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Effects of Maximal Versus Submaximal Intended Velocity Resistance Training on Muscular Fitness Adaptations in Older Adults: A Systematic Review and Meta-Analysis

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ABSTRACT

Purpose: This systematic review aimed to: 1) explore muscular fitness adaptations (e.g., muscle mass, muscle strength, functional performance) in older adults (≥ 60 years) following exercise with resistance training compared to control; and 2) investigate the moderating effects of load intensity, training frequency, and movement velocity on muscular fitness adaptations. **Methods:** Four databases were searched (April 2024, updated 2025). Pooled effects for each outcome were summarized using Standardized Mean Difference (*Hedges' g*) through a three-level meta-analysis model, and subgroup was used to explore moderators. The certainty of evidence was assessed using the GRADE approach. **Results:** Sixteen studies were eligible (n = 801), with data available from fifteen moderate quality randomized controlled trials. Compared to control, resistance training was effective in improving muscle mass (g = 0.16, I^2 = 67%), muscle strength (g = 0.55, I^2 = 11%), and functional performance (g = 0.76, I^2 = 62%). Muscular fitness was significantly moderated by load intensity, frequency, and movement velocity. SubmaxV (g = 0.47) resistance training with low intensity (g = 0.79) and high frequency (g = 0.79) was superior for improving muscle mass. SubmaxV (g = 0.56) resistance training with moderate intensity (g = 0.63) and moderate frequency (g = 0.55) was superior for improving muscle strength. MaxV (g = 0.93) resistance training with moderate intensity (g = 0.71) and low frequency (g = 0.64) was superior for improving functional performance. **Conclusions:** Resistance training effectively enhances muscular fitness in older adults. Load intensity, frequency, and movement velocity (SubmaxV was better for muscle mass and muscle strength compared to MaxV, and MaxV for functional performance) may significantly modulate improvements in muscular fitness adaptations.

Keywords: movement velocity, muscle mass, muscle strength, functional performance, older adults

PROSPERO Registration CRD42023489470

List of Abbreviations

1 RM: One-repetition maximum

MaxV: Maximal intended velocity

SubmaxV: Submaximal intended velocity

AQAP: As quickly as possible

RPE: Rate of perceived exertion

wk: Weeks

SMD: Standardized Mean Difference

Hedges' g: Hedges' g statistic

ci: Confidence interval

95%ci: 95% confidence interval

PI: Prediction interval

I^2: Heterogeneity statistic

τ^2: Between-study variance

K: Total number of effects included in the pooled effect size

Power: Statistical power for pooled effect size

P-value: Statistically significant *P* value

RCT: Randomized controlled trial

PROSPERO: International Prospective Register of Systematic Reviews

PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analyses

ROB2: Risk of Bias Tool 2

ROBINS-I: Risk of Bias In Non-Randomized Studies of Interventions

PEDro: Physiotherapy Evidence Database

GRADE: Grading of Recommendations Assessment, Development, and Evaluation

TUG: Timed-up-and-go test

STS: Sit-to-stand test

SPPB: Short physical performance battery

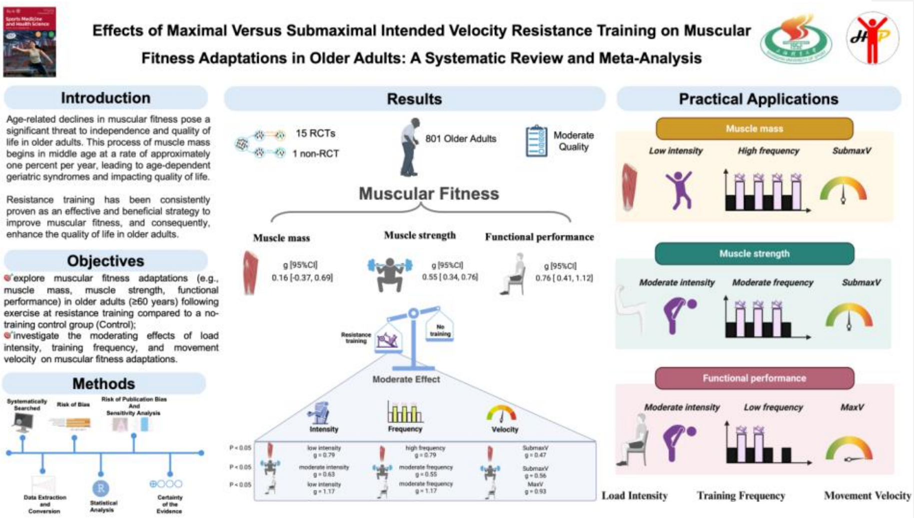
IL-6: Interleukin-6

BDNF: Brain-derived neurotrophic factor

Ca^{2+}: Calcium ion

Ca²+-ATPase: Calcium ATPase

mRNA: Messenger ribonucleic acid



GRAPHICAL ABSTRACT

Note: Load Intensity: "Low" = ≤ 60% 1 RM, "Moderate" = 60%–80% 1 RM; Training Frequency: "High" = >3 sessions/week, "Moderate" = 3 sessions/week, "Low" = < 3 sessions/week; Velocity labels: MaxV = maximal intended velocity, SubmaxV = submaximal intended velocity; 1 RM = One-repetition maximum.

1 INTRODUCTION

Age-related declines in muscular fitness (e.g., muscle mass, strength, and functional performance) pose a significant threat to independence and quality of life in older adults.[1,2] This process of muscle mass begins in middle age at a rate of approximately one percent per year,[3] leading to age-dependent geriatric syndromes and impacting quality of life.[4,5] Resistance training has been consistently proven as an effective and beneficial strategy to improve muscular fitness, and consequently, enhance the quality of life in older adults.[6,7]

Specifically, resistance training slows down the rate at which muscle atrophy occurs[8] and addresses age-related conditions such as osteoporosis, type II diabetes, and cardiovascular disease,[9,10] while also reducing fall incidence.[11] This form of training is characterized by multiple repetitions, sets and exercises, rest periods of varying durations, and varying movement velocities (e.g., controlled *vs.* explosive).[12] However different combinations of kinematic and kinetic variables and their contribution to adaptation may vary,[12] movement velocity may be a key acute training variable for negating muscle power decline and alleviating functional limitations in older adults.[13–15] Load (strength) and movement velocity are inversely related; therefore, heavy loads typically result in slower velocities. However, maintaining maximal intentional velocity at a given load may optimize neuromuscular adaptations critical for countering muscle power decline in older adults.[13–15] While the intention and suggestion to maximize movement velocity is well-documented for athletic performance benefits,[16] a consensus is lacking on whether resistance training for older adults should emphasize maximal (MaxV) or submaximal intended velocity (SubmaxV). MaxV refers to performing all repetitions at the maximum intended concentric velocity[17], and SubmaxV refers to the need for the subject to intentionally reduce the concentric velocity irrespective of load.[18]

However, it seems that velocity affects different indicators in older adults differently. It has been shown that SubmaxV resistance training enhanced muscle size and strength in older adults,[19,20] while MaxV resistance training appears to be beneficial for daily function and peak skeletal muscular power, again, in older adults.[21,22] MaxV resistance training at 10 RM has been shown to have more of a positive emotional response compared to high-intensity resistance training, which appears to be safe, even for older adults with hypertension.[23] Therefore, resistance training with either MaxV or SubmaxV can elicit positive physiological and psychological responses, providing a more comprehensive approach to the aging process.

Cross-sectional studies have reported that multifactorial issues such as reductions in: muscle mass (the total quantity of skeletal muscle),[24] muscle strength (an indicator of the force-generating capacity of skeletal muscle),[25] muscle power, and rapid force production are associated with declines in functional performance in older adults.[26] This may be because functional performance is an effective assessment tool for assessing the overall health status of older adults, reflecting the ability to perform daily living tasks and being more sensitive to improvements brought about by exercise interventions.[27,28] Therefore, we engaged in a meta-analysis of three indicators of muscle strength, muscle mass, and functional performance.

Different movement velocities, training frequencies, and load intensities appear to have different adaptations for muscular fitness. Pearson's[29] meta-analysis found that older adults who participated in MaxV resistance training had better improvements in timed-up-and-go and knee extension tests compared to SubmaxV, but he did not explore the effects of MaxV and SubmaxV resistance training on whole-body muscle strength and muscle mass. Pedro Lopez[17] conducted a meta-analysis of different functional performance indicators in older adults from 79 studies. Both MaxV and SubmaxV resistance training have been shown to improve functional outcomes such as fast walking speed, timed up and go test, and sit-to-stand performance, although the specific effects may vary depending on the exercise protocol.

Meanwhile, resistance training frequency also appears to be an important modulating factor affecting the outcomes of resistance training. Nascimento[30] explored the effects of different frequencies of resistance training on muscle mass and appendicular lean soft tissue in older women, and found that both training two and three times per week significantly improved muscle mass. Silva et al.[31] found no independent predictive role of frequency on strength gains, but they did not account for potential moderators like strength test protocols or sex differences. In contrast, Ralston et al.[32] reported superior strength improvements with medium (two sessions per week) / high-frequency (≥ 3 sessions per week) [vs. low-frequency (e.g. 1 session per week)] training, particularly when combined with multi-joint exercises and adjusted for baseline training levels. Beyond strength, Jackson et al.[33] proposed that lower frequency high-intensity or higher frequency low-intensity strategies may optimize lifelong muscle function.

Moreover, different load intensities of resistance training seem to produce varying degrees of impact. Nathan et al.[34] and colleagues used resistance training intensities of 20%, 50%, and 80% of one repetition maximum (1 RM) and found that higher training intensity resulted in significantly greater strength improvements. Sayers et al.[35] compared MaxV resistance training at 40% 1 RM with SubmaxV resistance training at 80% 1 RM, and found that the degree of improvement in peak power was similar between the two groups, but the former had lower perceived exertion.

To facilitate increased participation and adherence to resistance training in older adults, it is important to establish exercise selection guidelines for this population.[36] Therefore, we conducted this systematic review and meta-analysis to explore muscular fitness adaptations —muscle strength, mass, and functional performance—following resistance training compared to a control group in older adults (⩾ 60 years). Furthermore, we hypothesized that movement velocity, training frequency, and load intensity would moderate these adaptations.

2 METHODS

2.1 Protocol Registration

This systematic review and meta-analysis was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. The review protocol was prospectively registered with the International Prospective Register of Systematic Reviews (PROSPERO) under registration number CRD42023489470.

2.2 Search Strategy

PubMed, Medline, Cochrane Library, and Web of Science were searched from the database inception to 12 April 2024. A Medical Subject Heading (MeSH) search was performed to establish all related literature on MaxV or SubmaxV, older adults and muscular fitness. Specifically, the database searches were performed using the keywords and truncations in conjunction with using the following search criteria: (velocity based training OR Velocity-Based Resistance Training OR VBT OR movement velocity OR low-velocity resistance training OR high-velocity resistance training OR High-speed resistance training OR low-speed resistance training OR Velocity-Monitored Resistance Training OR slow-speed resistance training OR Slow movement resistance training OR High-speed power training OR velocity resistance exercise OR resistance training with slow movement OR Speed-power based training) AND (older adults OR elderly OR geriatric OR aging OR older people) AND (muscle mass OR Muscle Strength OR muscle power OR muscle size OR muscular hypertrophy OR strength parameters OR muscle architecture OR muscle quantity). The reference lists of relevant meta-analyses and articles were also screened. Two reviewers (TML and SYO) independently assessed the identified publications for eligibility, with any disagreements being resolved by a third reviewer (YMY).

2.3 Studies Selection

Studies were considered to be eligible for inclusion according PICOS criteria: (1) population: inclusion of older adult (≥ 60 years)[37] who included functional limitations; (2) intervention: the type of study was controlled between groups and consisted of a parallel randomized controlled trial or a pre-and post-randomized crossover trial; (3) comparison: training needed to involve a MaxV or SubmaxV intervention (MaxV versus no-training [Control] or SubmaxV versus Control or MaxV versus SubmaxV); (4) the period of training was longer than 8 weeks; (5) study: published in a peer-reviewed journal and full-text available in English; (6) outcome: the study included a quantitative analysis of the effect of MaxV or SubmaxV on at least one of the following outcome measures (statistical comparison of intervention to baseline/pre-training values): (a) functional performance [i.e., the ability to carry out activities of daily living, such as the timed-up-and-go test (TUG), sit to stand (STS), short physical performance battery

(SPPB)][38]; (b) muscle mass (i.e., morphological changes measured by biopsy, imaging, and/or densitometry; i.e., hypertrophy)[39,40]; (c) muscle strength (i.e., the maximum force a muscle or muscle group can generate at a specific velocity, such as grip strength, bicep curl , chest press, knee extension or leg press)[41].

2.4 Data Extraction and Conversion

Two independent reviewers (TML and SYO) extracted: the lead author's name, year of publication, participant characteristics, study design, training protocol, means, and standard deviations of outcome indicators at pre-and postintervention. In addition, data on adherence, dropout rates, and adverse events were collected as available. Any disagreements were resolved by consensus. If the information was missing, an attempt was made to contact the study investigators to obtain the necessary data. If the study authors were unresponsive or unreachable, the study was excluded.

We extracted the mean, *SD*, and sample size reported for each group pre- and post-intervention. We pooled effects using pre- and post-intervention differences ($M \pm SD$) for each outcome variable. The first step was to calculate the difference in means (raw mean difference between post and preintervention for each intervention group), where MD_{diff} is the raw mean difference, M_{post} is the reported mean post-intervention, and M_{pre} is the reported mean preintervention.[42]

$$MD_{diff} = M_{post} - M_{pre}$$

Then the *SD* of the difference in means (SD_{diff}) is calculated as follows:

$$SD_{diff} = \sqrt{SD_{pre}{}^{2} + SD_{post}{}^{2} - 2r \times SD_{pre} \times SD_{post}}$$

where *SDdiff* is the standard deviation of the difference in means, SD_{pre} is the standard deviation from pre-intervention, and SD_{post} is the standard deviation from post-intervention. [42] As the original studies included in the meta-analysis did not report Pearson's correlation coefficients (*r*) for pre-and post-intervention outcomes, meta-analyses with similar outcomes were referenced, resulting in $r = 0.5$[17] and $r = 0.52$[6] respectively, with $r = 0.5$ being the final choice.

2.5 Risk of Bias and Quality of Methods Assessment

TML and SYO independently assessed the selected studies. In case of disagreement on certain item scores, the item scores would be given after discussion. The risk of bias was assessed using the Cochrane Collaboration's Risk of Bias Tool 2 (Rob2),[43] which evaluates random sequence generation, random allocation concealment, blinding of outcome assessment, incomplete outcome data, and selective outcome reporting. Disagreements were resolved through discussion whenever possible. If consensus could not be reached, a third reviewer acted as an arbitrator. For non-randomized studies, Cochrane's Risk of Bias In Non-Randomized Studies of Interventions (ROBINS-I),[44] assessing bias across seven domains: confounding, participant selection, intervention categorization, adherence to intended interventions, handling of missing data, outcome measurement, and selection of reported results.

Additionally, the physiotherapy evidence database (PEDro) scale was used to assess the risk of bias and methodological quality of included studies.[45] The PEDro scale scores studies on a scale of 0-10; studies scoring ≥ 6 is considered high quality, those scoring 4-5 are considered moderate quality, and those scoring ≤ 3 are considered low quality.

2.6 Statistical Analysis

We first applied a traditional two-level meta-analysis based on a generic inverse-variance pooling method to pool *Hedges' g* and were conducted using the *meta* and *metafor* packages in the statistical software R (V.4.2.0).[46] For the two-level meta-analysis, we utilized the DerSimonian-Laird approach,[47] which is a random-effects model accounting for potential heterogeneity across studies. This model assumes that effect sizes are derived from a distribution of true effects rather than from a single homogeneous population. Given the variation in training protocol and populations, the random-effects model incorporates heterogeneity by assuming that the underlying effects follow a normal distribution,[40] leading to a more accurate and appropriate estimation of the overall effect size.[48]

In cases where studies included nested or multiple effect sizes (e.g., for outcomes such as muscle mass or muscle strength), these effect sizes were often correlated. Including all effect sizes simultaneously could violate the assumption of independence in traditional meta-analyses,[49] while considering only one effect size could be too conservative and fail to capture the true effect.[50] To address this issue, we applied a three-level meta-analysis following the methods of Assink & Wibbelink.[51] This approach allows for the decomposition of variance into sampling variance (level 1), within-study variance (level 2), and between-study variance (level 3), accounting for correlated and hierarchical effects.[52] By preserving valuable information from multiple effects within each study, the three-level meta-analysis enhances statistical power and provides a more accurate representation of effect sizes.[51] For the three-level model, parameters were estimated using the restricted maximum likelihood method, and the results were cross-verified using the maximum likelihood method to ensure stability.

95% confidence intervals (*CI*) were calculated for each effect size. Additionally, we computed the prediction intervals (*PI*) for metrics with > 5 included studies based on the t-distribution, which measures the treatment effect considering heterogeneity and provides useful additional information compared to the *CI* and used to estimate the range of the overall parameter and to account for the uncertainty of future observations,[53] especially considering the use of a random-effects model.[54,55] The between-study variability (i.e., heterogeneity) of the intervention effects within each intervention comparison was assessed by I^2,[56] and the magnitude of the between-study variance (τ^2) and estimated using the generalized DerSimonian and Laird[57] estimator and the Q-profile approach. Therefore, the main analysis reports I^2 with the following interpretations: 0%-25%, might not be important; 25%-50%, may represent moderate heterogeneity; 50%-75%, may represent substantial heterogeneity; and 75%-100%, considerable heterogeneity.[58] Additionally, the statistical power of the primary pooled effect was calculated, and the possibility of false negatives due to insufficient statistical power was considered. Statistical power calculations were performed using the *metameta* package.[59]

As this study outcome metrics typically involve multiple units of testing, and previous studies have suggested that effect sizes (Standardized Mean Difference [*SMD*]) should be used in priority. Given the small sample sizes of most of the included studies, Hedges' g, based on an exact formula and corrected for bias, was used as the effect size indicator for each study, with Hedges' *g* (*g*) classified as *trivial* (0.2), *small* (0.2–0.5), *medium* (0.5–0.8), and *lar*ge (> 0.8).[60] Statistical significance was set at $p < 0.05$.

Potential sources of heterogeneity and moderators were explored by subgroup analyses. A univariate meta-analysis was also performed separately for each primary outcome. We selected the following variables for subgroup analyses: (1) load intensity; (2) training frequency; and (3) movement velocity. Additionally, the statistical power of each subgroup was calculated to prevent the possibility of false negatives due to insufficient statistical power.[59]

2.7 Risk of Publication Bias and Sensitivity Analysis

The contour-enhanced funnel plot,[61] along with Egger's asymmetry test,[62,63] was employed to assess publication bias (when $k \geq 10$), with $p > 0.05$ indicating no risk of publication bias. Funnel plots and Egger's regression tests are primarily used to determine the symmetry of the overall effect size, either through subjective or quantitative measures, thereby assessing the risk of publication bias in the included studies. As the statistical power of funnel plots and Egger's regression test is too low to reliably detect publication bias with fewer than 10 studies, particularly for outcomes related to muscle mass and functional performance, the risk of publication bias is assessed using contour-enhanced funnel plots and Egger's asymmetry test in conjunction with qualitative analysis. This includes examining study characteristics such as the distribution of effect sizes, the presence of small-study effects, and potential sources of heterogeneity (e.g., differences in study design or participant characteristics).

Sensitivity analyses were conducted a leave-one-out analysis, sequentially removing each study to assess whether any single study significantly influenced the overall pooled effect.

2.8 Certainty of the Evidence

The risk of bias was considered in the interpretation of the results by applying the Grading of Recommendations Assessment, Development, and Evaluation (GRADE) methodology, which rates the certainty of evidence as "high", "moderate", "low" or "very low".[64] GRADE assessments were completed by one reviewer and reviewed by a second.

3 Results

3.1 Search Results

A flow diagram of the study selection process is presented in Fig. 1. Overall, 1 211 studies were identified in the initial database search. Following the removal of duplicates (*n* = 173), 1 038 titles and abstracts were screened against the inclusion criteria, and 1 012 studies were irrelevant. A full-text review of the remaining 26 studies excluded a further 16 studies due to being unavailable in English language (*n* = 3), additional intervention (*n* = 7), or irrelevant outcomes (*n* = 6). 16 studies were included following a full-text review. Meanwhile, the screening of reference lists identified six potential articles. Subsequent screening resulted in 16 studies eligible to be included in the meta-analysis.[20,65–79]

******Fig. 1. Here******

3.2 Study Characteristics

A total of 801 participants across the sixteen studies were included. Of the fifteen paper studied that reported sex (women, *n* = 441; men, *n* = 308; not reported,[80] *n* = 52). A detailed description of the study participants is in Table 1, the mean age across studies was (72.68 ± 10.91) years. Most studies described participants as being apparently healthy, not engaged in regular exercise or previous participation in resistance training in the past 6 months (14 out of 16 studies).

Training programs were supervised by members of the research team or physical therapists in twelve studies. The mean program length was (13.88 ± 9.22) weeks (range 10–48 weeks). Training frequency was three sessions per week for five studies, two sessions per week for nine studies, seven sessions per week for one study,[81] and one study examined the effect of one vs. two sessions per week.[71] Studies with MaxV or SubmaxV duration of 15-65 min, warm-up time of 5-10 min, and cool-down time of 5-10 min. MaxV resistance training intensity was a load between 40% and 75% of 1 RM, SubmaxV resistance training intensity was a load between 45% and 80% of 1 RM.

For this systematic review, and due to the fact velocity-monitoring devices may not have been used in the the majority of included studies, it was therefore deemed more appropriate to investigate MaxV and SubmaxV than high and low velocity. One study used elastic resistance bands and one study used body weight. The number of completed sets per exercise was three for ten studies, two for two studies, and ranged between two and three sets for four studies. MaxV group repetitions ranged from three to twenty per exercise and SubmaxV group repetitions ranged from five to fifteen per exercise (Table 1). Given that load intensity could not be uniformly quantified by continuous variables, it was qualitatively classified into “low (⩽ 60% 1 RM), moderate (60%–80% 1 RM) and high intensity (⩾ 80% 1 RM)”[82] by introducing a dummy variable; and given that the frequency was more concentrated, with 1-2, 2, 3 and 7 times per week, it was classified into high frequency (> 3), moderate frequency (3) and low frequency (< 3), therefore subgroups were analyzed.

******Table. 1. Here******

3.3 Muscle mass outcomes

Seven studies assessed the effects of resistance training versus Control on muscle mass. The meta-analysis found no significant differences between resistance training and Control on muscle mass. (Hedges' $g = 0.16$, 95%*CI* [-0.37, 0.69], $p = 0.48$, $I^2 = 67.40\%$, *95%PI* [-0.94, 1.27], Moderate GRADE).

Subgroup analyses revealed that SubmaxV ($g = 0.47$) resistance training had a greater effect on muscle mass compared to MaxV resistance training ($g = -0.35$); low intensity ($g = 0.79$) had a greater effect on muscle mass compared to moderate ($g = 0.00$) and high intensity ($g = -0.12$); high frequency ($g = 0.79$) had a greater effect on muscle mass compared to low frequency ($g = -0.06$).

******Fig. 2. Here******

******Fig. 3. Here******

3.4 Muscle strength outcomes

Twenty four studies assessed the effects of resistance training versus Control on muscle strength, which included upper extremity strength and lower extremity strength. The meta-analysis found a significant improvement effect of resistance training versus Control on muscle strength (Hedges' $g = 0.55$, 95%*CI* [0.34, 0.76], $p < 0.001$, $I^2 = 11.96\%$, 95%*PI* [0.02, 1.08], Lowe GRADE).

Subgroup analyses revealed that SubmaxV ($g = 0.56$) resistance training had a greater effect on muscle strength compared to MaxV resistance training ($g = 0.47$); moderate intensity ($g = 0.63$) had a greater effect on muscle strength compared to low intensity ($g = 0.29$) and high intensity ($g = 0.36$); moderate frequency ($g = 0.55$) had a greater effect on muscle strength compared to low frequency ($g = 0.51$).

3.5 Functional performance outcomes

Seven studies assessed the effects of resistance training versus Control on functional performance (TUG and STS). The meta-analysis found a significant improvement effect of resistance training versus Control (Hedges' $g = 0.76$, 95% CI [0.41, 1.12], $p = 0.002$, $I^2 = 62.70\%$, 95%PI [0.41, 1.12], Moderate GRADE).

Subgroup analyses revealed that MaxV ($g = 0.93$) resistance training had a greater effect on functional performance compared to SubmaxV resistance training ($g = 0.63$); moderate intensity ($g = 0.71$) had a greater effect on functional performance compared to low intensity ($g = 1.17$) and high intensity ($g = 0.41$); moderate frequency ($g = 0.64$) had a greater effect on functional performance compared to low frequency ($g = 1.17$).

See **Electronic Supplementary Material Appendix S1** for detailed consolidated forest plots for each outcome indicator. A visual plot of statistical power for the pooled results for all outcomes in **Electronic Supplementary Material Appendix S2**.

3.6 Risk of Bias and Quality of Methods

The risk of bias for each study is depicted in **Electronic Supplementary Material Appendix S5 Risk of bias**. Most studies did not disclose details about their randomization methods and allocation concealment, resulting in an assessment of "some concerns" for the randomization process. In summary, the majority of studies demonstrated a "some concerns" risk of bias. Additionally, only one study was a non-randomized controlled trial, and it did not disclose blinding measures for the outcome indicators, so there may be a moderate risk of bias.

The risk of publication bias was investigated using a funnel plot combined with Egger's test for the effects of included studies on muscular fitness (**Electronic Supplementary Material Appendix S3**). Egger's regression analysis suggested that there may be a risk of publication bias for muscle strength ($p < 0.001$), while there was no evidence of publication bias for muscle mass ($p = 0.63$) and functional performance ($p = 0.38$).

The average PEDro score of all studies was 5.94, indicating that the methodological quality of the included studies was generally moderate. (**Electronic Supplementary Material Appendix S6**).

3.7 Sensitivity Analysis

We conducted sensitivity analyses using a leave-one-out method for all primary pooled effects (**Electronic Supplementary Material Appendix S4**). The results indicated that the exclusion of any single study did not significantly alter the pooled outcome. This suggests that our findings are robust and reliable.

4 Discussion

This systematic review and meta-analysis aimed to explore the effects of resistance training on muscular fitness in older adults compared with a control group, and to examine the moderating roles of load intensity, frequency, and movement velocity

(MaxV and SubmaxV) in improving muscular fitness in older adults. The results showed that: 1) resistance training can improve muscular fitness, 2) SubmaxV resistance training with low intensity and high frequency was superior for improving muscle mass, 3) SubmaxV resistance training with moderate intensity and moderate frequency was superior for improving muscle strength, and 4) MaxV resistance training with moderate intensity and low frequency was superior for improving functional performance.

4.1 Muscle mass

We observed a slight improvement in muscle mass among older adults following resistance training. Grgic et al.[83] also reported similar results, suggesting that this may be due to neural adaptations to this form of resistance training rather than direct skeletal muscle hypertrophy. Furthermore, although increasing muscle mass is generally more challenging for older adults compared to younger populations,[84] this slight improvement in muscle mass may also be attributed to other factors. Specifically, resistance training helps to reduce metabolic risk and inflammation levels in older adults.[85] These positive changes are closely related to the upregulation of muscle factors, such as IL-6 and BDNF, which not only play a role in normal muscle physiology but also regulate metabolism and mitigate inflammatory responses.

We also found that the load intensity, frequency, and movement velocity of resistance training has significant modulatory effects on muscle mass ($p < 0.05$). Resistance training using SubmaxV is more effective in increasing muscle mass compared to MaxV. Notably, Pareja-Blanco et al.[13] found that monitoring the velocity of resistance training resulted in greater hypertrophy of the vastus lateralis and intermedius muscles, accompanied by a reduction in the percentage of myosin heavy chain IIX. This may explain why the findings of that study support the optimizing effect of SubmaxV on muscle mass in our experiment.[86]

Regarding load intensity, Pinto et al.[87] found that after three weeks of low-intensity resistance training in older adults, the muscle mass of the knee extensors increased by 14.8%. This coincides with the results of our subgroup analysis whereby low intensity training was found to be superior in increasing muscle mass compared to high intensity. In the studies we included into muscle mass all the groups were lower in intensity except for Lindberg's group, which was above 70% 1 RM.

Regarding frequency, we found that high frequency training is superior to low frequency training in promoting improvements in muscle mass. Research by Paulo et al.[85] indicates that resistance training can effectively improve obesity, metabolic risk, and inflammation in postmenopausal and older women. Higher training frequency, which corresponds to a higher total training volume, shows greater improvements in metabolic risk and inflammation compared to lower training frequency with a lower total training volume. This significant improvement is likely due to positive changes in myokines (such as IL-6, BDNF, etc.), which not only directly participate in the normal physiological functions of the muscles but also regulate metabolic levels and reduce inflammatory responses, positively impacting obesity, metabolic risk, and inflammation in older women.[88] Furthermore, maintaining long-term resistance training at a higher frequency can lead to an increase in muscle cross-sectional area, promote muscle fiber hypertrophy and growth, and enhance the density and arrangement of myofibrils.[89] Therefore, high frequency resistance training may be more effective than low frequency in enhancing muscle mass in older adults.

Furthermore, the high heterogeneity (I^2 = 67.4%) observed in the muscle mass analysis likely stems from the factors discussed above. The variable effectiveness of different training velocities, intensities, and frequencies across studies,[86] indicates that hypertrophic responses are not uniform. This variability, combined with the diversity of measurement techniques (e.g., biopsy, imaging, and/or densitometry)[39,40] and the wide range of participant baseline characteristics (mean age [72.68 ± 10.91] years)， contributes to the substantial statistical heterogeneity. In contrast, the low heterogeneity (I^2 = 11.96%) for muscle strength suggests a more consistent effect, potentially due to standardized assessment methods (e.g., 1 RM tests)[41] and the prominent role of early-phase neural adaptations.[20]

4.2 Muscle strength

The findings of our meta-analysis showed resistance training can significantly enhance whole-body maximal muscle strength in older adults. The improvement in muscle strength may be attributed to resistance training potentially enhancing neural recruitment capacity and motor unit discharge rates,[20] increasing Ca^{2+} uptake and Ca2+-ATPase activity,[90] and effectively reducing inflammation, thereby accelerating recovery and decreasing muscle inflammation and swelling.[91]

Regarding movement velocity, we found that SubmaxV resistance training had a superior effect on enhancing muscle strength compared to MaxV. Our study aligns with the findings of Matthew et al.,[92] indicating that SubmaxV resistance training significantly increased peak power in both male and female older adult populations. This might be due to a substantial increase in muscle cross-sectional area and the acute testosterone (T) response facilitating protein synthesis and reducing degradation, leading to greater muscle growth and strength.[93] However, this finding may differ from the results of Davies et al.[94] Their research primarily focused on healthy adult populations, and there may be differences in how various age groups enhance muscle strength.

The finding that moderate intensity has greater improvements in muscle strength in older adults also appears to be supported by other studies. For example, Schaun[95] found that mobility-limited older adults may improve muscle strength to a greater extent than their healthy counterparts after resistance training and these benefits may be achieved using only low to moderate intensity. This discovery implies that even with a moderate reduction in the intensity of each training session, it can still have a positive impact on the adaptability of muscle strength in older adults.[94]

Regarding frequency, we found that moderate-frequency resistance training is superior to low-frequency resistance training in enhancing muscle strength. The research perspective of Grgic et al.[96] primarily focuses on the moderating factors that influence resistance training frequency, but it does not directly investigate whether the frequency itself has a significant impact on muscle strength gains. The reason that moderate frequency may lead to greater improvements in muscle strength could be due to the increased training sessions promoting greater increases in protein content and higher mRNA expression levels. These physiological changes may facilitate better muscle growth and strength by regulating the balance between protein synthesis and degradation.[93]

4.3 Functional performance

Functional performance reflects the ability of older adults to accomplish daily activities and may be useful in monitoring functional limitations and changes in their fitness.[97] It appears to positively correlate with quality of life. Those with higher levels of physical activity have higher functional performance and quality of life. Thus, early detection of functional performance declines and increased levels of physical activity appear to improve the quality of life of older adults.[98]

Our results show that resistance training significantly improved functional performance compared to the control group (g = 0.77). This may be attributed to the enhancement of muscle strength resulting from resistance training, which in turn facilitated the improvement in functional performance,[99] and positively impacted quality of life.[100] Further analysis revealed that frequency, intensity, and movement velocity significantly moderated functional performance ($p < 0.05$).

Regarding movement velocity, we found that compared to SubmaxV resistance training, MaxV resistance training demonstrates greater advantages on functional performance, a finding supported by Pedro Lopez.[17] The neuromuscular changes induced by the intervention exhibit speed specificity, meaning that older adults can achieve greater improvements in targeted functions by selecting appropriate training methods based on different training goals. Specifically, while MaxV training may lead to a slight increase in metabolic stress (such as levels of blood lactate and ammonia), the concentrations of these metabolic byproducts remain within low to moderate ranges. Therefore, we have reason to believe that MaxV resistance training may provide a stronger stimulus for eliciting adaptive changes aimed at enhancing functional performance.[13]

Regarding load intensity, moderate intensity resistance training demonstrated significantly greater improvements in functional performance compared to both low and high intensities. Meanwhile, Vasilios et al.[101] compared the effects of high intensity and moderate intensity training on the functional performance of older adults and found no significant difference between the two. This finding suggests that even moderate-intensity resistance training may be sufficient to improve functional performance in older adults. This intensity level can effectively enhance functional outcomes while also promoting exercise adherence and enjoyment.[101] Additionally, this may be related to the specificity of our ability to perform daily activities, as reflected in functional performance. For instance, activities like hanging laundry, cleaning, retrieving cups from a cabinet, and watering plants are all common daily tasks. Therefore, considering specificity and adaptability, such high load intensity may not be necessary.[102]

Regarding frequency, we found that low frequency resistance training is sufficient to improve functional performance compared to moderate frequency. Most activities encompassed by functional performance do not require particularly high endurance levels. Moreover, there is a theoretically closer relationship between increases in muscle strength and enhancements in functional performance.[103] Therefore, from an economic efficiency perspective, opting for a lower frequency resistance training strategy can effectively achieve the goal of improving functional performance.

4.4 Practical Implications

This study on resistance training addresses key challenges in enhancing muscular fitness adaptation and outlines application strategies regarding load intensity, training frequency, and movement velocity (as shown in Figure 4).

******Fig. 4. Here******

4.5 Limitations and Directions for Future Research

The strengths of this study are as follows: (1) 15 of the 16 included studies were randomized controlled trials (RCTs), providing a high level of evidence to support the findings; and (2) subgroup analyses were performed to identify the minimum effective intervention doses for muscle mass, muscle strength, and functional performance in older adults, accounting for variations in training frequency load intensity, and movement velocity. These analyses significantly improve the precision and practical relevance of the results.

Potential limitations of this study still need to be noted: (1) Selection and publication bias may have existed because the study was searched from only 4 databases and peer-reviewed published literature. (2) Older adults were included in this study, and mixed-gender groups were not presented separately in the included studies, so we could not explore the different gender responses to training.(3) Velocity loss thresholds observed through velocity monitoring device are more accurate indicators (better reflecting the quality of the movements performed and more precise strength training load settings for older adults) than seconds of control during concentric and eccentric phases,[104] but few studies of resistance training in older adults have used devices to monitor older adults' current training status and velocity changes with this indicator.

5 Conclusion

Resistance training is effective in improving muscular fitness adaptations in older adults. Load intensity, frequency, and movement velocity (SubmaxV was better for muscle mass and muscle strength compared to MaxV, and vice versa for functional performance) may significantly modulate improvements in muscular fitness adaptations.

Manuscript Registration Statement

This systematic review and meta-analysis was conducted in accordance with the new PRISMA guidelines. The review protocol was prospectively registered with the International PROSPERO under registration number CRD42023489470.

Conflict of Interest Statement

No conflicts and interests are relevant to the content of this review.

Data Availability Statement

The data that support the findings of this study are openly accessible in the Open Science Framework (OSF). The supplementary materials, which include datasets and analysis code, are available at the following link: https://osf.io/eu7rw/files/osfstorage.

Ethical Statement

This review article does not involve human or animal experiments, and it is based exclusively on published literature. Therefore, a Statement of Ethics is not applicable.

Author Contributions

Meiling Tao: Data curation, Writing and Editing.; **Kaifang Liao:** Writing-Reviewing and Editing; **Mingyue Yin:** Methodology, Data curation; **Chenwen Zhu:** Software; **Yuou Song:** Data curation; **Zhili Chen:** Original draft; **Yuming Zhong:** Original draft; **Steve Thompson:** Reviewing; **Chris Bishop**: Reviewing; **Yongming Li:** Writing- Reviewing and Editing.

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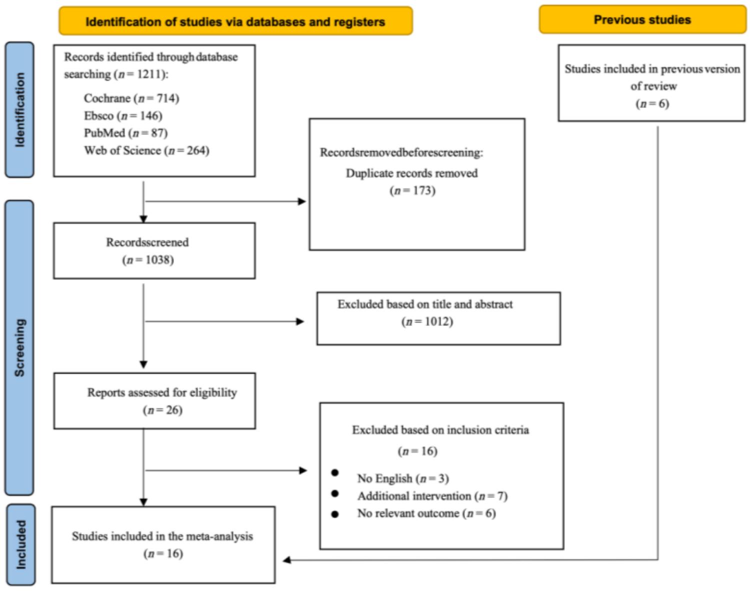

FIGURE 1. PRISMA flow diagram of the search strategy.

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Abbreviation: PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analyses.

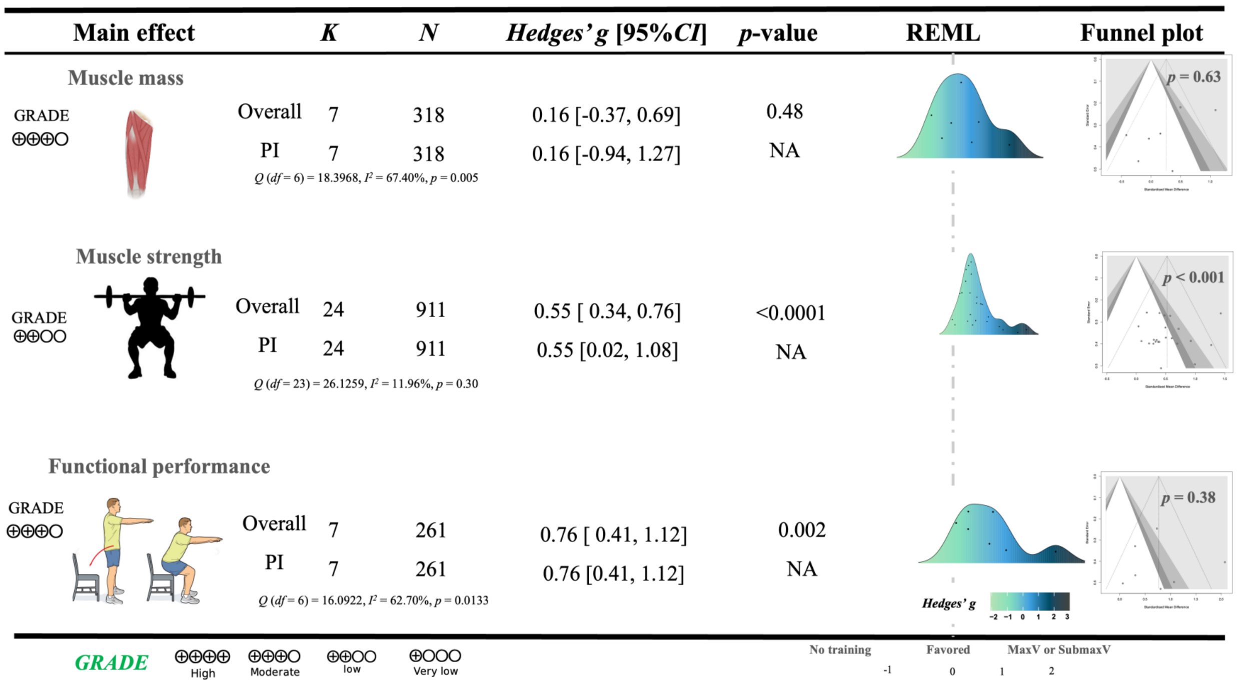

Figure 2. Primary pooled effect sizes for the outcomes (muscle mass, muscle strength, functional performance).

Note: K: The total number of effects included in the pooled effect size; *Hedges' g*: The effect size indicator used in the pooled analysis; 95% *CI*: 95% confidence interval; *p*-value: Statistically significant *p* value for pooled results; I^2: Quantitative indicator of heterogeneity; Power: Statistical power for pooled effect size; GRADE: Grading of Recommendations Assessment, Development, and Evaluation.

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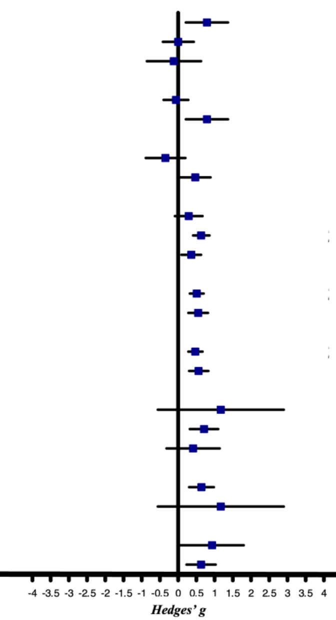
下同。

Outcome	Subgroup	Experimental	Control	*Hedges' g* [95%*CI*]	*Power*	I^2	*P*
Muscle mass	Intensity						
	low	84	88	0.79 [0.21, 1.37]	36.20%	71%	0.01
	moderate	43	49	0.00 [-0.42, 0.43]	39.50%	0%	0.98
	high	22	32	-0.12 [-0.86, 0.63]	24.40%	38%	0.76
	Frequency						
	low	65	81	-0.06 [-0.40, 0.28]	0.638	0%	0.73
	high	84	88	0.79 [0.21, 1.37]	0.362	71%	0.01
	Velocity						
	MaxV	27	32	-0.35 [-0.89, 0.20]	0.254	0%	0.21
	SubmaxV	122	137	0.47 [0.05, 0.89]	0.746	58%	0.03
Muscle strength	Intensity						
	low	48	60	0.29 [-0.09, 0.67]	13.60%	0%	0.14
	moderate	340	227	0.63 [0.41, 0.86]	60.30%	35%	0.01
	high	151	85	0.36 [0.09, 0.63]	26.10%	0%	<0.001
	Frequency						
	low	431	252	0.51 [0.32, 0.70]	72.30%	25%	<0.001
	moderate	108	120	0.55 [0.28, 0.82]	27.70%	0%	<0.001
	Velocity						
	MaxV	251	205	0.47 [0.28, 0.67]	52.90%	0%	<0.001
	SubmaxV	288	167	0.56 [0.30, 0.83]	47.10%	38%	<0.001
Functional performance	Intensity						
	low	56	28	1.17 [-0.56, 2.90]	31.70%	91%	0.19
	moderate	109	36	0.71 [0.32, 1.10]	44.80%	0%	<0.001
	high	18	14	0.41 [-0.32, 1.14]	23.60%	4%	0.27
	Frequency						
	low	127	50	0.64 [0.30, 0.98]	68.30%	0%	<0.001
	moderate	56	28	1.17 [-0.56, 2.90]	31.70%	91%	0.19
	Velocity						
	MaxV	84	82	0.93 [0.07, 1.80]	56.90%	78%	0.04
	SubmaxV	99	36	0.63 [0.23, 1.03]	43.10%	0%	0.002

Column groups: Moderate (Subgroup, Experimental, Control); Forest Plot (REML); Summary of Finding (*Hedges' g* [95%*CI*], *Power*, I^2, *P*)



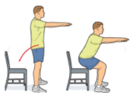


Figure 3. Subgroup analysis of moderating effects (movement velocity, training frequency, load intensity) on muscular fitness outcomes.

Note: MaxV: Maximal intended velocity; SubmaxV: Submaximal intended velocity; Frequency: Training frequency; *K*: The total number of effects included in the pooled effect size; *Hedges' g*: The effect size indicator used in the pooled analysis; 95% *CI*: 95% confidence interval; *p*-value: Statistically significant *p* value for pooled results; I^2: Quantitative indicator of heterogeneity; Power: Statistical power for pooled effect size.

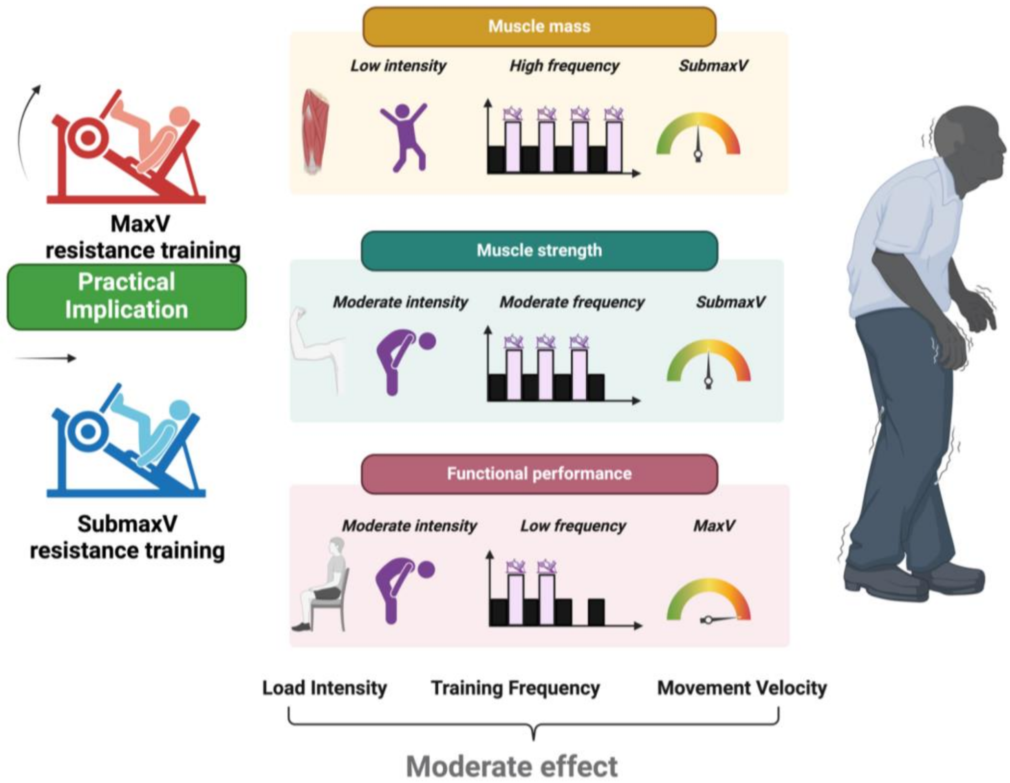


FIGURE 4. Practical Implications

Note: This figure presents targeted resistance training strategies for optimizing muscular fitness in older adults; Load Intensity: "Low" = ≤ 60% 1 RM, "Moderate" = 60%–80% 1 RM; Training Frequency: "High" = > 3 sessions/week, "Moderate" = 3 sessions/week, "Low" = < 3 sessions/week; Velocity labels: MaxV = maximal intended velocity, SubmaxV = submaximal intended velocity; 1 RM = One-repetition maximum.

Table 1 The characteristics of the included studies.

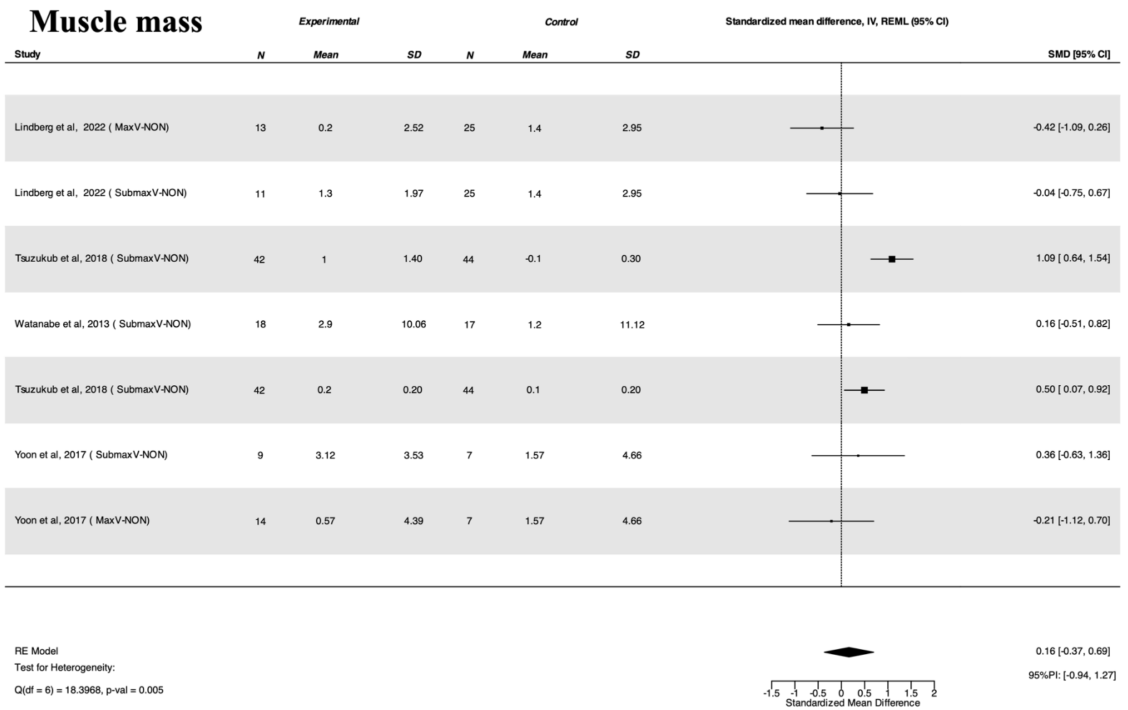
Study	Gender	Age(yr)	Frequency	Period(wk)	Intervention	Concentric phase	Eccentric phase	Load intensity
Yoon et al, 2017[66]	Female	75.0 ± 0.9	2/7	12 wk	MaxV	AQAP	exceeding 2 s	RPE: 12–13
		76.0 ± 1.3			SubmaxV	exceeding 2 s	exceeding 2 s	RPE:15–16
		78.0 ± 1.0			Control	n/a	n/a	n/a
Watanabe et al, 2013[20]	combined	66.8 ± 3.8	2/7	10 wk	SubmaxV	3s	3s	50% 1 RM
		66.8 ± 5.2			SubmaxV	1s	1s	50% 1 RM
Tsuzukub et al, 2018[79]	combined	72.5 ±2.1	7/7	12 wk	SubmaxV	4s	4s	body weight
		73.2 ±2.1			Control	n/a	n/a	n/a
Richardson et al, 2019[71]	combined	66 ± 5	1-2/7	10 wk	MaxV	AQAP	3s	40% 1 RM
		67 ± 6						
		67 ± 4			SubmaxV	exceeding 2 s	3s	80% 1 RM
		66 ± 6						
		65 ± 5			Control	n/a	n/a	n/a
Lindberg et al, 2022[70]	Male	68 ± 5	2/7	10 wk	MaxV	AQAP	2–3 s	<50% of 1 RM
		68 ± 5			MaxV	AQAP	2–3 s	>70% of 1 RM
		68 ± 5			SubmaxV	n/a	n/a	20%、50%、80% 1 RM
Gray et al, 2018[75]	combined	81.6 ± 5.9	2/7	48 wk	MaxV	AQAP	2s	50% 1 RM
		81.0 ± 5.5			SubmaxV	2s	2s	80% 1 RM
		81.3 ± 5.3			Control	2s	2s	body weight
Sayers et al, 2016[74]	combined	71.5 ± 6.8	3/7	12 wk	MaxV	AQAP	2–3 s	40 % 1 RM
		71.1 ± 6.1			Control	n/a	n/a	n/a

Marques et al, 2020[78]	combined	78.6 ± 7.6	2/7	10 wk	MaxV	AQAP	exceeding 2 s	40–65% 1 RM
		79.0 ± 6.0			Control	n/a	n/a	n/a
Fielding et al, 2002[73]	Female	73.2 ± 1.2	3/7	12 wk	MaxV	AQAP	2 s	70%1 RM
		72.1 ± 1.3			SubmaxV	exceeding 2 s	2s	70%1 RM
Reid et al, 2008[76]	combined	72.3 ± 6	3/7	12 wk	MaxV	AQAP	exceeding 2 s	70%1 RM
		73.1 ± 6			SubmaxV	exceeding 2 s	2s	70%1 RM
		79.7 ± 9			Control	n/a	n/a	n/a
Walker et al, 2017[77]	combined	69.12 ± 2.25	2/7	12 wk	SubmaxV	2s	2 s	50–60% 1 RM
		69.49 ± 2.73			Control	n/a	n/a	n/a
Tiggemann et al, 2016[69]	Female	64.4 ± 4.0	2/7	12 wk	MaxV	AQAP	2 s	45-65%1 RM
		65.6 ± 5.3			SubmaxV	2s	2 s	45-65%1 RM
Reid et al, 2015[65]	combined	78.3 ± 5	2/7	12 wk	MaxV	AQAP	2 s	40 % 1 RM
		77.6 ± 4			MaxV	AQAP	2 s	70% 1 RM
Ramírez-Campillo et al, 2014[72]	Female	66.3 ± 3.7	3/7	12 wk	MaxV	AQAP	3 s	45%–75% 1 RM
		68.7 ± 6.4			SubmaxV	3 s	3 s	45%–75% 1 RM
		66.7 ± 4.9			Control	n/a	n/a	n/a
Miszko et al, 2003[68]	combined	72.3 ± 6.7	3/7	16 wk	MaxV	1 s	2 s	40% 1 RM
		72.8 ± 5.4			SubmaxV	4 s	exceeding 2 s	n/a
		72.4 ±7.2			Control	n/a	n/a	n/a
Bottaro et al, 2007[67]	Male	66.55 ± 5.77	2/7	10 wk	MaxV	AQAP	2-3 s	n/a
		66.33 ± 4.80			SubmaxV	2-3 s	2-3 s	60% 1 RM

Abbreviations: wk: Weeks; MaxV: Maximal intended velocity; SubmaxV: Submaximal intended velocity; AQAP: As quickly as possible; RPE: Rate of perceived exertion; 1 RM: One-repetition maximum; RCT: Randomized controlled trial.

Electronic Supplementary Material Contents

Electronic Supplementary Material Appendix S1 (Forest Plots)



Abbreviations: SMD: Standardized Mean Difference; 95%*CI*: 95% confidence interval; PI: Prediction interval; Experimental means MaxV: Maximal intended velocity; Ccontrol means SubmaxV: Submaximal intended velocity.

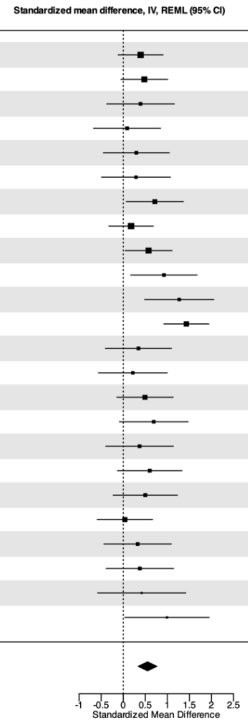
Electronic Supplementary Material Appendix S1 (Forest Plots)

Muscle strength

Study	Experimental N	Experimental Mean	Experimental SD	Control N	Control Mean	Control SD	SMD [95% CI]
Gray et al, 2018 (SubmaxV-NON)	41	7.06	1.72	24	6.43	1.30	0.39 [-0.11, 0.90]
Gray et al, 2018 (MaxV-NON)	34	8.21	4.66	24	6.43	1.30	0.48 [-0.05, 1.01]
Richardson et al, 2019 (SubmaxV-NON)	20	6.5	10.78	10	2	12.00	0.39 [-0.37, 1.16]
Richardson et al, 2019 (MaxV-NON)	20	3	10.75	10	2	12.00	0.09 [-0.67, 0.85]
Miszko et al, 2003 (SubmaxV-NON)	13	4.37	16.83	15	-0.18	12.96	0.30 [-0.45, 1.04]
Miszko et al, 2003 (MaxV-NON)	11	3.8	13.83	15	-0.18	12.96	0.29 [-0.49, 1.07]
Neiva et al, 2020 (MaxV-NON)	19	7.72	12.82	20	-0.35	9.02	0.72 [0.07, 1.36]
Gray et al, 2018 (SubmaxV-NON)	41	4.36	0.62	24	4.24	0.74	0.18 [-0.33, 0.68]
Gray et al, 2018 (MaxV-NON)	34	5.12	1.87	24	4.24	0.74	0.57 [0.04, 1.11]
Ramírez-Campillo et al, 2014 (SubmaxV-NON)	15	21.3	23.00	15	0	21.88	0.92 [0.17, 1.68]
Ramírez-Campillo et al, 2014 (MaxV-NON)	15	26	17.76	15	0	21.88	1.27 [0.49, 2.05]
Walker et al, 2017 (SubmaxV-NON)	81	12	8.00	22	1	6.00	1.43 [0.92, 1.94]
Miszko et al, 2003 (SubmaxV-NON)	13	19.66	49.62	15	4.1	38.22	0.34 [-0.40, 1.09]
Miszko et al, 2003 (MaxV-NON)	11	12.2	32.71	15	4.1	38.22	0.22 [-0.56, 1.00]
Neiva et al, 2020 (MaxV-NON)	19	10.21	22.96	20	-0.5	19.54	0.49 [-0.14, 1.13]
Richardson et al, 2019 (SubmaxV-NON)	20	25	33.46	10	0	38.51	0.69 [-0.09, 1.47]
Richardson et al, 2019 (MaxV-NON)	20	14.5	37.85	10	0	38.51	0.37 [-0.39, 1.14]
Ramírez-Campillo et al, 2014 (SubmaxV-NON)	15	2.35	5.03	15	-0.2	2.96	0.60 [-0.13, 1.33]
Ramírez-Campillo et al, 2014 (MaxV-NON)	15	1.9	4.96	15	-0.2	2.96	0.50 [-0.23, 1.23]
Neiva et al, 2020 (MaxV-NON)	19	-0.13	8.27	20	-0.35	0.75	0.04 [-0.59, 0.67]
Richardson et al, 2019 (SubmaxV-NON)	20	2.23	9.14	10	-1	10.58	0.33 [-0.44, 1.09]
Richardson et al, 2019 (MaxV-NON)	20	3	10.21	10	-1	10.58	0.38 [-0.39, 1.14]
Yoon et al, 2017 (SubmaxV-NON)	9	2.36	2.85	7	1.3	1.57	0.42 [-0.58, 1.42]
Yoon et al, 2017 (MaxV-NON)	14	4.75	3.89	7	1.3	1.57	0.99 [0.04, 1.95]
RE Model							0.55 [0.34, 0.76]
							95%PI: [0.02, 1.08]

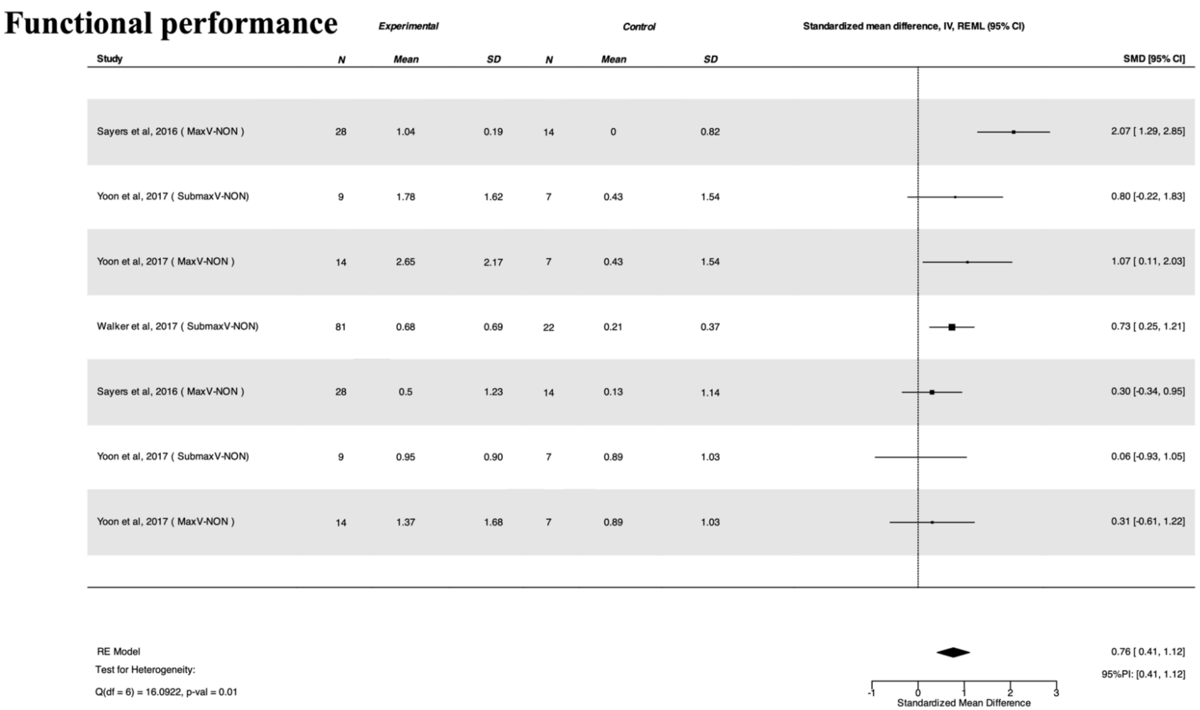
Test for Heterogeneity:

Q(df = 23) = 26.1259, p-val = 0.2950



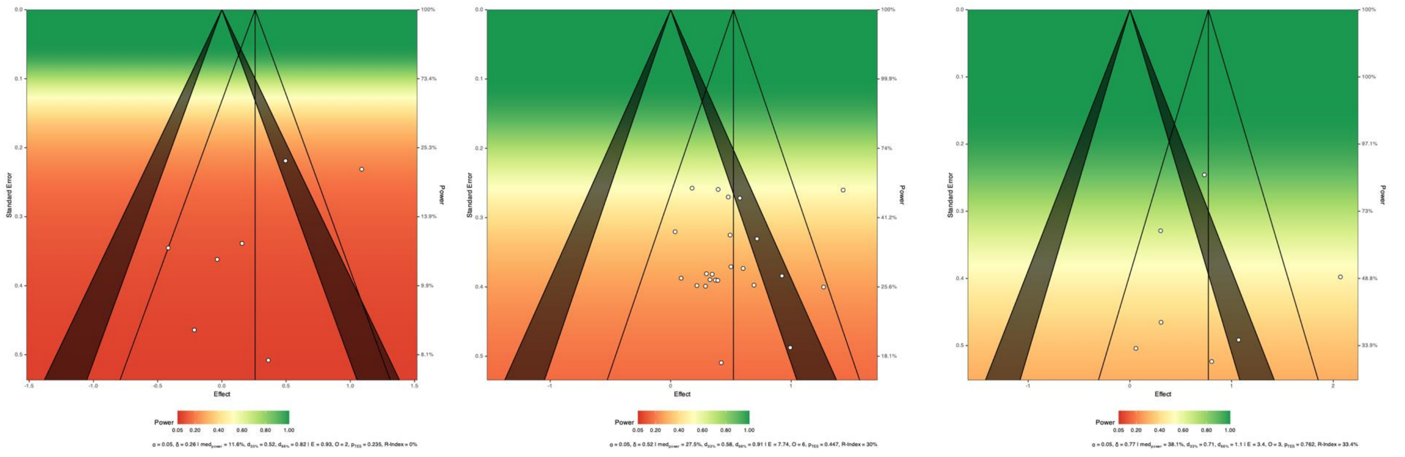
Abbreviations: SMD: Standardized Mean Difference; 95% *CI*: 95% confidence interval; PI: Prediction interval; Experimental means MaxV: Maximal intended velocity; Ccontrol means SubmaxV: Submaximal intended velocity.

Electronic Supplementary Material Appendix S1 (Forest Plots)



Abbreviations: SMD: Standardized Mean Difference; 95% *CI*: 95% confidence interval; PI: Prediction interval; Experimental means MaxV: Maximal intended velocity; Ccontrol means SubmaxV: Submaximal intended velocity.

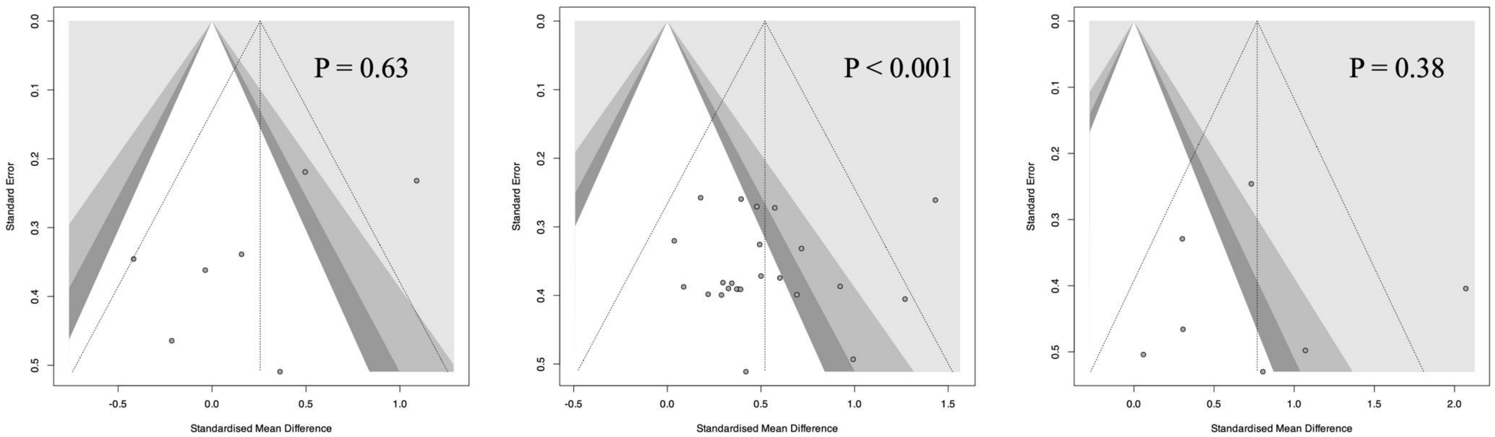
Electronic Supplementary Material Appendix S2 (Statistical power plot)



A. Muscle mass **B. Muscle strength** **C. Functional performance**

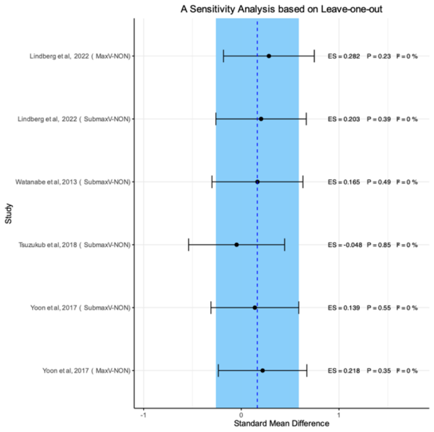
Note: The vertical solid line represents the pooled effect size, and the vertical dash line represents the adjusted pooled effect size. Significance contours at 0.05 and 0.01 levels are noted by the shaded area. manpower indicates the median power of all included effect sizes. d33% and d66% indicate the true effect sizes necessary for achieving 33% and 66% levels of median power. E, O, and PTES show the results of a test of excess significance. R-index denotes the expected replicability of findings.

Electronic Supplementary Material Appendix S3 (Funnel plot of included studies)

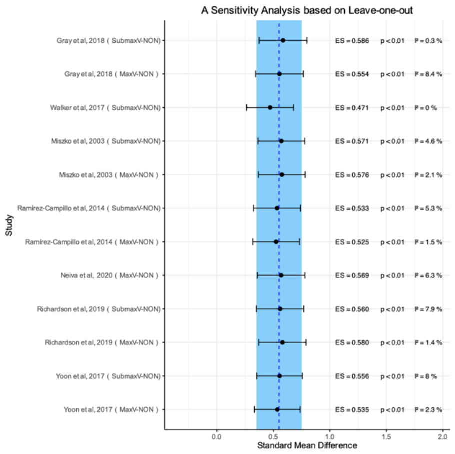


A. Muscle mass **B. Muscle strength** **C. Functional performance**

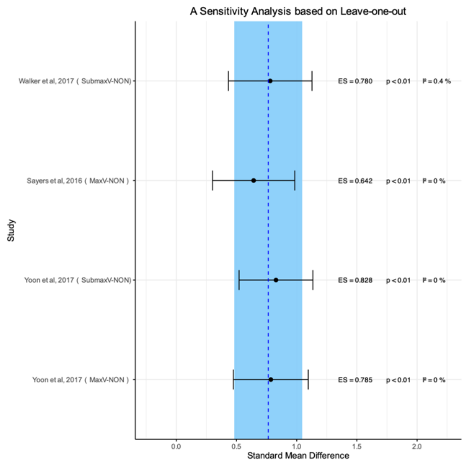
Electronic Supplementary Material Appendix S4 (A Sensitivity Analysis based on Leave-one-out)



A. Muscle mass



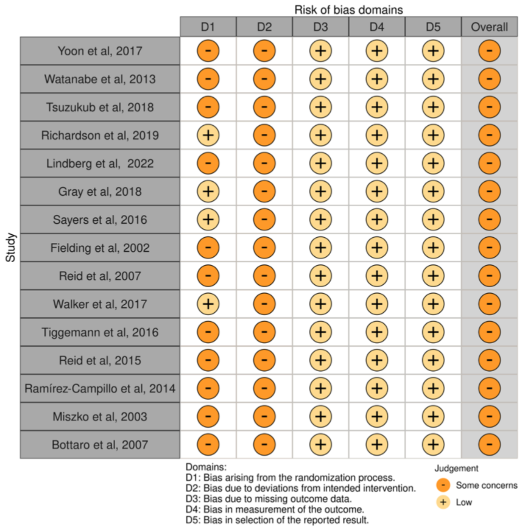
B. Muscle strength

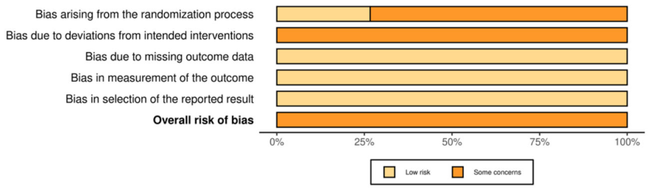


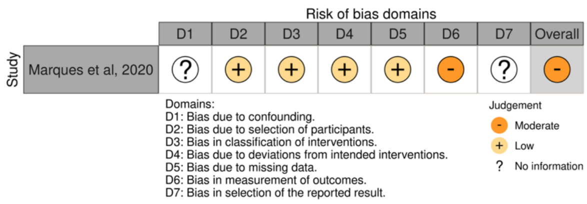
C. Functional performance

Electronic Supplementary Material Appendix S5 (Risk of bias for the included studies)

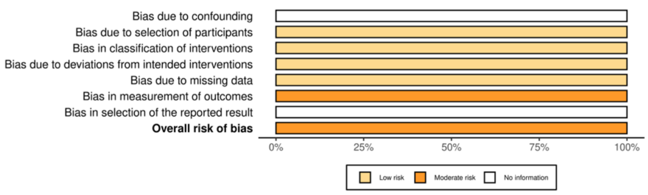
ROB2







ROBINS-I



Material Appendix S6 (Methodological quality assessment)

Study	Eligibility criteria	Random allocation	Concealed allocation	Similar baseline	Participant blinding	Investigator blinding	Assessor blinding	Completeness of follow-up	Intention to treat	Between-group comparisons	Point measures and variability	Total score
Yoon et al, 2017[66]	1	0	0	1	0	0	0	0	1	1	1	5
Watanabe et al, 2013[20]	1	0	0	1	0	0	0	0	1	1	1	5
Tsuzukub et al, 2018[79]	1	0	0	1	0	0	0	0	1	1	1	5
Richardson et al, 2019[71]	1	1	1	1	0	0	0	0	1	1	1	7
Lindberg et al, 2022[70]	1	0	0	1	0	0	0	0	1	1	1	5
Gray et al, 2018[75]	1	1	0	1	0	0	0	0	1	1	1	6
Sayers et al, 2016[74]	1	1	1	1	0	0	0	0	1	1	1	7
Marques et al, 2020[78]	1	0	0	1	0	0	0	0	1	1	1	5
Fielding et al, 2002[73]	1	0	0	1	0	0	0	0	1	1	1	5
Reid et al, 2008[76]	1	0	0	1	0	0	0	0	1	1	1	5
Walker et al, 2017[77]	1	1	1	1	0	0	0	0	1	1	1	7
Tiggemann et al, 2016[69]	1	0	0	1	0	1	0	0	1	1	1	6

Reid et al, 2015[65]	1	0	0	1	0	1	1	0	1	1	1	7
Ramírez-Campillo et al, 2014[72]	1	0	1	1	0	1	0	0	1	1	1	7
Miszko et al, 2003[68]	1	0	1	1	0	1	0	0	1	1	1	7
Bottaro et al, 2007[67]	1	0	0	1	0	1	0	0	1	1	1	6

Electronic Supplementary Material Appendix S7 (PRISMA 2020 checklist)

Section/topic	#	Checklist item	Reported on page #
Title	1	Identify the report as a systematic review, meta-analysis, or both.	1
Structured summary	2	Provide a structured summary including, as applicable: background; objectives; data sources; study eligibility criteria, participants, and interventions; study appraisal and synthesis methods; results; limitations; conclusions and implications of key findings; systematic review registration number.	2
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of what is already known.	5
Objectives	4	Provide an explicit statement of questions being addressed with reference to participants, interventions, comparisons, outcomes, and study design （PICOS）.	6
METHODS			
Protocol and registration	5	Indicate if a review protocol exists, if and where it can be accessed （e.g., Web address）, and, if available, provide registration information including registration number.	7
Eligibility criteria	6	Specify study characteristics （e.g., PICOS, length of follow-up） and report characteristics （e.g., years considered, language, publication status） used as criteria for eligibility, giving rationale.	7
Information sources	7	Describe all information sources （e.g., databases with dates of coverage, contact with study authors to identify additional studies） in the search and date last searched.	7
Search	8	Present full electronic search strategy for at least one database, including any limits used, such that it could be repeated.	7

Study selection	9	State the process for selecting studies (i.e., screening, eligibility, included in systematic review, and, if applicable, included in the meta-analysis).	7
Data collection process	10	Describe method of data extraction from reports (e.g., piloted forms, independently, in duplicate) and any processes for obtaining and confirming data from investigators.	8
Data items	11	List and define all variables for which data were sought (e.g., PICOS, funding sources) and any assumptions and simplifications made.	7, 8
Risk of bias in individual studies	12	Describe methods used for assessing risk of bias of individual studies (including specification of whether this was done at the study or outcome level), and how this information is to be used in any data synthesis.	9
Summary measures	13	State the principal summary measures (e.g., risk ratio, difference in means).	8-10
Synthesis of results	14	Describe the methods of handling data and combining results of studies, if done, including measures of consistency (e.g., I^2) for each meta-analysis.	9
Section/topic	#	Checklist item	Reported on page #
Risk of bias across studies	15	Specify any assessment of risk of bias that may affect the cumulative evidence (e.g., publication bias, selective reporting within studies).	11
Additional analyses	16	Describe methods of additional analyses (e.g., sensitivity or subgroup analyses, meta-regression), if done, indicating which were pre-specified.	11
RESULTS			
Study selection	17	Give numbers of studies screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally with a flow diagram.	11
Study characteristics	18	For each study, present characteristics for which data were extracted (e.g., study size, PICOS, follow-up period) and provide the citations.	11-12

Risk of bias within studies	19	Present data on risk of bias of each study and, if available, any outcome level assessment （see item 12）.	14
Results of individual studies	20	For all outcomes considered （benefits or harms）, present, for each study: （a） simple summary data for each intervention group （b） effect estimates and confidence intervals, ideally with a forest plot.	12-13
Synthesis of results	21	Present results of each meta-analysis done, including confidence intervals and measures of consistency.	12-13
Risk of bias across studies	22	Present results of any assessment of risk of bias across studies （see Item 15）.	14
Additional analysis	23	Give results of additional analyses, if done （e.g., sensitivity or subgroup analyses, meta-regression [see Item 16]）.	14
DISCUSSION			
Summary of evidence	24	Summarize the main findings including the strength of evidence for each main outcome; consider their relevance to key groups （e.g., healthcare providers, users, and policy makers）.	14
Limitations	25	Discuss limitations at study and outcome level （e.g., risk of bias）, and at review-level （e.g., incomplete retrieval of identified research, reporting bias）.	18
Conclusions	26	Provide a general interpretation of the results in the context of other evidence, and implications for future research.	18
FUNDING			
Funding	27	Describe sources of funding for the systematic review and other support （e.g., supply of data）; role of funders for the systematic review.	19

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