

Review article

Lower extremity muscle hypertrophy in response to resistance training in older adults: Systematic review, meta-analysis, and meta-regression of randomized controlled trials

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ABSTRACT

Objectives: This study aimed to investigate the effects of resistance training (RT) on knee extensor muscle hypertrophy in adults 65 years and older.

Methods: A systematic search was carried out in PubMed, Embase, and Scopus to review randomized controlled trials that assessed the effects of supervised RT on 1) muscle size, 2) fiber area, and 3) leg lean mass (LLM). Random-effects meta-analyses of standardized mean difference (SMD) and raw mean difference (RMD) for LLM were calculated. We performed a meta-regression to examine the interference of age, training volume, and duration on the results related to hypertrophy at muscle and fiber levels.

Results: Thirty-two studies were included in the review, and 28 were meta-analyzed. The meta-analysis found a significant effect of RT on muscle size (SMD = 0.34; 95 % CI: 0.16–0.52; $p < 0.001$) and fiber area (SMD = 0.54; 95 % CI: 0.24–0.84; $p < 0.001$), but not on LLM (RMD = 0.22; 95 % CI: –0.22–0.66 $p = 0.321$). A subanalysis of studies that assessed quadriceps femoris size (excluding isolated quadriceps femoris muscles from the analysis) also revealed a significant effect of RT (95 % CI: 0.20–0.69; $p < 0.001$). Regression analysis indicated a significant influence of intervention duration on type II fiber area ($p = 0.034$), while no significant influence was detected for weekly sets or age for any outcome measure.

Conclusions: RT promotes muscle hypertrophy in older adults at both whole-muscle and fiber levels, with training duration potentially influencing the response. Measures of leg lean mass may not capture RT-induced adaptation.

1. Introduction

Age-related muscle loss is a well-known physiological phenomenon that has received considerable attention in the last years in the settings of sarcopenia, physical frailty, and declining physical function (Janssen et al., 2002; Larsson et al., 2019). Lower limb muscles, especially those of the thigh, are more susceptible to age-related losses (Fuchs et al., 2023). Indeed, the quadriceps femoris (QF) shows the largest difference in volume between young and older men (Fuchs et al., 2023). QF morphology measured by magnetic resonance imaging (MRI), computerized tomography (CT), or ultrasonography (US), and lower limb lean mass estimated by dual X-ray absorptiometry (DXA) are the most

responsive indices of skeletal muscle to aging (Francis et al., 2017). CT and MRI are more sensitive than DXA in detecting changes (Fuchs et al., 2023).

The extent to which skeletal muscle mass contributes to strength and functional capacity is debated. However, its relevance to older individuals may be evident since that, in advanced age, a low muscle mass is associated with mortality (de Santana et al., 2021; Scheerman et al., 2021), number of falls (Cawthon et al., 2019; Van Ancum et al., 2018), and other negative health outcomes (Looijaard et al., 2021). In addition to its structural and mechanical function, the muscle plays a relevant role in glycemic control (Kalyani et al., 2014; Sugimoto et al., 2019) and regulation of bone metabolism (Liu et al., 2023). Furthermore, through

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to the systemic release of myokines, the muscle influences whole-body metabolism (Severinsen and Pedersen, 2020).

Resistance training (RT) is probably the most effective intervention currently available to maintain or increase muscle mass and strength, thereby preventing or reversing sarcopenia and physical frailty. While strength gains are typically observed in response to RT, findings from randomized clinical trials (RCTs) on morphological adaptations are mixed (Churchward-Venne et al., 2015). Meta-analyses conducted to verify the effects of RT on muscle function in older adults attempted to synthesize the muscle hypertrophy response (Bao et al., 2020; Borde et al., 2015; Escriche-Escuder et al., 2021; Grgic et al., 2020; Lai et al., 2018; Straight et al., 2020). However, substantial heterogeneity exists regarding eligibility criteria (e.g., participant age), experimental design (e.g., RCTs, non-RCTs), and training features (e.g., training modality, traditional or elastic-based, training supervision). More importantly, outcome measures differ significantly among studies. Besides inference of muscle mass gains from increases in lean mass, another issue lies in the fact that several studies included in meta-analyses evaluated muscle mass indexes or whole-body lean mass (Bao et al., 2020; Borde et al., 2015; Escriche-Escuder et al., 2021; Lai et al., 2018). However, most RT protocols focus on lower extremity muscles, especially QF, because of their clinical relevance and the possibility to collect biopsies more easily than in other muscle districts. Hence, the evaluation of whole-body lean mass may not accurately reflect the magnitude of QF adaptations.

Therefore, the purpose of this systematic review and meta-analysis was to examine the effects of RT on QF hypertrophy in adults 65 years and older. We chose to focus on QF hypertrophy as the main outcome because QF is the target muscle in most investigations involving RT and can therefore provide a meaningful appraisal of muscular morphological adaptations evoked by this training modality in older adults.

2. Methods

This review was registered in PROSPERO (CRD42023427479) and was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) recommendations.

2.1. Data sources and eligibility criteria

The search was performed on PubMed, Scopus, and Embase databases and was completed in March 2023. Additional screening was conducted by checking the reference list of previous related reviews. Details on the search strategy in each database and the list of all reviews screened are provided as supplementary material. Article selection was made on the Ryaan website by two independent reviewers (DAdS and PGS) based on abstracts and, subsequently, full texts. Disagreements were resolved by discussion. We included RCTs that investigated the effects of RT on QF hypertrophy in adults 65 years and older. Only articles published in the English language were considered, while there was no restriction regarding the publication date. The PICOS (population, intervention, comparison, outcomes, and study design) approach was adopted to establish eligibility criteria (Methley et al., 2014). Inclusion and exclusion criteria are listed in Table 1.

2.2. Data extraction

Data from all studies included in this review were extracted by one reviewer (DAdS) and checked independently by a second reviewer (PGS). Disagreements were checked against the full text and resolved by discussion. The outcome of interest was muscle hypertrophy [increases in cross-sectional area (CSA), thickness, or volume] indicated by measures of the QF, its muscles separately (vastus lateralis, rectus femoris, vastus intermedius, vastus medialis), or the mid thigh by US, MRI, or CT. We also included studies that investigated vastus lateralis fiber CSA by biopsy and those that estimated QF hypertrophy [i.e., leg lean mass (LLM) or thigh lean mass (TLM)] by DXA. Studies were scrutinized in a

spreadsheet and clustered according to the outcome measured (QF hypertrophy measures, fiber CSA, and LLM). Data extracted from all trials included those related to publication (first author, year of publication), participant characteristics (groups information, age, and sex of participants), training protocol (duration, intensity, repetitions, frequency, sets, exercises per quadriceps, weekly sets per quadriceps muscle, and adherence), outcome assessment (measure and assessment method), main results, and data related to muscle mass [mean $\pm$ standard deviation (SD)]. If muscle hypertrophy was assessed at multiple time points, only the first and last assessment data were considered. If muscle hypertrophy was assessed by different methods (e.g., biopsy and MRI) or in different areas (e.g., vastus lateralis and rectus femoris), all were extracted. For those studies that reported standard errors (SEs), we converted them to SDs using the equation

$$SD = SE^* (\sqrt{n})$$

When numerical data were not available, the WebPlotDigitizer version 4.5 was used to extract the mean $\pm$ SD shown in the figures. If no figures were available, an attempt was made to contact the authors. If authors were unresponsive, the study was eventually excluded from the quantitative analysis.

2.3. Quality assessment

The risk of bias was assessed using the PEDro scale by two reviewers (DAdS and PGS) (Maher et al., 2003). The scale takes into account the following domains: 1) eligibility criteria specified; 2) random allocation; 3) concealed allocation; 4) groups similar at baseline (muscle mass); 5) subject blinding; 6) instructor blinding; 7) assessor blinding; 8) $\leq 15\%$ dropouts; 9) intention-to-treat analysis; 10) between-group statistical comparisons; and 11) point measures and variability data. The total PEDro score is achieved by adding the ratings of items 2 to 11 for a combined total score ranging from 0 (very low methodological quality) to 10 (high methodological quality).

2.4. Certainty of evidence

Data were synthesized and the certainty of evidence was evaluated using the GRADE approach (<https://gdt.gradepro.org/>). The quality of evidence was graded as (1) high, indicating that further research is unlikely to change the confidence in the estimate of effect, (2) moderate, indicating that further research is likely to have an important impact on confidence in the estimate of effect and may change the estimate, (3) low, indicating that further research is very likely to have an important impact on the confidence in the estimate of effect and is likely to change the estimate, or (4) very low, indicating high uncertainty about the estimate.

2.5. Statistical analysis

Random-effects meta-analyses with adjustments for small samples were performed to assess the effects of RT on muscle hypertrophy for the following outcomes: (a) muscle size; (b) fiber area; and (c) LLM. Standardized mean difference (SMD) was calculated as the pre-test–post-test change difference between the training and control groups divided by the pooled pre-test SD (Morris, 2008). Raw mean difference (RMD) was calculated to verify the training effects on LLM. For analyses of muscle size, we considered measurements of the QF or its muscles when the total QF was not assessed. One study assessed hypertrophy in two different QF muscles (rectus femoris [CSA] and vastus lateralis [thickness]) without measuring the QF as a whole and reported them separately (Vezzoli et al., 2019). We calculated and included in the meta-analysis the summary effect of the two measures as recommended by Borenstein et al. (2009). A sub-analysis was performed on changes in muscle size with the studies that measured total QF, considering

Table 1
Eligibility criteria following the PICOS (population, intervention, comparison, outcomes, and study design) approach.

Category	Inclusion criteria	Exclusion criteria
Population	Individuals (women or men) aged 65 or older	Have recruited acutely ill individuals or diagnosed with neurodegenerative diseases or other chronic diseases which could potentially interfere with the results (e.g. cancer, heart failure, liver diseases, chronic obstructive pulmonary disease)
Intervention	Supervised Lower body resistance training program with a duration superior to 6 weeks using machines, free weights, or bodyweight exercises. Movements should be composed of concentric and eccentric contractions. Experimental interventions labeled "Power Training" were also included	Blood flow restriction resistance training interventions. Resistance training combined with endurance training (i.e., concurrent training). Home-based interventions, elastic band exercises, or vibratory training. Have associated resistance training with hormonal therapy or dieting changes
Comparison	Comparison with a non-exercising control group (Flexibility exercises allowed) of the same age	Have not mentioned clearly weekly frequency of training, intensity progression, exercises performed, or sets number per exercise
Outcomes	Measured morphological changes on quadriceps muscle, via biopsy, ultrasonography, magnetic resonance imaging, computed tomography, or reported leg lean mass estimated by dual-energy X-ray absorptiometry	No pre-test or post-test data. Bioelectrical impedance analysis. Studies that measured whole-body lean body mass or appendicular body mass, instead of leg lean mass
Study design	Randomized controlled trials	Non-randomized controlled trials, observational studies, or reviews.

different activation levels during exercises among the quadriceps muscles and that measuring thigh CSA could under- or overestimate the results. Additional sub-analyses were conducted considering the outcome measured (i.e., CSA, thickness, or volume). When multiple whole-QF measures were available, we chose the best measure (e.g., high-density QF CSA vs. total quadriceps CSA). For fiber area, we recorded data from each fiber type described in a study and computed their summary effects as previously recommended (Borenstein et al., 2009). Also, sub-analyses were conducted considering the muscle fiber type (I, IIa, and II [others than IIa or when the study reported fibers II together]).

All differences in SMD are presented with their 95 % confidence intervals (95 % CIs) and interpreted as “small” (≤ 0.39), “medium” (0.40–0.74), and “large” (> 0.74) as recommended for studies in gerontology (Brydges, 2019). A funnel plot was used to assess the publication bias in the meta-analysis on whole-muscle hypertrophy and all outcomes together (Higgins et al., 2019). Heterogeneity was assessed using the inconsistency test (I^2), with values of ≤ 50 %, 50–75 %, and > 75 % indicating low, moderate, and high levels of heterogeneity, respectively. Studentized residuals and Cook’s distances were used to examine whether studies may be outliers or influential in the context of the model adopted. As a formal check for publication bias, the tests of Egger were implemented. To ensure the robustness of our results, we ran sensitivity analyses excluding two studies that did not report age properly (Hennessey et al., 2001; Reeves et al., 2004). Additional sensitivity analyses were conducted when one study could be an outlier or be overly influential.

To assess the potential confounding effects of study-level moderators on muscle size and fiber area, three covariates were chosen for inclusion in the meta-regression: total sets per muscle group per week (continuous variable), age category (mean age < 75 or ≥ 75), and intervention

duration. These covariates were meta-regressed individually and combined in a random-effects meta-regression model. Two additional meta-regressions on SMDs were performed with the total sets per muscle group per week categorized as lower (< 13) or higher (≥ 13) and the type of assessment tool (MRI, CT, or US) for muscle size (including all measures and whole-QF only). The total of weekly sets performed for the QF was calculated in each study according to the following formula: weekly frequency $\times$ quadriceps-target movements $\times$ sets per movement. Previous meta-analyses adopted a lower number of sets per category (> 5 , 5–9, and > 9 as low, medium, and high, respectively) (Schoenfeld et al., 2017). However, weekly sets were calculated only considering the leg extension exercise. For the present study, we considered other movements as quadriceps-targeting, such as squat, leg press, and lunges. In those studies where the number of sets was changed during the training program, a mean value was considered. All statistical analyses were performed using the Jamovi software, version 2.3.21.0, while the Comprehensive Meta-Analysis (CMA) software, version 3.3.070, was used to run the meta-regression analysis. Group differences were considered statistically significant at $p < 0.05$.

3. Results

3.1. Study selection

The initial search yielded 14,016 records. After removing duplicates, the titles and abstracts of 8337 records were examined. Following screening, 171 full-text papers were assessed for eligibility and 25 articles were eventually included. Secondary searches performed by checking the reference lists of related reviews yielded nine papers, of which seven were included. Finally, we systematically reviewed 32 studies. Of them, three studies were excluded from the meta-analyses due to missing data that we were unable to obtain (Marsh et al., 2009; Reid et al., 2008; Tracy et al., 2004) and one that did not provide further explanation on data (Lovell et al., 2010). For the same reason, we did not include in the quantitative analysis the thigh lean mass (TLM) measured by Taaffe et al. (1996). The search process is depicted in Fig. 1.

3.2. Study characteristics

A summary of the characteristics of the included studies is presented in Table 2. Overall, 913 participants (mean age 75.6 years; 56.5 % women) were assigned to exercise ($n = 486$) or control ($n = 427$) groups. Most studies involved exclusively community-dwelling older adults (81.5 % of the studies) and nine of them specified the condition of the individuals (frail, sarcopenic, or at risk of mobility limitations). Regarding the outcome, 17 studies explored muscle size (CSA [14 studies], thickness [3 studies], or volume from QF or QF muscles [1 study]), eight measured muscle fiber area (9 intervention groups), and eight estimated quadriceps muscle adaptations by measuring LLM. QF size was assessed in 11 studies (11 intervention groups). The training protocols lasted from 8 to 52 weeks, had a frequency of 2–3 days per week, and comprised mainly leg press and/or leg extension exercises for quadriceps, with exception of two interventions. The training intensity ranged from 40 % to 100 % 1-RM (≥ 60 % 1RM, 85 % of the studies) and only one study reported intensity as perceived effort (Borg scale) (Vikberg et al., 2019). Due to the differences in training frequency, number of exercises performed, and sets per exercise, the total weekly sets per quadriceps ranged between 4 and 36.

3.3. Methodological quality

The average score on the PEDro scale was 5.6 (range 0–11 points) (Table 3). None of the studies was classified as being of fair methodological quality and 57 % were considered good or excellent. Scores on all items of the checklist are reported in the supplementary material. The average score of the studies that measured whole-muscle hypertrophy,

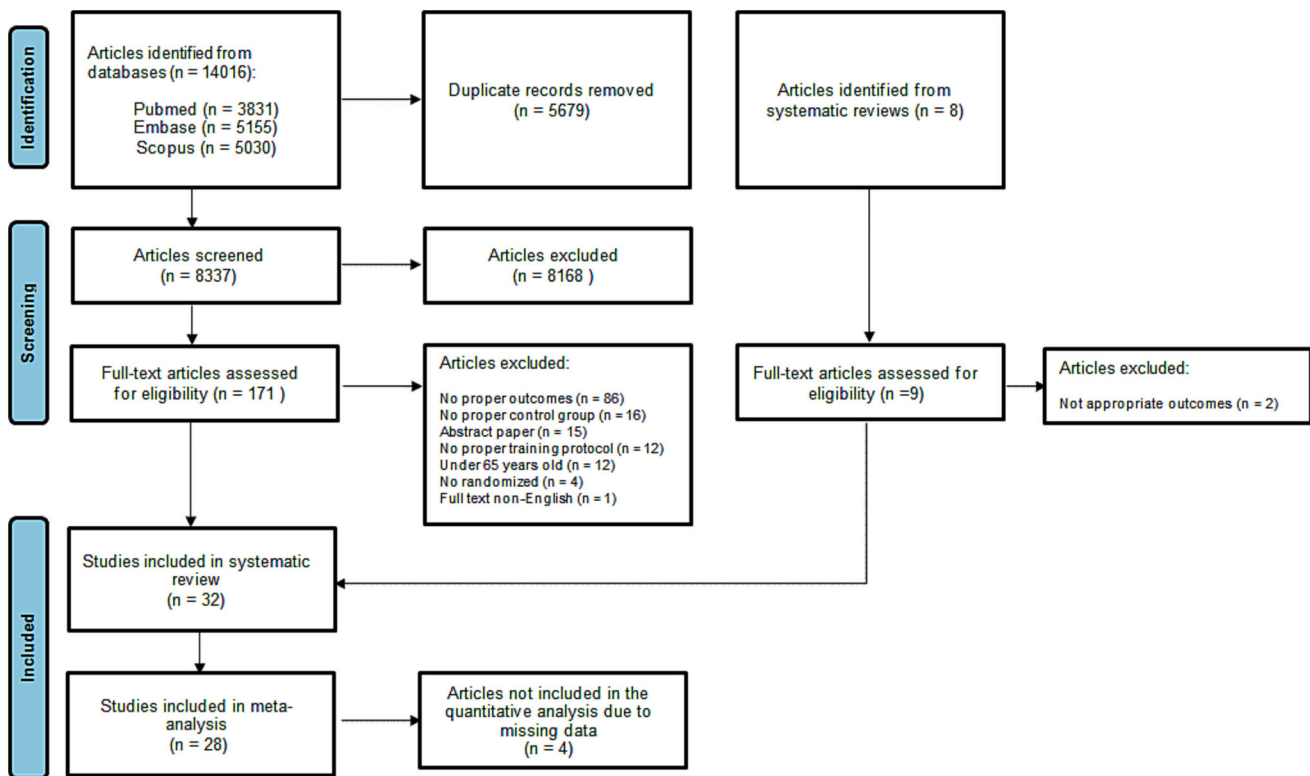


Fig. 1. Selection of studies included in the meta-analysis.

fiber hypertrophy, and LLM was 5.8, 5, and 5.8, respectively. Because blind subjects and trainers were not possible to achieve, the absence of concealed allocation, blind assessors, and intention-to-treat analysis were the main issues found in the studies.

3.4. Meta-analysis results

3.4.1. Muscle size

The meta-analysis found a significant effect of RT on muscle hypertrophy (SMD = 0.34; 95 % CI: 0.16–0.52; $p < 0.001$; $I^2 = 0\%$; $k = 17$) (Fig. 2). Neither the rank correlation nor the regression test indicated any funnel plot asymmetry ($p = 0.50$ and $p = 0.59$, respectively). A sensitivity analysis after excluding the study by Reeves et al. (2004) still found a significant effect of RT consistent with the previous analysis (SMD = 0.34; 95 % CI: 0.16–0.51; $p < 0.001$; $I^2 = 0\%$; $k = 16$). Additional meta-analysis was conducted only on studies that measured QF, excluding measures of its muscles. Yet, a significant effect of RT was found (SMD = 0.44; 95 % CI: 0.20–0.69; $p < 0.001$; $I^2 = 0\%$; $k = 11$), which, however, was moderate in contrast with the small effect of previous analyses (Fig. 2). Finally, meta-analyses according to the measurement type indicated that muscle CSA (SMD = 0.43; 95 % CI: 0.22–0.63; $p < 0.001$; $I^2 = 0\%$; $k = 14$) but not muscle thickness (SMD = 0.04; 95 % CI: −0.36–0.45; $p = 0.835$; $I^2 = 0\%$; $k = 2$) or muscle volume (SMD = −0.02; 95 % CI: −0.83–0.78; $p = 0.96$; $I^2 = 0\%$; $k = 1$) significantly improved in response to RT.

3.4.2. Fiber area

For muscle fiber area, the meta-analysis found a significant moderate effect of RT (SMD = 0.54; 95 % CI: 0.24–0.84; $p < 0.001$; $I^2 = 0\%$; $k = 9$) (Fig. 3). Neither the rank correlation nor the regression test indicated any funnel plot asymmetry ($p = 0.07$ and $p = 0.37$, respectively). There was no indication of outliers in this model. A sensitivity analysis excluding the study conducted by Hennessey et al. (2001) yielded consistent results (SMD = 0.54; 95 % CI: 0.23–0.86; $p < 0.001$; $I^2 = 0\%$; $k = 8$). Meta-analyses according the fiber type found a significant

moderate effect of RT on type I muscle fibers (SMD = 0.55; 95 % CI: 0.17–0.92; $p = 0.004$; $I^2 = 0\%$; $k = 7$) and type II muscle fibers in general (SMD = 0.46; 95 % CI: 0.08–0.83; $p = 0.016$; $I^2 = 0\%$; $k = 7$), but a non-significant effect on type IIa muscle fibers (SMD = 0.32; 95 % CI: −0.32–0.96; $p = 0.33$; $I^2 = 0\%$; $k = 2$).

3.4.3. Leg lean mass

The meta-analysis found a non-significant effect of RT on LLM (RMD = 0.22; 95 % CI: −0.22–0.66; $p = 0.321$; $I^2 = 0\%$; $k = 7$) (Fig. 3). Neither the rank correlation nor the regression test indicated any funnel plot asymmetry ($p = 0.7195$ and $p = 0.7178$, respectively). There was no indication of outliers, but the study conducted by Binder et al. (2005) could be considered to be overly influential. A sensitivity analysis excluding that study found a higher effect, but still non-significant (RMD = 0.30; 95 % CI: −0.26–0.87; $p = 0.293$; $I^2 = 0\%$; $k = 6$).

3.5. Meta-regression results

Weekly sets per quadriceps or age did not explain any of the variance in changes in muscle size (weekly sets per quadriceps, $p = 0.197$; age, $p = 0.461$) or fiber area (weekly sets per quadriceps, $p = 0.525$; age, $p = 0.683$). Likewise, no significant effect was found when studies were categorized in low and high weekly sets for muscle size and fiber area ($p = 0.347$ and $p = 0.714$, respectively) or by assessment tool for muscle size ($p = 0.239$). However, there was a significant influence of the assessment tool on QF size ($p = 0.049$) and a trend for an effect of weekly sets per quadriceps on muscle CSA ($p = 0.078$). Regarding the full-model regression, no significant effects were observed (muscle size, $p = 0.350$; fiber area, $p = 0.376$). Regarding intervention duration, no significant effect was found on fiber area ($p = 0.142$). However, we found a significant effect on type II fiber area ($p = 0.034$) and a tendency to significance on muscle size ($p = 0.083$).

Table 2
Summary of studies included in the review.

Study	Groups (no. and age, years)	Females (n)	Intervention duration and frequency / adherence	RT protocol	Resistance exercise (s) and weekly sets for quadriceps	Outcomes (assessment method)	Main findings
Aas et al. (2020)	RT: $n = 12$; 86.6 $\pm$ 6.9 CG: $n = 13$; 84.5 $\pm$ 7.2	16	10 weeks; 2 days per week. Minimum of 80 %	WBT 2–4 sets per exercise performed for 6–12RM	Leg press and knee extension; 8–16	QF CSA (CT) VL fiber CSA (biopsy) LLM (DXA)	$\leftrightarrow$ VL fiber CSA $\leftrightarrow$ LLM $\uparrow$ QF CSA
Ades et al. (1996)	RT: $n = 12$; 69.9 $\pm$ 4.0 CG: $n = 12$; 70.7 $\pm$ 5.0	13	12 weeks; 3 days per week. Not reported	WBT comprising 3 sets per exercise performed for 8 repetitions with 80 % 1RM	Squat and knee extension; 18	LLM (DXA)	$\uparrow$
Bechshøft et al. (2017)	RT: $n = 12$; 87.7 $\pm$ 3.7	10	12 weeks; 3 days per week.	WBT comprising 2–5 sets per exercise performed for 6–12 repetitions with 70–85 % 1RM	Leg press and knee extension; 12–30	QF CSA (MRI) VL fiber CSA (biopsy)	$\uparrow$ QF CSA $\leftrightarrow$ VL fiber CSA
Karlsen et al. (2019)	CG: $n = 13$ –14 ^a ; 86.2 $\pm$ 2.6		Average adherence of 90 %			LLM (DXA)	$\leftrightarrow$ LLM
Benavent-Caballer et al. (2014)	RT: $n = 22$; 85.5 $\pm$ 4.7 CG: $n = 23$; 83.6 $\pm$ 5.6	30	16 weeks; 3 days per week. 78 % of participants completed all sessions	LBT comprising 3 sets per exercise performed for 15 repetitions with 40 % 1RM	Knee extension; 9	RF CSA (US)	$\uparrow$
Binder et al. (2005)	RT: $n = 53$; 83 $\pm$ 3 CG: $n = 38$; 84 $\pm$ 4	49	12 weeks; 3 days per week. Minimum of 70 %	WBT comprising 1–3 sets per exercise performed for 6–12 repetitions with 65–100 % 1RM	Leg press and knee extension; 6–18	LLM (DXA)	$\uparrow$
Cadore et al. (2014)	RT: $n = 11$; 93.4 $\pm$ 3.2 CG: $n = 13$; 90.1 $\pm$ 1.1	17	12 weeks; 2 days per week. Average adherence of >90 %	WBT comprising 2–3 sets per exercise performed for 8 repetitions with 40–60 % 1RM	Leg press and knee extension; 6–18	QF CSA (CT)	$\uparrow$
Cook et al. (2017); Cook and Cleary (2019)	RT: $n = 11$; 76.7 (71.3–82.0) CG: $n = 12$; 74.8 (69.6–79.9)	13	12 weeks; 2 days per week 100 %	LBT comprising 3 sets per exercise performed for 15 repetitions with 70 % 1RM	Leg press and knee extension; 12	QF CSA (MRI)	$\uparrow$
da Silva et al. (2022)	RT: $n = 12$; 71 $\pm$ 5.3 CG: $n = 11$; 72 $\pm$ 5	10	12 weeks; 2 days per week. 9 participants attended >80 % of the sessions and 2 participants 62 %	WBT comprising 3–4 sets per exercise performed for 8–14RM	Leg press and knee extension; 12–16	QF thickness (US)	$\leftrightarrow$
Eriksen et al. (2018)	RT: $n = 9$; 69 $\pm$ 2.2 CG: $n = 10$; 68 $\pm$ 1.5	9	12 weeks; 3 days per week. Average adherence of 71 %	WBT comprising 2–5 sets per exercise performed for 6–12 repetitions with 70–85 % 1RM	Leg press and knee extension; 12–30	QF CSA (MRI)	$\leftrightarrow$
Fiatarone et al. (1994)	RT: $n = 25^a$; 86.2 $\pm$ 5	30	10 weeks; 3 days per week.	LBT comprising 3 sets per exercise performed for 8 repetitions with 80 % 1RM	Leg press and knee extension; 18	Mid-thigh CSA (CT)	$\leftrightarrow$
Fiatarone Singh et al. (1999)	CG: $n = 26^a$; 89.2 $\pm$ 4		Average adherence of 97 %			VL fiber CSA (biopsy)	$\leftrightarrow$
Flor-Rufino et al. (2023)	RT: $n = 11$; 79.9 $\pm$ 9.2 CG: $n = 11$; 79.6 $\pm$ 7.7	22	6 months; 2 days per week. 75 % of participants attended >65 % of the sessions	WBT comprising 3 sets per exercise performed for 10–15 repetitions with 70 % 1RM	Leg press and knee extension; 12	QF volume (MRI)	$\leftrightarrow$
Frank et al. (2016)	RT: $n = 12$; 71.4 $\pm$ 3.6 CG: $n = 9$; 72 $\pm$ 4.2	11	8 weeks; 3 days per week. Not reported	WBT comprising 3 sets per exercise performed for 12 repetitions with 75–80 % 1RM	Leg press and knee extension; 18	VL fiber CSA (biopsy)	$\leftrightarrow$
Frontera et al. (2003)	RT: $n = 7$; 73.7 $\pm$ 3.4 CG: $n = 7$; 74.3 $\pm$ 3.8	14	12 weeks; 3 days per week. Average adherence of 98 %	LBT comprising 4 sets per exercise performed for 8 repetitions with 65–80 % 1RM	Knee extension; 12	QF CSA (CT) VL fiber CSA (biopsy)	$\uparrow$ QF CSA $\leftrightarrow$ VL fiber CSA
Hennessey et al. (2001)	RT: $n = 8$; 73.8 $\pm$ 5.1 CG: $n = 8$; 68.8 $\pm$ 2.5	6	25 weeks; 3 days per week Not reported	WBT comprising 3 sets per exercise performed for 8 repetitions with 20–90 % 1RM	Knee extension; 9	VL fiber CSA (biopsy)	$\leftrightarrow$
Hvid et al., 2016)	RT: $n = 16$; 82.3 $\pm$ 1.3 CG: $n = 21$; 81.6 $\pm$ 1.1	14	12 weeks; 2 days per week. Minimum of 80 %	WBT comprising 3 sets per exercise performed for 8–10 repetitions with 70–80 % 1RM	Leg press; 6	VI and RF thickness (US)	$\leftrightarrow$
Lovell et al. (2010)	RT: $n = 12$; 75.2 $\pm$ 0.8 CG: $n = 12$; 73.7 $\pm$ 1	0	16 weeks; 3 days per week Average adherence of >98 %	LBT comprising 3 sets per exercise performed for 8 repetitions with 75–90 % 1RM	Incline squat machine; 9	TLM (DXA)	$\uparrow$
Marsh et al. (2009)	RT: $n = 4$; NR* PT: $n = 5$; NR* CG: $n = 5$; NR*	NR	12 weeks; 3 days per week. Average adherence of 90 and 79 % in RT and PT groups, respectively	WBT comprising 3 sets per exercise performed for 8–10 repetitions with 70 % 1RM	Leg press and knee extension; 18	Mid-thigh CSA (CT)	$\leftrightarrow$ in both training groups

(continued on next page)

Table 2 (continued)

Study	Groups (no. and age, years)	Females (n)	Intervention duration and frequency / adherence	RT protocol	Resistance exercise (s) and weekly sets for quadriceps	Outcomes (assessment method)	Main findings
McCartney et al. (1995)	RT (females): $n = 20$; 71 ± 1.8 CG (females): $n = 23$; 73 ± 3.5 RT (males): $n = 17$; 73 ± 3.1 CG (males): $n = 8$; 72 ± 2.8	43	42 weeks; 2 days per week. Average adherence of 88 %	WBT comprising 2–3 sets per exercise performed for 12 repetitions with 50–80 % 1RM	Unilateral leg press; 4–6	QF CSA (CT)	↑*
Reeves et al. (2004)	RT: $n = 9$; 74.3 ± 3.5 CG: $n = 9$; 67.1 ± 2.1	10	14 weeks; 3 days per week. Not reported	WBT comprising 2 sets per exercise performed for ~10 repetitions with ~70 % 1RM	Leg press and knee extension; 12	VL CSA and volume (US)	↔ for both measures
Reid et al. (2008)	RT: $n = 22$; 73.1 ± 6 PT: $n = 23$; 72.3 ± 6 CG: $n = 19$; 79.7 ± 9	19	12 weeks; 3 days per week. Average adherence of 82 and 77 % in RT and PT groups, respectively	LBT comprising 3 sets per exercise performed for 8 repetitions with 70 % 1RM	Leg press and knee extension; 18	LLM (DXA)	↔ in both training groups
Sipilä and Suominen (1995); Sipilä et al. (1997)	RT: $n = 12^b$; 76 – 78 CG: $n = 11^b$; 76 – 78	23	18 weeks; 3 days per week. Average adherence of 78 %	LBT comprising 3–4 sets per exercise performed for 8–10 repetitions with 60–75 % 1RM	Leg press and knee extension; 18–24	QF CSA (CT) VL fiber CSA (biopsy)	↑ QF CSA ↔ VL fiber CSA
Strandberg et al. (2015)	RT: $n = 21$; 68 ± 2 CG: $n = 21$; 68 ± 1	42	24 weeks; 2 days per week. Average adherence of 87 %	WBT comprising 3 sets per exercise performed for 8–12 repetitions with 75–85 % 1RM	Squat, leg press, and knee extension; 18	LLM (DXA)	↔
Taaffe et al. (1996)	LI RT: $n = 7^c$; 67 ± 0.5 HI RT: $n = 7^c$; 67.6 ± 1.3 CG: $n = 7$; 69.6 ± 3.4	14	52 weeks; 3 days per week. Average adherence of 79 %	HI: LBT comprising 3 sets per exercise performed for 7 repetitions with 80 % 1RM LI: LBT 3 sets per exercise performed for 14 repetitions with 40 % 1RM	Leg press and knee extension; 18	VL fiber CSA (biopsy) TLM (DXA)	↔ TLM (DXA) ↑ VL fiber CSA
Timmons et al. (2018)	RT: $n = 21$; 69.6 ± 4.9 CG: $n = 21$; 69 ± 3.3	24	12 weeks; 3 days per week. Average adherence of 86 %	WBT comprising 4 sets per exercise performed for 15 repetitions with 60 % 1RM	Leg press and Knee extension; 24	LLM (DXA)	↔
Tracy et al. (2004)	RT: $n = 11$; 73.1 ± 4.9 CG: $n = 9$; 74.2 ± 4.9	11	16 weeks; 3 days per week. Not reported	LBT comprising 3 sets per exercise performed for 15 repetitions with 80 % 1RM	Knee extension	QF volume (MRI)	↑
Vezzoli et al. (2019)	RT: $n = 20$; 73 ± 5.5 CG: $n = 15$; 71.7 ± 3.4	19	12 weeks; 3 days per week. Not reported	WLT comprising 3 sets per exercise performed for 14–16 repetitions with 60 % 1RM	Leg press; 9	VL thickness and RF CSA (US)	↑ for both measures
Vikberg et al. (2019)	RT: $n = 36$; 70.9 ± 0.28 CG: $n = 34$; 70 ± 0.29	38	10 weeks; 3 days per week. Average adherence of 91 %	WBT comprising 3–4 sets per exercise performed for 10 repetitions with perceived exertion of 6–7 on the Borg CR-10 scale	Squats, chair stands, half lunges; 27–36	LLM (DXA)	↑
Yoon et al. (2017)	RT: $n = 6$; 72.68 ± 2.73 CG: $n = 7$; 70.43 ± 3.1	13	12 weeks; 3 days per week. Minimum of 90 %	LBT comprising 3 sets per exercise performed for 15–18 repetitions with 60 % 1RM	Leg extension; 9	QF CSA (CT)	↔

↔ = non-significant changes compared to control group ($p \geq 0.05$); ↑ = significant increase compared to control group ($p < 0.05$); CG = control group; CSA = cross-sectional area; CT = computerized tomography; DXA = dual-energy X-ray absorptiometry; HI = high-intensity training; LI = low-intensity training; LBT = lower body training; LLM = leg lean mass; MRI = magnetic resonance imaging; PT = power training; QF = quadriceps femoris; RF = rectus femoris; RM = repetitions maximum; RT = resistance training; TLM = thigh lean mass; US = ultrasonography; WBT = whole-body training; VI = vastus intermedius; VL = vastus lateralis.

Weekly sets are calculated as frequency training $\times$ exercises per quadriceps $\times$ sets per exercise.

Whole-body training was defined as a routine comprising at least one exercise for the lower body and one for the upper body.

*When data are collapsed across age and sex $\times$ time interactions (this study involved two groups composed of individuals aged 60–70 years and two groups of individuals aged 70–80 years).

^a14 participants in one study and 13 in another.

^bMuscle biopsies were obtained from a subsample of seven participants from each group.

^cMuscle biopsies were obtained from a subsample of 5 participants from each group.

Age is reported as mean $\pm$ standard deviation or mean (confidence interval).

3.6. Certainty of evidence

The GRADE approach suggested a high quality of evidence (GRADE score = 4) for all outcomes. We did not remove any point of quality of original studies (none of the studies were classified as being of fair

methodological quality and most was considered as being of good or excellent) or for indirect evidence (all studies tested the effects of the intervention and included a control group for comparisons). There was no publishing bias (Egger test p -value >0.05), no imprecision (total sample size of 446, 257, 149, and 344 to whole muscle [including QF,

Table 3
Quality assessment (PEDro Scale).

Study	EC	RA	CA	BC	BS	BT	BA	AF	IT	BG	PE	Final score*
Aas et al. (2020)	+	+	–	+	–	–	+	–	–	+	+	5
Ades et al. (1996)	+	+	–	+	–	–	–	–	–	+	+	4
Bechshøft et al. (2017); Eriksen et al. (2018); Karlsen et al. (2019)	+	+	+	+	–	–	+	+	–	+	+	7
Benavent-Caballer et al. (2014)	+	+	+	+	–	–	+	+	+	+	+	8
Binder et al. (2005)	+	+	+	+	–	–	+	–	–	+	+	6
Cadore et al. (2014)	+	+	+	+	–	–	+	+	–	+	+	7
Cook et al. (2017); Cook and Cleary (2019)	+	+	–	+	–	–	+	+	–	+	+	6
da Silva et al. (2022)	+	+	+	+	–	–	+	+	+	+	+	8
Fiatarone et al. (1994); Fiatarone Singh et al. (1999)	+	+	+	+	–	–	+	–	+	+	+	7
Flor-Rufino et al. (2023)	+	+	+	+	–	+	–	–	–	+	+	6
Frank et al. (2016)	+	+	–	+	–	–	–	+	–	+	+	5
Frontera et al. (2003)	+	+	–	+	–	–	+	–	–	+	+	5
Hennessey et al. (2001)	+	+	–	+	–	–	–	–	–	+	+	4
Hvid et al., 2016)	+	+	+	+	–	–	+	–	–	+	+	6
Lovell et al. (2010)	+	+	–	+	–	–	–	+	+	+	+	6
Marsh et al. (2009)	+	+	+	–	–	–	–	–	+	+	+	5
McCartney et al. (1995)	+	+	–	+	–	–	–	–	–	+	+	4
Reeves et al. (2004)	+	+	–	+	–	–	–	+	–	+	+	5
Reid et al. (2008)	+	+	+	+	–	–	–	+	–	+	+	6
Sipila and Suominen (1995); Sipilä et al. (1997)	–	+	–	+	–	–	–	+	–	+	+	5
Strandberg et al. (2015)	+	+	+	+	–	–	–	–	–	+	+	5
Taaffe et al. (1996)	+	+	–	+	–	–	–	–	–	+	+	4
Timmons et al. (2018)	+	+	+	+	–	–	+	+	+	+	+	8
Tracy et al. (2004)	+	+	–	–	–	–	+	–	–	+	+	5
Vezzoli et al. (2019)	+	+	–	+	–	–	–	+	+	+	+	6
Vikberg et al. (2019)	+	+	+	+	–	–	+	+	–	+	+	7
Yoon et al. (2017)	+	+	–	+	–	–	–	–	–	+	+	4

EC = eligibility criteria; RA = random allocation; CA = concealed allocation; BC = baseline comparability; BS = blind subjects; BT = blind therapists; BA = blind assessor; AF = adequate follow-up; IT = intention-to treat analysis; BG = between-group comparisons; PE = point estimates and variability.

* Sum of items 2 to 11.

isolated QF muscles, and thigh measurements], only QF, fiber, and LLM analyses, respectively), or inconsistency ($I^2 = 0\%$).

4. Discussion

4.1. Main findings

The main finding of this systematic review and meta-analysis was that RT significantly increases quadriceps muscle hypertrophy in those 65 years or older, but the magnitude of the response seems to be dependent on the measurement tool. We observed a medium and significant SMD for QF hypertrophy at muscle and fiber levels, a small but significant SMD for assessing muscle hypertrophy when included in the analysis of QF muscles and whole thigh measurements, and a small non-significant RMD for lower extremity lean mass. To the best of our knowledge, this is the first meta-analysis to specifically examine the effects of RT on QF adaptations in individuals 65 years or older.

4.2. Muscle hypertrophy

Several systematic reviews and meta-analyses attempted to provide a comprehensive view of potential effects of RT on muscle hypertrophy in older adults. However, non-negligible methodological issues, including the use of lean mass instead of direct measures of muscle size, prevent from drawing solid conclusions on the matter.

A first meta-analysis of RCTs and non-RCTs conducted by Peterson et al. (2011) concluded that RT increases lean mass in adults 50 years or older. These findings were confirmed by Borde et al. (2015) who observed that RT increases muscle mass in healthy individuals aged 60 years or more based on results from eight RCTs. Findings from these two initial reviews were relevant to confirm that the skeletal muscle of older individuals can adequately respond to stimuli. However, the two meta-analyses have important limitations. While both included studies evaluating whole-body lean mass, Borde et al. (2015) also analyzed together results from different muscles (e.g., biceps brachialis, plantar flexor) and

excluded studies with frail individuals. Subsequent reviews on the effects of RT in older adults did not find a significant effect on muscle mass (Bao et al., 2020; Escriche-Escuder et al., 2021; González-Rocha et al., 2022; Lai et al., 2018). It should be noted that all those studies analyzed heterogeneous outcomes related to muscle and lean mass.

The present study found that RT induces muscle hypertrophy in adults 65 years and older when muscle mass is assessed by direct measures. The effect is even more evident for total QF CSA than single-muscle or thigh CSA measures. Our results are consistent with those by Grgic et al. (2020) who also reviewed only studies assessing muscle mass estimated by direct measures, although they analyzed together other muscles besides QF (i.e., knee flexors, adductors, plantar flexors). As indicated by the meta-regression analysis, the magnitude of the response may be influenced by the assessment tool used, suggesting a greater effect size in studies measuring QF by CT. Indeed, CT has been proposed as a reference standard to assess muscle mass in aging and sarcopenia (Albano et al., 2020).

One may conclude that muscle hypertrophy adaptations in response to RT can be more accurately captured when CSA changes are assessed instead of muscle thickness or volume. Despite our results, such a claim is premature since few studies included in our analyses assessed muscle thickness ($k = 3$) or volume ($k = 1$). One of the studies included in the systematic review but not in the meta-analysis found a positive effect of RT on muscle volume (Tracy et al., 2004). In this context, it was observed that muscle thickness correlated with muscle CSA at a single point, and its changes were associated with CSA changes over time (Franchi et al., 2018). Regarding muscle volume, muscle CSAs at multiple slice levels are required to correctly estimate volume since muscle hypertrophy within muscle heads is not homogeneous, differing from distal and medial regions (Tanaka and Kanehisa, 2014; Zabaleta-Korta et al., 2020).

4.3. Muscle fiber hypertrophy

A meta-analysis of the post-pre baseline differences concluded that

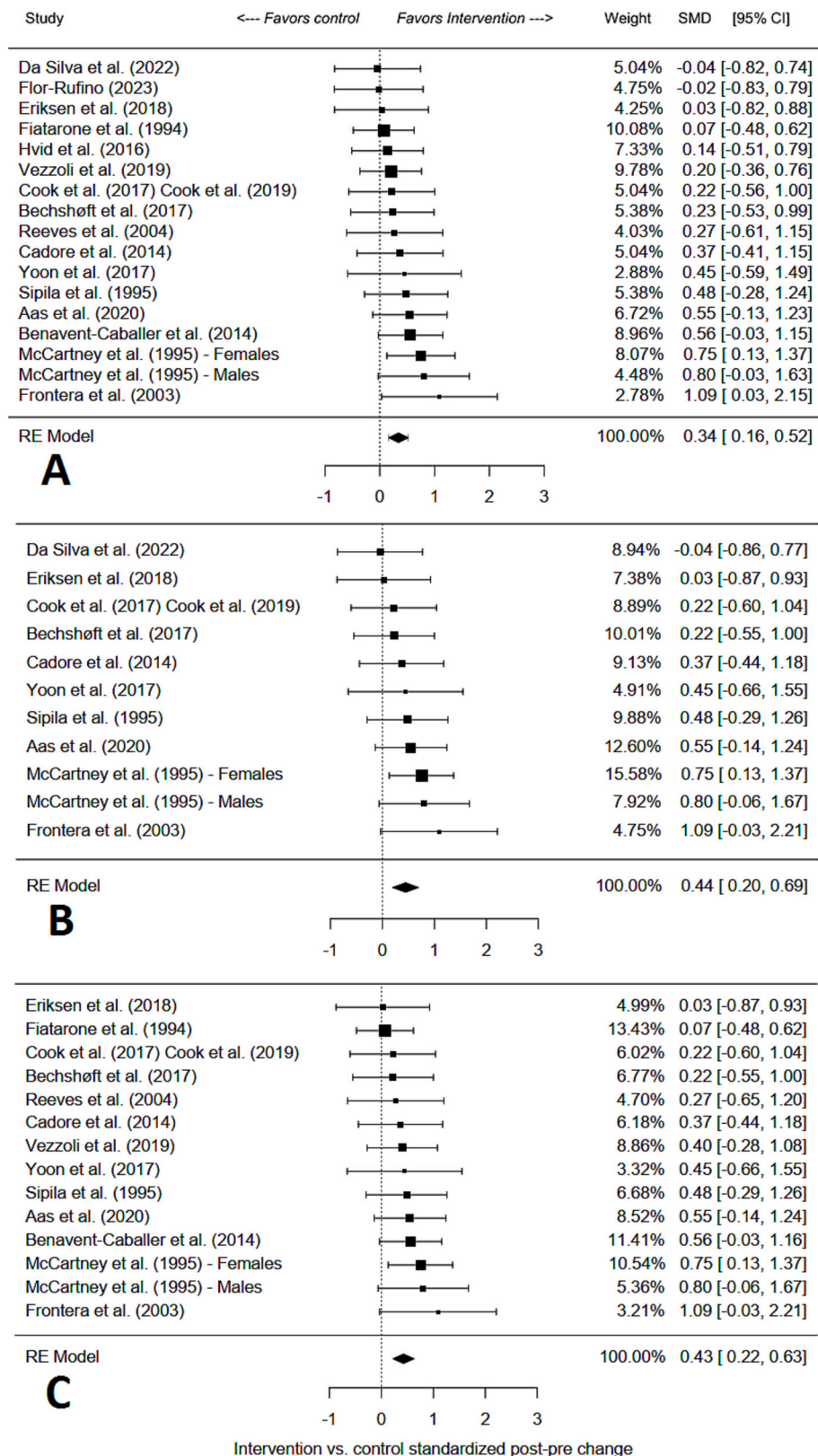


Fig. 2. Meta-analysis of the effects of resistance training on muscle size in older adults, including quadriceps muscles and thigh measures (A), only quadriceps femoris size (B), and muscle cross-sectional area (C). The x-axis shows standardized mean differences (SMDs). Whiskers denote 95 % confidence intervals (CIs).

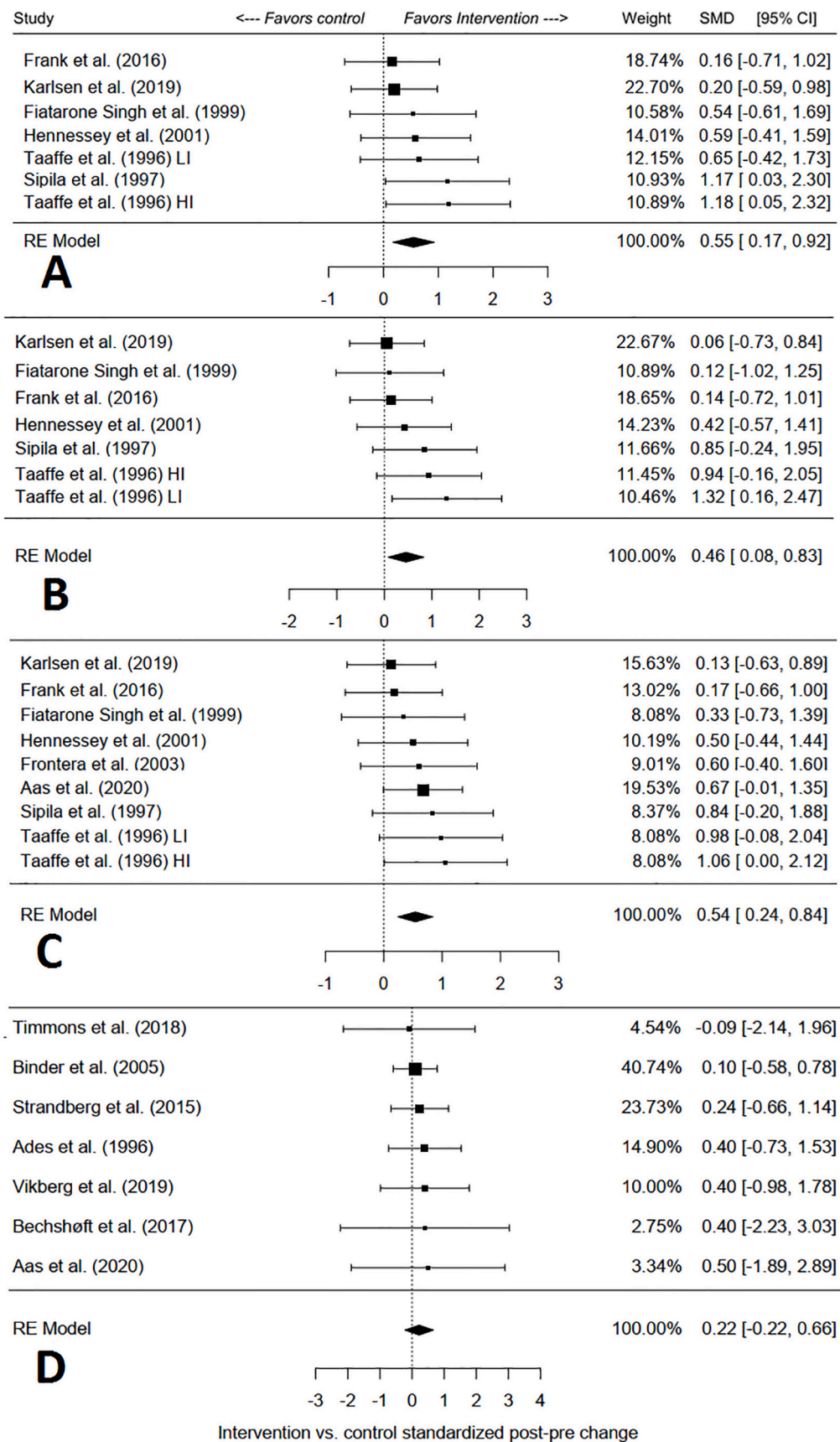


Fig. 3. Meta-analysis of the effects of resistance training on type I muscle fiber size (A), type II muscle fiber size (B), all muscle fibers combined (C), and leg lean mass changes (D) in older adults. The x-axis shows standardized mean differences (SMDs) in A, B, and C, and raw mean differences (RMDs) in D. Whiskers denote 95 % confidence intervals (CIs). HI = high-intensity; LI = low-intensity.

RT induces muscle fiber hypertrophy independent of fiber type, although the hypertrophic response may be reduced with advancing age (Straight et al., 2020). This finding is corroborated by the non-significant effect of RT on fiber hypertrophy ($ES = 0.33$) in individuals aged 75 and over obtained by Grgic et al. (2020). Our results indicate that muscle hypertrophy at the fiber level can be an accurate marker of the effects of RT on morphological parameters and that both types I and II muscle fibers are responsive to RT. The fact that type IIa muscle fibers did not show significant hypertrophy in response to RT in this meta-analysis may be due to the few studies analyzed ($k = 2$).

4.4. Leg lean mass

To the best of our knowledge, this was the first review to analyze exclusively LLM. As expected, we found a small effect on LLM compared with other outcomes. We acknowledge that the effect may have been smaller considering that three of the seven meta-analyzed studies (Binder et al., 2005 [RMD = 0.10]; Bechshøft et al., 2017 [RMD = 0.40]; Ades et al., 1996 [RMD = 0.40]) included knee flexor exercise in the training protocol, which may have promoted hamstring hypertrophy and increased ES. Also, since estimates of muscle mass gains from LLM are influenced by adaptations of other lean tissues, notably bone mass, and significant bone adaptations generally occur with long-term training protocols (>1 year) (Gómez-Cabello et al., 2012), shorter-duration training protocols may underestimate muscle mass results and provide a smaller ES. The evaluation of lower extremity lean mass to infer muscle mass gains can be preferred over whole-body measures, but it may not be enough sensitive to detect small changes. It is worth noting that whole-body lean mass assessment may still be relevant, since most RT programs target multiple muscles and improvements in body composition is a major goal in some clinical contexts (e.g., management of sarcopenic obesity).

One might suppose that the lack of significant lean mass gains may be due to differences in training programs (i.e., lower training volume). However, it is interesting to note that the mean duration of experimental protocols (18.8 weeks) and the mean training volume (quantified by the number of weekly sets) (18.5 sets) of the studies that evaluated lean mass were greater than those of the studies that evaluated QF size (14.8 weeks and 14 sets) or fiber area (17.4 weeks; 16.9 sets). These observations align with the results of the meta-regression on the advantage of adopting a lower number of weekly sets per muscle group.

Furthermore, TLM may better estimate muscle mass gains compared to LLM. In this review, eight studies assessed LLM, while two assessed TLM. Both studies assessing TLM were excluded from the quantitative analysis due to missing data and presented controversy results (Lovell et al., 2010; Taaffe et al., 1996). Thus, whether TLM is more accurate than LLM to detect these changes has yet to be established.

4.5. Potential factors interfering in hypertrophic response

We analyzed the influence of age, training volume quantified by weekly sets per QF, and training duration on muscle hypertrophy response to RT. Training variables commonly thought to play a role in muscle mass responses to RT include training intensity, volume, and frequency. We did not analyze training intensity because most studies adopted intensities starting from 60 % 1RM (except three intervention groups) and current evidence suggests that muscle hypertrophy can be achieved from diverse intensities when higher and lower loads are “work-matched” (Csapo and Alegre, 2016). We considered training volume quantified by weekly sets to encompass frequency and volume, as frequency may not be relevant when sets performed by groups are equalized in older adults (Kneffel et al., 2021; Pina et al., 2020).

The main finding of our meta-regression was that longer training protocols evoked greater type 2 muscle fiber hypertrophy. This result is consistent with Borde et al. (2015) but not with Peterson et al. (2011). Because most study protocols have durations ranging from 12 to 16

weeks, the potential effect of RT may be overlooked. Moreover, as evidence related to fiber hypertrophy in very old individuals is contradictory (Grgic et al., 2020; Karlsen et al., 2019; Kryger and Andersen, 2007), it is reasonable to speculate that significant fiber hypertrophy can be achieved in the oldest-old engaged in longer interventions (Fiatarone Singh et al., 1999; Frank et al., 2016; Karlsen et al., 2019).

Finally, we did not find any influence of weekly sets on the outcomes, although a trend toward greater SMDs for fewer weekly sets (<13) on muscle hypertrophy was observed. In practical terms, this implies that there would not be an advantage to perform more than two sets per exercise if the training program includes leg extension and leg press and is performed three times a week, at least during the first months of training. This view is in line with previous studies supporting low training volumes (Marques et al., 2023). On this topic, caution should be made when quantifying training volume by the number of sets per muscle group, considering that the degree of activation of the quadriceps muscles varies according to the exercises performed (e.g., single vs. multi-joint) (Schoenfeld et al., 2019). In the present review, each set of exercises involving knee extension was considered as one set for quadriceps because (1) the most adopted exercises were leg press and knee extension, and all of these have a significant activation of at least one of the QF muscles, especially vastus lateralis, the main QF muscle assessed here (Ema et al., 2016); and (2) only one study that evaluated the rectus femoris adopted multi-joint exercises (leg press; Vezzoli et al., 2019). It is known that the rectus femoris shows lower activation in multi-joint exercises (Ema et al., 2016).

4.6. Assessing muscle mass: Are we missing something?

Findings from previous meta-analyses may not provide solid evidence due to methodological issues, especially regarding the outcomes analyzed. For example, a recent meta-analysis concluded that RT is ineffective ($ES = 0.09$) in improving muscle hypertrophy in older adults with cancer (Lee, 2022). Nevertheless, from all studies reviewed, only one directly assessed muscle hypertrophy (muscle fiber CSA) and showed the greater ES (0.49).

Two reviewed studies (Aas et al., 2020; Bechshøft et al., 2017) assessed muscle hypertrophy from direct measurements and through muscle mass estimated by lean mass. Both studies indicated significant changes in muscle size of older individuals (QF CSA) but not in muscle mass, corroborating the findings of the meta-analysis and suggesting that the differences in hypertrophy results may be related to the accuracy of the measurement or specific muscle adaptations. Despite this, analyzing those SMDs for lean mass individually, it is noted that the values are comparable to those for muscle size.

In this context, it is reasonable to assume that the lack of significant results regarding muscle mass is due, at least partly, to the limited accuracy of DXA compared to other direct methods since it cannot discriminate muscle groups or detect intramuscular fat (Haun et al., 2019). However, estimating muscle mass through DXA remains valid, especially because it is a noninvasive and low-cost technique compared to other measurement techniques. Furthermore, it can be speculated that using DXA to assess increases in muscle mass may be more relevant in whole lower-limb training programs (i.e., exercises for QF, hamstrings, and adductors). Tavoian et al. (2019) questioned the use of DXA in clinical trials to assess changes in muscle mass over time as they found little agreement between DXA and MRI after 10 weeks of training. However, despite assessing thigh measurements, the training consisted of only one quadriceps exercise. It is worth noting that most of the meta-analyzed studies in this review that assessed LLM ($k = 4$) did not train any thigh muscle other than the quadriceps. Future studies are needed to establish the ability of DXA to assess changes in whole lower-limb muscle mass compared to other measurement techniques.

4.7. Study limitations

The present review provides an overview of the effects of traditional supervised RT on muscle hypertrophy with a high certainty of evidence. However, limitations to the present review should be acknowledged. First, because only three databases were searched, potentially relevant publications might have not been identified. To reduce the risk of missing relevant articles and, therefore, biasing the results, we searched relevant databases and manually searched reference lists from previous studies. Second, the minimum age limit adopted in this review may raise concerns about the generalizability of results. Of note, we did not include two studies with a minimum age of 64 that found a positive effect of RT on fiber hypertrophy (Charette et al., 1991) and no significant effect on whole-muscle hypertrophy (Turpela et al., 2017). Setting an age limit is not a simple task, and we acknowledge that studies with a lower minimum age could provide a larger sample size. Since we included only studies testing traditional supervised RT, the extrapolation of findings to other RT modalities, such as elastic and home-based, should be made with caution. Although we recognize that such training modalities are relevant, especially to frail and sarcopenic individuals, the exclusion of those protocols decreased the heterogeneity of studies, thereby increasing the strength of the evidence. Also, the hypertrophic response may vary among the muscles comprising the QF (Häkkinen et al., 2001). It might be argued that vastus lateralis fiber hypertrophy may not reflect QF hypertrophy. Additionally, measuring thigh CSA may under- or overestimate QF adaptations. Our subanalysis excluding QF muscles and thigh measurements eliminated this bias. Finally, differences in dietary patterns between individuals were not taken into account. Future investigations in this field should account for the possible effects of habitual protein and energy intake (Houston et al., 2008). Considering that older individuals may have anabolic resistance (Aragon et al., 2023), investigations focusing on strength training and not involving nutritional interventions should be encouraged to report participant dietary habits. This will provide additional data to understand the results observed.

5. Conclusions

The results of this review support the notion that muscle hypertrophy occurs in individuals aged 65 or older participating in supervised traditional RT programs and that the ability to capture the response may depend on the assessment tool. We also found that age does not substantially influence this response and that individuals engaged in RT programs can be more responsive as they remain committed to such programs for longer time, especially regarding fiber muscle hypertrophy. Although training volume does not influence the response, our results indicate that higher (>12) weekly sets per QF may not be necessary in this population.

Ethical approval

Ethical approval and informed consent were not required because all data used in this study were obtained from previously published articles.

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Register

This study was prospectively registered in the International Prospective Register of Systematic Reviews (PROSPERO) under the ID: CRD42023427479.

CRedit authorship contribution statement

Davi Alves de Santana: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Pedro Godoi Scolfaro:** Writing – review & editing, Methodology, Investigation. **Emanuele Marzetti:** Writing – review & editing, Supervision, Formal analysis. **Cláudia Regina Cavaglieri:** Writing – review & editing, Supervision, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.exger.2024.112639>.

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