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REVIEW

Resistance training effects on gait parameters in older adults—a systematic review with multilevel meta-analysis and meta-regression

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Abstract Falls are a leading cause of morbidity in older adults, and muscle weakness accompanied by gait impairments is a major contributing risk factor. Although current guidelines refer to resistance training, the literature lacks high-quality moderator analyses to evidentially guide clinicians to best treatment practice. This systematic review with meta-analysis opposed pooled resistance training effects to passive controls or active alternative interventions to distinguish specific resistance training effects from generally enhanced physical activity on gait and falls relevant outcomes. Effect sizes (ES) were pooled using robust variance estimation generally and for potential moderators. Ninety-two (92) studies with 5932 participants (mean age 73.1 ± 4.9 years) revealed large improvements in strength (ES = 0.86, $p < 0.001$) and moderate magnitude effects on gait outcomes (ES = 0.59, $p < 0.001$). Largest effects were reached for timed up-and-go (ES = 0.97), followed by gait distance (ES = 0.65), sit-to-stand (ES = 0.42), and gait speed (ES = 0.41) when compared with passive control. Active comparator analyses (stretching, walking, multicomponent exercises) outlined superior effectivity in the timed up-and-go performance (ES = 0.42) only. Supervision, progressive intensity regulation, and inclusion of multi-joint lower-limb exercises (leg press, squat, ankle plantarflexion, knee extension) positively affected results. Spatiotemporal and kinetic gait parameters were not significantly affected in general. Although some positive effects were observed when compared against a passive control, for most outcomes, the analysis questioned current guidelines as the specificity of resistance training effects was blurred by neglectable differences to alternative training interventions. This could be attributed to a dearth of high-quality evidence (long-term studies, reasonable intensity, and volume) on gait parameters in older adults.

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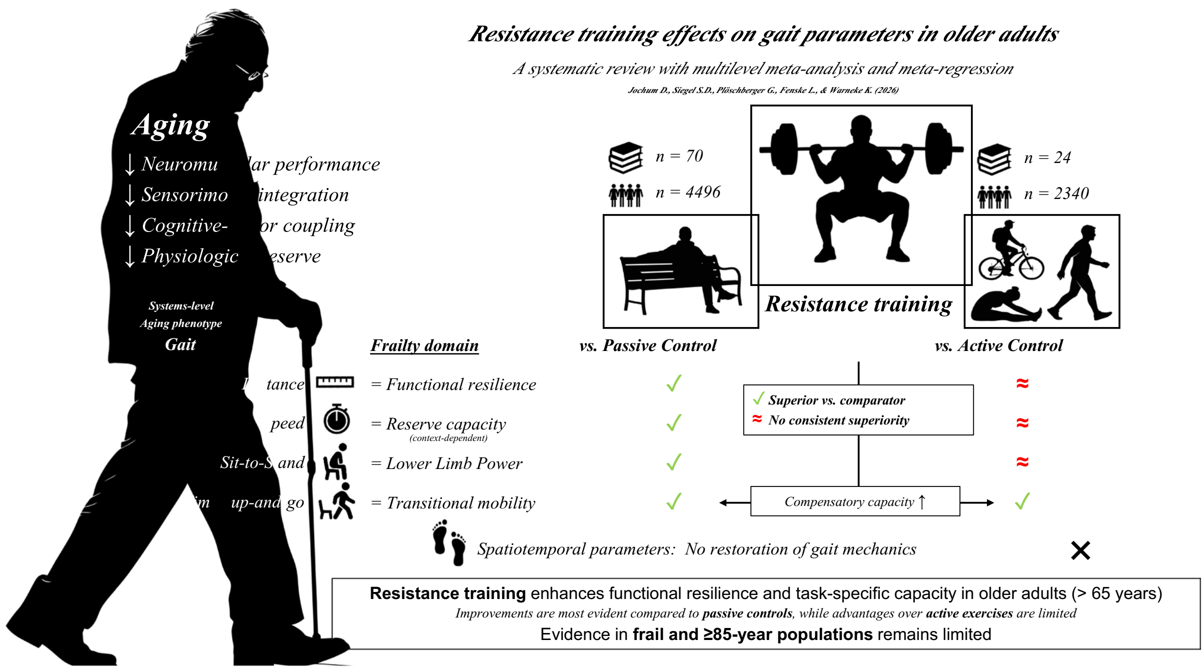
Graphical Abstract



Keywords Elderly · Fall prevention · Functional performance · Strength · Walking

Introduction

The demographic change is one of the biggest health-economical challenges of our times [1]. Forecasts indicate that individuals over 65 years will constitute more than 20% of the population in many countries by 2050 [2] facing societies—especially healthcare systems—with unprecedented challenges. Herein, frailty is described as a geriatric syndrome which manifests in a reduced function of numerous physiological systems and a generally enhanced vulnerability to extrinsic stressors to cause serious health problems [3]. The frailty (index) classification is based on the accumulation of age-related deficits [4, 5]. Despite a generally increased mortality including metabolic and cardiorespiratory diseases accompanying aging populations [6], sarcopenia is closely linked to frailty [7]. The age-related substantial muscle mass and strength declines have fatal consequences for health parameters including sociopsychological outcomes, e.g. quality of life and independence [8], but also (and bilaterally related) orthopaedic risk factors, e.g. for falls [9, 10].

Falls must be considered a multifactorial construct influenced by, among others, medication, osteoarthritis, depression, dizziness, or sarcopenia [11] inducing disturbances in balance and gait. Related injuries reflect a substantial percentage of orthopaedic indications in older adults with a strong association [12]. In 2008, the World Health Organization (WHO) estimates that approximately 28–35% over 65 years and even up to 42% of people over 70 years fall once per year, causing substantial financial costs with meaningful reductions in quality of life [13]—with an increasing tendency prognosed since decades [14]. One serious consequence of falls is hip fractures, with about 250,000 cases alone in the USA [15] and hospitalization times five times higher than other injuries [16] such that about 17 million years of life were lost from fall-related injuries [17].

Although frailty-related falls might be preventable, evidence for interventions to prevent the onset or progression of frailty is scarce [18]. The WHO has called for intensified research to identify predictors of falls and to develop effective prevention and rehabilitation strategies, including clinically relevant exercise interventions for vulnerable populations—a position supported by several geriatric researchers [3, 10, 13, 19]. A close epidemiological, biological, and clinical link between frailty, sarcopenia, and falls has been outlined [7]. This relationship finds application in current frailty concepts, listing strength production capability, unintentional weight loss, and gait velocity as three out of five frailty criteria to differentiate older adults having frailty from those with pre-frailty or no frailty [3]. Accordingly, gait performance, described as the interaction of neuromuscular strength, sensorimotor integration, balance control, and cognitive-motor coupling [20], was significantly associated with lower-limb force production [21].

When seeking for enhanced strength parameters, resistance training is the most recommended and applied exercise intervention to counteract age-related muscle- [22] and strength loss [23–25] with indicated positive effects on gait parameters (straight-line walking speed) [26]. This previous review included 28 studies but herewith missed substantial body of evidence on numerous physical function outcomes in older adults [24]. Although resistance training is included in the 2022 world guidelines for falls prevention and management for older adults [27], a comprehensive review with effect size (ES) quantification considering resistance training moderator variables such as intensity, frequency, or intervened muscle groups in combination with up-to-date meta-analytical procedures is urgently needed to avoid drawing invalid conclusions for exercise recommendations in older populations [18]. Furthermore, previous systematic reviews [23, 26] opposed resistance training to a passive control, which allows conclusions if resistance training is one viable option, but effects can hardly be specifically attributed to resistance training. To differentiate resistance training effects and explicitly recommend it as a necessary prevention strategy, the effectivity must significantly surpass effects of alternatives.

This work has therefore two objectives. Firstly, the systematic review will synthesize currently available high-quality evidence on the effects of strength training interventions on gait parameters and other functional outcomes commonly implemented in older adult testing batteries. Secondly, existing guidelines calling for the implementation of resistance training into prevention and treatment programmes will be critically reviewed by opposing resistance training to alternative interventions to differentiate specific effects from generalized enhanced physical activity effects on critical gait outcomes.

Methods

To answer the research question whether and to which extent resistance training improved gait parameters, a systematic review with robust variance estimation meta-analysis with subgroup analyses and meta-regression was conducted. The exact procedure adhered to ethical publishing standards [28] and was pre-registered in the International Prospective Register for Systematic Reviews (PROSPERO) (CRD42024587830). The structure of the review follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [29] guidelines. The PRISMA-Checklist is attached in the Supplemental Material; see SM01.

The analysis is divided into two parts. In the first part, the study investigates if resistance training is a viable intervention to positively affect gait parameters. Therefore, resistance training routines are opposed to a passive control condition. Since the comparison to a passive condition does not provide any information on specific resistance training effects, as potential parameter moderation might stem from solely enhanced physical activity, the second part of the study opposes resistance training effects to an active comparison to synthesize whether resistance training is advisable compared to other interventions. The detailed procedure is described in the following.

Eligibility criteria

The search term was built following the PICO (Participants/Patients, Intervention, Comparison, Outcome) guidelines [30, 31]: Original Research articles in English language were included if they used:

P: generally healthy participants with a mean age older than 65 years
I: lower body resistance training interventions. To discriminate resistance training interventions

from alternative treatments, the resistance training definition from Rath [32] was adopted. "Strength training is a type of physical exercise specializing in the use of resistance to induce muscular contraction which builds the anaerobic endurance, size of skeletal muscles and strength. […] The terms weight training and resistance training are also called strength training and used synonymously by coaches and trainers for the development of strength. Resistance training is any exercise that causes the muscles to contract against an external resistance with the expectation of an increase in strength, tone, mass and muscular endurance. The external resistance can be dumbbells, free weights, rubber bands, your own body weight (…). Weight training is also performed through barbell with weight plates, single station weight machines, multi gym, dumbbells (…). Strength training is a method of improving muscular strength by gradually increasing the ability to resist force through these free weights, machines and players' own body weight." (P. 37).

C: The analysis was divided into two parts. Firstly, resistance training effects were opposed to a passive control (is resistance training a viable intervention to improve gait parameters). Secondly, an active control comparison was opposed to discriminate specific resistance training effects against sole enhanced physical activity effects in older adults. Active control condition was defined as comparison to another group with an alternative training (e.g. walking, stretching, multicomponent exercises without resistance training).

O: gait and walking parameters (Specifically: gait speed, distance or time to cover a certain distance or climb a certain stair; single repetition sit-to-stand as part of the timed up-and-go test; other spatiotemporal step parameters, e.g. length, width, cadence; joint moments during walking; phase distributions of stand and swing phase). Strength output development was extracted as a secondary control variable to investigate the general effectivity of the training intervention.

Studies on patients were not considered eligible. Furthermore, if authors did not report mean (M) or standard deviations (SD), nor could these be imputed from graphical illustrations or the authors did not respond to our request to provide the original values, the evidence could not be considered under highest quality standards to this analysis. Also, studies in which the active control group performed the same intervention but modified the intensity (e.g. high versus low intensity resistance training) or combined interventions were excluded. Training interventions were considered combined or multicomponent exercises if the resistance training intervention was just a by-product, meaning that the objective of the study was to investigate not sole resistance training effects. If a study applied different exercises as a warm-up, the study remained eligible, as warm-up routines are oftentimes considered a mandatory component of safe resistance training programmes.

Literature search

The search-term guided literature screening was conducted in three online databases (Web of Science™, MEDLINE (PubMed), and Scopus) in February 2025. Specific search terms based on the requirements of each database were produced with the exemplary PubMed database search term provided in the following:

("Strength training"[Title/Abstract] OR "Power training"[Title/Abstract] OR plyometrics[Title/Abstract] OR "resistance training" [Title/Abstract] OR "muscle training" [Title/Abstract] OR strengthening [Title/Abstract]) AND ("dynamic balance"[Title/Abstract] OR "Timed up and go"[Title/Abstract] OR "Time up and go"[Title/Abstract]OR Walking[Title/Abstract] OR walk[Title/Abstract] OR Gait[Title/Abstract] OR Stride[Title/Abstract] OR "functional mobility"[Title/Abstract]) AND (Elderly OR elderlies OR seniors OR senior OR old)

Further database-specific search terms are provided in the Supplemental Material (Supplemental Table ST01). The search was conducted independently by three researchers (DJ, GP, and LF).

Methodological study quality and risk of publication bias

The Physiotherapy Evidence Database (PEDro) scale [33, 34] was used to assess risk of bias by two independent investigators (DJ and GP). In case of no consensus, the final decision was made by a third examiner (SDS).

Additionally, the risk of publication bias [35] was assessed by visually inspecting the modified funnel plots for multiple study outcomes [36]. Quantification was supplemented via the Egger's regression tests with an extension for intra-study effect size dependence [36].

Certainty of evidence

Recommendations, Assessment, Development, and Evaluation (GRADE) criteria [37] were applied to rate certainty of evidence. As per guidelines, certainty of evidence including randomized controlled trials was classified as high and potentially downgraded by one to two levels in case of the risk of bias score (−1 if PEDro score indicated moderate risk of bias and −2 in case of high risk of bias), inconsistency (−1 if some heterogeneity is present and −2 if severe heterogeneity is present but it has not been possible to identify through subgroup analysis why variability is present), indirectness (−1 if some indirectness regarding population, intervention, comparator or outcomes exists and −2 in case of severe indirectness from several sources), imprecision (−1 if not more than 400 participants are available), and reporting bias (−1 if few studies are included and funnel plots appear asymmetrical). In contrast, large effect sizes (+1 if studies yield large magnitude intervention effects, +2 if studies yield very large and consistent magnitude intervention effects) indicated dose-response gradient (+1 if there is a relationship between training intensity and the ES) and plausible confounders (+1 if all confounding factors were controlled). Accordingly, potential certainty of evidence categorization comprised: "very low" (effect estimate very uncertain), "low" (further research very likely changing the effect estimate), "moderate" (further research may change the effect estimate), or "high" (further research unlikely to change the effect estimate).

Treatment characteristics

Resistance training was typically described with the following parameters presented in Fig. 1.

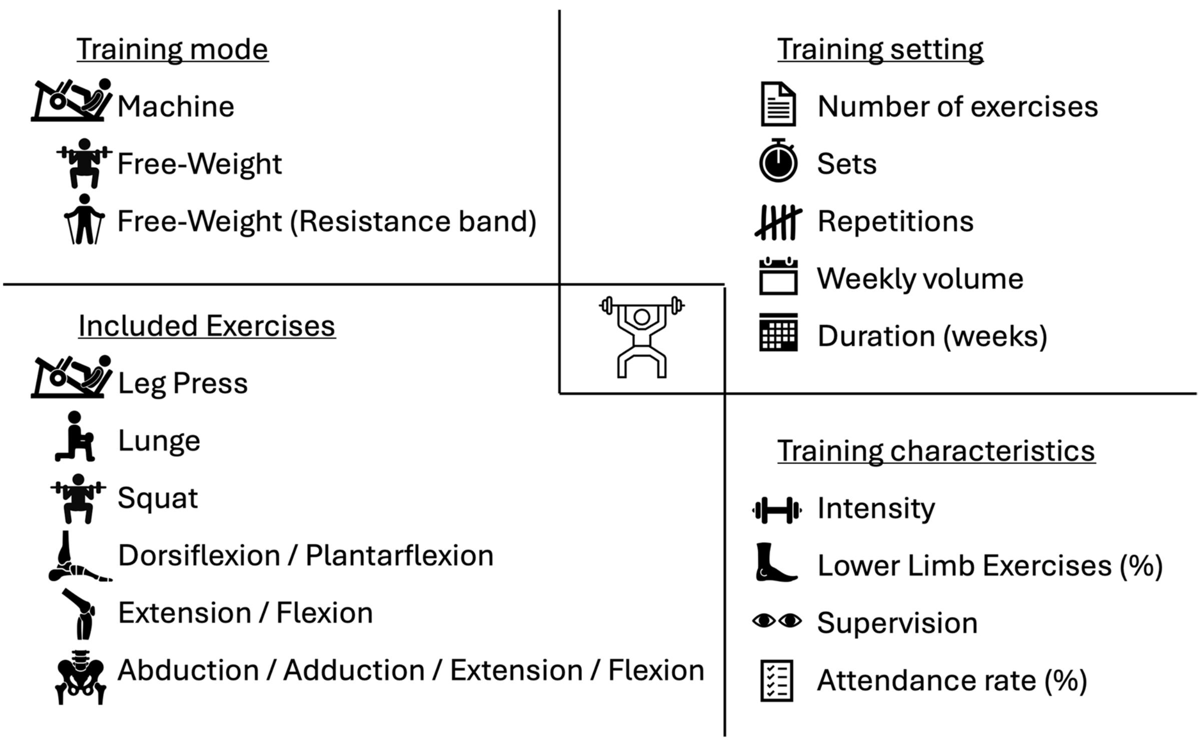


Fig. 1 The descriptive parameters of resistance training interventions

Definitions and terms

Gait outcomes generally included parameters assessing walking performance through measures of gait speed or walking distance. These outcomes were based on direct measurements of walking velocity, the time required to cover a predefined distance, the distance covered within a fixed time interval, or combinations of these. In addition, several studies reported outcome measures that combined gait performance with elements of functional strength or strength endurance [38, 39]. To provide a comprehensive clustering, the following categories were evaluated:

Gait speed (level walking) was defined as either a direct measure of walking velocity or the time required to cover a predefined distance on level ground. This category included short-distance walking tests commonly used to assess habitual or fast-paced walking performance [40–42].

Walking Distance (flat) was defined as the distance covered within a fixed time period during continuous walking. These outcomes were used to quantify endurance-related walking performance and sustained mobility capacity [43, 44].

Sit-to-stand (single repetition) quantifies the time required to rise from a seated position for one complete repetition. This task represents a fundamental functional movement frequently assessed in older adults and reflects lower-limb functional performance [45, 46].

Timed up-and-go (TUG) integrates sit-to-stand performance, dynamic balance, turning capacity, and short-distance walking into a single indicator of transitional mobility [47].

Stair climbing performance was defined as either the velocity or the time required to ascend a predefined number of steps. Stair negotiation was considered a demanding functional mobility task and was included when assessed as a timed or velocity-based outcome [48, 49].

Step-based and obstacle negotiation tests were defined as tasks requiring walking over obstacles or elevated surfaces within a predefined distance or time. These outcomes were used to assess task-specific walking performance under increased mechanical or coordination demands [50, 51].

Spatiotemporal parameters were analyzed as a separate category. These included spatial parameters (e.g. step length) and temporal parameters (step time and cadence), phase-related parameters (temporal parameters as a percentage of total gait cycle) as well as measures of gait variability and kinetic parameters such as joint moments. Muscle activity during walking was not involved.

Strength parameters generally included a measure of external load or resistance that was moved in the following clustered joint or functional movements according to specific strength training exercises (see Fig. 2). Noteworthy, multiple repetitions sit-to-stand tests were classified as strength parameters [52] and distinguished from the functional single repetition sit-to-stand gait parameter.

Data processing and statistics

Data were extracted independently and double-checked by DJ, GP, and LF. For further processing,

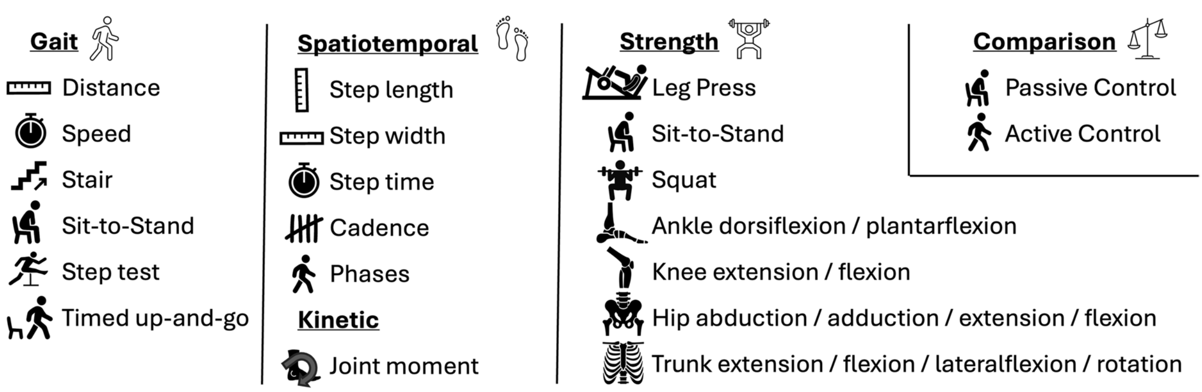


Fig. 2 An overview of the parameters investigated in the review

collected means (M) and standard deviations (SD) were inserted in an Excel spreadsheet, and mean differences as well as pooled standard deviations were calculated using the following formulas, as required for the robust variance estimation (RVE) package in R [53]:

$$M_{DIFF} = M(posttest) - M(pretest)$$

Standard deviations were pooled as follows:

$$SD_{pooled} = \sqrt{\frac{\left(n_1 - 1\right) * SD_1^2 + \left(n_2 - 1\right) * SD_2^2}{\left(n_1 - 1\right) + (n_2 - 1)}}$$

As suggested by Fisher and Tipton [53], the RVE meta-analytical calculation model was chosen to account for dependent multiple study outcomes with unknown origin of variance [54–56]. The effect sizes (ES) for the resistance training group and comparisons (passive control and alternative intervention) are given as standardized mean differences (SMD) and 95% confidence intervals (CI).

Pooled ES were interpreted as follows: $0 \leq ES < 0.2$ trivial, $0.2 \leq ES < 0.5$ small, $0.5 \leq ES < 0.8$ moderate, and $ES \geq 0.8$ large [57]. All calculations were performed using R and the robumeta package [53], considering study design (parallel and cross-over design). Results were visualized with Microsoft Excel (Version 16.84, Microsoft Corporation, Redmond, WA, USA).

Sensitivity analyses

To minimize methods and outcome heterogeneity (τ^2), subgroup analyses were performed for controls (passive, active), further active controls (walking, stretching), sex (women, men), training mode (machine-based, free-weight, resistance bands) [58], supervision (supervised, unsupervised) [59], studies with blinded assessors, incorporated exercises (leg press, lunge, squat, ankle dorsiflexion, ankle plantarflexion, knee extension, knee flexion, hip abduction, hip adduction, hip extension, hip flexion), and intensity assessment (percentage of 1RM, rating of perceived exertion, colour of resistance band, feeling).

Meta-regression

Furthermore, meta-regression was conducted to assess ES correlation with participants' mean age, the proportion of lower-limb strength exercises, the PEDro score, the intensity (%1RM), strength training frequency (weekly volume, total sessions), and the reported attendance rate. Additionally, the ES of the strength measurements was used to investigate if higher strength increases (leg press, sit-to-stand, knee extension, knee flexion, ankle plantarflexion, ankle dorsiflexion, hip extension, hip flexion, hip adduction, hip abduction, trunk extension, trunk flexion, trunk lateral flexion, trunk rotation) led to higher effects on gait parameters.

Results

Qualitative analysis

Search results

Figure 3 illustrates the literature search procedure, which resulted in 92 studies [40–46, 48–51, 60–140] meeting the inclusion criteria. Study characteristics are summarized in Supplemental Table ST02.

In case of missing original values (M and SD), data were requested from the authors or imputed from graphics if possible. Accordingly, studies could exclusively be considered for further inclusion if (1) authors sent the requested data, or (2) M and SD could be imputed from graphics [115, 128, 131]. Some studies reported standard error ($n = 9$) [42, 50, 51, 61, 63, 75, 122, 130, 131] or 95% CI ($n = 4$) [64, 113, 123, 129], from which the SD was calculated [141].

Participants

In total, 92 studies were included that incorporated 5932 participants with a peak sample size of 388 participants [85]. Analysis was performed on 5260 participants (minimum, $n = 16$ [49]; maximum, $n = 352$ [85]) with 3545 females and 1645 males as the overall drop-out rate summed up to 672 participants (maximum, 64 [121]). This number is influenced by reporting, as some studies described the sex distribution including later drop-outs (women = 558, men = 361), while most studies reported them without (women = 2987, men = 1284). Four studies did not account for sex distribution [46, 62, 76, 77, 90]. Twenty studies included just women ($n = 965$) [45, 69, 72, 75,

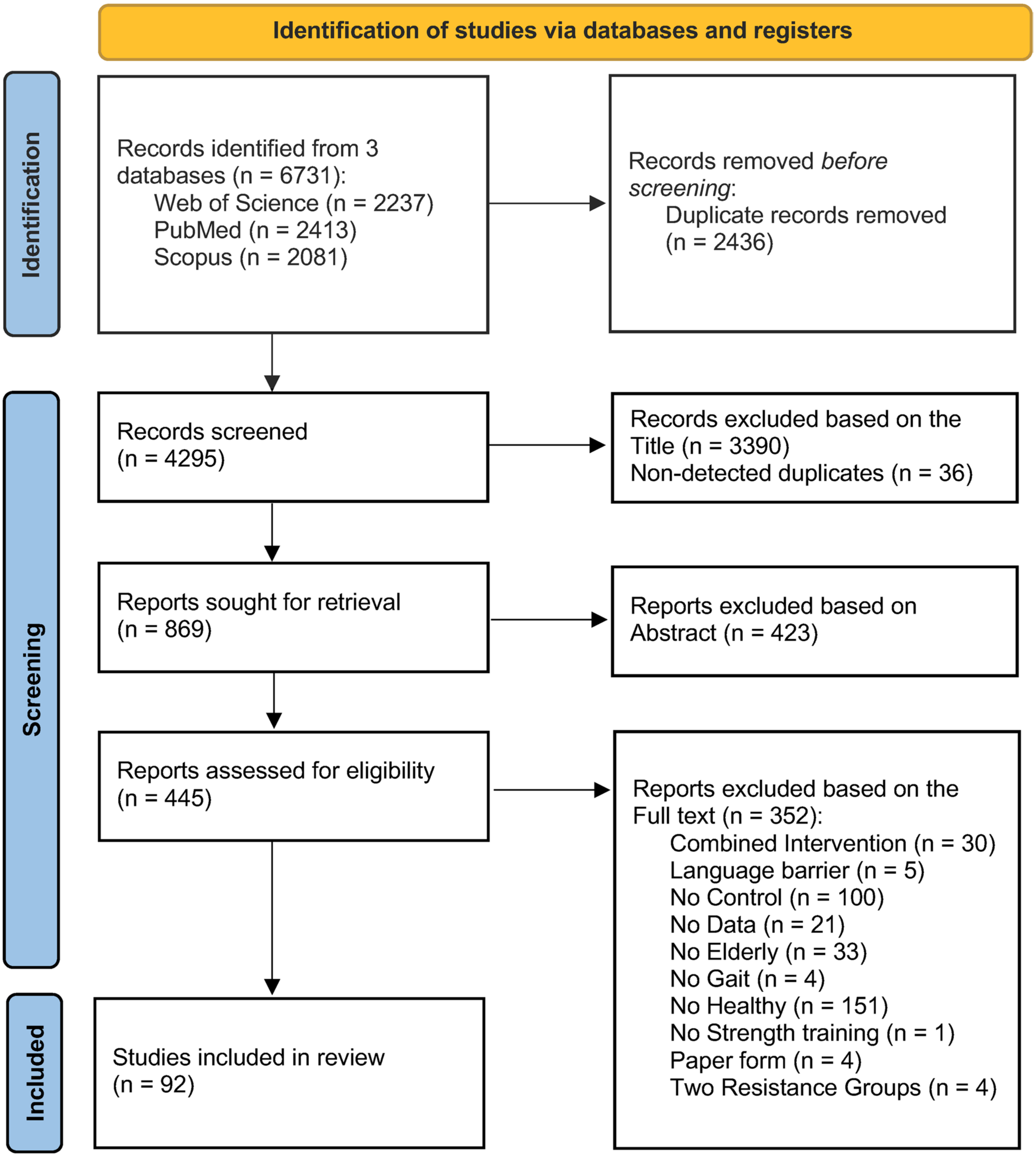


Fig. 3 The PRISMA flow chart with the search procedure including title, abstract, and full-text screening

78, 82, 84, 86, 94, 95, 101, 102, 106, 113, 117, 118, 128, 132, 135] and two studies included men only ($n = 165$) [79, 140]. The overall mean age was 73.1 ± 4.9 years (minimum, 65 years [124]; maximum, 90 years [69]).

Methodological quality, risk of bias, and certainty of evidence

Overall, the quality of the 92 included studies averaged 5.4 ± 1.4 (range 2–9) on the PEDro scale indicating fair methodological quality (Supplemental Table ST03). Certainty of evidence was initially rated as high as almost all included studies were randomized controlled trials and was downgraded for risk of bias (1 level, PEDro score being fair). As the heterogenous gait parameters reported similar effect direction and as several subgroup analyses were performed, inconsistency due to heterogeneity as well as indirectness regarding comparators was diminished but still need to be considered in the overall analysis of all gait parameters. Further, as the population (healthy older adults with a mean age > 65 years), intervention (resistance training), and outcomes (clinically relevant gait parameters) present directness, we see no need to downgrade. Imprecision seems unlikely due to the high number of participants ($n = 5260$) but seems reasonable in some subgroup analyses with only a few studies. Publication bias was reviewed using funnel plots and showed overall (Fig. 4) a slight asymmetry, with more small studies showing positive effects, but seems not severely distorted. Therefore, as all other criteria did not lead to either down- or upgrading, certainty of evidence was finally rated as moderate for resistance training effects on gait parameters.

Treatment characteristics

Most of the resistance training was supervised ($n = 60$) [40, 41, 44, 48, 49, 51, 61, 63, 66–68, 70–72, 74–76, 78, 80–87, 89–92, 95, 97–103, 105–107, 109, 111–114, 118–120, 122–125, 127, 129, 133–138]. Four studies performed unsupervised training [93, 98, 132, 139], while six studies used a combined approach [45, 46, 64, 77, 130, 131]. This includes, for instance, one supervised session at the facility and two home-based trainings [77]. The remaining 21 studies did not provide information about exercise supervision [42, 50, 60, 62, 65, 69, 79, 88, 94, 96, 104, 108, 110, 115–117, 121, 126, 128, 140].

Training was performed on machines ($n = 26$) [44, 50, 71, 79, 83, 86, 89–91, 99, 102, 103, 110, 116, 118, 121, 123, 124, 126, 128, 129, 133, 134, 136] or with free weights ($n = 41$) [45, or a mix of both ($n = 14$) [42, 68, 70, 72, 76, 78, 82, 95, 100, 111, 113, 114, 117, 119]. Combined with free-weight training, 28 studies incorporated resistance bands in their training [45, 46, 49, 51, 65–67, 69, 74, 77, 84, 85, 92, 93, 96, 104, 106–108, 112, 115, 120, 122, 130, 132, 135, 138, 140]. Two studies did not report the mode of training [48, 75].

The number of different exercises averaged around 7 exercises, ranging from 1 [124, 133, 134] to 21 [111] exercises. Three studies did not report the number of exercises [49, 112, 120].

From the description of exercises, lower body exercises constituted on average 58.9% of the workout programme. Eight studies incorporated leg exercises only [46, 51, 124–126, 128, 133, 134]. In contrast, three studies focused exclusively on trunk exercises [87, 127, 132]. Thirty-four studies used the leg press [40, 41, 44, 60, 62, 68, 70–72, 79, 83, 85, 86, 89–91, 95, 98, 103, 110, 114, 116–119, 121, 123, 126, 128, 133–136], 33 involved the squat [46, 49, 65, 66, 70, 72, 73, 75, 77, 78, 80–82, 84, 88, 92, 94, 99, 102–104, 106, 111, 113, 119, 122, 124, 129, 130, 135, 137–139], and four studies performed lunges [64, 84, 111, 115]. Furthermore, the knee extension was trained in 43 studies [40–46, 48, 50, 62, 63, 67, 69, 71, 73, 74, 78, 79, 82, 86, 89, 90, 94–97, 100, 102, 105–109, 113, 117–119, 123, 125, 126, 128, 135, 136] and the knee flexion in 39 studies [40–45, 48, 50, 62, 63, 69, 71–75, 79, 82, 86, 89, 90, 94–97, 100–102, 107–109, 117–119, 123, 128, 130, 135, 136]. Ankle plantar flexors were targeted in 45 studies [40, 41, 44, 48, 50, 60, 62, 67–70, 74, 75, 77, 78, 80, 81, 85, 86, 89, 91, 92, 94–98, 100–102, 104, 105, 107, 108, 113, 116, 120, 121, 123, 126, 128, 130, 135, 136, 139] and the ankle dorsiflexion in 15 studies [42, 44, 69, 74, 77, 85, 92, 96, 100, 104, 107, 108, 113, 120, 130]. The remaining studies were conducted to strengthen the hip abduction ($n = 22$) [42, 44, 45, 51, 67, 69, 74, 77, 85, 92, 94, 96, 97, 101, 104, 107, 108, 113, 126, 135, 139, 140], hip adduction ($n = 14$) [44, 45, 51, 67, 69, 74, 77, 78, 96, 104, 107, 108, 113, 126], hip flexion ($n = 26$) [45, 46, 49, 50, 67, 69, 74, 77, 80, 81, 85, 94, 96, 99, 104–108, 113, 115, 129, 130, 138–140], and hip extension ($n = 15$) [42, 45, 50, 69, 74, 77, 85, 96, 97, 104, 107, 108, 111, 119, 126].

The training characteristics were typically described in a target range, e.g. 8 to 12 repetitions [92]. The training duration and load typically progressed over the course of the study, e.g. 30 min in weeks 1 to 4 up to 60 min in weeks 16 to 24 with weight increases when completing 12 repetitions easily [94]. For quantitative representation, the maximum value was used, normally at the end of the study. On average, the studies comprised 3 sets (range

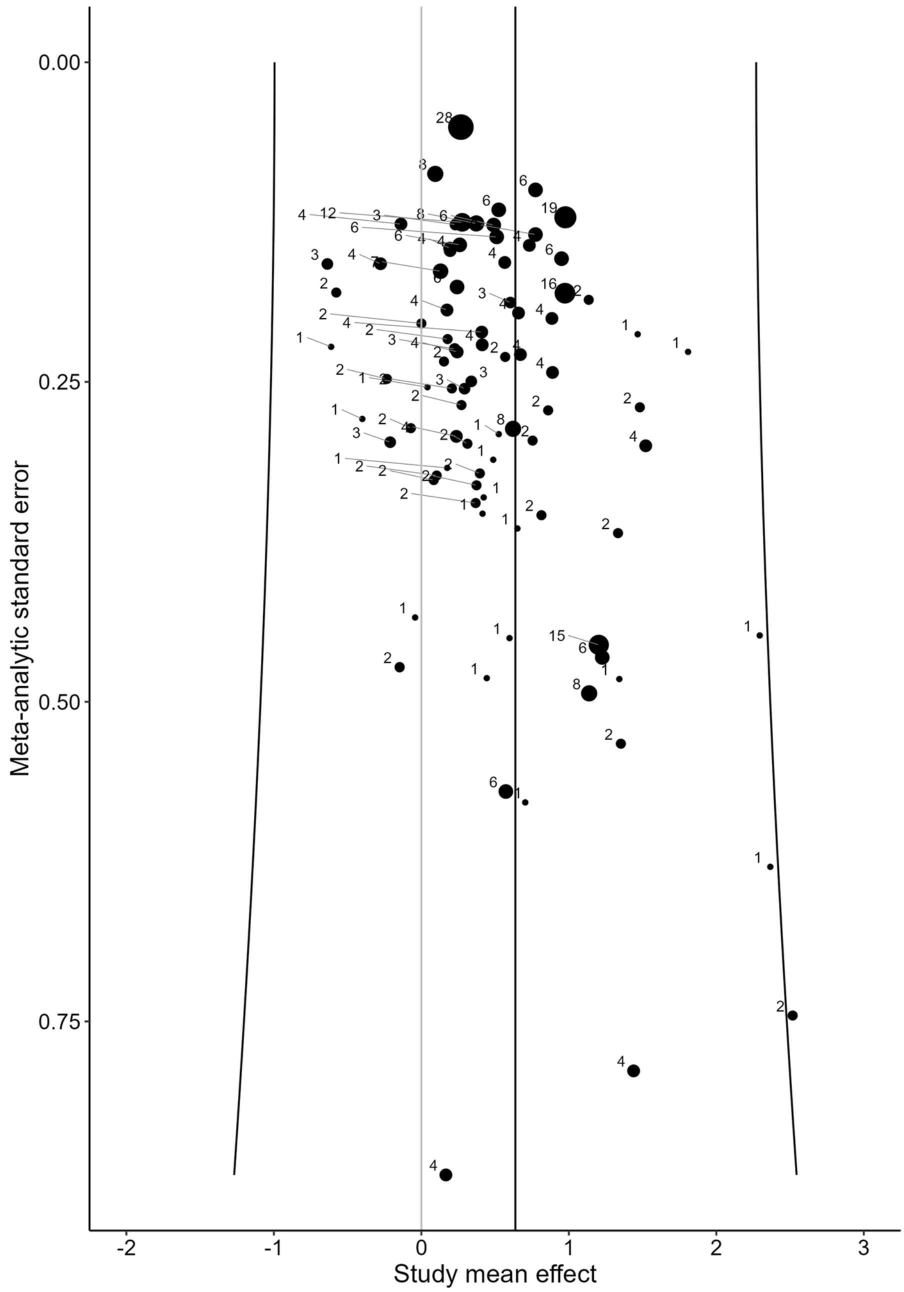


Fig. 4 The funnel plot for the overall gait parameter analysis

1 to 10) of 12 repetitions (range 1 to 45) in workouts of 52 min (range 15 to 90 min). Participants were asked to perform 2.6 sessions per week (range 1 to 14 sessions) over 15 weeks (minimum, 5 weeks [83]; maximum, 52 weeks [68]), averaging 41 sessions (minimum, 10 sessions [83]; maximum, 364 [132].

Intensity of training was quantified using percentage of 1RM ($n=31$) [42–44, 50, 63, 68, 73, 74, 76, 79, 80, 82, 86, 89–91, 99–101, 103, 106, 110, 116–118, 125, 126, 128, 133, 134, 136], percentage of maximum weight of several repetitions (e.g., 3RM) ($n=6$) [40, 41, 62, 70, 71, 78], percentage of peak power [83], rating of perceived exertion ($n=14$) [48, 64, 75, 84, 85, 88, 92, 94, 97, 105, 108, 113, 135, 138], other feeling descriptions ($n=6$) [46, 77, 87, 107, 127, 130], or the colour of the resistance band ($n=4$) [51, 67, 115, 120]. Twenty-nine studies did not provide information on intensity estimation [45, 49, 60, 65, 66, 69, 72, 81, 93, 95, 96, 98, 102, 104, 109, 111, 112, 114, 119, 121–124, 129, 131, 132, 137, 139, 140].

Attendance rate to exercise sessions was reported in 65 studies [41, 42, 44–46, 48–51, 60, 61, 64–68, 70–72, 74, 75, 77–82, 84–87, 89, 90, 92, 93, 99–102, 106, 107, 110–114, 116–118, 121–131, 135–137, 139] and averaged 86%. The lowest attendance rate was 43% [121], while five studies reported 100% compliance with the training programme [78, 86, 90, 118, 139].

Quantitative analysis

Strength parameters

Resistance training induced strength effects were monitored as a control parameter and confirmed the effectivity of resistance training on force production capacity in the overall analysis by a large effect size (ES = 0.86, $p < 0.001$, $\tau^2 = 0.65$, n/ES = 73/361) (Fig. 5) as well as for individual muscle groups. Most effects were reported for knee extension maximum strength (ES = 0.59, $p < 0.001$, $\tau^2 = 0.29$, n/ES = 41/122) and knee flexion strength (ES = 0.60, $p = 0.030$, $\tau^2 = 0.27$, n/ES = 16/53). Largest effects were obtained for ankle plantarflexion (ES = 1.25, $p = 0.036$, $\tau^2 = 1.38$, n/ES = 10/25), hip abduction (ES = 1.07, $p = 0.014$, $\tau^2 = 0.00$, n/ES = 6/14), trunk flexion (ES = 0.62, $p = 0.003$, $\tau^2 = 0.00$, n/ES = 2/3), and multi-joint movements leg press (ES = 1.29, $p = 0.012$, $\tau^2 = 0.89$, n/ES = 11/22). Multiple muscle groups were involved in the sit-to-stand test showing large resistance training induced performance increases (ES = 0.93, $p < 0.001$, $\tau^2 = 0.58$, n/ES = 35/74). The overall strength effect of resistance training was larger when compared to a passive control group (ES = 0.97, $p < 0.001$, $\tau^2 = 0.78$, n/ES = 58/272) than an active control intervention (ES = 0.56, $p = 0.003$, $\tau^2 = 0.26$, n/ES = 20/89). No further subgroup analyses were performed as strength was used as a control parameter.

Gait performance and functional mobility

Moderate certainty of evidence revealed moderate magnitude positive gait effects (Fig. 6) (ES = 0.59,

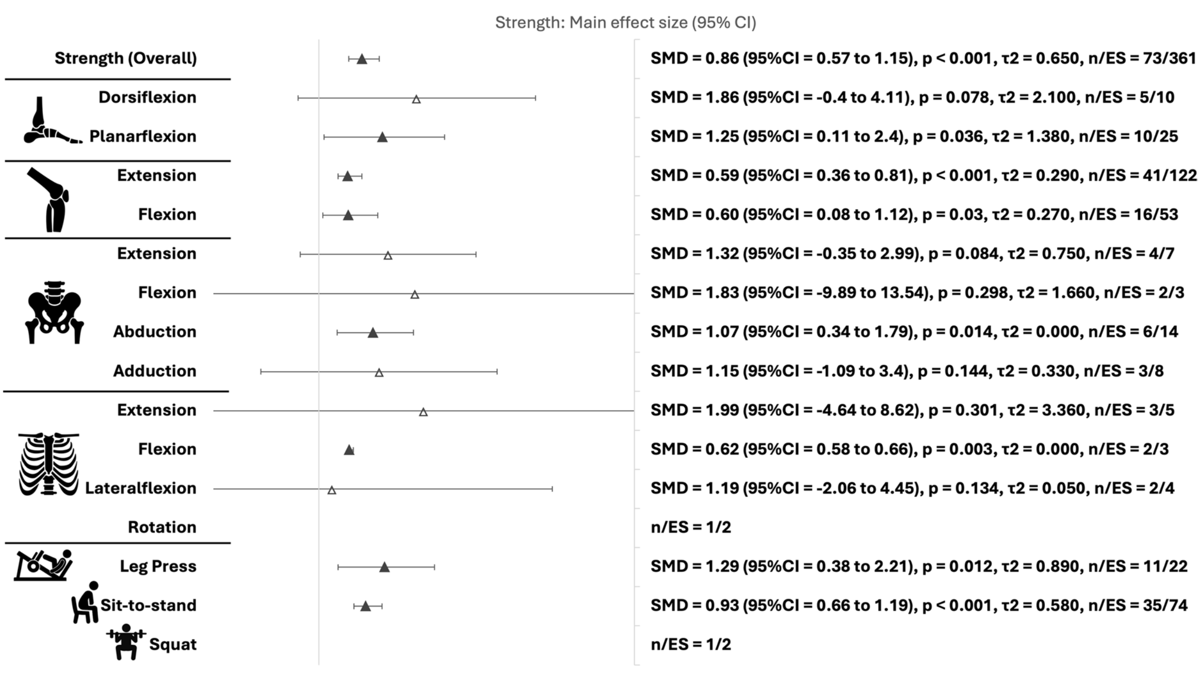


Fig. 5 The meta-analysis results for resistance training effects against both active and passive controls on strength in older adults extracted from the included gait studies with subgroup analyses

$p < 0.001$, $\tau^2 = 0.45$, n/ES = 91/360). Gait velocity was the most investigated gait parameter and showed significant resistance training induced improvements (ES = 0.41, $p < 0.001$, $\tau^2 = 0.28$, n/ES = 61/137), while the largest effects were found in the timed up-and-go performance (ES = 0.97, $p < 0.001$, $\tau^2 = 0.75$, n/ES = 48/109). Also, in the overall analysis, the other gait parameters such as gait distance (ES = 0.65, $p = 0.003$, $\tau^2 = 0.42$, n/ES = 20/56), stair climb (ES = 0.29, $p = 0.028$, $\tau^2 = 0.02$, n/ES = 12/32), and single-repetition sit-to-stand (ES = 0.42, $p = 0.017$, $\tau^2 = 0.11$, n/ES = 11/20) were positively influenced as well.

To differentiate specific resistance training effects from generally enhanced physical activity effects, intervention effects were evaluated against the passive control (Part I) and active control (Part II) comparisons with a focus on most evaluated parameters and where a sufficient number of studies were available. These comprise gait speed, gait distance, sit-to-stand, and timed up-and-go.

Subgroup analyses against passive control Moderate certainty of evidence exists for moderate magnitude resistance training effects on gait parameters when opposed to passive controls (ES = 0.73, $p = 0.001$, $\tau^2 = 0.48$, n/ES = 69/266). Further gait analyses distinguished between velocity parameters (ES = 0.51, $p < 0.001$, $\tau^2 = 0.28$, n/ES = 48/101) and walking distance (ES = 0.81, $p = 0.003$, $\tau^2 = 0.37$, n/ES = 15/46). Frailty-related neuromuscular strength/power tests, e.g. the sit-to-stand (ES = 0.62, $p = 0.008$, $\tau^2 = 0.01$, n/ES = 8/13) and the timed up-and-go (ES = 1.20, $p < 0.001$, $\tau^2 = 0.82$, n/ES = 37/78), revealed positive effects as well (Supplemental Figure SF01).

Subgroup analyses showed influence of several moderators. With respect to training-related parameters, higher ES were observed when training was performed using machines and free weights (ES = 0.45–1.14; $p = 0.005$–0.031), while programmes relying on elastic resistance bands did not significantly improve gait speed (ES = 0.37, $p = 0.132$) and timed up-and-go performance (ES = 1.24, $p = 0.133$). Training programmes incorporating leg press and plantarflexion exercises were associated with moderate to large improvements in gait speed, walking distance, and timed up-and-go performance (ES = 0.49–1.46; $p < 0.001$–0.048). Additional exercises, including squat, knee flexion, knee extension, and hip flexion, were associated with improvements in timed up-and-go and gait speed (ES = 0.53–1.26; $p = 0.001$–0.031). Highest effects were observed on gait speed, with hip abduction (ES = 0.62; $p = 0.043$) and leg press showing the highest effects for the timed up-and-go performance (ES = 1.46; $p = 0.001$). Regarding training intensity, the largest effects were observed in programmes prescribing resistance training based on a percentage of 1RM (ES = 0.66–1.02; $p < 0.001$–0.004). Furthermore, the effectivity of training was improved by supervision (supervised: ES = 0.45–1.37; $p < 0.001$–0.026; unsupervised: not enough studies for analysis). In contrast, when assessors were blinded, ES diminished (ES = 0.36–1.09; $p = 0.006$–0.499). Sex subgroup analyses were not applicable due to missing sole male studies. For detailed information, see Supplemental Tables ST04 –ST08.

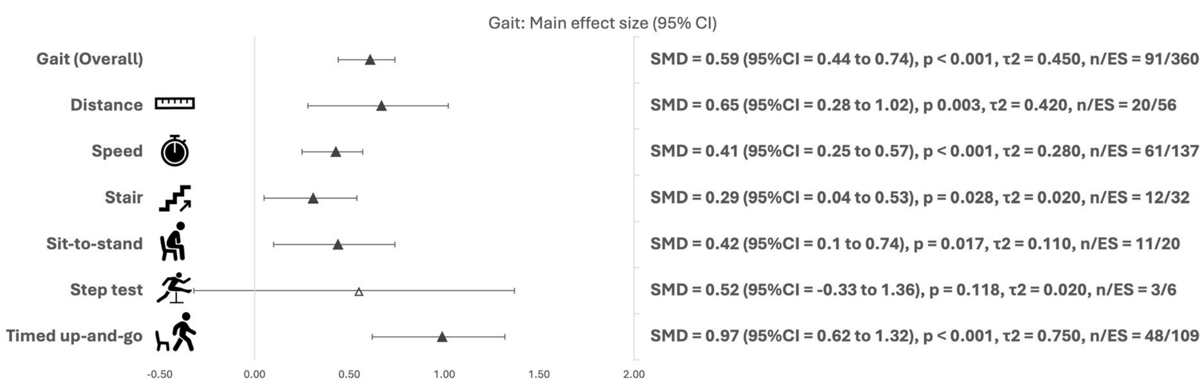


Fig. 6 Resistance training effects on gait parameters, showing falls-related gait tests separately as subgroup analyses

Subgroup analyses against active control Active control conditions comprising stretching, walking, agility, cycling, and multi-component exercise training were opposed to resistance training effects in 28 studies. With moderate certainty of evidence (Supplemental Figure SF02), resistance training effects still showed a significant but reduced ES against all active control conditions (ES = 0.22, $p = 0.013$, $\tau^2 = 0.12$, n/ES = 28/94). The effects for walking distance (ES = −0.07, $p = 0.720$, $\tau^2 = 0.09$, n/ES = 6/10), gait speed (ES = 0.17, $p = 0.096$, $\tau^2 = 0.06$, n/ES = 18/36), and sit-to-stand (ES = 0.10, $p = 0.690$, $\tau^2 = 0.02$, n/ES = 5/7) even dissipated when compared to the active control. The only exception was timed up-and-go performance, which dropped from large (Passive: ES = 1.20) to moderate (ES = 0.42, $p = 0.010$, $\tau^2 = 0.03$, n/ES = 14/31) when opposed to an active control condition. Exercise choice still moderated the effectivity. Only free-weight (ES = 0.32; $p = 0.029$) and resistance band training (ES = 0.36; $p = 0.038$) had significantly superior effects compared to alternatives (comprising walking, stretching, and multi-component exercises with balance aspects), with dorsiflexion training (ES = 0.26; $p = 0.045$) and hip abduction (ES = 0.29; $p = 0.020$) being the only exercises reaching the level of significance. For timed up-and-go performance, supervision had superior effects (ES = 0.48; $p = 0.029$), while not enough explicitly unsupervised studies were available for analysis ($n = 2$; ES = 4). Remaining moderators, e.g. sex, assessor blinding, or intensity did not moderate effects (Supplemental Tables ST09 – ST14).

Meta-regression Meta-regression analyses identified several training-related determinants of resistance training effects on gait and functional mobility outcomes. A higher proportion of lower-body exercises within the training programme was significantly associated with greater improvements in gait outcomes when compared with active control interventions ($b = -0.007$; $p = 0,028$; Supplemental Table ST16). In addition, strength gains induced by resistance training were positively related to improvements in gait and functional mobility (Supplemental Table ST22). Specifically, improvements in sit-to-stand performance were associated with greater effects across all gait outcomes ($b = 0.440$; $p = 0.010$), as well as walking distance, gait speed, and timed up-and-go performance ($b = 0.390$–0.551; $p = 0.007$–0.050). Further associations were observed for hip abduction strength in comparisons with active controls ($b = 7.571$; $p = 0.040$), hip flexion strength for gait speed versus passive controls ($b = 0.416$; $p = 0.033$), and trunk extension strength for timed up-and-go performance ($b = 1.633$; $p = 0.019$).

Beyond training-related factors, increasing age was associated with a decline in resistance training effects on gait outcomes overall and on timed up-and-go performance ($b = -0.041$; $p = 0.041$; Supplemental Table ST15).

In contrast, no significant associations were observed between gait outcomes and study quality (PEDro score), participant attendance, prescribed training intensity relative to one-repetition maximum, total number of training sessions, or weekly training volume ($p = 0.125$–0.989; Supplemental Tables ST17–S21).

Spatiotemporal and kinetic parameters

Spatiotemporal and kinetic parameters were not significantly influenced by resistance training ($p = 0.140$–0.577) (Fig. 7). Only a few studies ($n = 2$–8, ES = 4–25) could be clustered for the different kinematic parameters in comparison to both active and passive controls.

Discussion

The progressing demographic change faces societies with serious health-economic burdens, as frailty-related vulnerability increases falls risk, subsequent hospitalization, and mortality, calling for specialized and effective interventions targeting frailty prevention [3]. In accordance with the frailty diagnosis proposed by Fried et al. [4], frailty is conceptualized as a physical phenotype defined by the presence of three or more of the following criteria: muscle weakness, slow gait speed, low physical activity, exhaustion, and unintentional weight loss. Therefore, gait- and mobility-related outcomes and strength represent highly relevant functional outcomes, not only as indicators of peak performance, but as a marker for mobility and the maintenance of independence under conditions of multisystem biological aging [18]. Against this background, the present study synthesized the current

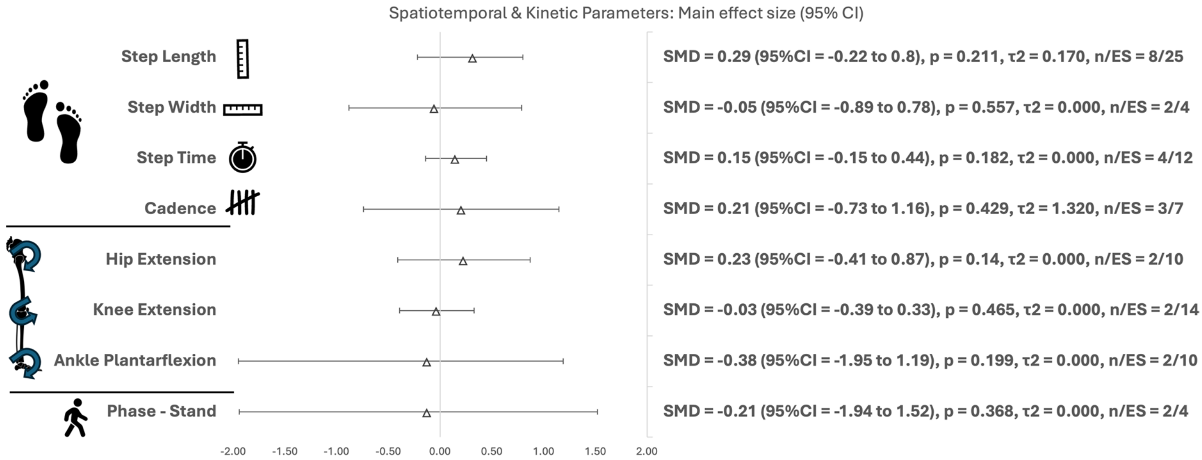


Fig. 7 Resistance training effects on spatiotemporal gait parameters

evidence on the effects of resistance training on gait- and mobility-related outcomes in older adults. To comprehensively summarize and interpret the findings, the study was divided into two study parts: Study part I, comparing resistance training with a passive control and study part II, comparing resistance training with an active control, with particular attention to the challenges in interpreting the results of this meta-analysis.

Resistance training effects

Assuming a causal relationship between general joint stability and functional strength capacity for daily tasks, e.g. walking, it was hypothesized that resistance training induced strength increases positively affected gait parameters [142, 143]. The first premise, therefore, is that resistance training induced significant strength increases as a control variable in this meta-analysis. The analysis of included resistance training studies against a passive control revealed large magnitude and positive effects on maximal strength tests in general (ES = 0.59–1.29). In accordance with previous analyses [144], this result confirmed the effectivity of resistance training in older adults on strength capacity.

It remains debated whether age-related declines in strength are driven primarily by biological aging or by reduced physical activity in older adults [25, 145]. Irrespective of causality, losses in muscle mass, strength, and neuromuscular control—together with neural and sensory decline—contribute to impaired gait stability and are central to frailty-related mobility decline [145–147]. In this context, it is well established that resistance training can counteract sarcopenia and associated strength loss in older adults [23, 142, 148–150].

Improvements in strength following resistance training are commonly attributed to neuromuscular adaptations, including more efficient activation and coordination of muscle groups, as well as enhanced recruitment and firing rate of motor units [151]. The physiological intent of resistance training is to induce high levels of neuromuscular tension [152], typically through progressive high-intensity loading approaching momentary muscle failure or a defined percentage of 1RM. This mechanical load activates anabolic signalling pathways [150], which drive muscle protein synthesis and hypertrophy [142], and promote muscle satellite cells activation [23], thereby supporting muscle repair and growth. However, in frail or inexperienced older participants, such loading schemes may be difficult to realize safely due to joint limitations, comorbidities, or lack of motor control [25, 153]. Consequently, strength gains in these populations may rely more strongly on neural and coordinative adaptations, including enhanced neuromuscular coordination and muscle fibre recruitment, rather than on maximal loading–induced hypertrophy [23].

Resistance training induced effects on gait and mobility

Results from 69 studies including 3980 participants revealed moderate to large magnitude effects

(ES = 0.51–1.20) of resistance training on gait- and mobility-related outcomes (τ^2 = 0.01–0.48), with largest magnitude effects on timed up-and-go. These findings indicate that resistance training not only reduces muscle weakness in older adults, but also improves gait speed, walking distance, stair climbing, and sit-to-stand performance—outcomes closely related to the second frailty criterion. In contrast, both passive and active control analyses revealed limited effects on spatiotemporal and kinetic gait parameters, suggesting that resistance training primarily enhances the capacity to perform strength-dependent functional tasks, while habitual gait control strategies remain largely unchanged.

Regarding training prescription, the results indicate that exercise mode and task relevance are more influential for gait improvements than load-based prescription. Programmes using free weights and machines that focus on the lower extremity, such as leg press, squat, and ankle strengthening, were associated with greater effects. In contrast, programmes using resistance bands showed limited or no effects, particularly when compared with passive controls. In addition, subgroup analyses indicated that both multi-joint (e.g. leg press and squat) and single-joint exercises of the lower limb were appropriate. This resonates with biomechanical models of gait, which emphasize ankle plantar flexor and knee extensor strength as key contributors to propulsion [154, 155] and stability [156] during walking. Although prescribed training intensity nor methods of intensity monitoring emerged as robust moderators of gait outcomes, supervised training was associated with larger effects. This may indicate that, without supervision, participants were less able to train within the prescribed workload.

While these results align, in parts, with previous analyses showing increased habitual [157], straight-line walking speed [26], and timed up-and-go [22, 158], the earlier conducted research lacked the quantitative comparison against a passive [26] or an active control group [159]. This is, however, necessary to determine whether observed effects are attributable to resistance training itself or merely reflect responses to generally enhanced physical activity and related fitness increases.

Interpretation problems on resistance training-induced strength effects on gait

When contrasted with active comparators, effects were markedly reduced (ES = 0.22) and remained significant only for the timed up-and-go (ES = 0.41). Despite this attenuation, resistance training continued to improve performance in time- and task-based outcomes closely related to fall risk and functional independence [160–163].

However, caution in interpretation is warranted. All included studies were performed in untrained participants, in parts community-dwelling populations [40, 41, 48, 49, 51, 60, 62, 63, 66, 70, 72, 82, 85, 87, 98–100, 105, 106, 110, 116, 122, 123, 125, 126, 129–134, 136–138] or were described as sedentary populations [43, 49, 71, 89]. Though some studies considered their participants as active [75, 78, 83, 111, 126], others described them as frail [46, 69, 97, 122, 138], limited in function [77, 91] or overweight [61, 84, 89]. In such samples, recent years evidence showed that so-called minimalist training approaches (including almost every exercise routine) were also sufficient to improve maximal strength [164]. These, however, did not exclusively perform resistance training in its common sense (see definition in Methods) but reached significant improvements even with few seconds isometric contractions per day [165], stretching [166], or other types of "exercise snacks" [167] which can hardly be understood as resistance training routines. Nevertheless, it must be noted that resistance training routines showed still positive effects in the active comparator analysis only for the timed up-and-go performance. However, ES magnitude diminished to ES = 0.42. This result calls current recommendations that emphasize resistance training specifically to improve gait speed and walking distance into question. Instead, these findings support the alternative interpretation that overall engagement in physical activity, rather than resistance training per se, may be sufficient to counteract frailty-related declines in habitual gait performance.

The intensity problem

Drawing valid conclusions from this type of resistance training literature is complicated by several methodological limitations. It is widely accepted that innervation properties and related effects crucially depend on the induced mechanical tension [152], thus training intensity. Physiologically, the area of mechanotransduction describes how mechanical stimuli were translated into specific physiological responses, underscoring the relevance of specific training stimuli when seeking specific central nerval responses. The large heterogeneity in training methods induced via free weights [45, 46, 49, 51, 65–67, 69, 73, 74, 77, 78, 80, 81, 84, 85, 87, 88, 92–94, 96–98, 104–108, 112, 115, 120, 122, 127, 130–132, 135, 137–140], some using resistance bands [45, 46, 49, 51, 65–67, 69, 77, 84, 85, 92, 93, 96, 104, 106–108, 112, 115, 120, 122, 130, 132, 135, 138, 140], exercise machines [40, 41, 43, 44, 48, 50, 60–63, 68, 71, 79, 83, 86, 89–91, 102, 103, 109, 110, 116, 118, 121, 123–126, 128, 129, 133, 134, 136], or combined approaches [42, 64, 70, 72, 75, 76, 82, 95, 99–101, 111, 113, 114, 117, 119] complicates performing comparable subgroup analyses or meta-regression for intensity.

Obviously, intensity quantifications via the colour of a resistance band [51, 67, 115, 120] lack scientific quality standards, though similar training intensity like machine-based training was proposed to be achievable [168]. This may reflect the less accurate load progression [169] achievable with elastic resistance bands. From the included 92 studies, 14 determined the training intensity via rating of perceived exertion [48, 64, 75, 84, 85, 88, 92, 94, 97, 105, 108, 113, 135, 138], while 31 studies provided 1RM percentage-based training intensity prescriptions.

The reliability–validity problem in the intensity

While being the most common form of intensity determination, the validity of percentage-based approaches using the 1RM determination must be reasonably questioned in older, untrained, and, in parts, sedentary populations. While 1RM testing was described to be reliable in trained individuals [144], reliability is highly dependent on prior experience, task familiarity, and habituation and cannot be assumed to transfer across populations [170]. Evidence suggests that untrained older adults may require multiple familiarization sessions to achieve stable 1RM measurements [171, 172], raising concerns about the appropriateness of percentage-based intensity prescriptions in frail or exercise-inexperienced populations.

It seems questionable that it was possible to determine the actual 1RM in participants at the mean age of > 65 years with a peak of > 90 years [69]. This limitation comes to a head as only a few studies [44, 71, 76, 78, 91, 96, 101, 116, 117, 124, 125, 136, 139] provided their own reliability metrics to account for habituation effects and invested effort to prove their data were internally valid. In turn, if the percentage-based resistance training intensity determination is of variable quality in the currently available evidence, percentage-based approaches (although being common) might meaningfully under- or overestimate submaximal intensities. Therefore, variability in already highly heterogenous study protocols and intensities (ranging from 40 to 90% of 1RM) even increased, significantly hampering statements about intensity. In front of this problem, the studies using "high load" [74, 82, 86], which provided a reasonable stimulus to improve neuromuscular parameters as well as proprioceptive and balance-related capacity, in principle, should be revisited carefully. Further caveats can be reviewed in individual studies. De Carvalho et al. [74] used elastic bands, dumbbells, and ankle weights, while the resistance was determined as 80% of a maximum repetition, individually through the 10 repetitions test [173]. Forte et al. [82] reached the target intensity of 80% 1RM by instructing participants to reach for a RPE of 15–17 [174].

Low and, in parts, insufficient intensities to reasonably call the intervention "resistance training" [175] could contribute to diminishing ES when opposing the so-called resistance training protocols against active comparators. For instance, Sayers et al. [149] used only 40% of 1RM, but in a high-speed power training approach distorting the intensity regression as—though low load—it is intensive training. Motalebi et al. [107] performed resistance training using a subjective moderate intensity, with replacing the resistance band with the next colour, when one participant could perform three sets of eight repetitions with little exertion (how is little exertion objectively quantified?). Though this seems counterintuitive, meta-regressions have shown similar strength gains across a wide range of "repetitions in reserve" [176]. For aging populations, low- and moderate-intensity resistance training had also advantages in terms of efficacy, safety and also acceptance [177].

The training period problem

When individuals are exposed to novel and unfamiliar training stimuli, rapid performance improvements are commonly observed during the initial weeks of training, largely driven by neuromuscular adaptations such as improved inter- and intramuscular coordination and reduced co-contraction [140, 178, 179]. In untrained populations with low baseline performance, these early adaptations can result in large ES when interventions are compared with passive control conditions. Importantly, such early strength gains are not specific to resistance training, as comparable improvements have been reported following alternative interventions such as stretching, endurance training, or high-intensity interval training [58, 180, 181], highlighting that short-term strength increases may reflect general responsiveness to physical activity rather than modality-specific effects.

From a practical perspective, in reasonably trained participants, such large magnitude increases were impossible, questioning the generalizability of specific resistance training recommendations based on currently available evidence. In most of the included studies, assuming the intervention induced an unfamiliar training stimulus, the training effects might be attributable to improved neuromuscular task coordination rather than structural and systematic resistance training-specific adaptations. This speculation is underpinned by significantly diminishing number and magnitude of significant effects when contrasting resistance training effects to active instead of passive controls. The active control conditions, including 29 studies using walking (aerobic training), stretching, cycling, and multi-component exercises as interventions, showed similar effectivity on gait speed (ES = 0.17), distance (ES = −0.07), and sit-to-stand (ES = 0.02) performance.

Further moderators

These examples illustrate a dearth of studies performing reasonably long intervention periods with training intensities and exercises justifying the intervention being called resistance training in older adults [175]. Naturally, there are some administrative burdens, making extensive test and task habituation as well as intervention supervision mandatory [182]. It is noteworthy that supervision was not just necessary for the participants' safety [59]. The presented analysis found significantly higher effects when training interventions were supervised (ES = 0.76), underscoring the importance to correct technique, adherence, and progressive overload and maybe provide motivation in older populations [183]. Results are in line with previous works, pointing out that resistance training supervision was necessary to positively affect balance outcomes [59] as well as neuromuscular function and structure [184]. In contrast, if exercise was unsupervised, e.g. performed in a home-based and prescribed exercise protocol, such benefits were not observed. These effects might be attributable to improved intervention adherences under supervised conditions. If participants performed training on their own as protocoled, e.g. in training diaries [45, 46, 77, 93, 130], safety and exercise execution concerns especially in untrained participants might have caused extreme caution when performing on their own. This might have led participants to use less intensity or reduced volume, while it can also not be excluded that movement execution was inappropriate [59].

Clinical translation for frailty

Gait dysfunctions are proposed to accumulate functional deficits that increase the risk of disability, hospitalization, and mortality in older adults [5, 185]. Especially slowed gait speed and impaired transitional mobility reflect diminished physiological reserve and neuromuscular vulnerability in the Fried physical frailty model [4]. Although resistance training positively affects gait parameters, the heterogeneity of the listed study methods as well as diminished effects when compared to active comparisons call for future high-quality investigations in the frailty and fall prevention programmes. Specific resistance training induced benefits were observed only for the timed up-and-go test as a key combined test for neuromuscular control, strength, and mobility [186].

In a best-case scenario, based on the current results, resistance training can be explicitly recommended when seeking for timed up-and-go performance enhancement, while especially for spatiotemporal and gait parameters had either no effect overall (spatiotemporal parameters) or no additional benefits over active controls. Therefore, for specific outcomes, resistance training focusing on free-weight training should be prioritized in older adults with manifest lower-limb weakness, impaired transitional mobility, or early frailty. Improvements in task-specific capacity and functional resilience are most likely to translate into reduced vulnerability to prevent functional decline [187]. For a more pessimistic perspective, the systematic review outlined meaningful and substantial methodological concerns that prohibit clear evidence-based recommendations with necessary scientific quality.

Limitations

Heterogeneity in intervention characteristics (e.g. duration, frequency, and intensity) was considerable. While subgroup analyses and meta-regression addressed some of this variability, residual heterogeneity remains and likely reflects the broad diversity of training approaches in practice. Therefore, the qualitative comparison of ES between overall and subgroup analysis of several gait parameters might be influenced by the number of included studies and therefore by sphericity. Automatically, due to differing numbers of included studies per subgroup, it was not possible to directly oppose subgroups to receive a valid classification of the group differences (inference statistics). The statements concerning "higher" or "similar" ES in comparison to the overall analysis must therefore be interpreted with caution. Although risk of bias was moderate for most studies, a considerable proportion did not blind assessors or failed to report training parameters, which may have inflated effect estimates. In this manner, publication bias cannot be ruled out, as suggested by asymmetries in funnel plots. Lastly, three databases with > 4000 hits were carefully screened. Nevertheless, due to unclear and variating resistance training definitions used in the literature, it cannot be entirely ruled out that individual studies were not included in the systematic search and were missed in the manual search performed afterwards. Due to the large number of included studies, these individual effects would, however, not resolve outlined problems regarding heterogeneity. Therefore, evidence remains uncertain.

Conclusions

Although resistance training indicated some positive tendencies on functional gait parameters, long-term studies with appropriate intensity determination and implementation in older adults are scarce. Meaningfully decreased positive effects of resistance training when opposing interventions to an active control prohibit drawing clear and high-quality conclusions about specific resistance training effects on various gait parameters. As a practical recommendation, the study provides evidence that (especially free-weight and complex) resistance training might be a sufficient exercise intervention, while to date, literature provides limited evidence to recommend it as a necessary exercise modality, while it seems more important to increase the general fitness level. Although over 90 studies were included in this systematic review, this research area is an optimal fit to address the WHO request on extending research effort to counteract demographical change associated health problems with a paramount relevance for quality of life, health economics, and hospital care capacities. Accordingly, high-quality long-term studies including, at best, supervised free-weight resistance protocols on functional (and morphological) associates to falls are required that allow distinguishing between specific resistance training effects and generally enhanced physical activity.

Author contribution DJ led the project, coordinated the literature search, and took the lead in data extraction and evidence synthesis, as well as writing the first draft in collaboration with KW. GP and LF assisted in evidence screening, quality assessment, and data extraction. SDS performed the statistical calculations. KW developed the idea for the project, supervised the project, and collaborated in drafting the article. All authors discussed, contributed to the paper, and agreed to the final version.

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Data availability Original data can be provided upon reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

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