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SYSTEMATIC REVIEW

Comparison of Muscle Growth and Dynamic Strength Adaptations Induced by Unilateral and Bilateral Resistance Training: A Systematic Review and Meta-analysis

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Abstract

Background Currently, great debate exists over the proposed superiority of some resistance exercises to induce muscular adaptations. For example, some argue that unilateral exercise (meaning one limb at a time) is superior to bilateral exercises (meaning both limbs). Of note, an evidence-based answer to this question is yet to be determined, particularly regarding muscle hypertrophy.

Objective This systematic review and meta-analysis aimed to compare the effects of unilateral versus bilateral resistance training on muscle hypertrophy and strength gains.

Methods A thorough literature search was performed using PubMed, Scopus, and Web of Science databases. The Cochrane Risk of Bias tool 2 (RoBII) tool was used to judge the risk of bias. Meta-analyses were performed using robust variance estimation with small-sample corrections.

Results After retrieving 703 studies, 9 met the criteria and were included in the meta-analyses. We found no significant differences in muscle hypertrophy between bilateral and unilateral training [effect size (ES): − 0.21, 95% confidence interval (95% CI): − 3.56 to 3.13, $P = 0.57$]. Bilateral training induced a superior increase in bilateral strength (ES: 0.56, 95% CI: 0.16–0.96, $P = 0.01$). In contrast, unilateral training elicited a superior increase in unilateral strength (ES: − 0.65, 95% CI: − 0.93 to − 0.37, $P = 0.001$). Overall, studies presented moderate risk of bias.

Conclusion On the basis of the limited literature on the topic, we found no evidence of differential muscle hypertrophy between the two exercise selections. Strength gains appear to follow the principle of specificity.

1 Introduction

Exercise selection is a fundamental aspect when designing resistance training programs aiming to optimize muscular adaptations (e.g., muscle hypertrophy and strength) [1]. Among the several features that differentiate resistance exercises, one of the main ones that may affect adaptations is whether it is performed bilaterally (meaning both limbs simultaneously) or unilaterally (meaning one limb at time) [2, 3]. Traditionally, bilateral exercises (e.g., back squat, bilateral knee extension, barbell biceps curl) are selected as the main exercises. In contrast, equivalent unilateral exercises (e.g., rear elevated split squat, one-leg knee extension, one-arm biceps curl) are selected as supplementary, in the context of reducing inter-limb asymmetry or rehabilitation [2]. Of note, nowadays some researchers and coaches have been arguing that unilateral/single-limb exercises may be as, or in some cases, more, effective than bilateral/double-limb exercises to induce muscular adaptations [2–6]. The reason for this may lie in the differences between the two types of resistance exercises—e.g., differences in the total

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Key Points

Bilateral exercises (meaning both limbs) are the standard choice when writing resistance training programs for inducing muscular adaptations (e.g., increased strength and muscle hypertrophy).

However, recently, some have suggested that unilateral exercises (meaning one limb at time) may induce greater adaptations. Of note, an evidence-based answer to this question is yet to be determined, particularly on muscle hypertrophy.

We conducted a systematic review and meta-analysis, and on the basis of the limited literature on the topic, we found no evidence of differential muscle hypertrophy between the two exercise selections. Strength gains appear to follow the principle of specificity.

amount of muscle mass involved and force production—and physiological-related consequences [2, 5, 7].

Different lines of investigation have shown that large muscle mass exercise induces a greater cardiovascular response [8, 9], a quicker time to task failure [4, 10], and less local muscle fatigue [5] than small muscle mass exercises in response to a similar maximal workload. This indicates that even in maximal effort, the stimulus to a target muscle may be limited during large muscle mass exercises [4, 5]. Parallel to this, the production of force generated when both limbs contract simultaneously is frequently lower than the summed forces from each limb—a phenomenon referred to as a bilateral force deficit. Although the mechanisms explaining bilateral deficit are unclear, one hypothesis is that there is a reduced neural drive to the target muscle when contracting two limbs simultaneously [11]. On the basis of these observations, it has been suggested that unilateral resistance exercises (i.e., smaller muscle mass exercise) would enhance muscular adaptations in comparison with bilateral exercises (i.e., larger muscle mass exercise) [2, 4, 5]. However, findings on muscle hypertrophy are controversial, with studies reporting similar muscle growth [12], or results more favorable for unilateral training [13]. This makes it difficult to know whether bilateral and unilateral resistance training have differential effects on muscle hypertrophy.

Regarding strength, the most parsimonious hypothesis is that adaptations would follow the principle of specificity; that is, bilateral training induces greater bilateral strength gains than unilateral training, and unilateral training elicits greater unilateral strength gains than bilateral training. Alternatively, it has been suggested that the existence of bilateral force deficit may affect the magnitude of strength adaptations induced by bilateral and unilateral resistance training [2, 3]. Specifically, by observing that force production during unilateral movements can account for more than 50% of the total force produced during equivalent bilateral exercise, some argue that unilateral training would confer an advantage, in part, due to the possibility of training with higher load per limb [2]. On this basis, it has been suggested that unilateral training would elicit more favorable strength gains [2], e.g., greater unilateral strength gains parallel to similar bilateral strength improvements compared to bilateral training.

In fact, a recent meta-analysis provides some support for this hypothesis [14]. Zhang et al. [14] found that unilateral training increased unilateral strength more than bilateral training, whereas bilateral training did not result in greater bilateral strength gains than unilateral training [14]. However, another meta-analysis on this topic observed opposite findings [15]; Liao et al. [15] found that bilateral training increased bilateral strength more than unilateral training, but unilateral training did not result in greater unilateral strength gains than bilateral training [15]. The conflicting data between studies may be attributed to differences in the variables analyzed as a proxy for maximum strength—Zhang et al. [14] included exclusively isotonic strength measurements whereas Liao et al. [15] included different strength measurements (e.g., one-repetition maximum, isokinetic peak torque)—and how the authors dealt with correlated effect sizes; neither study used a meta-analysis model that took into account the dependence between effect sizes when certain studies presented more than one strength measure [14, 15].

Thus, it remains to be determined whether there is differential muscle growth and dynamic maximum strength adaptations between bilateral and unilateral resistance training. In parallel with a scientific inquiry perspective, determining potential differences between the two resistance exercise modes is fundamental to enable coaches and practitioners to make evidence-based decisions on exercise selection. In this context, a synthesis of evidence on the effects of bilateral and unilateral training on muscle growth is imperative, as well as a meta-analysis that overcomes the limitations of previous meta-analytical studies (i.e., includes more homogeneous dynamic strength measurements and adopts a meta-analysis model that considers the dependence between effect sizes when this is the case), would be of great value. Thus, in this systematic review and meta-analysis, we aimed to compare the effects of unilateral versus bilateral resistance training on muscle hypertrophy and maximum strength changes.

2 Methods

2.1 Research Question

This systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Review and Meta-Analysis Protocol (PRISMA) and Prisma in Exercise, Rehabilitation, Sport Medicine, and Sports Science (PERSiST) [16, 17]. This meta-analysis was not pre-registered. The research questions were defined according to the population, intervention, comparator, and outcomes (PICO) framework, as follows:

Population: Individuals with or without resistance training experience, with no restrictions on sex or age. Investigations including individuals with chronic diseases, musculoskeletal disorders, or injuries were excluded.

Intervention: Longitudinal randomized trials employing parallel-group design comparing unilateral (i.e., training one limb at a time) and bilateral (i.e., training both limbs at the same time) resistance training programs lasting ≥ 3 weeks.

Comparator: An experimental trial comparing unilateral versus bilateral dynamic resistance exercises.

Outcomes: Changes in muscle hypertrophy (assessed by muscle thickness, cross-sectional area, volume, or muscle mass) and/or changes in dynamic strength [assessed by repetition-maximum (1 – 5 RM) strength tests]. Studies including only non-specific strength measures (e.g., isometric, or isokinetic strength) were not included.

2.2 Literature Search

To conduct the review, we searched PubMed/MEDLINE, Web of Science, and Scopus electronic databases up to December 2023. Only peer-reviewed articles in English were selected for inclusion; citations from scientific conferences were excluded from analysis. We used a "subject-key-term + free word" search format. The following keywords inclusive of five main terms as unilateral, bilateral, resistance training, muscle hypertrophy, and strength were used and combined under Boolean's language with operators AND and OR. Term 1: "unilateral", "single limb", "one limb", "one leg", "one arm". Term 2: "bilateral", "double limb", "two limbs", "two legs", "two arms". Term 3: "resistance training", "resistance exercise", "strength training", "strength exercise". Term 4: "muscle hypertrophy", "muscle thickness", "cross-sectional area", "muscle mass", "muscle size", "muscle volume". Term 5: "maximum strength", "maximum force", "one-repetition maximum", "repetition maximum". The title and abstract of each study were inspected for relevance, and the full texts were then scrutinized for those initially appearing to meet inclusion criteria. Studies for which the abstracts did not provide enough information according to our inclusion criteria were retrieved for full-text evaluation. In the selected articles, the reference lists and Google Scholar citations were screened for additional manuscripts. In addition, the lists of articles that cited the included studies were screened. The first author (W.K.) completed the search.

2.3 Study Coding, Data Extraction, and Risk of Bias

The following data were extracted from the included studies: study characteristics (author, year, sample size, and study design), participant demographics (age, sex, and resistance training experience), resistance training program (duration, frequency, resistance exercise, number of sets, rest interval), and outcome measures. We then coded data for the included studies' pretraining and posttraining means and standard deviations. W.K. and J.P.N. independently extracted the data from the included papers. After the data extraction, B.C. confirmed the precision of the extracted data. The quality assessment of included articles was performed using the Cochrane the Risk of Bias tool 2 (RoBII). Articles were assessed for hypertrophy/strength outcomes bias: (1) arising from the randomization process, (2) due to deviations from intended interventions, (3) due to missing outcome data, (4) in the measurement of the outcome, and (5) in the selection of reported results. Each domain was determined to be of high, moderate, or low risk of bias. Then the studies were given an overall classification of high, moderate, or low risk of bias. Traffic light and weighted summary risk of bias plots for included studies were produced by the online risk of bias (robvis) tool (https://mcguinlu.shinyapps.io/robvis/) [18]. W.K. and J.P.N. independently evaluated the quality of the included studies, and any disagreement was resolved by consensus.

2.4 Statistical Analysis

All data were analyzed by two investigators (W.K. and J.L.) in an effort to maximize accuracy. Because we were interested in capturing the magnitude of the variability within the intervention itself, we calculated the effect sizes for each study using the mean difference and the standard deviation (SD) of the difference (commonly known as Cohen's d) [19]. However, we also calculated the effect sizes as mean difference divided by the pooled SD of the pre- and rerun data to provide the size of the effect relative to the spread of the sample [20]. If the SD of the difference was not presented but the exact P-value was, we calculated the t-value using the inverse of the cumulative distribution function. The t-value was then used to calculate the change score deviation. If the variability of the change was not provided (and could not be obtained from available data), the SD of the change was estimated using the following formula:

$$SD_{\text{of change}} = \sqrt{\left[(\text{SDPretest})^2 + (\text{SDPosttest})^2 - (2r \times \text{SDPretest} \times \text{SDPosttest})\right]}.$$

SD represents the standard deviation, and *r* represents the correlation coefficient between the pretest and the posttest values. We used 0.8 as the pre–post correlation. The standardized effect size and the standard error of this effect size were computed as follows [21]:

$$\text{Standardized ES} = \frac{\text{change}_{\text{bilateral}} - \text{change}_{\text{unilateral}}}{\sqrt{\frac{(N_1-1)v_1+(N_2-1)v_2}{N_1+N_2-2}}},$$

$$\text{Standardized SE} = \sqrt{\frac{(N_1 + N_2)}{N_1 \times N_2} + \frac{ES^2}{2(N_1 + N_2)}}.$$

ES represents the effect size, N_1 represents the sample size of the bilateral group, N_2 represents the size of the unilateral group, v_1 represents the variance of the bilateral group, v_2 represents the variance of the unilateral group, and *SE* represents the standard error.

A robust variance meta-analysis model was used to account for correlated effect sizes within studies [22]. This meta-analysis model is specifically designed for and used when dealing with dependent effect sizes (e.g., several measures for a specific outcome assessed within a single study). Statistics were performed using the robumeta package (version 2.1) within R statistical software (version 3.6.3, R foundation for Statistical Computing, Vienna, Austria) and R Studio (version 1.4.1103, RStudio, Inc., Boston, MA, USA). In robumeta we performed a correlated effects model with small-sample corrections. We adopted the default correlation of 0.8. Model weights were determined using the default setting (CORR) and effect sizes are presented in standardized units. We also performed a sensitivity analysis to determine the effect of rho and tau-squared. Tau-squared represents the between-study variance component in the correlated effects meta-regression model and is calculated using the method-of-moments estimator provided in Hedges et al. [23]. I^2 was also provided and is used to quantify the amount of variability in effect size estimates due to effect size heterogeneity. We also implemented the metafor package (version 3.0–2, Restricted ML) to report the prediction intervals. To reduce issues associated with using a normal distribution, we used the argument tdist = TRUE with rma.mv function, which applies the Knapp and Hartung adjustment to the analysis. Three separate comparisons were made: (1) hypertrophic effects of bilateral versus unilateral training; (2) bilateral muscular strength changes of bilateral versus unilateral training; and (3) unilateral muscular strength of bilateral versus unilateral training. Data are presented as effect size, standard error, and 95% confidence interval and prediction intervals. An Eggers test for publication bias was not performed due to the small number of studies included (a general rule of thumb is to have at least ten studies).

3 Results

The search strategy initially yielded 699 articles plus 4 studies found through citations searching and another source. Following the deletion of duplicates, the literature search yielded 303 records. A total of 288 articles were excluded on the basis of the title and abstract screen; 19 articles were obtained in full text (15 from initial searching and 4 from citation searching and another source), and the selection criteria were applied. Reasons for exclusion included: article did not include outcomes of interest, contained data from the same sample, did not present retrievable data, employed isometric training, compared exercises that differ more than in the number of limbs exercised, training and strength testing did not match, or had participants changing exercises at each training session and each participant progressing to the next exercise at different times within the training program (in one group but not the other). Finally, nine studies were included in the meta-analyses. The PRISMA flow diagram is shown in Fig. 1.

3.1 Study Characteristics

Details from the nine studies ($n = 200$ participants) included in the final analysis are presented in Table 1. Resistance training interventions were performed on male-only samples in seven studies [24–30], and female-only samples in two studies [12, 13]. A total of seven studies investigated lower-limb exercises [12, 24, 25, 27–30], one investigated upper-limb [26], and one investigated upper- and lower-limb exercises [13]. The most frequent resistance exercises investigated were bilateral back squat versus equivalent unilateral variations such as rear elevated split squat, Bulgarian split squat, and step-up followed by bilateral versus unilateral knee extension and bilateral versus unilateral leg press. One study assessed changes in muscle hypertrophy using muscle thickness [12] and one upper- and lower-limb lean tissue mass [13]. Strength outcome was analyzed by 1 RM tests in eight studies [12, 13, 24–29] and 5 RM tests in one study [30]; eight studies assessed bilateral and

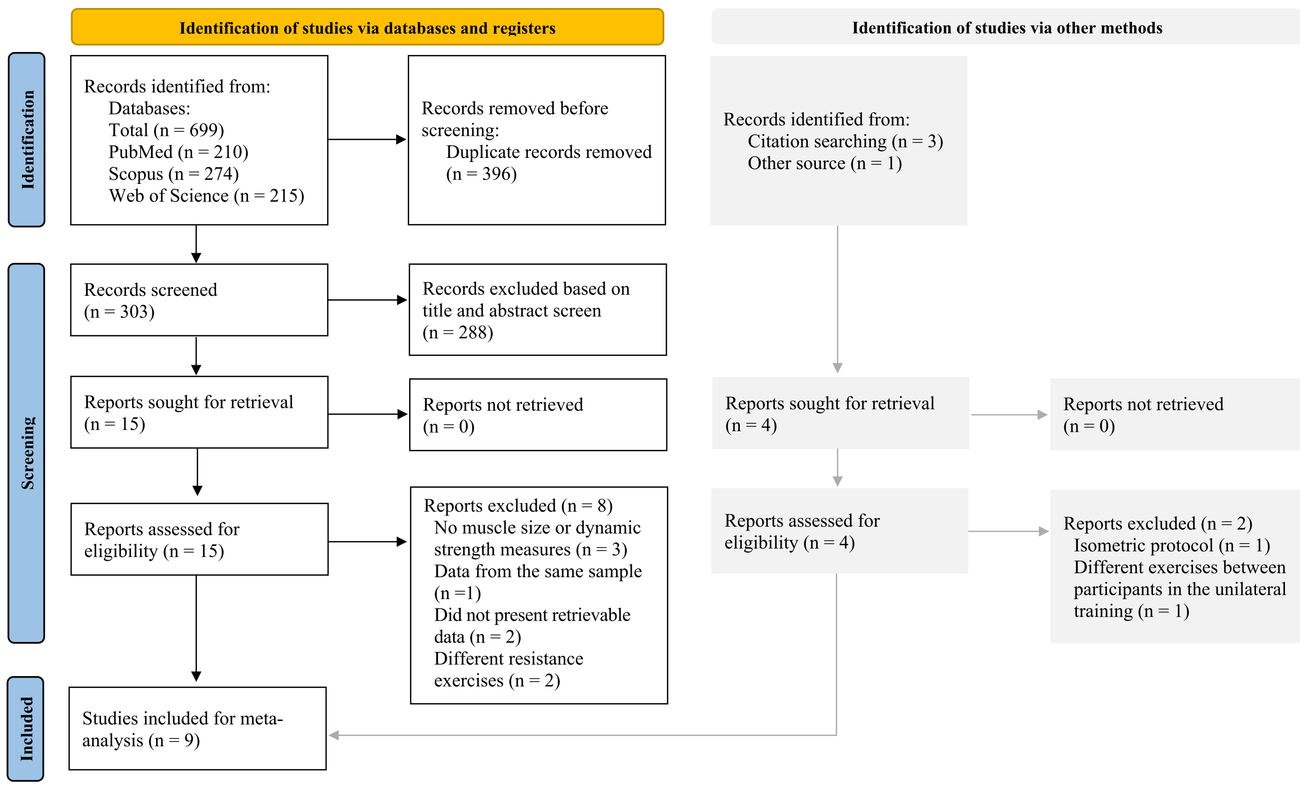

Fig. 1 PRISMA flow diagram

unilateral strength [12, 13, 24–26, 28–30], while two assessed bilateral strength only [27]. For unilateral strength tests, two studies provided data from the dominant limb [28, 30], two studies presented the average values between both limbs [24, 29], two presented the values for both limbs [13, 26], one used the sum of the values of both limbs [12], and one did not specify [25].

3.2 Muscle Hypertrophy: Bilateral Training Versus Unilateral Training

The overall between-group effect on muscle hypertrophy using change score variability was − 0.21, with a standard error of 0.26, and a 95% confidence interval of − 3.56 to 3.13 (Fig. 2, $P = 0.570$, $df = 1$). I^2 was 55.4 and tau-squared was 0.19. Sensitivity analysis demonstrated that this effect was stable across different Rho values. However, this effect should be interpreted with caution due to the few studies available. The 95% prediction intervals from metafor ranged from − 6.09 to 5.51.

The overall between-group effect on muscle hypertrophy using SD of pre was − 0.03, with a standard error of 0.06, and a 95% confidence interval of − 0.83 to 0.77 ($P = 0.696$, studies: $df = 1$). I^2 was 0.00 and tau-squared was 0.00. Sensitivity analysis demonstrated that this effect was stable across different Rho values. However, this effect should be interpreted with caution due to the few studies available. The 95% prediction intervals from metafor ranged from − 0.79 to 0.68.

3.3 Bilateral Dynamic Strength: Bilateral Training Versus Unilateral Training

The overall between-group effect on bilateral strength using change score variability was 0.56, with a standard error of 0.17, and a 95% confidence interval of 0.16 to 0.96 (Fig. 3, $P = 0.011$, studies: $df = 7.72$). I^2 was 26.3 and tau-squared was 0.07. Sensitivity analysis demonstrated that this effect was stable across different Rho values. The 95% prediction intervals from metafor ranged from − 0.47 to 1.60.

The overall between-group effect on bilateral strength using SD of pre was 0.33, with a standard error of 0.12, and a 95% confidence interval of 0.04 to 0.63 ($P = 0.030$, $df = 7.55$). I^2 was 0.00 and tau-squared was 0.00. Sensitivity analysis demonstrated that this effect was stable across different Rho values. The 95% prediction intervals from metafor ranged from − 0.38 to 1.05.

3.4 Unilateral Dynamic Strength: Bilateral Training Versus Unilateral Training

The overall between-group effect on unilateral strength using change score variability was − 0.65, with a standard error

Table 1 Characteristics of included studies

Study	Participants	Training program					Outcomes
	Identity	Duration/frequency	Sets per exercise per session	Repetitions	Bilateral resistance exercises	Unilateral resistance exercises	Muscle hypertrophy and strength measurements
Appleby et al. [24]	Resistance-trained young men ($n=23$)	8 weeks, 2 days/week	6–8 sets	4–8 repetitions[a]	Bilateral squat	Step-up	1RM step-up and 1RM squat
Botton et al. [12]	Non-resistance-trained young women ($n=29$)	12 weeks, 2 days/week	2 sets in weeks 1–3, 3 sets in weeks 4–9, and 4 sets in weeks 10–12	12–15 RM in weeks 1–3, 9–12 RM in weeks 4–6, 7–10 RM in weeks 7–9, and 5–8 RM in weeks 10–12	Bilateral knee extension	Unilateral knee extension	Overall quadriceps muscle thickness (sum of rectus femoris, vastus lateralis, medialis, and intermedius) for both limbs followed by the sum of the right and left thighs Bilateral and unilateral 1RM-strength assessed in knee extension exercise
Janzen et al. [13][b]	Non-resistance-trained post-menopausal women ($n=26$)	26 weeks, 3 days/week	2 sets	8–10 RM	Lower limbs: leg press, knee extension, and hamstring curl Upper limbs: lat pull-down, biceps curl, shoulder press, and chest press	Lower limbs: leg press, knee extension, and hamstring curl Upper limbs: lat pull-down, biceps curl, shoulder press, and chest press	Lean tissue mass of upper and lower limbs measured by dual energy X-ray absorptiometry Bilateral and unilateral 1RM-strength assessed in leg press, lat pull-down, and knee extension
Krajewski et al. [25]	Non-resistance-trained men ($n=15$)	4 weeks, 3 days/week	3 sets	2–6 repetitions	Bilateral back squat and stiff legged deadlift	Bulgarian split squat and single leg stiff legged deadlift	1 RM back squat and 1 RM Bulgarian split squat
Lee et al. [26]	Resistance-trained men ($n=30$)	6 weeks, 3 days/week	3 sets	10 repetitions	Bilateral barbell chest press and barbell biceps curl	Unilateral dumbbell chest press and dumbbell biceps curl	Bilateral and unilateral 1 RM-strength assessed in chest press and biceps curl
Ramirez-Campillo et al. [27]	Young male soccer players ($n=18$)	8 weeks, 1 day/weeks	3 sets	10 repetitions	Bilateral knee extension and knee flexion	Unilateral knee extension and knee flexion	Bilateral 1 RM assessed in knee extension and knee flexion
Speirs et al. [28]	Resistance-trained men ($n=18$)	5 weeks, 2 days/week	4 sets	3–6 repetitions	Bilateral back squat	Rear elevated split squat	1 RM bilateral back squat and 1 RM rear elevated split squat

Table 1 (continued)

Study	Participants	Training program					Outcomes
	Identity	Duration/frequency	Sets per exercise per session	Repetitions	Bilateral resistance exercises	Unilateral resistance exercises	Muscle hypertrophy and strength measurements
Stern et al. [29]	Resistance-trained youth male soccer players ($n=23$)	6 weeks, 2 days/week	4 sets	6 repetitions	Bilateral back squat	Rear elevated split squat	1 RM bilateral back squat and 1 RM rear elevated split squat
Zhao et al. [30]	Resistance-trained youth male rugby players ($n=18$)	5 weeks, 2 days/week	4 sets	2–7 repetitions	Bilateral leg press	Unilateral leg press	Bilateral and unilateral 5 RM in leg press

[a] For unilateral exercise, the repetitions are the total for the set (e.g., 4 repetitions indicate 2 on each leg); *1 RM* one-repetition maximum, *RM* repetition maximum

[b] Upper limb exercises performed in machines that had split lever arms, which allowed the participants to do unilateral training

of 0.11, and a 95% confidence interval of − 0.93 to − 0.37 (Fig. 4, $P=0.001$, $df=6.56$). I^2 was 0.0 and tau-squared was 0.00. Sensitivity analysis demonstrated that this effect was stable across different Rho values. The 95% prediction intervals from metafor ranged from − 1.01 to − 0.17.

The overall between-group effect on bilateral strength using SD of pre was − 0.42, with a standard error of 0.08, and a 95% confidence interval of − 0.63 to − 0.21 ($P=0.002$, $df=6.56$). I^2 was 0.0 and tau-squared was 0.00. Sensitivity analysis demonstrated that this effect was stable across different Rho values. The 95% prediction intervals from metafor ranged from − 0.78 to − 0.15.

3.5 Risk of Bias

From the risk of bias assessment, we observed that the nine studies presented "some concerns." The domains that most frequently presented some concerns were "randomization process" (seven studies), "measurement outcome" (eight studies), and "selection of the reported result" (eight studies). Concerns arose most due to the lack of information on allocation sequence concealment, whether evaluators were aware of the intervention received, and prespecified analysis procedures. Figure 5 shows the weighted summary risk of bias plots. Figure 6 shows the traffic light risk of bias plots.

4 Discussion

This systematic review with meta-analysis aimed to compare the effects of bilateral versus unilateral resistance training on muscle hypertrophy and strength adaptations. The current findings suggest that exercise selection, whether bilateral or unilateral, appears to influence strength changes, but there is great uncertainty on the hypertrophic responses. More specifically, the main results were that: (1) from the limited studies available thus far, there was no evidence of a difference in the magnitude of muscle hypertrophy induced by bilateral and unilateral training (though this model is not stable due to insufficient data); (2) bilateral resistance training induced a superior effect on increasing bilateral dynamic strength in comparison with unilateral training; and (3) unilateral resistance training elicited a superior increase in unilateral dynamic strength in comparison with bilateral training. In the ensuing paragraphs, we discuss these results in the context of the available evidence, proposing potential explanations and the limitations of current literature as well as making suggestions for future studies on this topic.

4.1 Muscle Strength

The results of the present meta-analysis support the notion that strength increases are greater in the task that individuals

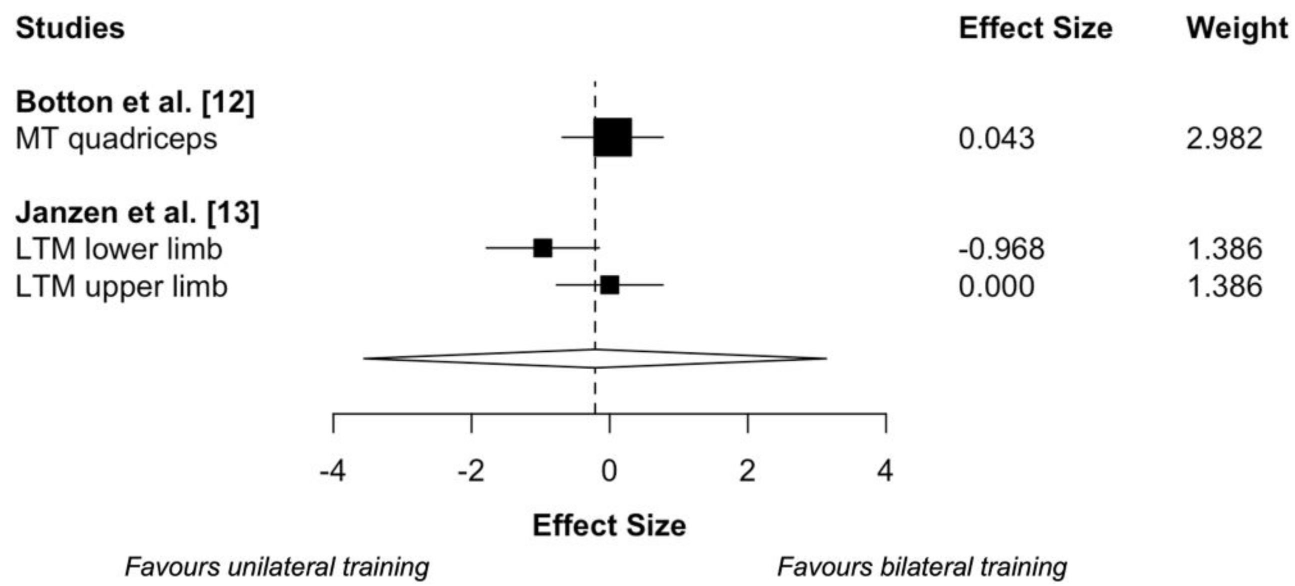

Fig. 2 Forest plot showing comparative effect of bilateral and unilateral training on muscle hypertrophy. Values represent Cohen's *d* (95% confidence interval). Each study is listed on the left side of the plot with squares representing the effect size for each study and 95% confidence interval. The square size varies according to the weights assigned to the different studies. The overall effect is included at the bottom of the plot as a diamond with a width corresponding to the confidence interval for the estimated effect; *MT* muscle thickness, *LTM* lean tissue mass

trained, following the principle of specificity. Interestingly, the two meta-analytic studies on this topic observed ambiguous results. Zhang et al. [14] observed greater gains in unilateral maximal strength after unilateral training while bilateral strength gains were not different between unilateral and bilateral training, thus indicating more favorable results for unilateral training. In contrast, Liao et al. [15] observed greater gains in bilateral strength after bilateral training while unilateral strength gains were not different between the two exercises selections. We speculate that the conflicting data between these studies may be attributed to (i) differences in study inclusion criteria (e.g., inclusion of data from theses and dissertations [14]); (ii) inclusion of different strength measures (e.g., isotonic, isokinetic, power) to infer about strength [15]; and (iii) failure to take into account correlated effect sizes in the meta-analytic model [14]. In the present meta-analysis, we included only studies published in peer-reviewed journals that assessed maximal strength outcome through isotonic strength measurements (i.e., 1–5 RM). In addition, we included all dynamic strength measurements (e.g., 1 RM leg press and knee extension) from the same study adopting a meta-analytic model that allowed us to take into account the dependence between effect sizes. Putting this into perspective, such factors together may conceivably help to explain, in part, such divergent data.

Previously, some suggested that unilateral training might result in more favorable maximal strength gains (e.g., greater unilateral strength gains and similar bilateral strength gains than/to bilateral training). This proposition was made on the basis of the frequent, but not unanimous, observation that force production during unilateral movements can account for more than 50% of the total force produced during equivalent bilateral exercise [2, 3, 31]. This could confer an advantage of unilateral training compared with bilateral training (i.e., training heavier per limb) [2]. However, the findings of the present meta-analysis do not support this hypothesis. Of note, in addition to bilateral deficits not always being observed [31], some reports actually suggested bilateral facilitation (i.e., when the force produced during bilateral contraction is greater than the sum of the unilateral forces of the two limbs) [2, 32, 33] and this observation could in theory confer an advantage of bilateral training; but again, the findings of the present meta-analysis do not support this hypothesis.

We found that bilateral strength gains were greater when training was performed bilaterally, and unilateral strength gains were greater when training was performed unilaterally. Although it is beyond the scope of this review, we can speculate on some mechanisms that may explain these findings. For example, it has been suggested that after a period of resistance training, improvements in task-specific coordination occur, which facilitate greater strength increases in the trained task [34, 35]. Other possible explanations may lie in neural changes [e.g., electromyographic (EMG) signal amplitude and voluntary activation]. For example, a correlation was observed between changes in the EMG of both legs and changes in bilateral maximal strength induced by 12 weeks of bilateral knee extension training [32]; the same

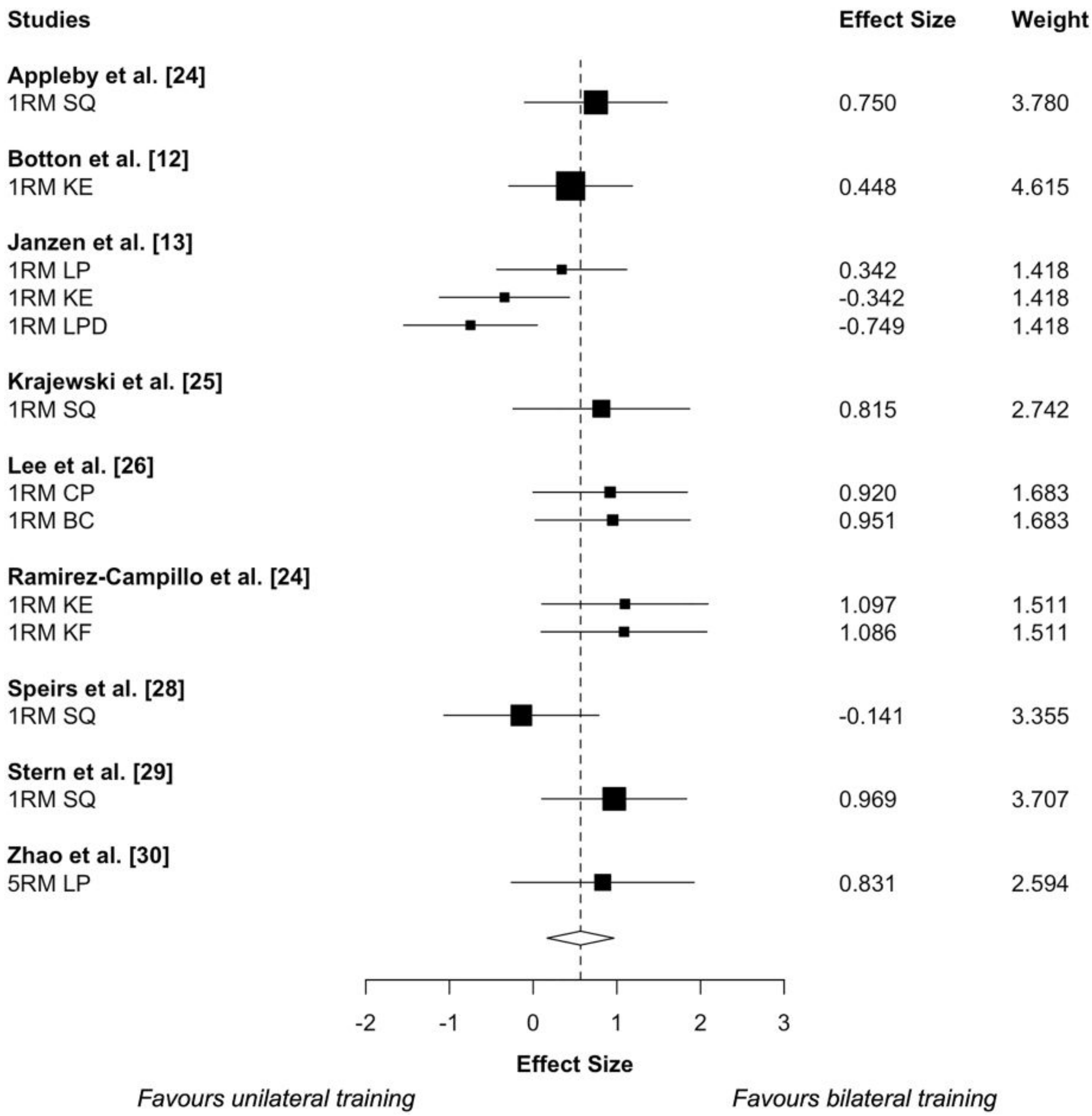

Fig. 3 Forest plot showing comparative effect of bilateral and unilateral training on bilateral strength. Values represent Cohen's *d* (95% confidence interval). Each study is listed on the left side of the plot with squares representing the effect size for each study and 95% confidence interval. The square size varies according to the weights assigned to the different studies. The overall effect is included at the bottom of the plot as a diamond with a width corresponding to the confidence interval for the estimated effect; *1 RM* one-repetition maximum, *SQ* squat, *KE* knee extension, *LP* leg press, *KF* knee flexion, *LPD* lat pull down, *CP* chest press, *BC* biceps curl, *5 RM* 5-repetition maximum

was observed for changes in the EMG values of the right leg and unilateral maximal strength of the right leg (same for the left leg) [32]. In the same study [32], bilateral training increased EMG of both legs more than unilateral training. However, unilateral training did not increase EMG of the right or left legs more than bilateral training [32]. Reinforcing the conflicting scenario, in another report there was an increase in quadriceps EMG amplitude signal only after unilateral knee extension resistance training [12]. Therefore, it remains to be determined whether changes in EMG—and other proxies of neural adaptations such as voluntary activation—are a mechanism to help explain why strength gains induced by the two exercise selections follow the principle of specificity.

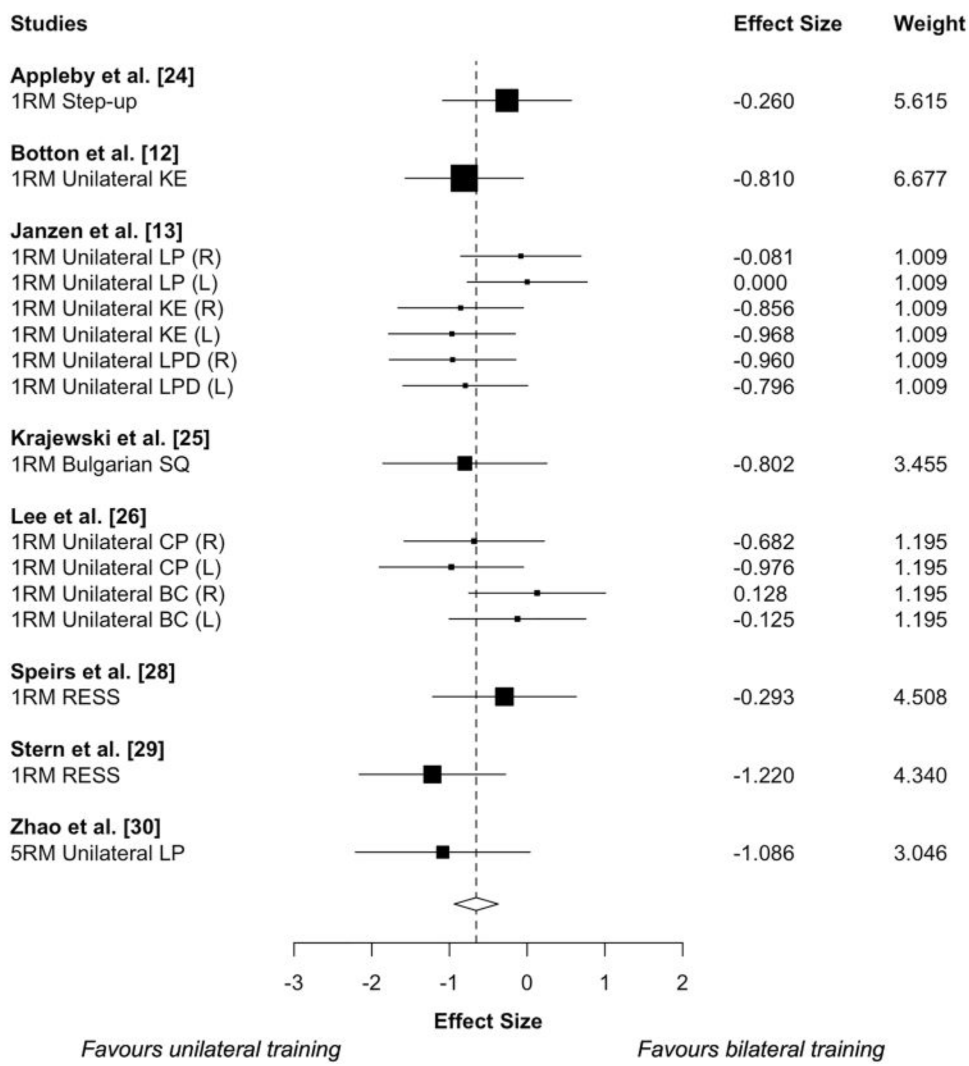

Fig. 4 Forest plot showing comparative effect of bilateral and unilateral training on unilateral strength. Values represent Cohen's *d* (95% confidence interval). Each study is listed on the left side of the plot with squares representing the effect size for each study and 95% confidence interval. The square size varies according to the weights assigned to the different studies. The overall effect is included at the bottom of the plot as a diamond with a width corresponding to the confidence interval for the estimated effect; *1 RM* one-repetition maximum, *KE* knee extension, *LP* leg press, *R* right side, *L* left side, *LPD* lat pull down, *CP* chest press, *BC* biceps curl, *RESS* rear elevated split squat, *5 RM* 5-repetition maximum

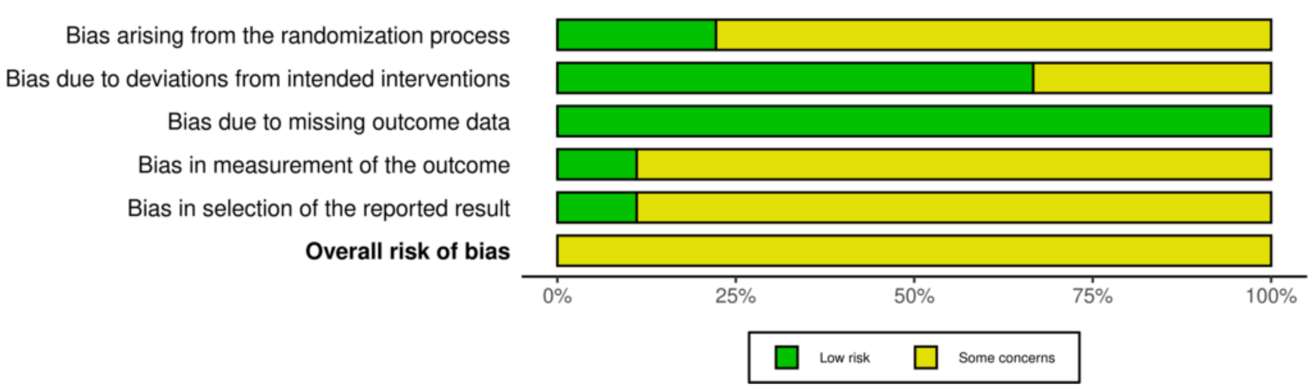

Fig. 5 Weighted summary risk of bias plots

4.2 Muscle Hypertrophy

Two studies measured changes in muscle size. One measured muscle thickness using ultrasound, and another measured changes in lean tissue mass using dual energy X-ray absorptiometry. From results of our meta-analysis, we found no evidence for a difference between unilateral and bilateral training on muscle size changes. Traditionally, bilateral exercises have been considered more effective in inducing muscular adaptations [36], partly because the individual

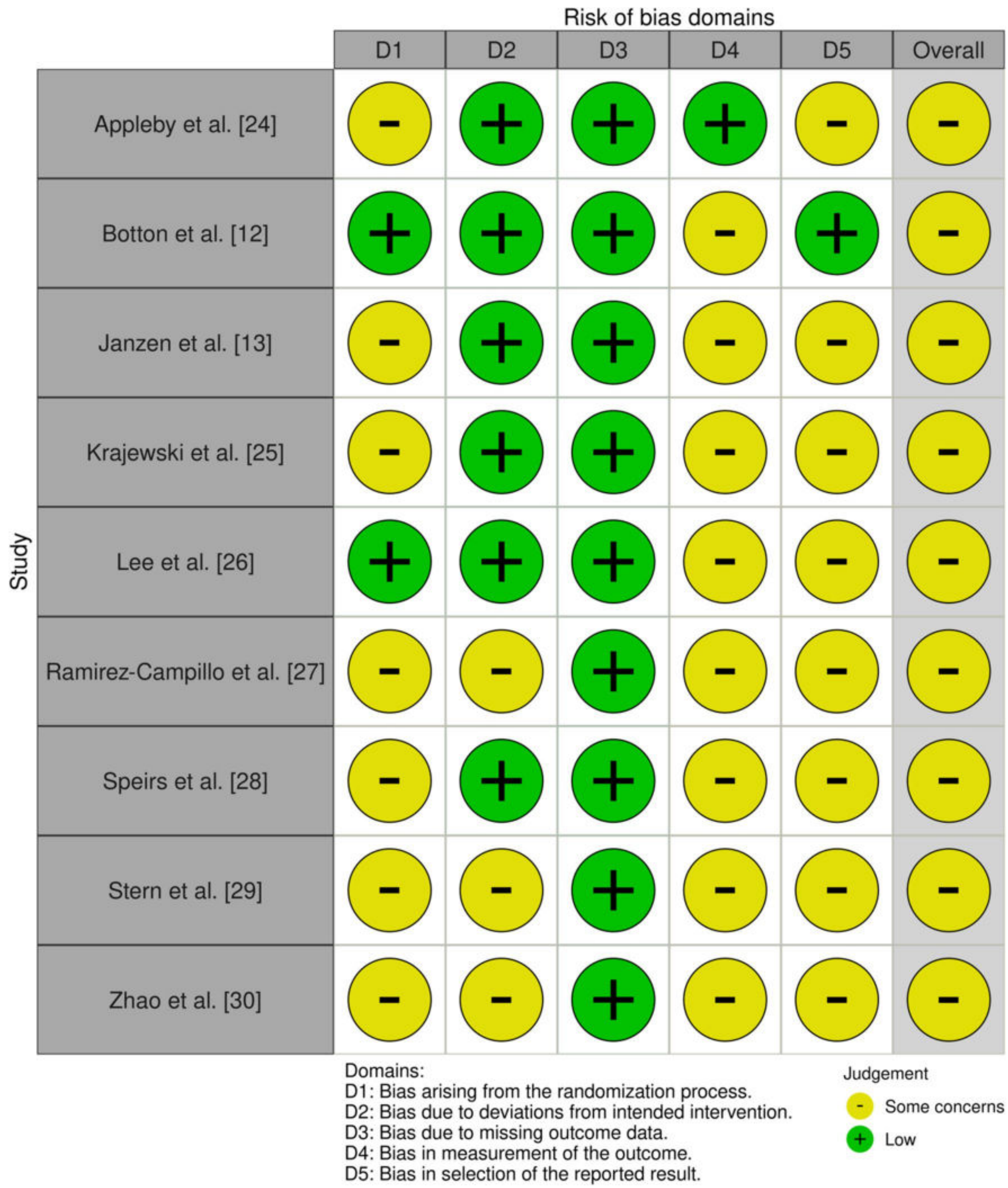

Fig. 6 Traffic light risk of bias plots

can lift more weight per repetition than unilateral equivalent exercises, which is frequently accompanied by greater electromyographic activity [36]. Of note, the hypothesis that lifting high loads could result in greater hypertrophy has been refuted [37, 38], and the relationship between greater electromyographic activity and hypertrophy has also been challenged [39, 40]. In this sense, more recently, some have argued that unilateral exercises could be similar to or, in some cases, more effective in inducing muscular adaptations [2]. Among the arguments, one that receives attention is the potential influence of the amount of muscle mass involved.

Theoretically, larger muscle mass exercises (e.g., bilateral leg press and knee extension) could result in interruption of the exercise due to several factors other than local fatigue of the target muscle [4, 5]. In contrast, smaller muscle mass exercises (e.g., unilateral leg press and knee extension) would be interrupted more specifically by local fatigue of the target muscle [4, 5]. However, although some differences in the acute response are often observed (e.g., greater peripheral fatigue and time-to-task failure in unilateral exercises) [4, 5, 7], we have no evidence of a difference in muscle growth magnitude. Of note, we do not completely rule out this hypothesis. For example, in the Janzen et al. [13] study, only the unilateral training group—which performed leg press, knee extension, and leg curl—increased lean tissue mass compared with the control; the bilateral group did not. In contrast, Botton et al. [12] observed increases in quadriceps thickness in both training groups compared with control when performing exclusively unilateral and bilateral knee extension. In another study [32], not included in the meta-analysis due to insufficient data, individuals performed knee extension exclusively, and the increase in quadriceps cross-sectional area between bilateral and unilateral training was not different. Therefore, from the inspection of individual studies, it is possible to suggest the amount of muscle mass may play a role when exercises involve a greater difference in muscle mass (e.g., leg press, squat). However, that remains speculative and needs to be tested.

4.3 Gaps, Limitations, and Research Recommendations

To our knowledge, this is the first systematic review and meta-analysis on muscle hypertrophy in response to bilateral and unilateral resistance training. The synthesis of the available literature aids in a better understanding of the role of exercise selection in muscular adaptations and in identifying research gaps on this topic. Notably, our meta-analysis has limitations that need to be highlighted. The number of studies included in the muscle hypertrophy meta-analysis was small. In addition, most studies did not clearly describe some characteristics of the training and the exercise execution. For example, studies rarely described whether there was a rest interval between limbs in the unilateral group and whether the exercise was performed to or close to task failure. Therefore, future studies should make the training program description more detailed. Some of the studies included in the strength meta-analysis estimated the 1 RM. In this sense, it is difficult to know whether this affected muscle strength results.

Another potential limitation of the available data is the duration of the intervention. For example, most reports (i.e., eight studies) were 4–12 weeks in duration, with only one study [13] lasting > 20 weeks. Some argue that there may be differences in the time course of adaptations between the two types of exercise [3], but this remains speculative. Furthermore, unilateral exercises can vary substantially in terms of stability degree and contralateral limb contribution [2, 3, 41]. Some unilateral exercises, such as unilateral leg extension, are performed on machines with a higher degree of stability, while others are performed with free weights and a lower degree of stability, such as rear elevated split squat with free barbell. However, the potential influence of these factors on muscle growth and strength adaptations is unknown and needs further investigation. Moreover, future studies should consider having a group perform both types of exercise and observe whether unilateral and bilateral strength gains are greater than selecting just one or the other. Finally, on the basis of the risk of bias assessment, all the studies presented some concerns, particularly for not establishing whether allocation sequence was concealment, whether evaluators were aware of the intervention received, and not presenting information about prespecified analysis procedures. Thus, readers should be cautious with this interpretation of current data. Future studies should focus on these points to reduce the risk of bias.

5 Conclusions

Our findings suggest that exercise selection, whether bilateral or unilateral, appears to influence dynamic strength adaptations. Regarding muscle growth, there was no evidence of differential hypertrophic adaptations, but the literature is almost nonexistent. More specifically, bilateral resistance training is more effective than unilateral training for increasing bilateral strength, while unilateral resistance training is more effective than bilateral training for increasing unilateral strength. Regarding muscle size changes, the magnitude of muscle growth does not appear to differ between bilateral and unilateral training (but more data are needed). From a practical point of view, coaches and practitioners should consider selecting bilateral exercises when the objective is to optimize bilateral strength increases, while unilateral exercises can be prioritized to increase unilateral strength. For muscle hypertrophy, both types of exercise should be considered. Coaches and practitioners can take into account other factors to determine exercise selection, such as time availability to train, personal preferences, individual needs, and equipment availability. Considering the minimum amount of information available at this point, future information could alter the current conclusion and practical recommendations.

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Declarations

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Conflict of Interest Jeremy Loenneke is an Editorial Board member of Sports Medicine but was not involved in the selection of peer reviewers for the manuscript nor any of the subsequent editorial decisions. Witalo Kassiano, João Pedro Nunes, Bruna Costa, Alex S. Ribeiro, and Edilson S. Cyrino declare that they have no conflicts of interest relevant to the content of this review.

Data Availability All data and code are available on the Open Science Framework project page (https://osf.io/rkgfm/).

Author Contributions W.K. conceived the idea for this review and conducted the literature search. W.K. and J.P.L. worked together in the acquisition, analysis, and interpretation of the data for the study. W.K. and J.P.L. interpreted the data, carefully reviewed the results, and edited the manuscript. W.K. wrote the first draft of the manuscript. J.P.N., B.C., A.S.R., J.P.L., and E.S.C. revised the original manuscript. All authors read and approved the final version.

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