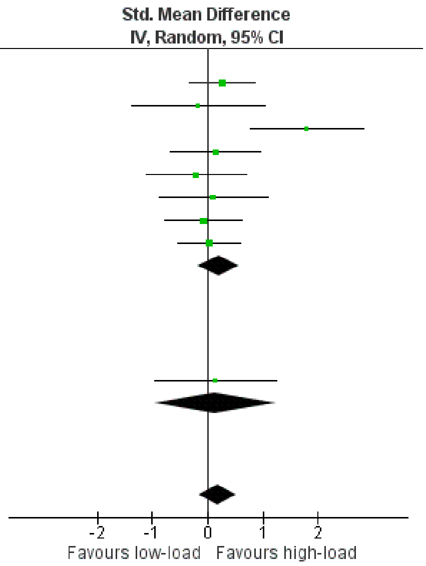
Supplementary Figure 7. Influence of high-load vs. low-load RT on dynamic 1-RM strength development with subgroup analyses based on studies in untrained vs. trained participants. Point estimates and error bars signify the standardised mean difference between high-load and low-load groups and 95% confidence interval (CI) values, respectively.

Study or Subgroup	High-load Mean	High-load SD	High-load Total	Low-load Mean	Low-load SD	Low-load Total	Weight	Std. Mean Difference IV, Random, 95% CI
1.4.2 Untrained								
Fink 2016	6.9	19.5	7	-6.3	15	7	6.0%	0.71 [-0.38, 1.80]
Hisaeda 1996	39	24.9	6	46.2	31.1	5	5.4%	-0.24 [-1.43, 0.96]
Holm 2008	37	12.2	11	15	13.6	11	6.8%	1.64 [0.65, 2.63]
Ikezoe 2017	53.3	48.9	8	60	42	7	6.6%	-0.14 [-1.15, 0.88]
Jenkins 2017	59.2	46.8	7	26.8	58.9	8	6.4%	0.57 [-0.47, 1.61]
Mitchell 2012	67	34.8	12	59	37.1	12	8.4%	0.21 [-0.59, 1.02]
Ogasawara 2013	4	4.7	9	2.3	4.9	9	7.2%	0.34 [-0.60, 1.27]
Popov 2006	143	20.8	9	84	22.1	9	4.6%	2.62 [1.28, 3.96]
Schoenfeld 2020	7.1	43.3	13	8.8	53.2	13	8.7%	-0.03 [-0.80, 0.73]
Tanimoto 2006	29.2	55.6	8	7.6	76.6	8	6.8%	0.31 [-0.68, 1.29]
Van Roie 2013 a	15.2	57.8	12	4	56.7	24	9.5%	0.19 [-0.50, 0.89]
Van Roie 2013 b	7.1	43.3	18	8.8	53.2	38	10.9%	-0.03 [-0.59, 0.53]
Subtotal (95% CI)			**120**			**151**	**87.3%**	**0.42 [0.04, 0.80]**
Heterogeneity: Tau² = 0.22; Chi² = 22.97, df = 11 (P = 0.02); I² = 52%								
Test for overall effect: Z = 2.18 (P = 0.03)								
1.4.3 Unknown training status								
Aagaard 1994	28.9	34.7	7	-13.2	39	6	5.4%	1.07 [-0.13, 2.26]
Hortobagyi 2001	70	55.2	9	80	74	9	7.3%	-0.15 [-1.07, 0.78]
Subtotal (95% CI)			**16**			**15**	**12.7%**	**0.40 [-0.78, 1.58]**
Heterogeneity: Tau² = 0.44; Chi² = 2.47, df = 1 (P = 0.12); I² = 60%								
Test for overall effect: Z = 0.66 (P = 0.51)								
Total (95% CI)			**136**			**166**	**100.0%**	**0.41 [0.07, 0.76]**
Heterogeneity: Tau² = 0.20; Chi² = 25.45, df = 13 (P = 0.02); I² = 49%								
Test for overall effect: Z = 2.33 (P = 0.02)								
Test for subgroup differences: Chi² = 0.00, df = 1 (P = 0.97), I² = 0%								



Supplementary Figure 8. Influence of high-load vs. low-load RT on isometric (MVIC) strength development with subgroup analyses based on studies in untrained vs. trained participants. Point estimates and error bars signify the standardised mean difference between high-load and low-load groups and 95% confidence interval (CI) values, respectively.

Study or Subgroup	High-load Mean	High-load SD	High-load Total	Low-load Mean	Low-load SD	Low-load Total	Weight	Std. Mean Difference IV, Random, 95% CI
2.2.2 Untrained								
Beneka 2005	6.5	14.5	32	2.8	13.2	16	16.6%	0.26 [-0.34, 0.86]
Hisaeda 1996	15.1	27.7	6	20.3	29.3	5	6.3%	-0.17 [-1.36, 1.02]
Holm 2008	26	10.2	11	5	12.3	11	8.1%	1.79 [0.77, 2.81]
Kalapotharakos 2004	9.5	24.8	11	5.7	26.2	12	11.3%	0.14 [-0.68, 0.96]
Lim 2019	13.5	56.5	7	25.5	52.8	14	9.7%	-0.21 [-1.12, 0.70]
Tanimoto 2006	13.6	50.2	8	8.7	48.8	8	8.6%	0.09 [-0.89, 1.07]
Van Roie 2013 a	6.1	31.8	12	8.5	32.1	24	14.1%	-0.07 [-0.77, 0.62]
Van Roie 2013 b	3.7	29.5	18	2.9	30.6	38	17.9%	0.03 [-0.53, 0.59]
Subtotal (95% CI)			**105**			**128**	**92.7%**	**0.19 [-0.17, 0.56]**
Heterogeneity: Tau² = 0.10; Chi² = 11.51, df = 7 (P = 0.12); I² = 39%								
Test for overall effect: Z = 1.05 (P = 0.29)								
2.2.3 Unknown training status								
Aagaard 1994	15.6	44.6	7	9.6	32.4	6	7.3%	0.14 [-0.95, 1.23]
Subtotal (95% CI)			**7**			**6**	**7.3%**	**0.14 [-0.95, 1.23]**
Heterogeneity: Not applicable								
Test for overall effect: Z = 0.25 (P = 0.80)								
Total (95% CI)			**112**			**134**	**100.0%**	**0.19 [-0.14, 0.51]**
Heterogeneity: Tau² = 0.07; Chi² = 11.51, df = 8 (P = 0.17); I² = 31%								
Test for overall effect: Z = 1.11 (P = 0.27)								
Test for subgroup differences: Chi² = 0.01, df = 1 (P = 0.93), I² = 0%								



Supplementary Figure 9. Influence of high-load vs. low-load RT on isokinetic strength development with subgroup analyses based on studies in untrained vs. trained participants.

Point estimates and error bars signify the standardised mean difference between high-load and low-load groups and 95% confidence interval (CI) values, respectively.

Supplementary File A. Microsoft Excel document containing all raw data extracted from the included studies used for the meta-analysis.