Sports Medicine (2020) 50:1983–1999
https://doi.org/10.1007/s40279-020-01331-7

SYSTEMATIC REVIEW

Effects of Resistance Training on Muscle Size and Strength in Very Elderly Adults: A Systematic Review and Meta-Analysis of Randomized Controlled Trials

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Published online: 1 August 2020

Abstract

Background Effects of resistance training on muscle strength and hypertrophy are well established in adults and younger elderly. However, less is currently known about these effects in the very elderly (i.e., 75 years of age and older).

Objective To examine the effects of resistance training on muscle size and strength in very elderly individuals.

Methods Randomized controlled studies that explored the effects of resistance training in very elderly on muscle strength, handgrip strength, whole-muscle hypertrophy, and/or muscle fiber hypertrophy were included in the review. Meta-analyses of effect sizes (ESs) were used to analyze the data.

Results Twenty-two studies were included in the review. The meta-analysis found a significant effect of resistance training on muscle strength in the very elderly [difference in ES = 0.97; 95% confidence interval (CI) 0.50, 1.44; $p = 0.001$]. In a subgroup analysis that included only the oldest-old participants (80 + years of age), there was a significant effect of resistance training on muscle strength (difference in ES = 1.28; 95% CI 0.28, 2.29; $p = 0.020$). For handgrip strength, we found no significant difference between resistance training and control groups (difference in ES = 0.26; 95% CI − 0.02, 0.54; $p = 0.064$). For whole-muscle hypertrophy, there was a significant effect of resistance training in the very elderly (difference in ES = 0 30; 95% CI 0.10, 0.50; $p = 0.013$). We found no significant difference in muscle fiber hypertrophy between resistance training and control groups (difference in ES = 0.33; 95% CI − 0.67, 1.33; $p = 0.266$). There were minimal reports of adverse events associated with the training programs in the included studies.

Conclusions We found that very elderly can increase muscle strength and muscle size by participating in resistance training programs. Resistance training was found to be an effective way to improve muscle strength even among the oldest-old.

Key Points

We found that very elderly adults can increase their muscle strength and size by participating in resistance training programs.

These effects were observed with resistance training interventions that generally included low weekly training volumes and frequencies.

There were minimal reports of adverse events associated with the training programs.

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1 Introduction

Dynapenia is the age-associated loss of muscle strength [1]. Low muscle strength increases the risk of mobility limitations and mortality in older adults [1–4]. Sarcopenia is a progressive skeletal muscle characterized by a degenerative loss of muscle mass and function [5]. It is associated with an increased likelihood of physical disability, falls, fractures, and mortality [5]. Resistance training is the most widely recognized mode of exercise for increasing muscle strength and muscle size. The effectiveness of resistance training in achieving these outcomes among youth, adults, and older adults is well established [6–8]. The effects of resistance training on older adults have been recently reviewed by Fragala et al. [9]. However, this review considered studies conducted among adults aged 50 years and older, with less focus placed on the effects of resistance training on muscle strength and hypertrophy in the very elderly (i.e., 75 years of age and older) [10, 11].

Muscle hypertrophy occurs when muscle protein synthesis exceeds muscle protein degradation over time [12]. Research has established that, compared to their younger counterparts, older adults experience a reduced muscle protein synthetic response to protein intake, a physiological adaptation termed "anabolic resistance" [13]. Muscle hypertrophy in response to resistance training is associated with myonuclear addition via satellite cell recruitment [14]. In this context, data suggest that resistance training induces significant addition of myonuclei per muscle fiber in young adults [15]. However, no significant satellite cell or myonuclear addition was found in older adults that performed 12–16 weeks of resistance training [15, 16]. Therefore, some researchers speculate that there might be an age-related ceiling above which an individual cannot further increase muscle size with resistance training [17]. Additionally, there are estimates that older individuals have up to a 47% reduction in the number of motor units, and this reduction might be associated with compromised gains in muscle strength with resistance training in this population [18, 19].

The seminal work by Fiatarone et al. [20] suggested that participation in resistance training increases muscle strength and muscle size, even at the advanced stages of aging. In this single-arm study, ten participants with an average age of 90 years (range 86–96 years) performed 8 weeks of resistance training. After the intervention, knee extension one-repetition maximum (1RM) strength improved by 15 kg, accompanied by an increase in quadriceps muscle size of 9%. However, in a more recent randomized controlled study [16], 12 weeks of resistance training in a group of participants aged 83–94 years did not significantly increase their muscle size.

In 2013, a systematic review by Stewart et al. [11] provided a summary of studies that explored the effects of different modes of physical training (including resistance training) on muscle size and strength in adults aged 75 years or older. Even though this review concluded that resistance training is an effective exercise intervention for increasing muscle size and strength in this age group, the conclusions were based only on two included studies. It is important to note that several studies that satisfied the inclusion criteria of Stewart et al. [10] were not identified and included in the review [21–29]. Furthermore, since 2013, new original studies have been published on this topic, adding new relevant data to further our understanding of muscular adaptations to resistance training in very elderly adults [16, 30–34].

The aim of this systematic review and meta-analysis was, therefore, to examine the effects of resistance training on strength and muscle size in very elderly individuals. A systematic review on this topic is needed, given that: (a) the evidence presented in studies examining the effects of resistance training in this age group is conflicting; and (b) there are no recent systematic reviews on this topic. Findings on this topic could have a substantial public health impact because the very elderly represent one of the fastest-growing age groups in the population, and it is estimated that only 8.7% of adults aged 75 years or older participate in muscle-strengthening activities [35, 36].

2 Methods

2.1 Search Strategy

For this systematic review, we followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines [37]. In total, we searched through nine databases: Academic Search Elite, CINAHL, ERIC, Open Access Theses and Dissertations, Open Dissertations, PsycINFO, PubMed/MEDLINE, Scopus, and SPORTDiscus. In all of these databases, we used the following search syntax (or equivalent) to search through titles, abstracts, and keywords of indexed documents: ("very elderly" OR "oldest old" OR "oldest-old" OR "very old" OR "advancing age" OR "advancing years" OR "old-old" OR "old old" OR septuagenarian* OR nonagenarian* OR octogenarian* OR centenarian* OR "75 and older" OR "80 and older" OR "85 and older" OR "90 and older" OR "95 and older" OR "75 years" OR "80 years" OR "85 years" OR "90 years" OR "95 years") AND ("resistance training" OR "resistance exercise" OR "weight lifting" OR "weightlifting" OR "strength exercise" OR "strength training" OR "strengthening" OR "resistive exercise" OR "resistive training") AND ("muscle hypertrophy" OR "muscular hypertrophy" OR "muscle mass" OR "lean body mass" OR "fat-free mass" OR "fat free mass" OR "muscle fiber" OR "muscle size" OR "muscle fibre" OR "muscle thickness" OR "cross-sectional area" OR "cross sectional area" OR "computed tomography" OR "magnetic resonance imaging" OR "muscle power" OR "strength" OR "1RM" OR "isokinetic" OR "isometric"). We also performed secondary searches that consisted of the following: (a) screening the reference lists of studies that were included in the review and (b) examining the reference lists of previous related reviews [7, 11, 38–43]. To reduce the probability of study selection bias, two authors of the review (JG and AG) conducted the study selection independently. After both authors completed their searches, the lists of included and excluded studies were compared between them. Any discrepancies between the two authors in the included and excluded studies were resolved through discussion and agreement. The databases were searched on January 20, 2020.

2.2 Inclusion Criteria

Studies that satisfied the following criteria were included in the review: (a) the participants were aged 75 years or older; (b) the participants were randomized into the intervention and control group(s); (c) the exercise intervention was comprised of resistance training while the control group did not exercise; (d) the study assessed muscle strength and/or muscle size pre- and post-intervention; and (e) the training protocol lasted for a minimum of 6 weeks. All forms of strength tests, including isotonic, isometric, isokinetic, and handgrip tests were deemed relevant. For muscle hypertrophy, we considered studies that assessed changes at the whole-muscle (macroscopic methods) and/or muscle fiber level (microscopic methods).

2.3 Data Extraction

In each of the included studies, we extracted the following data: (a) author names and year of publication; (b) characteristics of the sample size, including their age and sex; (c) specifics of the resistance training intervention (e.g., the number of performed sets, exercise selection); (d) adverse events reported during the intervention (if any); (e) exercise used for the muscle strength test and/or body site and tool used for the muscle hypertrophy assessment; and (f) pre and post-intervention mean ± standard deviation (SD) of the strength and/or hypertrophy outcomes. For the studies that reported standard errors, we converted them to SDs. Two authors of the review (JG and FS) performed the data extraction independently. After both authors completed the data extraction from all studies, the coding sheets were compared between the authors. In case of any discrepancies in the data extraction files, the data were re-checked from the studies.

2.4 Methodological Quality

The methodological quality of the included studies was assessed using the 27-item Downs and Black checklist [44]. This checklist evaluates different aspects of the study design, with items 1–10 referring to reporting, items 11–13 referring to external validity, items 14–26 referring to internal validity, and item 27 referring to statistical power. Given that the included studies explored the effects of a resistance training intervention, the standard 27-item checklist was modified by adding two items, item 28 and item 29. Item 28 was on the reporting of adherence to the training program, while item 29 was related to training supervision. For each item—including items 28 and 29—one point was allocated to the study if the criterion was satisfied; no points were allocated if the criterion was not satisfied. The maximum possible score on the modified version of the Downs and Black checklist was, therefore, 29 points. Based on the summary score, studies that had 21–29 points were classified as being of 'good quality', studies with 11–20 points were classified as being of 'moderate quality', while studies that scored less than 11 points were considered to be of 'poor quality' [45, 46]. The methodological quality assessment was performed independently by two authors (JG and AG), with discussions and agreement for any observed differences in the initial scoring.

2.5 Statistical Analysis

The meta-analyses for strength and hypertrophy outcomes were performed on the training intervention minus control difference in relative effect sizes (ESs). The data for strength and hypertrophy were converted to relative ES, calculated as the posttest-pretest mean change in each group, divided by the pooled pretest SD, with an adjustment for small sample bias [47]. The variance of the ESs depends on the within-subject posttest–pretest correlation. Given that this correlation was not reported in any of the included studies, when possible it was estimated by back-solving from paired *t* test *p* values or SDs of posttest–pretest change scores. Among studies for which the correlation could be derived from the available data, the median value was 0.85. A more conservative value of 0.75 was used for all studies. Sensitivity analyses (not presented) were performed using correlations ranging from 0.25 to 0.85, and their results were consistent with those using 0.75. In order to account for correlated ESs within studies, we used a robust variance meta-analysis model, with an adjustment for small samples [48]. In the main meta-analysis for muscle strength, we included all available studies. A sensitivity analysis was performed by excluding the two studies [26, 29] that used upper-body exercises for the strength test. In a subgroup analysis, we explored the effects of resistance training on muscle strength only among the "oldest-old" (i.e., 80 + years). Handgrip strength was analyzed separately from other strength tests as this test is commonly used alone in predicting mortality and functional declines in the very elderly [49]. For hypertrophy, the following meta-analyses were performed: (a) for whole-muscle hypertrophy outcomes; and (b) for muscle fiber cross-sectional area (CSA). All differences in ESs were presented with their 95% confidence intervals (95% CIs). These differences were interpreted as: "trivial" (≤ 0.20); "small" (0.21–0.50); "medium" (0.51–0.80); and "large" (> 0.80). The potential presence publication bias was checked by examining funnel plot asymmetry and calculating trim-and-fill estimates. The trim-and-fill estimates (not presented) were similar to the main results. Heterogeneity was explored using the I^2 statistic, with values of ≤ 50%, 50–75%, and > 75% indicating low, moderate, and high levels of heterogeneity, respectively. All meta-analyses were performed using the robumeta package within R version 3.6.1 and the trim-and-fill analyses were calculated using the metafor package [50, 51]. Group differences were considered statistically significant at $p < 0.05$.

3 Results

3.1 Study Selection

The total number of search results in the nine databases was 2076. After excluding 2016 search results based on title or abstract, 60 full-text papers were read. Of the 60 full-text papers, 17 studies were included. Secondary searches resulted in another 1559 search results and with the inclusion of five additional papers (Fig. 1). Therefore, the final number of included studies was 22 [16, 21–34, 52–58]. Of note, in two cases, the strength and whole-muscle hypertrophy data were published separately from muscle fiber CSA data, even though the data collection was carried out in the same cohort [16, 30, 52, 53]. Additionally, one group of authors published the data on strength, whole-muscle CSA, and muscle fiber CSA in three separate papers, even though the data were collected in a single study [54–56].

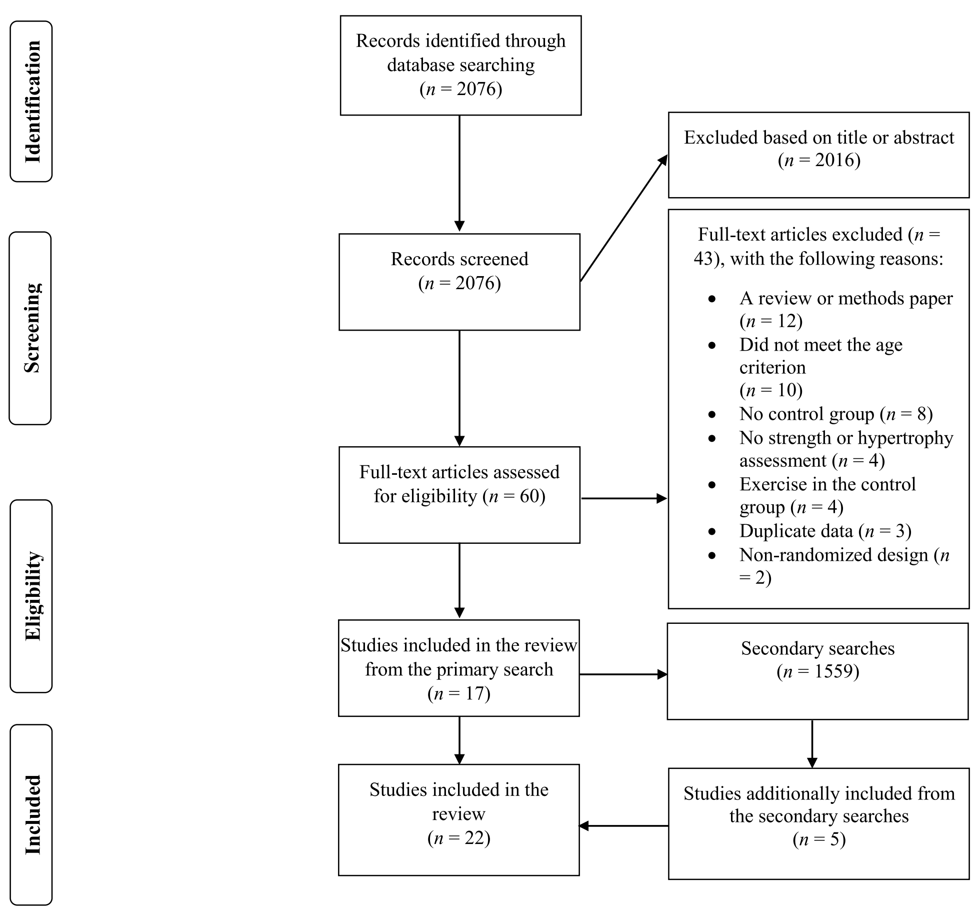

Fig. 1 Flow diagram of the search process

3.2 Study Characteristics

3.2.1 Muscle Strength Outcomes

In the 17 studies that explored muscle strength outcomes and met the inclusion criteria, the pooled number of participants was 880 (84% females; Table 1). The median sample size per study was 38 (range 14–144 participants). The interventions lasted from 8 to 18 weeks. Training frequency was from 1 to 3 days per week. Eleven studies used isometric strength tests, four used isotonic strength tests, and three used isokinetic tests (one used both isometric and isokinetic tests). Two studies employed tests on upper-body exercises, while the remaining studies used lower body exercises (Table 2). Eight studies assessed handgrip strength (Table 2).

3.2.2 Hypertrophy Outcomes

In the nine studies that explored hypertrophy outcomes and met the inclusion criteria, the total sample size was 204 participants (67% females; Table 1). The median sample size per study was 26 participants (range 23–49 participants). The interventions lasted from 10 to 18 weeks, with a training frequency of 2–3 days per week. Six studies reported data on whole-muscle hypertrophy. For this outcome, studies used computed tomography (three studies), B-mode ultrasound (two studies), and magnetic resonance imaging (one study). Three studies explored changes at the muscle fiber level. All studies assessed lower-body hypertrophy. The training programs used in the studies are summarized in Table 2.

3.3 Methodological Quality

The average score on the modified 29-item Downs and Black checklist was 25 (range 21–28 points). All studies were classified as being of good methodological quality. Scores on all items of the checklist are reported in Table 3.

3.4 Meta-Analysis Results for Muscle and Handgrip Strength

The meta-analysis found a significant effect of resistance training on muscle strength in the very elderly (difference in ES = 0.97; 95% CI 0.50, 1.44; $p = 0.001$; $I^2 = 87\%$; Fig. 2). In the sensitivity analysis, there was a significant effect of resistance training on lower-body muscle strength in the very elderly (difference in ES = 0.96; 95% CI 0.48, 1.45; $I^2 = 87\%$; $p = 0.001$). In a subgroup analysis that included only the oldest-old participants (80 + years of age), there was a significant effect of resistance training on muscle strength (difference in ES = 1.28; 95% CI 0.28, 2.29; $p = 0.020$; $I^2 = 86\%$; Fig. 3). For handgrip strength, we found no significant difference between resistance training and control groups (difference in ES = 0.26; 95% CI − 0.02, 0.54; $p = 0.064$; $I^2 = 51\%$; Fig. 4).

3.5 Meta-Analysis Results for Whole-Muscle and Muscle Fiber Hypertrophy

For whole-muscle hypertrophy, there was a significant effect of resistance training in the very elderly (difference in ES = 0.30; 95% CI 0.10, 0.50; $p = 0.013$; $I^2 = 0\%$; Fig. 5). We found no significant difference in muscle fiber hypertrophy between resistance training and control groups (difference in ES = 0.33; 95% CI − 0.67, 1.33; $p = 0.266$; $I^2 = 7\%$; Fig. 6).

4 Discussion

The main finding of this systematic review and meta-analysis was that resistance training increases muscle strength in very elderly people, even among the oldest-old. We also found that resistance training results in muscle hypertrophy at the whole-muscle level in very elderly. The ES for strength and whole-muscle hypertrophy was large and small, respectively. Even though the pooled ES favored resistance training for muscle fiber hypertrophy and handgrip strength, these effects were not statistically significant.

4.1 Muscle Strength

We found that resistance training produced substantial increases in muscle strength in the very elderly. Increases in muscle strength were also observed in a subgroup analysis of studies that included the oldest-old, suggesting that resistance training enhances muscle strength even at an advanced stage of aging. Xue et al. [59] reported that dynapenia is associated with increased mortality risk. Findings from the "Health, Aging and Body Composition Study" further indicated that knee extension strength—as measured by isokinetic dynamometry—is associated with a reduced risk of mortality [3]. Dynapenia also increases the risk of physical disability and reduces physical performance [1]. Therefore, muscle strength is identified as one of the key muscle qualities for physical independence in the very elderly [1, 4]. After the age of 75 years, muscle strength annually declines by about 2–4% (ES 0.17–0.24) for those who do not perform regular resistance exercise [60–62]. Our findings suggest that participation in resistance training over 8–18 weeks, with a frequency of 1–3 days per week, can restore strength that has been potentially lost over several years of inactivity. Research has also established that lower limb muscle weakness is an important risk factor for falls in the older population [63]. When considering only the studies that used lower-body exercise for the strength test, an ES of 0.96 (95% CI 0.48, 1.45) was found. These data

Table 1 Characteristics of individual study samples

Study	Participants	Sex: M/F	Age (years)	Minimum and maximum age (years)	Mass (kg)	Height (cm)
Bechshøft et al. [30] and Karlsen et al. [16]	Resistance training: $n = 12$	8/4	87.7 ± 3.7	83–94	70.5 ± 13.5	164.8 ± 10.2
	Control: $n = 13–14$[a]	8/6	86.2 ± 2.6	83–94	69.5 ± 14.8	168.7 ± 12.7
Benavent-Caballer et al. [31]	Resistance training: $n = 22$	7/15	85.5 ± 4.7	75–96	65.1 ± 11.3	153 ± 7
	Control: $n = 23$	8/15	83.6 ± 5.6	75–96	64.7 ± 9.8	154 ± 7
Bruunsgaard et al. [21]	Resistance training: $n = 9$	0/9	86.6	86–95	NR	NR
	Control: $n = 10$	0/10	90.6	86–95	NR	NR
Cadore et al. [32]	Resistance training: $n = 11$	3/8	93.4 ± 3.2	85[b]	NR	NR
	Control: $n = 13$	3/10	90.1 ± 1.1	85[b]	NR	NR
Caserotti et al. [22]	Resistance training: $n = 10$	0/10	81.8 ± 2.7	80–89	65.4 ± 7.5	158.6 ± 5.2
	Control: $n = 12$	0/12	81.8 ± 2.7	80–89	68.5 ± 16.3	157.6 ± 4.4
Fiatarone et al. [52] and Fiatarone Singh et al. [53]	Resistance training: $n = 25$[c]	9/16	87.2 ± 6.0	76–98	NR	NR
	Control: $n = 24$[c]	7/17	85.7 ± 5.9	75–97	NR	NR
Giné-Garriga et al. [23]	Resistance training: $n = 22$	9/13	83.9 ± 2.8	80–90	71.5 ± 13.2	159.7 ± 10.0
	Control: $n = 19$	7/12	84.1 ± 3	80–90	72 ± 14	158.6 ± 9.9
Hruda et al. [24]	Resistance training: $n = 18$	5/13	84.4 ± 4.8	76–94	60.7 ± 11.3	156.9 ± 8.9
	Control: $n = 7$	1/6	80.6 ± 4.6	75–87	70.0 ± 13.4	159.3 ± 7.0
Hvid et al. [57]	Resistance training: $n = 16$	7/9	82.3 ± 5.2	76–93	76.5 ± 12.4	164.2 ± 6.4
	Control: $n = 21$	7/14	81.6 ± 5.0	76–93	73.4 ± 14.2	163.7 ± 8.2
Judge et al. [25]	Resistance training: $n = 28$	17/11	80.3 ± 4.0	75[b]	70 ± 10	164 ± 10
	Control: $n = 27$	16/11	80.6 ± 4.5	75[b]	73 ± 13	164 ± 10
Kalapotharakos et al. [26]	Resistance training: $n = 7$	7/0	83.4 ± 2.8	80–88	81.7 ± 7.6	169 ± 5
	Control: $n = 7$	7/0	82.5 ± 3.0	80–88	82.5 ± 3.0	167 ± 8
Kim et al. [27]	Resistance training: $n = 34$	0/34	79.5 ± 2.9	75[b]	39.5 ± 5.5	147.1 ± 6.7
	Control: $n = 37$	0/37	79.2 ± 2.8	75[b]	40.1 ± 3.2	145.8 ± 4.5
	Resistance training: $n = 36$	0/36	79.0 ± 2.9	75[b]	41.1 ± 4.7	147.7 ± 4.4
	Control: $n = 37$	0/37	78.7 ± 2.8	75[b]	40.4 ± 3.9	146.5 ± 4.9
Kim et al. [58]	Resistance training: $n = 29$	0/29	81.1 ± 3.7	75[b]	43.7 ± 4.1	145.0 ± 5.5
	Control: $n = 30$	0/30	80.0 ± 4.0	75[b]	42.4 ± 5.7	145.6 ± 4.9
	Resistance training: $n = 30$	0/30	79.6 ± 4.2	75[b]	41.5 ± 4.5	145.9 ± 5.8
	Control: $n = 28$	0/28	80.2 ± 5.6	75[b]	42.7 ± 5.0	145.9 ± 5.4
Kim et al. [33]	Resistance training: $n = 33$	0/33	81.1 ± 2.8	75[b]	48.6 ± 9.0	147.8 ± 6.7
	Control: $n = 32$	0/32	80.3 ± 3.3	75[b]	47.7 ± 8.7	144.3 ± 5.8
	Resistance training: $n = 33$	0/33	81.0 ± 2.6	75[b]	46.1 ± 7.5	147.7 ± 5.4
	Control: $n = 32$	0/32	81.0 ± 2.8	75[b]	47.1 ± 8.7	146.1 ± 5.5
Sahin et al. [34]	Resistance training: $n = 16$	NR	84.5 ± 4.8	77–93	NR	NR
	Control: $n = 16$	NR	85.4 ± 4.7	76–93	NR	NR
Serra-Rexach et al. [28]	Resistance training: $n = 19$	4/15	92 ± 2	90–96	55.9 ± 11.3	148 ± 9
	Control: $n = 19$	4/15	92 ± 2	90–97	60.9 ± 11.3	149 ± 9
Sipilä and Suominen [54], Sipilä et al. [55], and Sipilä et al. [56]	Resistance training: $n = 12$[c]	0/12	76–78	76–78	66.9 ± 9.4	159.5 ± 3.5
	Control: $n = 11$[c]	0/11	76–78	76–78	67.6 ± 12.3	158.7 ± 5.4
Skelton et al. [29]	Resistance training: $n = 20$	0/20	Median 79.5	76–93	54.1 ± 9.1	154 ± 7
	Control: $n = 20$	0/20	Median 79.5	75–90	61.5 ± 11.4	157 ± 7

Age, height and mass data are reported as mean ± standard deviation or range

M males, *F* females, *NR* not reported

[a]14 participants in one study and 13 in another

[b]Maximum age was not reported

[c]Muscle biopsies were obtained from a subsample of 7 participants

Table 2 Summary of studies included in the review

Study	Resistance training protocol	Resistance exercise(s) employed in the program	Study duration; training frequency	Outcomes	Adherence	Adverse events associated with training
Bechshøft et al. [30] and Karlsen et al. [16]	2–5 sets per exercise performed for 6–12 repetitions with 70–85% 1RM	Knee extension, leg press and leg flexion	12 weeks; 3 days per week	Quadriceps muscle CSA; muscle fiber CSA; isometric and isokinetic knee extension peak torque	Average adherence of 90%	"Compression fracture of epicondylus medialis femoris triggered by the training but caused by a fragile bone"
Benavent-Caballer et al. [31]	3 sets per exercise performed for 15 repetitions with 40% 1RM; 3 min of rest between sets	Knee extension	16 weeks; 2 days per week	Quadriceps muscle CSA; handgrip strength	78% of participants completed all sessions	None
Bruunsgaard et al. [21]	3 sets per exercise performed for 8 repetitions with 50–80% 1RM; 2 min of rest between sets	Knee extension and leg flexion	12 weeks; 3 days per week	Knee extensor and flexor 1RM strength	Average adherence of 84%	None reported
Cadore et al. [32]	1 sets per exercise performed for 8 repetitions with 40–60% 1RM	Knee extension and seated bench press	12 weeks; 2 days per week	Quadriceps, knee flexor, and adductor muscle CSA; isometric hip flexion and knee extension; handgrip strength	Average adherence of more than 90%	None
Caserotti et al. [22]	4 sets per exercise performed for 8–10 repetitions with 75–80% 1RM; first set in each exercise was performed with 35–40% 1RM	Bilateral knee extension, horizontal and inclined leg press, leg flexion, and calf raises	12 weeks; 2 days per week	Isometric leg press strength	Not reported	Exacerbation of preexisting osteoarthritis in one participant
Fiatarone et al. [52] and Fiatarone Singh et al. [53]	3 sets per exercise performed for 8 repetitions with 80% 1RM; 2 min of rest between sets	Knee extensions, exercise for the hip musculature, and leg press	10 weeks, 3 days per week	Quadriceps muscle CSA; muscle fiber CSA; 1RM strength in six different exercises	Average adherence of 97%	One participant dropped out of the study due to soreness after the first session
Giné-Garriga et al. [23]	2 sets per exercise performed for 6–15 repetitions with exertion intensity of 12–14 on the RPE scale	Rising from a chair, stair climbing, knee bends, floor transfer, lunges, squat, leg extension, leg flexion, calf raise, and abdominal curl	12 weeks; 1 day per week	Isometric knee extension strength	Average adherence of 90%	None
Hruda et al. [24]	1 set per exercise performed for 4–8 repetitions with body weight; elastic bands were added for resistance as the participants progressed	Leg crosses, hip rotations, ankle rotations, rising from a seated position, heel raises, squats, leg lifts, and leg flexion	10 weeks, 3 days per week	Concentric and eccentric knee extension peak torque	Average adherence of 71%	None reported

Table 2 (continued)

Study	Resistance training protocol	Resistance exercise(s) employed in the program	Study duration; training frequency	Outcomes	Adherence	Adverse events associated with training
Hvid et al. [57]	3 sets per exercise performed for 8–10 repetitions with 70–80% 1RM	Leg press and plantar flexion	12 weeks; 2 days per week	Quadriceps muscle thickness; isometric knee extension strength	Minimum of 80%	None
Judge et al. [25]	2–3 sets per exercise performed to muscle failure with 30–75% 1RM; sandbags and body weight were used for resistance in some exercises; 2–3 min of rest between sets	Exercises that included knee extension and ankle dorsiflexion, hip extension, hip abduction, knee flexion, and ankle plantar flexors	12 weeks; 3 days per week	Isokinetic hip extension, hip flexion, hip abduction, hip adduction, knee extension, knee flexion, ankle flexion, and ankle extension	Average adherence of 82%	Some musculoskeletal complaints
Kalapotharakos et al. [26]	3 sets per exercise performed for 7 repetitions with 70% 3RM	Knee extension, chest press, knee flexion, latissimus pull down, arm curls, and triceps extension	14 weeks; 2 days per week	Knee extension, knee flexion, elbow flexion, elbow extension, latissimus pull-down, and chest press 3RM	Average adherence of 90%	None
Kim et al. [27]	1–2 sets per exercise performed for 8–10 repetitions with elastic bands and ankle weights used for resistance	Toe raises, heel raises, knee lifts, knee extensions, hip flexions, lateral leg raises, leg extension and hip flexion, double-arm pull downs and biceps curls	12 weeks; 2 days per week	Isometric knee extension strength	Average adherence of 70–80% (depending on the group)	None
Kim et al. [58]	1–2 sets per exercise performed for 8–10 repetitions with elastic bands and ankle weights used for resistance	"Strengthening of the leg muscles focused on hip extensors and adductors, knee flexors and extensors, and ankle dorsi and plantar flexors."	12 weeks; 2 days per week	Isometric knee extension strength; handgrip strength	Not reported	None
Kim et al. [33]	1–2 sets per exercise performed for 8–10 repetitions with elastic bands and ankle weights used for resistance	"Lower body exercises consisted of leg extensions, hip flexions, and more. Upper body exercises included double-arm pull downs, bicep curls, and others."	12 weeks; 2 days per week	Isometric knee extension strength; handgrip strength	Not reported	None

Table 2 (continued)

Study	Resistance training protocol	Resistance exercise(s) employed in the program	Study duration; training frequency	Outcomes	Adherence	Adverse events associated with training
Sahin et al. [34]	1 set per exercise performed for 4–8 repetitions with 40% 1RM	Exercises that included hip flexion, extension and abduction, knee flexion, extension and dorsiflexion and plantar flexion, shoulder flexion and abduction, and elbow flexion and extension	8 weeks; 3 days per week	Hip flexor, hip abductor, knee extensor, and dorsi flexor isometric strength; handgrip strength	Not reported	None
Serra-Rexach et al. [28]	1–3 sets per exercise performed for 8–10 repetitions with 30–70% 1RM; 1–2 min of rest between sets	Leg press, biceps curls, arm extensions, arm side lifts, shoulder elevations, seated bench presses, and calf raises	8 weeks; 3 days per week	Leg press 1RM; handgrip strength	Average adherence of 75%	Mild pain during the performance of the leg press exercise
Sipilä and Suominen [54], Sipilä et al. [55], and Sipilä et al. [56]	3–4 sets per exercise performed for 8–10 repetitions with 60–70% 1RM; 30 s of rest between sets	Leg press, knee extension, knee flexion, and heel raises	18 weeks; 3 days per week	Quadriceps, knee flexor, and calves CSA; muscle fiber CSA; isometric knee extension and knee flexion strength	Average adherence of 78%	None
Skelton et al. [29]	3 sets per exercise performed for 4–8 repetitions with bodyweight, rice bags, or elastic bands	Exercises that targeted shoulder and hip abductors, adductors, flexors and extensors, elbow flexors and extensors, and knee flexors and extensors (specific exercises were not reported)	12 weeks; 3 days per week[a]	Isometric knee extension and elbow flexion strength; handgrip strength	Minimum of 80%	Muscle soreness in the first 2 weeks of training

RM repetition maximum, *CSA* cross-sectional area, *RPE* rating of perceived exertion

[a]Only two sessions per week were supervised

Table 3 Results of the methodological quality assessment using the modified Downs and Black checklist

Study	Reporting (items 1–10)										External validity (items 11–13)			Internal validity (items 14–26)													Power, compliance, supervision (items 27, 28, 29)			Total score
Items	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	
Bechshøft et al. [30] and Karlsen et al. [16]	1	1	1	1	1	1	1	1	1	0	1	1	1	0	1	1	1	1	1	1	1	1	1	0[a]	1	1	1	1	1	26
Benavent-Caballer et al. [31]	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0[a]	1	0[a]	1	1	1	1	1	26
Bruunsgaard et al. [21]	1	1	1	1	1	1	1	0	0	1	0	0	1	0	0	1	1	1	1	1	1	0[a]	1	0[a]	1	1	1	1	1	21
Cadore et al. [32]	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0[a]	1	0[a]	1	1	1	1	1	26
Caserotti et al. [22]	1	1	1	1	1	1	1	1	1	1	1	0	1	0	0	1	1	1	0[a]	1	1	0[a]	1	0[a]	1	1	1	0	1	22
Fiatarone et al. [52] and Fiatarone Singh et al. [53]	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	0[a]	1	1	1	1	1	27
Giné-Garriga et al. [23]	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	0[a]	1	1	1	1	1	27
Hruda et al. [24]	1	1	1	1	1	1	1	0	0	0	1	0	1	0	0	1	1	1	1	1	1	0[a]	1	0[a]	1	1	1	1	1	21
Hvid et al. [57]	1	1	1	1	1	1	1	1	1	0	1	1	1	0	1	1	1	1	1	1	1	0	1	0[a]	1	1	1	1	1	25
Judge et al. [25]	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	0[a]	1	1	1	1	1	27
Kalapotharakos et al. [26]	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	0[a]	1	0[a]	1	1	1	1	1	25
Kim et al. [27]	1	1	1	0	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	0[a]	1	1	1	1	1	26
Kim et al. [58]	1	1	1	1	1	1	1	0	0	1	1	1	1	0	1	1	1	1	0[a]	1	1	1	1	0[a]	1	1	1	0	1	23
Kim et al. [33]	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0[a]	1	1	1	1	0[a]	1	1	1	0	1	25
Sahin et al. [34]	1	1	0	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	0[a]	1	1	0[a]	1	0a	1	1	1	0	1	23
Serra-Rexach et al. [28]	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0[a]	1	1	1	1	1	28
Sipilä and Suominen [54], Sipilä et al. [55], and Sipilä et al. [56]	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	0[a]	1	0[a]	1	1	1	1	1	25
Skelton et al. [29]	1	1	1	0	1	1	1	1	0	1	1	0	1	0	0	1	1	1	1	1	1	0[a]	1	0[a]	1	1	1	1	1	22

1 = criterion met; 0 = criterion not met

[a]Item was unable to be assessed, scored 0

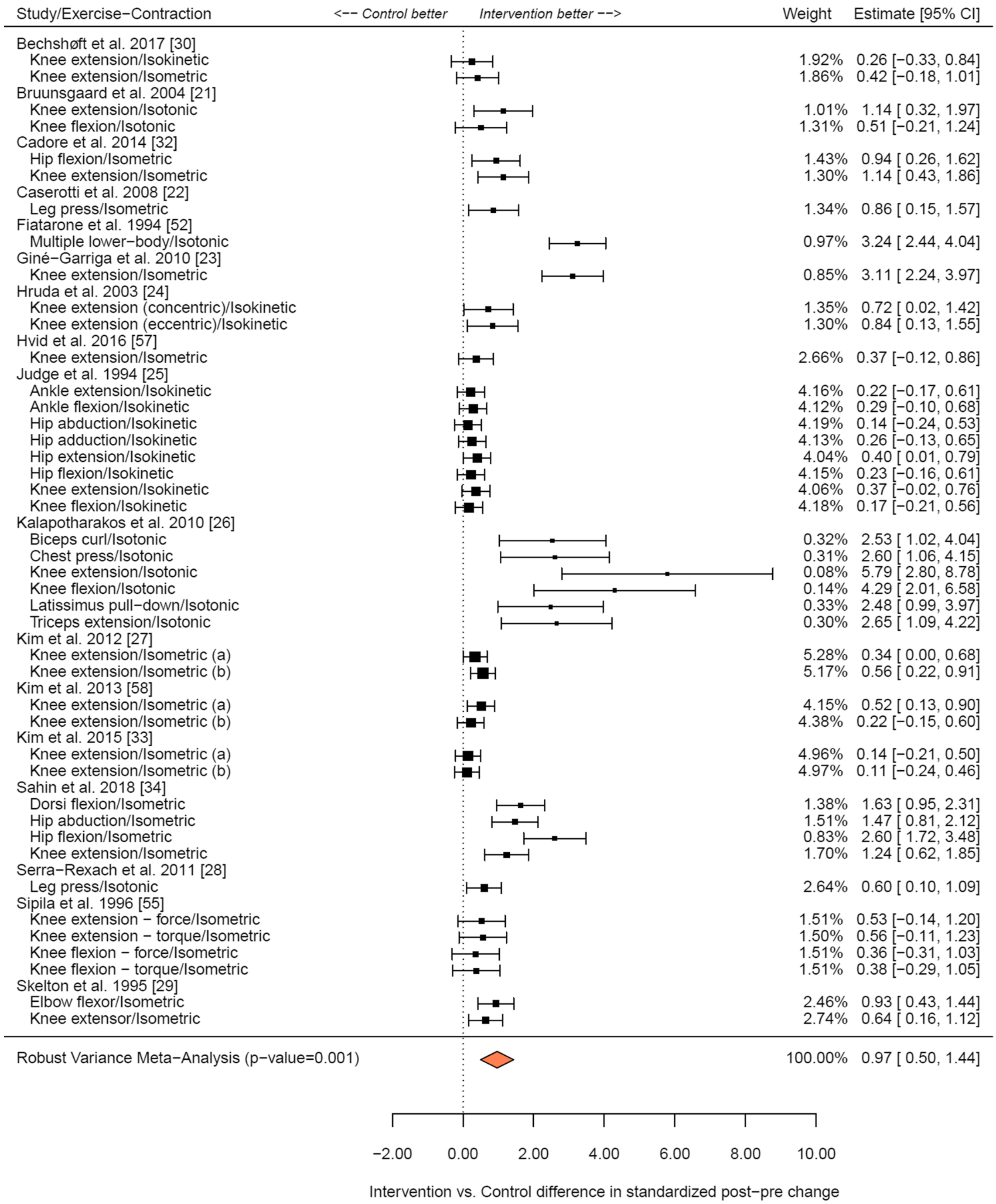

Fig. 2 Meta-analysis of the effects of resistance training on muscle strength in the very elderly. The *x*-axis denotes the difference in effect size (ES). The whiskers denote 95% confidence intervals (CIs). For studies that had multiple study groups, the effects are presented independently and are marked as (a) and (b)

highlight that increasing muscle strength through resistance training participation could be of great health benefit for the very elderly. Our findings are, therefore, highly relevant from a public health perspective. Moreover, data suggest that only 8.7% of adults aged 75 years and older participate in muscle-strengthening activities [36]. Thus, it is clear that finding ways to further promote participation and adherence to muscle-strengthening activities in this age group is of considerable public health interest.

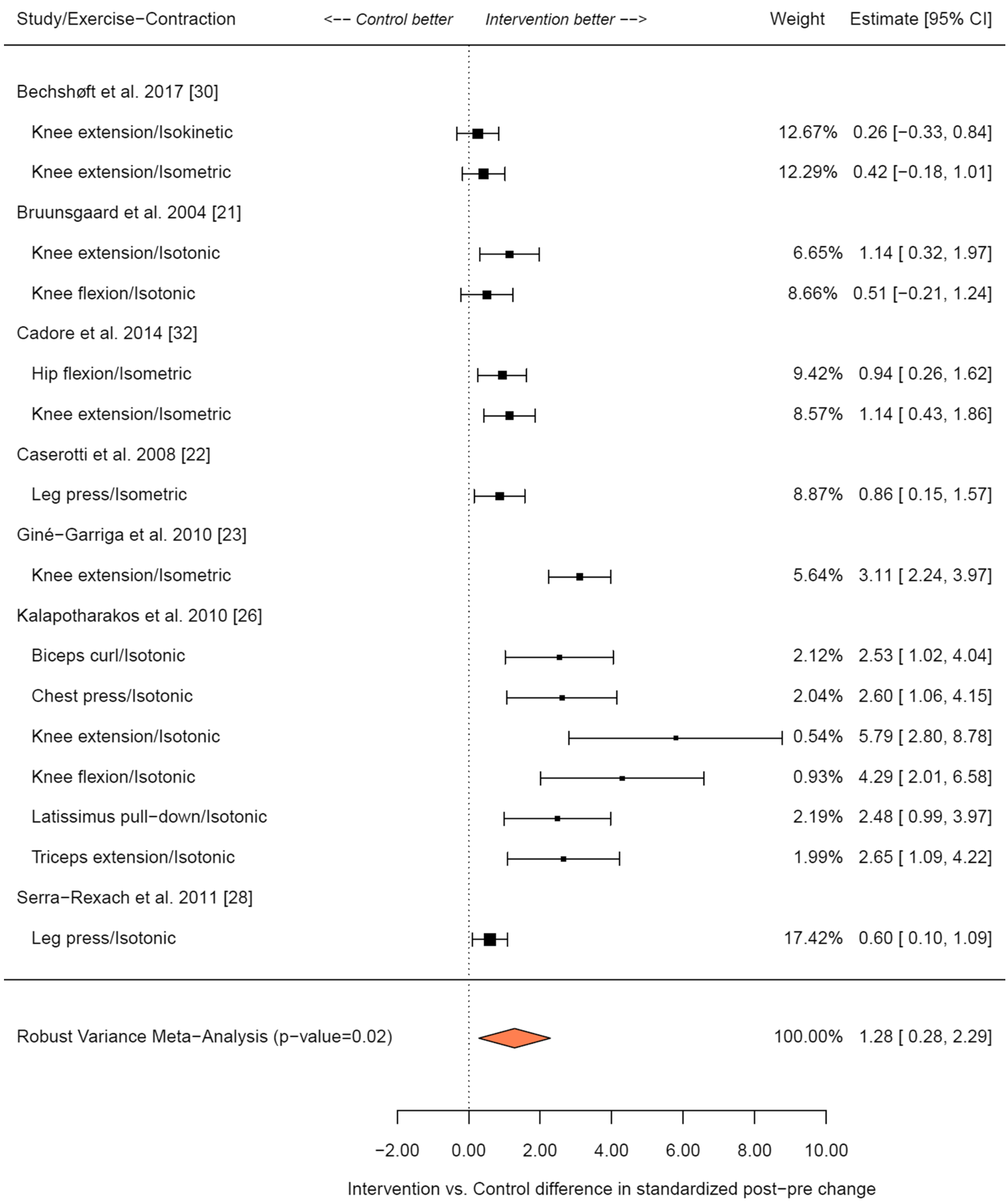

Fig. 3 Meta-analysis of the effects of resistance training on muscle strength in the oldest-old. The *x*-axis denotes the difference in effect size (ES). The whiskers denote 95% confidence intervals (CIs). For studies that had multiple study groups, the effects are presented independently and are marked as (a) and (b)

4.2 Handgrip Strength

The handgrip strength test is widely used to evaluate muscle strength as it is noninvasive and inexpensive [64]. Given its simplicity, this test is often utilized in epidemiological studies [49]. In the sample of included studies, the pooled ES favored resistance training condition, but the effect was not statistically significant ($p = 0.064$). In one of the included studies, resistance training focused exclusively on the lower body, but strength was evaluated using the handgrip test [31]. This might not be entirely appropriate, given that the largest increases in strength are expected for the muscle groups that were covered in the training program [65, 66]. Indeed, one study reported that 24 weeks of whole-body

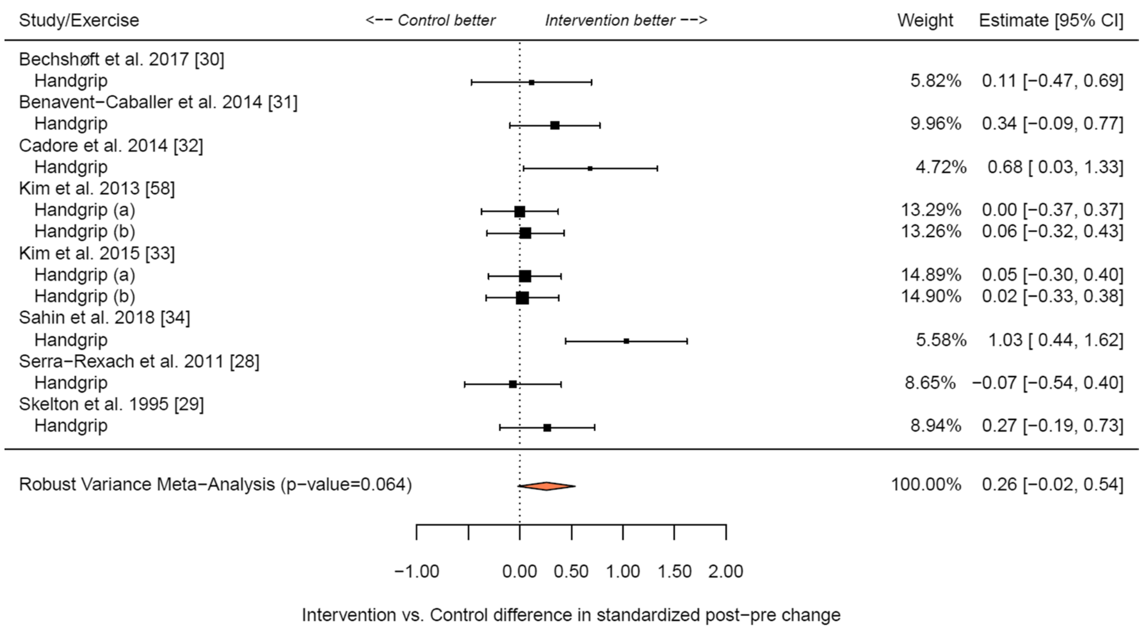

Fig. 4 Meta-analysis of the effects of resistance training on handgrip strength in the very elderly. The *x*-axis denotes the difference in effect size (ES). The whiskers denote 95% confidence intervals (CIs). For studies that had multiple study groups, the effects are presented independently and are marked as (a) and (b)

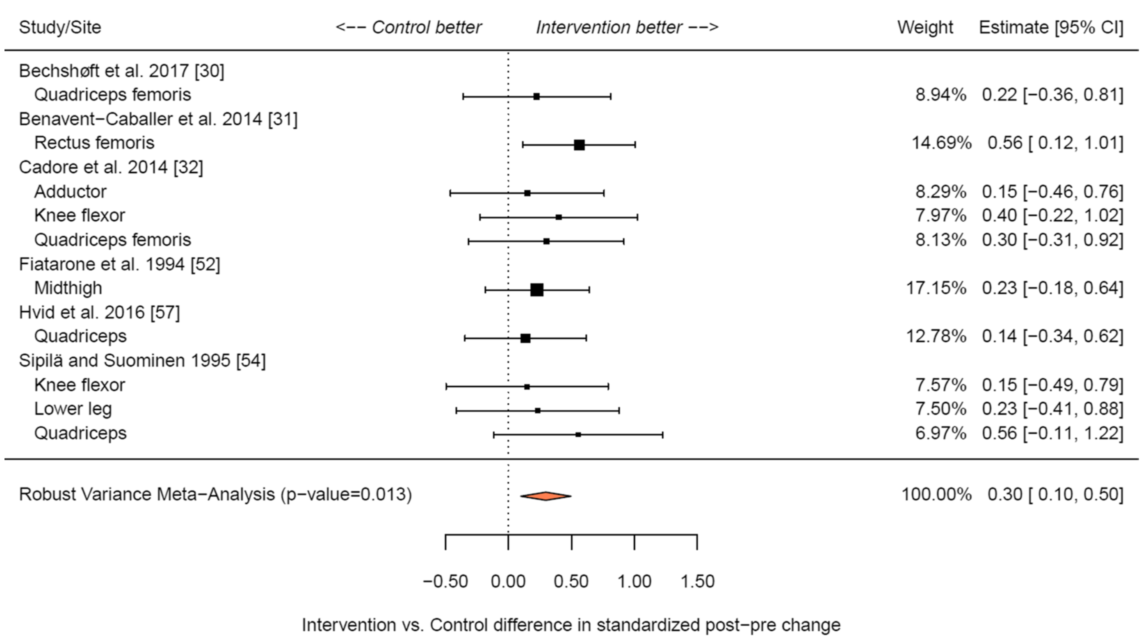

Fig. 5 Meta-analysis of the effects of resistance training on whole-muscle hypertrophy in the very elderly. The *x*-axis denotes the difference in effect size (ES). The whiskers denote 95% confidence intervals (CIs)

resistance training produced a substantial increase in 1RM knee extension and leg press strength (on average by 21 and 45 kg, respectively), that were not accompanied by any significant changes in handgrip strength [67]. In line with this finding, some authors have speculated that there is only a limited ability to increase handgrip strength in adulthood [68]. While handgrip strength testing can certainly provide valuable information about physical functioning, the use of this test may, in some cases, provide limited insights into the efficacy of a given resistance training program.

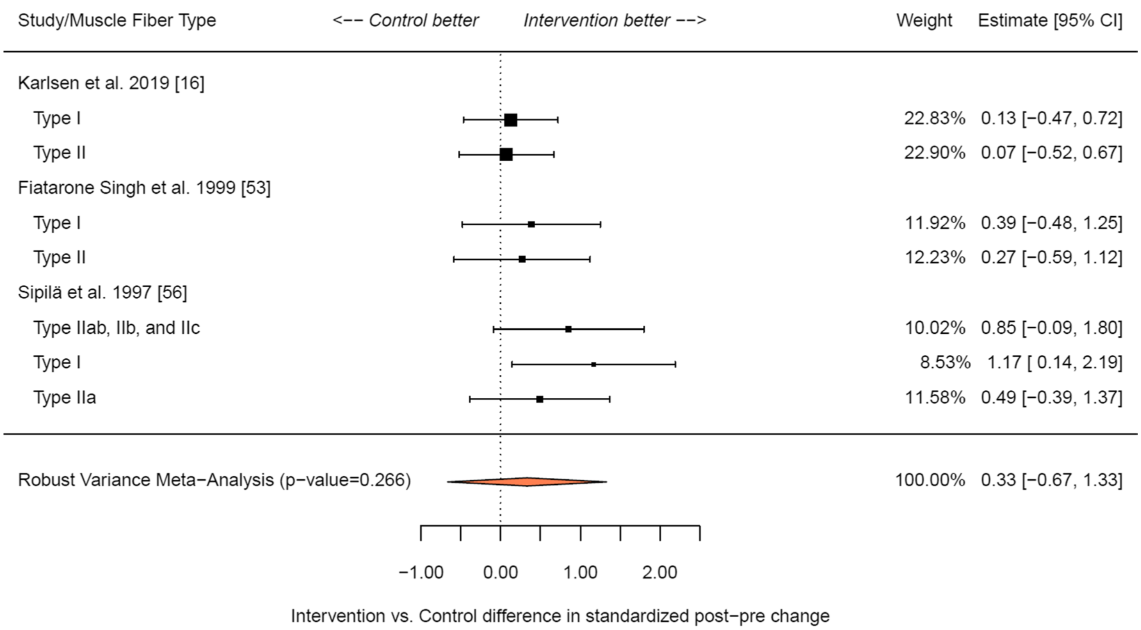

Fig. 6 Meta-analysis of the effects of resistance training on muscle fiber hypertrophy in the very elderly. The *x*-axis denotes the difference in effect size (ES). The whiskers denote 95% confidence intervals (CIs)

4.3 Whole-Muscle Hypertrophy

We found that very elderly individuals can increase muscle size despite their advancing age, although the expected improvements may be small to modest (ES = 0.30; 95% CI 0.10, 0.50). Nonetheless, the finding that the very elderly can increase their muscle size is highly relevant, given that sarcopenia may increase the risk of falls and fractures, increase frailty, decrease functional independence and quality of life as well as increase the risk of chronic disease and all-cause mortality [4]. There are estimates that in the very elderly, muscle size is reduced at a rate of 0.64–0.98% per year (ES 0.14–0.23) [60, 62]. Our results suggest that resistance training interventions lasting from 10 to 18 weeks with a training frequency of 2–3 days per week can increase muscle size that was potentially lost over multiple years of aging. This finding is of public great health importance, if we consider estimates that the prevalence of sarcopenia in adults older than 75 years ranges from 27 to 60% [69].

4.4 Muscle Fiber Hypertrophy

Despite the findings observed for whole-muscle hypertrophy, we did not find significant increases in muscle fiber CSA, even though in the sample of included studies the pooled ES of 0.33 favored resistance training. The lack of a significant finding in this analysis could be attributed to the small pooled sample size. Specifically, only three studies with a combined sample of 53 participants were included in this analysis. The small sample sizes in individual studies for this outcome were probably due to the difficulties in collecting muscle biopsy samples in this age group. In a group of 87 older adults that were considered for a Bergstrom needle muscle biopsy, only 19–59% of participants had adequate levels of muscle mass needed for biopsy sampling (depending on factors such as sex, age, and frailty) [70]. Furthermore, some participants had suboptimal muscle thickness, suggesting that multiple samples might be required to obtain an adequate amount of muscle for the analysis. While future studies are needed to elucidate possible effects of resistance training on muscle fiber hypertrophy in the very elderly, there may be challenges in collecting the necessary data.

4.5 Adverse Events

A recent systematic review reported that fear of a heart attack, stroke, or even death, is one of the most common barriers to participation in resistance exercise for older adults [71]. Therefore, when conducting exercise intervention studies among older adults, the reporting of adverse events associated with the training intervention is essential. The included studies reported minimal adverse events (Table 2). Specifically, in some studies, there were reports of muscle soreness following the exercise sessions, and in one study there was an exacerbation of preexisting osteoarthritis in one participant (Table 2). There were no reported serious events directly related to exercise interventions. These results suggest that resistance training can be safe, even for the very elderly.

4.6 Methodological Quality

All included studies were of good methodological quality. Therefore, the results presented herein were not confounded by studies with poor methodological quality. Nonetheless, it is worth noting that four included studies did not report participants' adherence to the training program [22, 33, 34, 58]. Adherence to a given training program is one of the key variables that influence its overall efficacy [72]. Therefore, future studies should ensure that adherence data are reported.

4.7 Strengths and Limitations of the Review

The strengths of this review are that: (a) the search for studies was conducted through nine databases using a search syntax with a broad range of relevant search terms; and (b) 17 studies with over 800 participants were included in the analysis for muscle strength, which allowed for an additional subgroup analysis including only the oldest-old. This review's main limitation is that the meta-analysis on muscle fiber hypertrophy included only three studies with a combined sample of 53 participants. Besides, there was high heterogeneity in the analysis for muscle strength. However, it should be considered here that the effects from all studies in this analysis were in the same direction (i.e., favoring resistance training), but their overall effectiveness varied. The variation in ESs could be associated with the differences between studies in duration, training programs, and strength tests.

4.8 Suggestions for Future Research

The included studies generally utilized only one type of strength test. Given that the studies used isotonic training programs, it might be expected that resistance training would have the greatest effect on isotonic strength [73, 74]. However, the majority of studies used isometric tests to evaluate changes in muscle strength. Ultimately, the small number of studies employing isotonic and isokinetic strength assessments limits the ability to further subanalyze the effects of resistance training on strength in different tests. Isotonic and isokinetic strength tests were used only in four and three studies, respectively (Table 2). Therefore, future studies on the topic may consider utilizing isotonic, isometric, and isokinetic strength measures in the same group of participants to directly explore if the effects of resistance training in the very elderly vary between different strength tests.

5 Conclusion

This systematic review and meta-analysis found that the very elderly can increase their muscle strength and size by participating in resistance training programs. Moreover, resistance training was found to be an effective way to improve muscle strength even among the oldest-old. Importantly, the resistance training interventions generally included low weekly training volumes and frequencies, suggesting that a relatively low time commitment is needed to reap these benefits. There were minimal reports of adverse events associated with the training programs in the included studies, thus suggesting that resistance training can be a safe mode of exercise for the very elderly. More research is needed on the effects of resistance training on handgrip strength and muscle fiber hypertrophy.

Declaration

Funding No sources of funding were used to assist in the preparation of this article.

Conflict of interest Jozo Grgic, Alessandro Garofolini, John Orazem, Filip Sabol, Brad J. Schoenfeld and Zeljko Pedisic have no conflicts of interest that are directly relevant to the content of this article.

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Availability of data and material The datasets generated and analyzed during the current systematic review and meta-analysis are available from the corresponding author on reasonable request.

Code availability Not applicable.

Author Contributions JG conceived the idea for the review. JG and AG conducted the study selection quality assessment. JG and FS conducted the data extraction. JO performed the statistical analysis. JG drafted the initial manuscript. All authors contributed to data interpretation, writing of the manuscript, and its revisions.

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