

Effects of maximal versus submaximal intended velocity resistance training on muscular fitness adaptations in older adults: A systematic review and meta-analysis

TAO, Meiling <<http://orcid.org/0009-0000-1332-8062>>, LIAO, Kaifang <<http://orcid.org/0000-0001-6893-1491>>, YIN, Mingyue, CHEN, Zhili, ZHONG, Yuming, ZHU, Chenwen, SONG, Yuou, THOMPSON, Steve <<http://orcid.org/0000-0001-7674-3685>>, BISHOP, Chris and LI, Yongming <<http://orcid.org/0000-0001-9654-0199>>

Available from Sheffield Hallam University Research Archive (SHURA) at:

<https://shura.shu.ac.uk/37283/>

This document is the Published Version [VoR]

Citation:

TAO, Meiling, LIAO, Kaifang, YIN, Mingyue, CHEN, Zhili, ZHONG, Yuming, ZHU, Chenwen, SONG, Yuou, THOMPSON, Steve, BISHOP, Chris and LI, Yongming (2026). Effects of maximal versus submaximal intended velocity resistance training on muscular fitness adaptations in older adults: A systematic review and meta-analysis. *Sports Medicine and Health Science*, 8 (4), 365-376. [Article]

Copyright and re-use policy

See <http://shura.shu.ac.uk/information.html>



Review Article

Effects of maximal versus submaximal intended velocity resistance training on muscular fitness adaptations in older adults: A systematic review and meta-analysis

Meiling Tao^{a,b,1}, Kaifang Liao^{b,c,1}, Mingyue Yin^{a,d}, Zhili Chen^a, Yuming Zhong^{a,e},
Chenwen Zhu^a, Yuou Song^a, Steve Thompson^f, Chris Bishop^g, Yongming Li^{a,h,i,*}

^a School of Athletic Performance, Shanghai University of Sport, Shanghai, China

^b Department of Physical Education, Chengdu Sport University, Chengdu, China

^c Department of Strength and Conditioning, Guangdong Vocational Institute of Sport, Guangzhou, China

^d The Mary MacKillop Institute for Health Research, Australian Catholic University, Melbourne, VIC, 3000, Australia

^e School of Medical and Health Sciences, Centre for Human Performance, Edith Cowan University, Joondalup, 6027, Australia

^f School of Sport and Physical Activity, College of Health, Wellbeing and Life Sciences, Sheffield Hallam University, Sheffield, UK

^g Faculty of Science and Technology, London Sport Institute, Middlesex University, London, NW4 4BT, UK

^h School of Coaching, Shanghai University of Sport, Shanghai, China

ⁱ China Institute of Sport Science, Beijing, China

ARTICLE INFO

Keywords:

Movement velocity
Muscle mass
Muscle strength
Functional performance
Older adults

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.

Prospero registration: CRD42023489470

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

* Corresponding author. School of Athletic Performance, Shanghai University of Sport, Shanghai 200438, China.

E-mail address: liyongming@sus.edu.cn (Y. Li).

Peer review under the responsibility of Editorial Board of Sports Medicine and Health Science

¹ These authors contributed equally to this work.

List of abbreviations

1 RM	One-repetition maximum	RCT	Randomized controlled trial
MaxV	Maximal intended velocity	PROSPERO	International Prospective Register of Systematic Reviews
SubmaxV	Submaximal intended velocity	PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
AQAP	As quickly as possible	ROB2	Risk of Bias Tool 2
RPE	Rate of perceived exertion	ROBINS-I	Risk of Bias In Non-Randomized Studies of Interventions
wk	Weeks	PEDro	Physiotherapy Evidence Database
SMD	Standardized Mean Difference	GRADE	Grading of Recommendations Assessment, Development, and Evaluation
Hedges' <i>g</i>	Hedges' <i>g</i> statistic	TUG	Timed-up-and-go test
CI	Confidence interval	STS	Sit-to-stand test
95%CI	95% confidence interval	SPPB	Short physical performance battery
PI	Prediction interval	IL-6	Interleukin-6
I^2	Heterogeneity statistic	BDNF	Brain-derived neurotrophic factor
τ^2	Between-study variance	Ca ²⁺	Calcium ion
<i>K</i>	Total number of effects included in the pooled effect size	Ca ²⁺ -ATPase	Calcium ATPase
Power	Statistical power for pooled effect size	mRNA	Messenger ribonucleic acid
<i>p</i> -value	Statistically significant <i>p</i> value		

fitness, and consequently, enhance the quality of life in older adults.^{6,7}

Specifically, resistance training slows down the rate at which muscle atrophy occurs⁸ 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's²⁹ 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 Lopez¹⁷ 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. Nascimento³⁰ 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 April 12, 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 SD_{diff} 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 & Wibbenliet.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 Laird⁵⁷ 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 *large* (> 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.^{Fig. 2}

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.^{20,22,65–78}

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,⁶⁵ $n = 52$). 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,⁷⁸ 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 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 ($\leq 60\%$ 1 RM), moderate (60%–80% 1 RM) and high intensity ($\geq 80\%$ 1 RM)"¹⁷ 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.

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

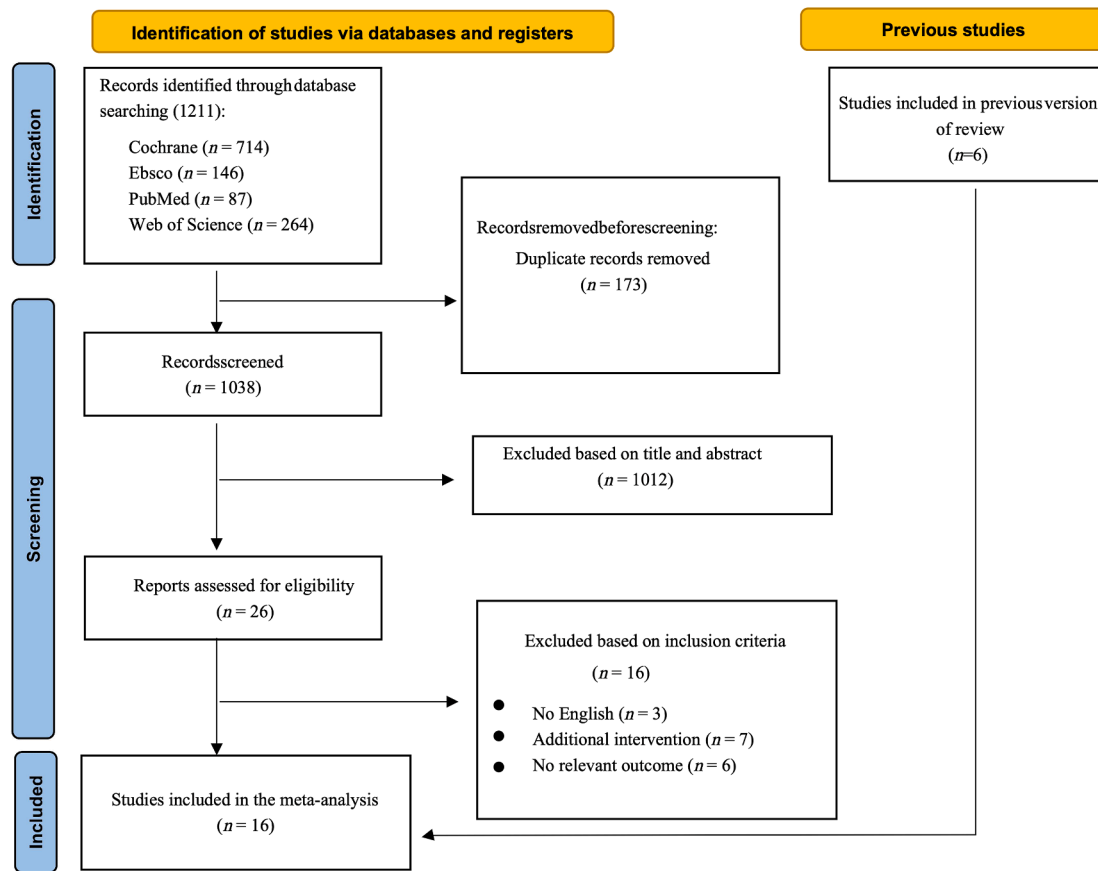


Fig. 1. PRISMA flow diagram of the search strategy. Abbreviation: PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analyses.

Main effect	K	N	Hedges' g [95%CI]	p-value	REML	Funnel plot
Muscle mass						
GRADE ⊕⊕⊕⊕	Overall 7	318	0.16 [-0.37, 0.69]	0.48		
	PI 7	318	0.16 [-0.94, 1.27]	NA		
<i>Q (df = 6) = 18.3968, I² = 67.40%, p = 0.005</i>						
Muscle strength						
GRADE ⊕⊕⊕⊕	Overall 24	911	0.55 [0.34, 0.76]	<0.0001		
	PI 24	911	0.55 [0.02, 1.08]	NA		
<i>Q (df = 23) = 26.1259, I² = 11.96%, p = 0.30</i>						
Functional performance						
GRADE ⊕⊕⊕⊕	Overall 7	261	0.76 [0.41, 1.12]	0.002		
	PI 7	261	0.76 [0.41, 1.12]	NA		
<i>Q (df = 6) = 16.0922, I² = 62.70%, p = 0.0133</i>						
GRADE	⊕⊕⊕⊕ High	⊕⊕⊕⊙ Moderate	⊕⊕⊙⊙ low	⊕⊙⊙⊙ Very low	 No training -1 Favored 0 MaxV or SubmaxV 1 2	

Fig. 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; I²: Quantitative indicator of heterogeneity; Power: Statistical power for pooled effect size; GRADE: Grading of Recommendations Assessment, Development, and Evaluation.

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 76.0 ± 1.3 78.0 ± 1.0	2/7	12 wk	MaxV SubmaxV Control	AQAP exceeding 2 s n/a	exceeding 2 s exceeding 2 s n/a	RPE: 12–13 RPE:15–16 n/a
Watanabe et al., 2013 ²⁰	combined	66.8 ± 3.8 66.8 ± 5.2	2/7	10 wk	SubmaxV SubmaxV	3s 1s	3s 1s	50% 1 RM 50% 1 RM
Tsuzukub et al., 2018 ⁷⁸	combined	72.5 ± 2.1 73.2 ± 2.1	7/7	12 wk	SubmaxV Control	4s n/a	4s n/a	body weight n/a
Richardson et al., 2019 ⁷¹	combined	66 ± 5 67 ± 6 67 ± 4 66 ± 6 65 ± 5	1-2/7	10 wk	MaxV SubmaxV Control	AQAP exceeding 2 s n/a	3s 3s n/a	40% 1 RM 80% 1 RM n/a
Lindberg et al., 2022 ⁷⁰	Male	68 ± 5 68 ± 5 68 ± 5	2/7	10 wk	MaxV MaxV SubmaxV	AQAP AQAP n/a	2–3 s 2–3 s n/a	< 50% of 1 RM > 70% of 1 RM 20%, 50%, 80% 1 RM
Gray et al., 2018 ⁷⁴	combined	81.6 ± 5.9 81.0 ± 5.5 81.3 ± 5.3	2/7	48 wk	MaxV SubmaxV Control	AQAP 2 s 2 s	2 s 2 s 2 s	50% 1 RM 80% 1 RM body weight
Sayers et al., 2016 ²²	combined	71.5 ± 6.8 71.1 ± 6.1	3/7	12 wk	MaxV Control	AQAP n/a	2–3 s n/a	40 % 1 RM n/a
Marques et al., 2020 ⁷⁷	combined	78.6 ± 7.6 79.0 ± 6.0	2/7	10 wk	MaxV Control	AQAP n/a	exceeding 2 s n/a	40–65% 1 RM n/a
Fielding et al., 2002 ⁷³	Female	73.2 ± 1.2 72.1 ± 1.3	3/7	12 wk	MaxV SubmaxV	AQAP exceeding 2 s	2 s 2 s	70%1 RM 70%1 RM
Reid et al., 2008 ⁷⁵	combined	72.3 ± 6 73.1 ± 6 79.7 ± 9	3/7	12 wk	MaxV SubmaxV Control	AQAP exceeding 2 s n/a	exceeding 2 s 2 s n/a	70%1 RM 70%1 RM n/a
Walker et al., 2017 ⁷⁶	combined	69.12 ± 2.25 69.49 ± 2.73	2/7	12 wk	SubmaxV Control	2 s n/a	2 s n/a	50–60% 1 RM n/a
Tiggemann et al., 2016 ⁶⁹	Female	64.4 ± 4.0 65.6 ± 5.3	2/7	12 wk	MaxV SubmaxV	AQAP 2 s	2 s 2 s	45-65%1 RM 45-65%1 RM
Reid et al., 2015 ⁶⁵	combined	78.3 ± 5 77.6 ± 4	2/7	12 wk	MaxV MaxV	AQAP AQAP	2 s 2 s	40 % 1 RM 70% 1 RM
Ramírez-Campillo et al., 2014 ⁷²	Female	66.3 ± 3.7 68.7 ± 6.4 66.7 ± 4.9	3/7	12 wk	MaxV SubmaxV Control	AQAP 3 s n/a	3 s 3 s n/a	45%–75% 1 RM 45%–75% 1 RM n/a
Miszko et al., 2003 ⁶⁸	combined	72.3 ± 6.7 72.8 ± 5.4 72.4 ± 7.2 66.55 ± 5.77	3/7	16 wk	MaxV SubmaxV Control	1 s 4 s n/a	2 s exceeding 2 s n/a	40% 1 RM n/a n/a
Bottaro et al., 2007 ⁶⁷	Male	66.33 ± 4.80	2/7	10 wk	MaxV SubmaxV	AQAP 2-3 s	2-3 s 2-3 s	n/a 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.

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 ($g = -0.06$).

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], Low 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.⁷⁹ 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,⁸⁰ 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.⁸¹ 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.⁸²

Regarding load intensity, Pinto et al.⁸³ 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.⁸¹ indicates that resistance training can effectively improve obesity, metabolic risk, and inflammation in post-menopausal 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.⁸⁴ 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.⁸⁵ 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,⁸² 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 $[72.68 \pm 10.91]$ 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 Ca^{2+} -ATPase activity,⁸⁶ and effectively reducing inflammation, thereby accelerating recovery and decreasing muscle inflammation and swelling.⁸¹

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.,⁸⁷ 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.⁸⁸ However, this finding may differ from the results of Davies et al.⁸⁹ 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, Schaun⁹⁰ 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.⁸⁹

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.⁹¹ 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.⁸⁸

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.⁹² 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.⁹³

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,⁹⁴ and positively impacted quality of life.⁹⁵ 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.⁹⁶ 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.⁹⁶ 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.⁹⁷

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.⁹⁴ Therefore, from an economic efficiency perspective, opting for a lower frequency resistance training strategy can effectively achieve the goal of improving functional performance (see Fig. 3).

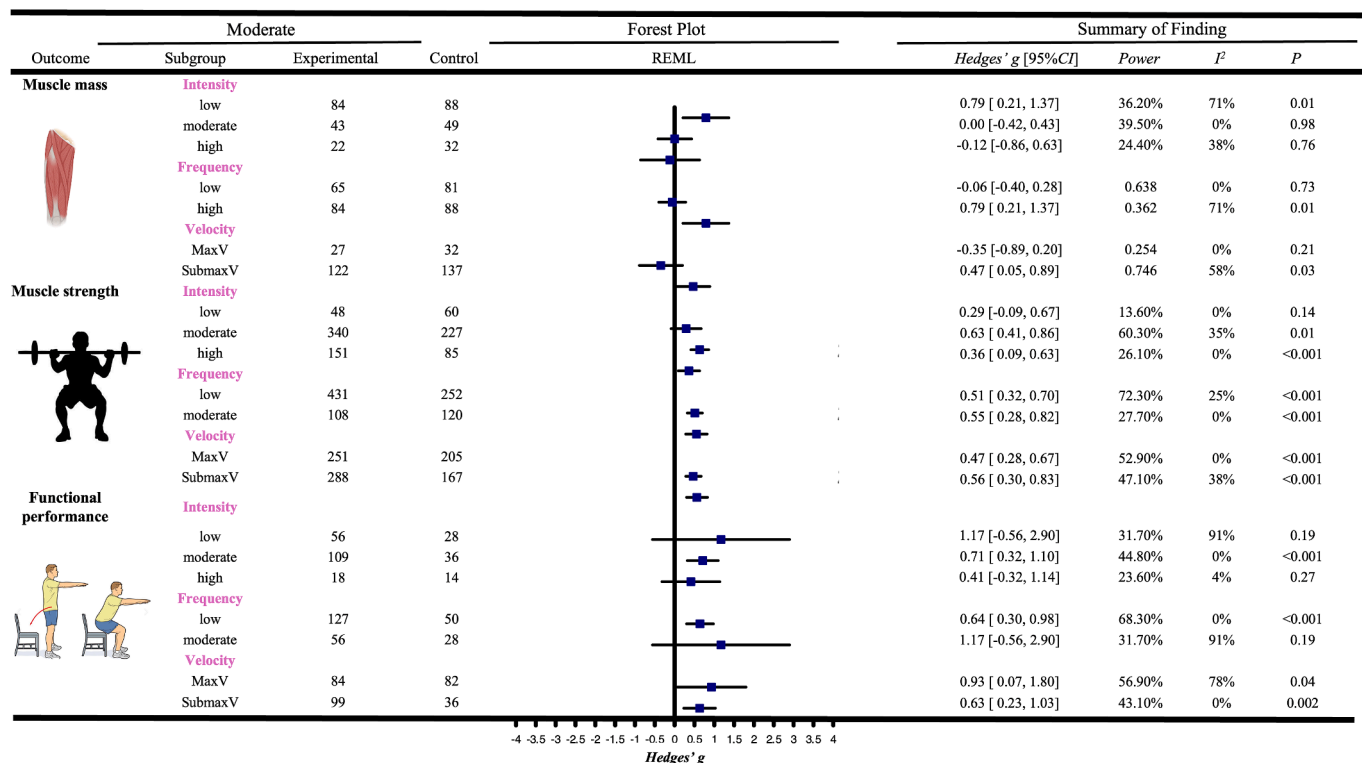


Fig. 3. Subgroup analysis of moderating effects (movement velocity, training frequency, load intensity) on muscular fitness outcomes.

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; I²: Quantitative indicator of heterogeneity; Power: Statistical power for pooled effect size.

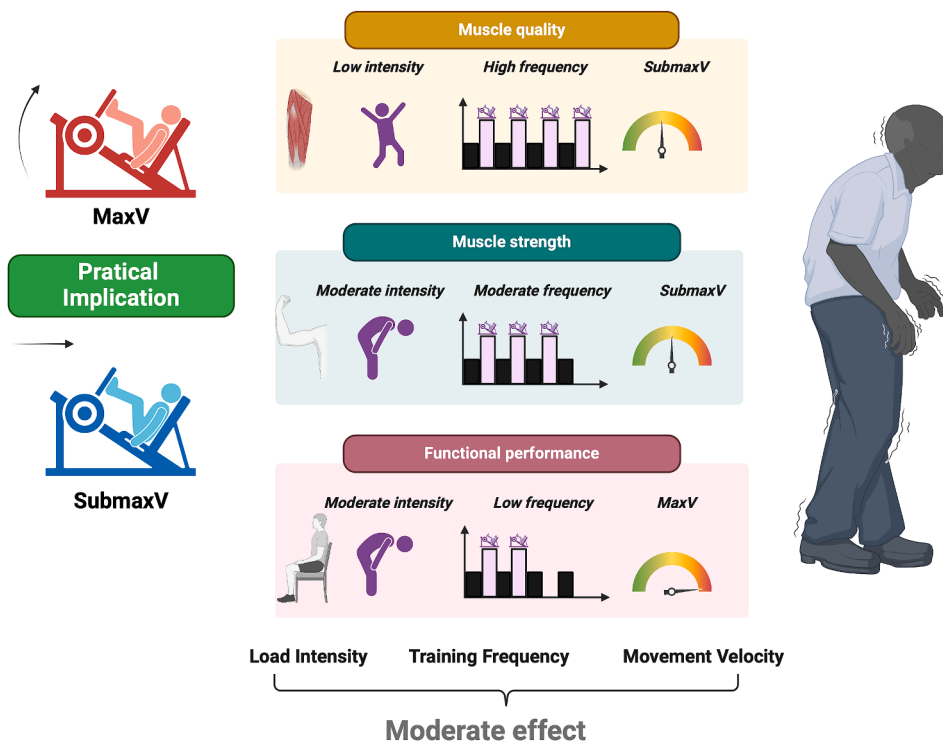


Fig. 4. Practical Implications

Note: This figure presents targeted resistance training strategies for optimizing muscular fitness in older adults; Load Intensity: "Low" = $\leq 60\%$ 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.

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 Fig. 4).

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,⁹⁸ 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.

CRediT authorship contribution statement

Meiling Tao: Writing – original draft, Visualization, Software, Data curation, Conceptualization. **Kaifang Liao:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Mingyue Yin:** Writing – review & editing, Supervision, Software. **Zhili Chen:** Writing – review & editing, Data curation. **Yuming Zhong:** Writing – review & editing, Data curation. **Chenwen Zhu:** Writing – review & editing, Data curation. **Yuou Song:** Writing – original draft, Software, Data curation. **Steve Thompson:** Writing – review & editing. **Chris Bishop:** Writing – review & editing, Conceptualization. **Yongming Li:** Writing – review & editing, Writing – original draft, Supervision, Data curation, Conceptualization.

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.

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.

Funding

This work was supported by the Humanities and Social Sciences

Foundation of the Ministry of Education of China (Grant No. [23YJC890023]).

Declaration of competing interest

All authors declare no conflict of interest. This study was independently conducted without financial or non-financial influence from any third party.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.smhs.2026.03.001>.

References

- Larsson L, Degens H, Li M, et al. Sarcopenia: aging-related loss of muscle mass and function. *Physiol Rev*. 2019;99(1):427–511. <https://doi.org/10.1152/physrev.00061.2017>.
- Tieland M, Trouwborst I, Clark BC. Skeletal muscle performance and ageing. *J Cachexia Sarcopenia Muscle*. 2018;9(1):3–19. <https://doi.org/10.1002/jcsm.12238>.
- Wilkinson DJ, Piasecki M, Atherton PJ. The age-related loss of skeletal muscle mass and function: measurement and physiology of muscle fibre atrophy and muscle fibre loss in humans. *Ageing Res Rev*. 2018;47:123–132. <https://doi.org/10.1016/j.arr.2018.07.005>.
- Baltasar-Fernandez I, Alcazar J, Martín-Braojos S, et al. Power-oriented resistance training combined with high-intensity interval training in pre-frail and frail older people: comparison between traditional and cluster training set configurations on the force-velocity relationship, physical function and frailty. *Eur J Appl Physiol*. 2024;124(2):623–632. <https://doi.org/10.1007/s00421-023-05298-x>.
- Roubenoff R. Sarcopenia and its implications for the elderly. *Eur J Clin Nutr*. 2000;54(Suppl 3):S40–S47. <https://doi.org/10.1038/sj.ejcn.1601024>.
- O'Bryan SJ, Giuliano C, Woessner MN, et al. Progressive resistance training for concomitant increases in muscle strength and bone mineral density in older adults: a systematic review and meta-analysis. *Sports Med*. 2022;52(8):1939–1960. <https://doi.org/10.1007/s40279-022-01675-2>.
- Straight CR, Lindheimer JB, Brady AO, Dishman RK, Evans EM. Effects of resistance training on lower-extremity muscle power in middle-aged and older adults: a systematic review and meta-analysis of randomized controlled trials. *Sports Med*. 2016;46(3):353–364. <https://doi.org/10.1007/s40279-015-0418-4>.
- Fragala MS, Fukuda DH, Stout JR, et al. Muscle quality index improves with resistance exercise training in older adults. *Exp Gerontol*. 2014;53:1–6. <https://doi.org/10.1016/j.exger.2014.01.027>.
- Winett RA, Carpinelli RN. Potential health-related benefits of resistance training. *Prev Med*. 2001;33(5):503–513. <https://doi.org/10.1006/pmed.2001.0909>.
- Willey KA, Singh MAF. Battling insulin resistance in elderly obese people with type 2 diabetes: bring on the heavy weights. *Diabetes Care*. 2003;26(5):1580–1588. <https://doi.org/10.2337/diacare.26.5.1580>.
- Claudino JG, Afonso J, Sarvestan J, et al. Strength training to prevent falls in older adults: a systematic review with meta-analysis of randomized controlled trials. *J Clin Med*. 2021;10(14):3184. <https://doi.org/10.3390/jcm10143184>.
- Crewther B, Cronin J, Keogh J. Possible stimuli for strength and power adaptation: acute mechanical responses. *Sports Med*. 2005;35(11):967–989. <https://doi.org/10.2165/00007256-200535110-00004>.
- Pareja-Blanco F, Rodríguez-Rosell D, Sánchez-Medina L, Gorostiaga E, González-Badillo J. Effect of movement velocity during resistance training on neuromuscular performance. *Int J Sports Med*. 2014;35(11):916–924. <https://doi.org/10.1055/s-0033-1363985>.
- Schaun GZ, Bamman MM, Andrade LS, et al. High-velocity resistance training mitigates physiological and functional impairments in middle-aged and older adults with and without mobility-limitation. *GeroScience*. 2022;44(3):1175–1197. <https://doi.org/10.1007/s11357-022-00520-8>.
- Reid KF, Fielding RA. Skeletal muscle power: a critical determinant of physical functioning in older adults. *Exerc Sport Sci Rev*. 2012;40(1):4. <https://doi.org/10.1097/JES.0b013e31823b5f13>.
- Cronin J, Sleivert G. Challenges in understanding the influence of maximal power training on improving athletic performance. *Sports Med*. 2005;35(3):213–234. <https://doi.org/10.2165/00007256-200535030-00003>.
- Lopez P, Rech A, Petropoulou M, et al. Does high-velocity resistance exercise elicit greater physical function benefits than traditional resistance exercise in older adults? A systematic review and network meta-analysis of 79 trials. *J Gerontol A Biol Sci Med Sci*. 2023;78(8):1471–1482. <https://doi.org/10.1093/gerona/glac230>.
- González-Badillo JJ, Rodríguez-Rosell D, Sánchez-Medina L, Gorostiaga EM, Pareja-Blanco F. Maximal intended velocity training induces greater gains in bench press performance than deliberately slower half-velocity training. *Eur J Sport Sci*. 2014;14(8):772–781. <https://doi.org/10.1080/17461391.2014.905987>.
- Watanabe Y, Tanimoto M, Oba N, Sanada K, Miyachi M, Ishii N. Effect of resistance training using bodyweight in the elderly: comparison of resistance exercise movement between slow and normal speed movement. *Geriatr Gerontol Int*. 2015;15(12):1270–1277. <https://doi.org/10.1111/ggi.12427>.
- Watanabe Y, Tanimoto M, Ohgane A, Sanada K, Miyachi M, Ishii N. Increased muscle size and strength from slow-movement, low-intensity resistance exercise and tonic force generation. *J Aging Phys Act*. 2013;21(1):71–84. <https://doi.org/10.1123/japa.21.1.71>.
- Fielding R, LeBrasseur N, Cuoco A, Bean J, Mizer K, Fatarone Singh M. High-velocity resistance training increases skeletal muscle peak power in older women. *J Am Geriatr Soc*. 2002;50(4):655–662. <https://doi.org/10.1046/j.1532-5415.2002.50159.x>.
- Sayers SP, Gibson K, Bryan Mann J. Improvement in functional performance with high-speed power training in older adults is optimized in those with the highest training velocity. *Eur J Appl Physiol*. 2016;116(11-12):2327–2336. <https://doi.org/10.1007/s00421-016-3484-x>.
- Delmonico MJ, Harris TB, Visser M, et al. Longitudinal study of muscle strength, quality, and adipose tissue infiltration. *Am J Clin Nutr*. 2009;90(6):1579–1585. <https://doi.org/10.3945/ajcn.2009.28047>.
- Cruz-Jentoft AJ, Bahat G, Bauer J, et al. Sarcopenia: revised European consensus on definition and diagnosis. *Age Ageing*. 2019;48(1):16–31. <https://doi.org/10.1093/ageing/afy169>.
- Clark BC, Manini TM. Sarcopenia =/≠ dynapenia. *J Gerontol A Biol Sci Med Sci*. 2008;63(8):829–834. <https://doi.org/10.1093/gerona/63.8.829>.
- Foldvari M, Clark M, Laviolette LC, et al. Association of muscle power with functional status in community-dwelling elderly women. *J Gerontol A Biol Sci Med Sci*. 2000;55(4):M192–M199. <https://doi.org/10.1093/gerona/55.4.m192>.
- Cress ME, Buchner DM, Questad KA, Esselman PC, deLateur BJ, Schwartz RS. Continuous-scale physical functional performance in healthy older adults: a validation study. *Arch Phys Med Rehabil*. 1996;77(12):1243–1250. [https://doi.org/10.1016/s0003-9993\(96\)90187-2](https://doi.org/10.1016/s0003-9993(96)90187-2).
- Guralnik JM, Simonsick EM, Ferrucci L, et al. A short physical performance battery assessing lower extremity function: association with self-reported disability and prediction of mortality and nursing home admission. *J Gerontol*. 1994;49(2):M85–M94. <https://doi.org/10.1093/geronj/49.2.m85>.
- Pearson LT, Behm DG, Goodall S, Mason R, Stuart S, Barry G. Effects of maximal-versus submaximal-intent resistance training on functional capacity and strength in community-dwelling older adults: a systematic review and meta-analysis. *BMC Sports Sci Med Rehabil*. 2022;14(1):129. <https://doi.org/10.1186/s13102-022-00526-x>.
- Nascimento MAD, Gerage AM, Silva DRPD, et al. Effect of resistance training with different frequencies and subsequent detraining on muscle mass and appendicular lean soft tissue, IGF-1, and testosterone in older women. *Eur J Sport Sci*. 2019;19(2):199–207. <https://doi.org/10.1080/17461391.2018.1496145>.
- Silva NL, Oliveira RB, Fleck SJ, Leon ACMP, Farinatti P. Influence of strength training variables on strength gains in adults over 55 years-old: a meta-analysis of dose-response relationships. *J Sci Med Sport*. 2014;17(3):337–344. <https://doi.org/10.1016/j.jsams.2013.05.009>.
- Ralston GW, Kilgore L, Wyatt FB, Buchan D, Baker JS. Weekly training frequency effects on strength gain: a meta-analysis. *Sports Med Open*. 2018;4(1):36. <https://doi.org/10.1186/s40798-018-0149-9>.
- Fyfe JJ, Hamilton DL, Daly RM. Minimal-dose resistance training for improving muscle mass, strength, and function: a narrative review of current evidence and practical considerations. *Sports Med*. 2022;52(3):463–479. <https://doi.org/10.1007/s40279-021-01605-8>.
- de Vos NJ, Singh NA, Ross DA, Stavrinou TM, Orr R, Fatarone Singh MA. Optimal load for increasing muscle power during explosive resistance training in older adults. *J Gerontol A Biol Sci Med Sci*. 2005;60(5):638–647. <https://doi.org/10.1093/gerona/60.5.638>.
- Sayers SP, Gibson K. Effects of high-speed power training on muscle performance and braking speed in older adults. *J Aging Res*. 2012;2012:426278. <https://doi.org/10.1155/2012/426278>.
- Ribeiro AS, Nunes JP, Schoenfeld BJ. Selection of resistance exercises for older individuals: the forgotten variable. *Sports Med*. 2020;50(6):1051–1057. <https://doi.org/10.1007/s40279-020-01260-5>.
- World Health Organization. WHO's work on the UN Decade of Healthy Ageing (2021-2030). <https://www.who.int/initiatives/decade-of-healthy-ageing>. Accessed January 17, 2024.
- Wang TJ. Concept analysis of functional status. *Int J Nurs Stud*. 2004;41(4):457–462. <https://doi.org/10.1016/j.ijnurstu.2003.09.004>.
- Aube D, Wadhi T, Rauch J, et al. Progressive resistance training volume: effects on muscle thickness, mass, and strength adaptations in resistance-trained individuals. *J Strength Cond Res*. 2022;36(3):600. <https://doi.org/10.1519/JSC.0000000000003524>.
- Schoenfeld BJ, Ogborn D, Krieger JW. Dose-response relationship between weekly resistance training volume and increases in muscle mass: a systematic review and meta-analysis. *J Sports Sci*. 2017;35(11):1073–1082. <https://doi.org/10.1080/02640414.2016.1210197>.
- Kell RT, Bell G, Quinney A. Musculoskeletal fitness, health outcomes and quality of life. *Sports Med*. 2001;31(12):863–873. <https://doi.org/10.2165/00007256-200131120-00003>.
- Cumpston M, Li T, Page MJ, et al. Updated guidance for trusted systematic reviews: a new edition of the cochrane Handbook for Systematic Reviews of Interventions. *PubMed*. 2019;10(10):ED000142. <https://pubmed.ncbi.nlm.nih.gov/31643080/>. Accessed December 24, 2023.
- Sterne JAC, Savović J, Page MJ, et al. RoB 2: a revised tool for assessing risk of bias in randomised trials. *BMJ*. 2019;366:l4898. <https://doi.org/10.1136/bmj.l4898>.
- Sterne JA, Hernán MA, Reeves BC, et al. ROBINS-I: a tool for assessing risk of bias in non-randomised studies of interventions. *BMJ*. 2016;355:i4919. <https://doi.org/10.1136/bmj.i4919>.

45. de Morton NA. The PEDro scale is a valid measure of the methodological quality of clinical trials: a demographic study. *Aust J Physiother.* 2009;55(2):129–133. [https://doi.org/10.1016/s0004-9514\(09\)70043-1](https://doi.org/10.1016/s0004-9514(09)70043-1).
46. Viechtbauer W. Conducting meta-analyses in R with the metafor package. *J Stat Softw.* 2010;36:1–48. <https://doi.org/10.18637/jss.v036.i03>.
47. DerSimonian R, Kacker R. Random-effects model for meta-analysis of clinical trials: an update. *Contemp Clin Trials.* 2007;28(2):105–114. <https://doi.org/10.1016/j.cct.2006.04.004>.
48. Borenstein M, Hedges LV, Higgins JPT, Rothstein HR. A basic introduction to fixed-effect and random-effects models for meta-analysis. *Res Synth Methods.* 2010;1(2):97–111. <https://doi.org/10.1002/jrsm.12>.
49. Kadlec D, Sainani KL, Nimphius S. With great power comes great responsibility: common errors in meta-analyses and meta-regressions in strength & conditioning research. *Sports Med.* 2023;53(2):313–325. <https://doi.org/10.1007/s40279-022-01766-0>.
50. Van den Noortgate W, López-López JA, Marín-Martínez F, Sánchez-Meca J. Three-level meta-analysis of dependent effect sizes. *Behav Res Methods.* 2013;45(2):576–594. <https://doi.org/10.3758/s13428-012-0261-6>.
51. Assink M, Wibbelink CJM. Fitting three-level meta-analytic models in R: a step-by-step tutorial. *Tutorials Quant Methods Psychol.* 2016;12(3):154–174. <https://doi.org/10.20982/tqmp.12.3.p154>.
52. Cheung MWL. A guide to conducting a meta-analysis with non-independent effect sizes. *Neuropsychol Rev.* 2019;29(4):387–396. <https://doi.org/10.1007/s11065-019-09415-6>.
53. Spinelli LM, Pandis N. Prediction interval in random-effects meta-analysis. *Am J Orthod Dentofacial Orthop.* 2020;157(4):586–588. <https://doi.org/10.1016/j.ajodo.2019.12.011>.
54. Borg DN, Impellizzeri FM, Borg SJ, et al. Meta-analysis prediction intervals are under reported in sport and exercise medicine. *Scand J Med Sci Sports.* 2024;34(3):e14603. <https://doi.org/10.1111/sms.14603>.
55. IntHout J, Ioannidis JPA, Rovers MM, Goeman JJ. Plea for routinely presenting prediction intervals in meta-analysis. *BMJ Open.* 2016;6(7):e010247. <https://doi.org/10.1136/bmjopen-2015-010247>.
56. Nakagawa S, Noble DWA, Senior AM, Lagisz M. Meta-evaluation of meta-analysis: ten appraisal questions for biologists. *BMC Biol.* 2017;15(1):18. <https://doi.org/10.1186/s12915-017-0357-7>.
57. DerSimonian R, Laird N. Meta-analysis in clinical trials. *Control Clin Trials.* 1986;7(3):177–188. [https://doi.org/10.1016/0197-2456\(86\)90046-2](https://doi.org/10.1016/0197-2456(86)90046-2).
58. Cumpston M, Li T, Page MJ, et al. Updated guidance for trusted systematic reviews: a new edition of the Cochrane Handbook for Systematic Reviews of Interventions. *Cochrane Database Syst Rev.* 2019;10:ED000142. <https://doi.org/10.1002/14651858.ED000142>.
59. Quintana DS. A guide for calculating study-level statistical power for meta-analyses. *Adv Methods Pract Psychol Sci.* 2023;6(1):25152459221147260. <https://doi.org/10.1177/25152459221147260>.
60. Cohen J. *Statistical Power Analysis for the Behavioral Sciences.* second ed. Routledge; 1988. <https://doi.org/10.4324/9780203771587>.
61. Peters JL, Sutton AJ, Jones DR, Abrams KR, Rushton L. Contour-enhanced meta-analysis funnel plots help distinguish publication bias from other causes of asymmetry. *J Clin Epidemiol.* 2008;61(10):991–996. <https://doi.org/10.1016/j.jclinepi.2007.11.010>.
62. Egger M, Davey Smith G, Schneider M, Minder C. Bias in meta-analysis detected by a simple, graphical test. *BMJ.* 1997;315(7109):629–634. <https://doi.org/10.1136/bmj.315.7109.629>.
63. Fernández-Castilla B, Declercq L, Jamshidi L, Beretvas SN, Onghena P, Van den Noortgate W. Detecting selection bias in meta-analyses with multiple outcomes: a simulation study. *J Exp Educ.* 2021;89(1):125–144. <https://doi.org/10.1080/00220973.2019.1582470>.
64. Schünemann HJ, Higgins JP, Vist GE, et al. Completing 'Summary of findings' tables and grading the certainty of the evidence. In: *Cochrane Handbook for Systematic Reviews of Interventions.* John Wiley & Sons, Ltd; 2019:375–402. <https://doi.org/10.1002/9781119536604.ch14>.
65. Reid KF, Martin KI, Doros G, et al. Comparative effects of light or heavy resistance power training for improving lower extremity power and physical performance in mobility-limited older adults. *J Gerontol A Biol Sci Med Sci.* 2015;70(3):374–380. <https://doi.org/10.1093/gerona/glu156>.
66. Yoon DH, Kang D, Kim HJ, Kim JS, Song HS, Song W. Effect of elastic band-based high-speed power training on cognitive function, physical performance and muscle strength in older women with mild cognitive impairment. *Geriatr Gerontol Int.* 2017;17(5):765–772. <https://doi.org/10.1111/ggi.12784>.
67. Bottaro M, Machado SN, Nogueira W, Scales R, Veloso J. Effect of high versus low-velocity resistance training on muscular fitness and functional performance in older men. *Eur J Appl Physiol.* 2007;99(3):257–264. <https://doi.org/10.1007/s00421-006-0343-1>.
68. Miszko TA, Cress ME, Slade JM, Covey CJ, Agrawal SK, Doerr CE. Effect of strength and power training on physical function in community-dwelling older adults. *J Gerontol A Biol Sci Med Sci.* 2003;58(2):171–175. <https://doi.org/10.1093/gerona/58.2.m171>.
69. Tiggemann CL, Dias CP, Radaelli R, et al. Effect of traditional resistance and power training using rated perceived exertion for enhancement of muscle strength, power, and functional performance. *Age.* 2016;38(2):42. <https://doi.org/10.1007/s11357-016-9904-3>.
70. Lindberg K, Lohne-Seiler H, Fosstveit S, et al. Effectiveness of individualized training based on force-velocity profiling on physical function in older men. *Scand J Med Sci Sports.* 2022;32(6):1013–1025. <https://doi.org/10.1111/sms.14157>.
71. Richardson DL, Duncan MJ, Jimenez A, Juris PM, Clarke ND. Effects of movement velocity and training frequency of resistance exercise on functional performance in older adults: a randomised controlled trial. *Eur J Sport Sci.* 2019;19(2):234–246. <https://doi.org/10.1080/17461391.2018.1497709>.
72. Ramírez-Campillo R, Castillo A, de la Fuente CI, et al. High-speed resistance training is more effective than low-speed resistance training to increase functional capacity and muscle performance in older women. *Exp Gerontol.* 2014;58:51–57. <https://doi.org/10.1016/j.exger.2014.07.001>.
73. Fielding RA, LeBrasseur NK, Cuoco A, Bean J, Mizer K, Fiatarone Singh MA. High-velocity resistance training increases skeletal muscle peak power in older women. *J Am Geriatr Soc.* 2002;50(4):655–662. <https://doi.org/10.1046/j.1532-5415.2002.50159.x>.
74. Gray M, Powers M, Boyd L, Garver K. Longitudinal comparison of low- and high-velocity resistance training in relation to body composition and functional fitness of older adults. *Aging Clin Exp Res.* 2018;30(12):1465–1473. <https://doi.org/10.1007/s40520-018-0929-6>.
75. Reid KF, Callahan DM, Carabello RJ, Phillips EM, Frontera WR, Fielding RA. Lower extremity power training in elderly subjects with mobility limitations: a randomized controlled trial. *Aging Clin Exp Res.* 2008;20(4):337–343. <https://doi.org/10.1007/BF03324865>.
76. Walker S, Haff GG, Häkkinen K, Newton RU. Moderate-load muscular endurance strength training did not improve peak power or functional capacity in older men and women. *Front Physiol.* 2017;8:743. <https://doi.org/10.3389/fphys.2017.00743>.
77. Marques DL, Neiva HP, Marinho DA, Marques MC. Novel resistance training approach to monitoring the volume in older adults: the role of movement velocity. *Int J Environ Res Publ Health.* 2020;17(20):7557. <https://doi.org/10.3390/ijerph17207557>.
78. Tsuzuku S, Kajioka T, Sakakibara H, Shimaoka K. Slow movement resistance training using body weight improves muscle mass in the elderly: a randomized controlled trial. *Scand J Med Sci Sports.* 2018;28(4):1339–1344. <https://doi.org/10.1111/sms.13039>.
79. Grčić J, Garofolini A, Orazem J, Sabol F, Schoenfeld BJ, Pedisic Z. Effects of resistance training on muscle size and strength in very elderly adults: a systematic review and meta-analysis of randomized controlled trials. *Sports Med.* 2020;50(11):2315–2330. <https://doi.org/10.1007/s40279-020-01331-7>.
80. Jones MD, Weewe MA, Hackett DA, Keogh JW, Hagstrom AD. Sex differences in adaptations in muscle strength and size following resistance training in older adults: a systematic review and meta-analysis. *Sports Med.* 2021;51(3):503–517. <https://doi.org/10.1007/s40279-020-01388-4>.
81. Nunes PRP, Castro-E-Souza P, de Oliveira AA, et al. Effect of resistance training volume on body adiposity, metabolic risk, and inflammation in postmenopausal and older females: systematic review and meta-analysis of randomized controlled trials. *J Sport Health Sci.* 2024;13(2):145–159. <https://doi.org/10.1016/j.jshs.2023.09.012>.
82. Cunha PM, Tomeleri CM, Nascimento MA, et al. Improvement of cellular health indicators and muscle quality in older women with different resistance training volumes. *J Sports Sci.* 2018;36(24):2843–2848. <https://doi.org/10.1080/0264014.2018.1479103>.
83. Pinto RS, Correa CS, Radaelli R, Cadore EL, Brown LE, Bottaro M. Short-term strength training improves muscle quality and functional capacity of elderly women. *Age.* 2014;36(1):365–372. <https://doi.org/10.1007/s11357-013-9567-2>.
84. Pedersen BK, Febbraio MA. Muscles, exercise and obesity: skeletal muscle as a secretory organ. *Nat Rev Endocrinol.* 2012;8(8):457–465. <https://doi.org/10.1038/nrendo.2012.49>.
85. Maeo S, Balshaw TG, März B, et al. Long-term resistance trained human muscles have more fibers, more myofibrils, and tighter myofibril packing than untrained. *Med Sci Sports Exerc.* 2024;56(10):1906–1915. <https://doi.org/10.1249/MSS.0000000000003495>.
86. Hunter SK, Thompson MW, Ruell PA, et al. Human skeletal sarcoplasmic reticulum Ca²⁺ uptake and muscle function with aging and strength training. *J Appl Physiol.* 1999;86(6):1858–1865. <https://doi.org/10.1152/jappl.1999.86.6.1858>.
87. Ahtaiainen JP, Pakarinen A, Alen M, Kraemer WJ, Häkkinen K. Muscle hypertrophy, hormonal adaptations and strength development during strength training in strength-trained and untrained men. *Eur J Appl Physiol.* 2003;89(6):555–563. <https://doi.org/10.1007/s00421-003-0833-3>.
88. Lednev EM, Lvov LM, Vepkhvadze TF, et al. Proteomic and transcriptomic response of human skeletal muscle to 12-week resistance training. *Genes Cells.* 2024;19(2):279–295. <https://doi.org/10.17816/gc624325>.
89. Davies TB, Kuang K, Orr R, Halaki M, Hackett D. Effect of movement velocity during resistance training on dynamic muscular strength: a systematic review and meta-analysis. *Sports Med.* 2017;47(8):1603–1617. <https://doi.org/10.1007/s40279-017-0676-4>.
90. Schaun GZ, Bamman MM, Alberton CL. High-velocity resistance training as a tool to improve functional performance and muscle power in older adults. *Exp Gerontol.* 2021;156. <https://doi.org/10.1016/j.exger.2021.111593>. N.PAG.
91. Grčić J, Schoenfeld BJ, Davies TB, Lazinic B, Krieger JW, Pedisic Z. Effect of resistance training frequency on gains in muscular strength: a systematic review and meta-analysis. *Sports Med.* 2018;48(5):1207–1220. <https://doi.org/10.1007/s40279-018-0872-x>.
92. Lusardi MM, Pellecchia GL, Schulman M. Functional performance in community living older adults. *J Geriatr Phys Ther.* 2003;26(3):14–22. <https://doi.org/10.1519/00139143-200312000-00003>.
93. Prasad L, Fredrick J, Aruna R. The relationship between physical performance and quality of life and the level of physical activity among the elderly. *J Educ Health Promot.* 2021;10:68. <https://doi.org/10.4103/jehp.jehp.421.20>.

94. Levinger I, Goodman C, Hare DL, Jerums G, Selig S. The effect of resistance training on functional capacity and quality of life in individuals with high and low numbers of metabolic risk factors. *Diabetes Care*. 2007;30(9):2205–2210. <https://doi.org/10.2337/dc07-0841>.
95. Teixeira-Salmela LF, Santiago L, Lima RCM, Lana DM, Camargos FFO, Cassiano JG. Functional performance and quality of life related to training and detraining of community-dwelling elderly. *Disabil Rehabil*. 2005;27(17):1007–1012. <https://doi.org/10.1080/09638280500030688>.
96. Marques DL, Neiva HP, Marinho DA, Marques MC. Manipulating the resistance training volume in middle-aged and older adults: a systematic review with meta-analysis of the effects on muscle strength and size, muscle quality, and functional capacity. *Sports Med*. 2023;53(2):503–518. <https://doi.org/10.1007/s40279-022-01769-x>.
97. Farinatti PTV, Geraldes AAR, Bottaro MF, Lima MVIC, Albuquerque RB, Fleck SJ. Effects of different resistance training frequencies on the muscle strength and functional performance of active women older than 60 years. *J Strength Cond Res*. 2013;27(8):2225–2234. <https://doi.org/10.1519/JSC.0b013e318278f0db>.
98. González-Badillo JJ, Sánchez-Medina L, Ribas-Serna J, Rodríguez-Rosell D. Toward a new paradigm in resistance training by means of velocity monitoring: a critical and challenging narrative. *Sports Med Open*. 2022;8(1):118. <https://doi.org/10.1186/s40798-022-00513-z>.