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Review

Resistance Training Combined with Nutritional Supplementation in Older Adults with Sarcopenia: A Systematic Review and Meta-Analysis of Post-Exercise and Daily Supplementation Schedules

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Abstract

Background: The effects of resistance training combined with nutritional supplementation in older adults with sarcopenia may vary across supplementation schedules, but their relative effectiveness remains uncertain. **Methods**: PubMed, Web of Science, Embase, and the Cochrane Library were searched through 12 June 2026. Randomized controlled trials involving adults aged ≥ 60 years with sarcopenia were included. Effects on handgrip strength (HGS), gait speed, body mass index (BMI), muscle-mass-related measures, and lean mass (LM) or fat-free mass (FFM) were synthesized separately for post-exercise and daily supplementation using random-effects models. Evidence certainty was assessed using the Grading of Recommendations, Assessment, Development, and Evaluation (GRADE) approach. **Results**: Seventeen trials involving 905 participants were included. Across 13 trials, the overall HGS estimate favored the combined intervention: mean difference (MD) = 1.97 kg, 95% confidence interval (CI) [1.10, 2.84]; I^2 = 58%. Relative to study-specific comparators, the MD in HGS was 1.03 kg (95% CI [−0.19, 2.25]) for post-exercise supplementation and 2.50 kg (95% CI [1.52, 3.47]) for daily supplementation. Neither synthesis provided clear evidence of a gait-speed effect. For daily supplementation, BMI did not differ significantly between intervention and comparator groups (MD = 0.40 kg/m^2, 95% CI [−0.10, 0.90]). The daily muscle-mass-related estimate was positive but sensitive to study exclusion, whereas the post-exercise confidence interval included zero; the pooled synthesis of these muscle-mass-related measures should therefore be considered exploratory given the heterogeneity of the underlying constructs. LM/FFM estimates were positive in both schedule categories. Evidence certainty was moderate for HGS and BMI with daily supplementation and low or very low for the remaining comparisons. **Conclusions**: Resistance training combined with daily nutritional supplementation may improve handgrip strength in older adults with sarcopenia, whereas evidence for post-exercise supplementation remains inconclusive. Further comparative trials are needed to clarify the role of supplementation timing.

Keywords: sarcopenia; older adults; resistance training; nutritional supplementation schedules; systematic review; meta-analysis

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1. Introduction

Sarcopenia is an age-related skeletal muscle disease characterized by progressive loss of muscle mass and strength, with adverse consequences for physical function [1]. As research has advanced, diagnostic criteria have shifted from a primary focus on muscle mass toward greater emphasis on muscle strength and function [2,3].

The revised consensus of the European Working Group on Sarcopenia in Older People (EWGSOP2) identifies low muscle strength as the primary criterion for probable sarcopenia, low muscle mass as confirmatory evidence, and impaired physical performance as an indicator of severe disease [4]. Although diagnostic cutoffs vary across regions and consensus statements, muscle mass, muscle strength, and physical performance remain important for characterizing sarcopenia and its consequences [5]. The Asian Working Group for Sarcopenia (AWGS) 2025 update places muscle mass and muscle strength at the core of diagnosis and frames impaired physical performance principally as an outcome [3].

Resistance training is a cornerstone of nonpharmacological management for sarcopenia [2,6]. It can improve muscle strength, muscle mass, and physical function [7]. However, inadequate protein intake, chronic low-grade inflammation, and anabolic resistance in older adults with sarcopenia may attenuate adaptation to resistance training [8]. Evidence from other populations also suggests that combining exercise with supplementation may enhance selected aspects of physical performance, although the effects may vary with the training modality and supplement used [9]. Nutritional supplementation has therefore emerged as a potential adjunct, but uncertainty remains about how supplementation schedules are related to exercise-associated outcomes.

Despite extensive research on resistance training combined with nutritional supplementation, the role of the supplementation schedule remains uncertain. Previous reviews have primarily evaluated the overall effects of combined interventions [10–13] or compared nutritional components [14]. However, the effects associated with post-exercise and regular daily supplementation patterns in older adults with sarcopenia remain insufficiently characterized. Direct head-to-head evidence comparing these schedules is limited, and differences in supplement composition, dosage, frequency, resistance-training protocols, and comparator conditions further complicate interpretation. Post-exercise supplementation is often justified by the transient exercise-associated increase in anabolic responsiveness [15], whereas daily supplementation may address habitual nutrient inadequacy and distribute nutritional exposure across the intervention period [16].

This systematic review and meta-analysis synthesized randomized controlled trials (RCTs) of resistance training combined with nutritional supplementation in adults aged ≥ 60 years with sarcopenia. Effects on handgrip strength (HGS), gait speed, body mass index (BMI), muscle-mass-related measures, and lean mass (LM) or fat-free mass (FFM) were estimated separately for post-exercise and daily supplementation schedules, relative to the comparator used in each trial. Exploratory analyses examined whether HGS effects varied by intervention duration. These schedule-based syntheses were intended to characterize the available evidence rather than determine the relative effectiveness of the schedules. An overall pooled HGS estimate was also calculated across both supplementation-schedule categories.

2. Materials and Methods

This systematic review and meta-analysis was reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 statement [17]. The review was prospectively registered in the International Prospective Register of Systematic Reviews (PROSPERO; CRD420261418717) on 9 June 2026. After registration, the manuscript title was revised, and the roles of BMI as an exploratory secondary

anthropometric outcome and of heterogeneous muscle-mass-related measures as an exploratory synthesis were further clarified. These post-registration clarifications are reported transparently.

2.1. Search Strategies

We searched PubMed, Web of Science, Embase, and the Cochrane Library from inception through 12 June 2026. Eligible reports described RCTs of resistance training combined with nutritional supplementation in older adults with sarcopenia. The search combined free-text terms for sarcopenia, resistance training, nutritional supplementation, and RCTs. Supplementary Table S1 presents the complete search strategies for each database. No language restrictions were applied. We also hand-searched the reference lists of all included trials and relevant reviews to identify additional eligible studies.

2.2. Eligibility Criteria

Eligibility criteria were structured according to the population, intervention, comparator, outcomes, and study design (PICOS) framework. The population comprised adults aged ≥ 60 years with sarcopenia diagnosed using consensus criteria, including EWGSOP [18] or AWGS [19], or a study-specific operational definition. The intervention was resistance training combined with nutritional supplementation scheduled primarily after exercise or routinely each day. Eligible comparators included exercise plus placebo, exercise alone, nutritional supplementation alone, or usual lifestyle. The outcomes included HGS, gait speed, BMI, muscle-mass-related measures, and LM/FFM. Only RCTs were eligible. Two reviewers independently screened the titles and abstracts of the retrieved records according to the predefined eligibility criteria. Records considered potentially eligible by either reviewer were retrieved for full-text assessment. The full texts were then independently evaluated by both reviewers for final inclusion. Any disagreements regarding study eligibility were resolved through discussion or consultation with a third reviewer. Inter-rater agreement for study selection was quantified using Cohen's κ coefficient.

2.3. Data Extraction

Two reviewers independently extracted the study data using a standardized spreadsheet developed a priori. The extracted study characteristics are summarized in Table 1.

The extracted publication characteristics included the first author, year of publication, and country or region. Methodological characteristics included study design, group allocation, and sample size. Participant characteristics included age eligibility criteria or age range and sex distribution, when reported. Intervention characteristics included exercise modality, frequency, session duration, intervention duration, supplement composition, dose, frequency, and timing relative to exercise. Studies were classified as using primarily post-exercise or regular daily supplementation schedules, with the detailed classification criteria described in Section 2.4. The extracted outcomes included muscle strength, physical performance, and body composition. Disagreements were resolved through discussion or consultation with a third reviewer.

One trial [20] included two eligible intervention arms with a shared control group. For syntheses in which both intervention arms contributed, the sample size of the shared control group was divided approximately equally to avoid double-counting participants, as recommended in the Cochrane Handbook [21]. The control-group means and standard deviations (SDs) were unchanged. For analyses counting independent trials, the two eligible comparisons from this multi-arm trial were treated as a single trial; in leave-one-out sensitivity analyses, both comparisons were excluded together.

Table 1. Characteristics of the included studies.

Author (Year)	Participants	Intervention	Comparator	Supplementation Timing	Outcomes	Duration	Criteria	Setting
Post-exercise supplementation								
Zdzieblik (2015) [22]	*n* = 53; aged > 65 years; IG/CG: 26/27 all male	3 × 60 min/w RT and collagen peptides in 250 mL water.	3 × 60 min/w RT and silicon dioxide in 250 mL water.	Training days: within 1 h after RT. Nontraining days: same time of day.	FFM	12 weeks	EWGSOP	Community
Yoshimura (2019) [23]	*n* = 44; aged ≥ 65 years; IG/CG: 21/23 M/F: 14/30	Rehabilitation program (≤3 h/day), 40 min RT and LEAA.	Rehabilitation program (≤3 h/day), 40 min RT.	Training days: within 30 min after RT. Nontraining days: not reported.	HGS	8 weeks	AWGS	Hospital
Tokuda (2023) [24]	*n* = 31; aged ≥ 65 years; IG/CG: 16/15 M/F: NR	20 min warm-up, 40 min RT and EAA + TCC.	20 min warm-up, 40 min RT.	Training days: immediately after RT. Nontraining days: not reported.	SMM, GS, HGS	24 weeks	AWGS	Harima Care Center or community
Takeuchi (2019) [25]	*n* = 68; aged ≥ 65 years; IG/CG: 35/33 M/F: NR	Rehabilitation program (≤3 h/day) and BCAA + Vit D.	Rehabilitation program (≤3 h/day).	Training days: within 30 min after RT. Nontraining days: not reported.	HGS, BMI	8 weeks	AWGS	Hospital
Mori (2022) [26]	*n* = 46; aged ≥ 65 years; IG/CG: 23/23 M/F: NR	2 × 30–40 min/w RT and Leu-enriched WP.	2 × 30–40 min/w RT.	Training days: within 5 min after RT. Nontraining days: not reported.	HGS, GS	24 weeks	AWGS	Community
Meza-Valderrama (2024) [27]	*n* = 32; aged ≥ 65 years; IG/CG: 17/15 M/F: 8/24	3 × 50 min/w (5 min warm-up, 30 min RT, 10 min balance exercises, 5 min cool-down) and Ca-HMB.	3 × 50 min/w (5 min warm-up, 30 min RT, 10 min balance exercises, 5 min cool-down) and placebo supplementation.	Training days: immediately after RT. Nontraining days: same time of day.	HGS, GS, BMI, FFM	12 weeks	EWGSOP	Hospital

Table 1. *Cont.*

Author (Year)	Participants	Intervention	Comparator	Supplementation Timing	Outcomes	Duration	Criteria	Setting
Liao (2024) [28]	$n = 65$; aged ≥ 65 years; IG/CG: 30/35 M/F: NR	5 × 45–60 min/w (warm-up, RT and cool-down) and oral oligopeptide preparation.	5 × 45–60 min/w (warm-up, RT and cool-down).	Twice daily: once within 30 min after RT; once after lunch.	GS, BMI, HGS, SLM, SMM	16 weeks	AWGS	Community
Amasene (2019) [29]	$n = 28$; aged ≥ 70 years; IG/CG: 15/13 M/F: NR	2 × 60 min/w (warm-up, RT and cool-down) and WP + Leu.	2 × 60 min/w (warm-up, RT and cool-down) and placebo supplementation.	Training days: within 30 min after RT. Nontraining days: not reported.	BMI, TLM	12 weeks	EWGSOP	Hospital
Maltais (2016) [20]	$n = 26$; aged 60–75 years; EAAmilk/EAAsupp/CG: 8/8/10 all male	3 × 60 min/w (10 min warm-up, 50 min RT) in both intervention groups: EAAmilk group: chocolate milk supplemented with milk powder; EAAsupp group: soy beverage mixed with a commercial EAA powder.	3 × 60 min/w (10 min warm-up, 50 min RT) and chocolate-flavored rice milk.	Training days: immediately after RT. Nontraining days: not reported.	GS, BMI, MM	16 weeks	AMMI < 10.75 kg/m^2 or MMI < 18.04 kg/m^2	Research Center on Aging
Daily supplementation								
Yang (2023) [30]	$n = 34$; aged ≥ 65 years; IG/CG: 18/16 M/F: NR	2 × 40 min/w (5 min warm-up, 30 min RT, 5 min cool-down) and HMB.	2 × 40 min/w (5 min warm-up, 30 min RT, 5 min cool-down) and placebo supplementation.	Morning and evening.	HGS, GS, FFM, SMM	12 weeks	AWGS	Community

Table 1. *Cont.*

Author (Year)	Participants	Intervention	Comparator	Supplementation Timing	Outcomes	Duration	Criteria	Setting
Yamada (2019) [31]	$n = 17$; aged ≥ 65 years; IG/CG: 9/8 M/F: NR	2 × 30 min/w (5 min warm-up, 20 min RT, 5 min cool-down) and protein + Vit D.	2 × 30 min/w (5 min warm-up, 20 min RT, 5 min cool-down).	After breakfast.	HGS, GS, AMM	12 weeks	AWGS	Community
Sun (2025) [32]	$n = 110$; aged ≥ 65 years; IG/CG: 55/55 M/F: NR	2 × 20 min/w RT (chair-based exercise every other day, 10 min/session) and WPI + Ca-HMB + Vit D.	Maintained their usual dietary and lifestyle patterns.	With breakfast and in the afternoon.	HGS, GS, BMI, FFM, MM	12 weeks	AWGS	Community, rehabilitation hospital, long-term care, senior living
Rondanelli (2016) [33]	$n = 130$; aged ≥ 65 years; IG/CG: 69/61 M/F: 53/77	5 × 20 min/w (5 min warm-up, 5 min RT, 5 min balance and gait training, 5 min cool-down) and EAA + WP + Vit D.	5 × 20 min/w (5 min warm-up, 5 min RT, 5 min balance and gait training, 5 min cool-down) and placebo supplementation.	With lunch.	HGS, BMI, FFM	12 weeks	EWGSOP	Hospital
Liu (2025) [34]	$n = 60$; aged 60–75 years; IG/CG: 30/30 all female	3 × 70 min/w (10 min warm-up, 50 min RT, 10 min cool-down) and Vit C + Vit E.	3 × 70 min/w (10 min warm-up, 50 min RT, 10 min cool-down) and placebo supplementation.	Training days: 1–3 h before and within 1 h after training. Nontraining days: morning and evening.	HGS, GS, TLM, ALM	12 weeks	AWGS	Community
Kim (2012) [35]	$n = 70$; aged ≥ 75 years; IG/CG: 34/36 all female	2 × 60 min/w (5 min warm-up, 30 min RT, 20 min balance and gait training, 5 min cool-down) and EAA.	2 × 60 min/w (5 min warm-up, 30 min RT, 20 min balance and gait training, 5 min cool-down).	Timing not reported.	GS, BMI, MM	12 weeks	ASM/height^2 < 6.42 kg/m^2 plus low KES, low UWS, or low BMI	Community

Table 1. *Cont.*

Author (Year)	Participants	Intervention	Comparator	Supplementation Timing	Outcomes	Duration	Criteria	Setting
Kim (2013) [36]	$n = 59$; aged ≥ 75 years; IG/CG: 29/30 all female	2 × 60 min/w (5 min warm-up, 30 min RT, 20 min balance and gait training, 5 min cool-down) and TCC.	2 × 60 min/w (5 min warm-up, 30 min RT, 20 min balance and gait training, 5 min cool-down).	Timing not reported.	HGS, GS, MM	12 weeks	ASM/height^2 < 6.42 kg/m^2 plus low KES, low UWS, or low BMI	Community
Alves (2022) [37]	$n = 32$; aged ≥ 65 years; IG/CG: 17/15 all female	3 times/w (warm-up, RT) and fish oil.	3 times/w (warm-up, RT) and placebo supplementation.	With lunch and dinner.	HGS, GS, BMI	14 weeks	EWGSOP	Community

Notes: IG, intervention group; CG, comparison group; RT, resistance training; w, week; M/F, male/female; NR, not reported; HGS, handgrip strength; GS, gait speed; BMI, body mass index; FFM, fat-free mass; SMM, skeletal muscle mass; MM, muscle mass; SLM, soft lean mass; AMM, appendicular muscle mass; ALM, arm lean mass; TLM, total lean mass; ASM, appendicular skeletal muscle mass; EAA, essential amino acids; LEAA, leucine-enriched essential amino acids; BCAA, branched-chain amino acids; WP, whey protein; WPI, whey protein isolate; Leu, leucine; Leu-enriched WP, leucine-enriched whey protein; Vit, vitamin; TCC, tea catechins; HMB, β-hydroxy-β-methylbutyrate; Ca-HMB, calcium β-hydroxy-β-methylbutyrate; EWGSOP, European Working Group on Sarcopenia in Older People; AWGS, Asian Working Group for Sarcopenia; AMMI, appendicular muscle mass index; MMI, muscle mass index; KES, knee-extension strength; UWS, usual walking speed; EAAmilk, milk-based EAA group; EAAsupp, EAA-supplement group.

2.4. Classification of Supplementation Schedules

Studies were categorized according to the primary supplementation strategy specified in the original trial protocols, with particular consideration of administration timing relative to resistance exercise. Trials in which exercise-related supplementation was specifically scheduled after resistance training, without a prescribed exercise-related pre-training dose, were classified as using post-exercise supplementation. Trials emphasizing routine daily supplementation, including regimens involving both pre- and post-exercise dosing, were classified as using daily supplementation. For the operational classification used in this review, an explicitly prescribed post-training dose without a prescribed exercise-related pre-training dose took priority over administration at additional times or on nontraining days. Thus, the trials by Zdzieblik et al. [22], Meza-Valderrama et al. [27], and Liao et al. [28] were categorized as using post-exercise supplementation, whereas the trial by Liu et al. [34], whose protocol included both pre- and post-training doses, was categorized as using daily supplementation.

Four trials [22,27,28,34] were identified as having overlapping supplementation schedules involving exercise-related dosing and additional administration at other times or on nontraining days. These studies were retained in their respective categories for the primary analyses, and their influence was examined in a sensitivity analysis excluding all four trials.

2.5. Risk-of-Bias Assessment

Two assessors independently evaluated the risk of bias using version 2 of the Cochrane risk-of-bias tool for randomized trials (RoB 2) for the effect of assignment to intervention [38]. Disagreements were resolved through discussion with a third assessor. Judgments were reported as low risk of bias, some concerns, or high risk of bias across five domains: the randomization process, deviations from intended interventions, missing outcome data, measurement of the outcome, and selection of the reported result.

2.6. Statistical Analysis

Review Manager (RevMan) 5.4.1 and R software 4.6.0 were used for the meta-analysis. Random-effects models were used for all primary meta-analyses because genuine variation in intervention effects was anticipated owing to differences across trials in supplement composition and dosage, resistance-training protocols, participant characteristics, supplementation schedules, and comparator conditions. The inverse-variance method was used for pooling, with between-study variance (τ^2) estimated using the DerSimonian–Laird method. Mean differences (MDs) were used for HGS and BMI because these outcomes were expressed in comparable units across studies, whereas standardized mean differences (SMDs) were used for gait speed, heterogeneous muscle-mass-related measures, and LM/FFM. All pooled effect estimates are presented with 95% confidence intervals (CIs). Statistical heterogeneity was assessed using the I^2 statistic and τ^2. The two supplementation-schedule categories were synthesized separately against their study-specific comparators. Formal between-schedule subgroup-difference tests were also conducted for each outcome; however, these tests were considered exploratory because supplementation schedules were classified at the study level rather than randomized within trials. An overall pooled estimate was additionally calculated for HGS as the primary outcome, whereas secondary outcomes were analyzed separately by supplementation schedule. No formal adjustment for multiple testing was applied, and secondary-outcome and subgroup analyses were interpreted as exploratory. Small-study effects for the overall HGS synthesis (13 independent trials) were explored using a contour-enhanced funnel plot and Egger's regression test.

When multiple assessment time points were reported, data collected at the end of the intervention were selected. Change-from-baseline values were primarily used for quantita-

tive synthesis, and post-intervention values and change scores were not combined within the same conventional SMD analysis. When necessary, missing means and SDs were estimated from available summary statistics, including standard errors, confidence intervals, and medians with interquartile ranges, using established methods described in the Cochrane Handbook [21] and by Wan et al. [39]. Missing change-score SDs were estimated from baseline and post-intervention SDs assuming a within-participant correlation coefficient of 0.5. Outcome measurements were selected according to their underlying constructs and measurement scales, with heterogeneous muscle-mass-related measures synthesized separately as exploratory outcomes. Only one eligible outcome measure per independent comparison was included within each synthesis. To ensure consistency in the direction of treatment effects, the mean values of outcomes for which lower values indicated better performance were multiplied by −1 before meta-analysis, so that positive effect estimates consistently indicated improvement in the intervention group. Detailed data conversion procedures, assumptions, and outcome-selection rules are provided in Supplementary Methods S1.

Exploratory subgroup analyses were conducted for HGS according to intervention duration. Post-exercise supplementation trials were categorized as <12 weeks, 12 weeks, or >12 weeks, whereas daily-supplementation trials were categorized as 12 weeks or >12 weeks because no eligible daily-supplementation trial had a duration of <12 weeks. Given the small number of studies in several duration categories, these analyses were considered exploratory and hypothesis-generating.

Several sensitivity analyses were conducted to evaluate the robustness of the findings. (i) All primary meta-analyses were repeated with fixed-effect models using the same input data (Table S5). (ii) Four trials with overlapping supplementation schedules [22,27,28,34] were excluded, followed by a further exclusion of two daily-supplementation trials with unclear exercise-relative timing [35,36] (Table S6). (iii) The trial by Sun et al. [32] was separately excluded from the primary daily-supplementation analyses because participants in its comparator group maintained their usual diet and lifestyle (Table S6). (iv) Leave-one-out analyses excluded one independent trial at a time, with both Maltais intervention arms removed together (Table S7). (v) Restricted analyses examined protein-, amino acid-, or β-hydroxy-β-methylbutyrate (HMB)-containing supplements, explicitly reported EWGSOP/AWGS diagnostic criteria, and exclusion of trials at high overall risk of bias (Tables S8–S10). (vi) Exploratory between-schedule Wald tests, modified Hartung–Knapp–Sidik–Jonkman (HKSJ) adjustments, and approximate 95% prediction intervals were also calculated [40] (Tables S11 and S12).

2.7. Certainty of Evidence Assessment

For outcomes that were meta-analyzed, we evaluated the certainty of evidence according to the Grading of Recommendations, Assessment, Development, and Evaluation (GRADE) approach [41] following the guidance in the Cochrane Handbook for Systematic Reviews of Interventions [21] and the GRADE Working Group recommendations [42]. Two reviewers (Y.Y. and X.J.W.) independently assessed the certainty of evidence, and disagreements were resolved through discussion or, when necessary, consultation with a third reviewer (J.L.). Five domains were considered when assessing the certainty of evidence: risk of bias, inconsistency, indirectness, imprecision, and publication bias. GRADE classifies the certainty of evidence into four levels: high, moderate, low, and very low. Evidence profiles were created using the GRADEpro Guideline Development Tool (GRADEpro GDT; https://www.gradepro.org/, accessed on 9 October 2026). The overall HGS synthesis across both supplementation-schedule categories was assessed separately from the schedule-specific outcome comparisons.

3. Results

3.1. Study Selection

Database searches identified 3729 records: 631 from PubMed, 1519 from Embase, 1267 from Web of Science, and 312 from the Cochrane Library. After 1266 duplicates were removed, 2463 records remained. Of these, 2162 were excluded after title and abstract screening. The full texts of 301 reports were assessed for eligibility; 284 were excluded, leaving 17 trials for inclusion (Figure 1).

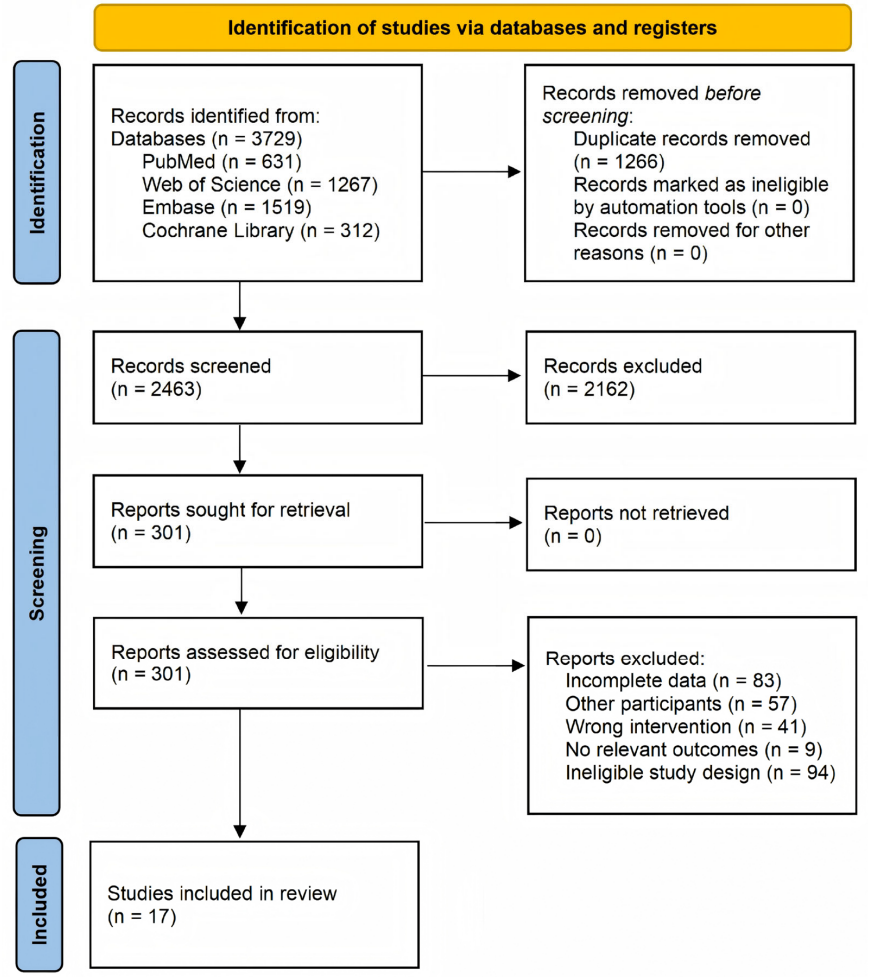


Figure 1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram of the search and study-selection process. RCT, randomized controlled trial.

3.2. Study Characteristics

Seventeen RCTs involving 905 adults aged ≥ 60 years with sarcopenia were included; 460 participants were assigned to the intervention groups, and 445 were assigned to the comparator groups. Participants were recruited from community, hospital, rehabilitation, long-term care, senior living, research center, and care center settings. Nine trials were categorized as using primarily post-exercise supplementation, and eight trials were categorized as using regular daily supplementation. The trials were published between 2012 and 2025 and lasted 8–24 weeks; 10 used a 12-week intervention. The study characteristics are presented in detail in Table 1.

The trials were conducted in China, Germany, Japan, Spain, Canada, Brazil, and Italy. Definitions and operational assessments of sarcopenia varied across trials. Some trials used

EWGSOP [18] or AWGS [19] criteria, whereas others used study-specific definitions or diagnostic indicators rather than a single standardized framework.

The comparator conditions varied and included exercise plus placebo, exercise alone, and usual lifestyle. The outcomes included muscle strength, physical performance, and body composition. HGS was treated as a muscle-strength outcome and gait speed was treated as a physical-performance outcome; body-composition outcomes included BMI, an exploratory synthesis of heterogeneous muscle-mass-related measures, and LM/FFM. The specific muscle-related constructs, extracted variables, and reported measurement methods and instruments are summarized in Supplementary Table S2.

3.3. Nutritional Intervention Protocols

For post-exercise supplementation, two studies used leucine-enriched whey protein [26,29]; one study used collagen peptides [22]; one study used a leucine-enriched amino acid supplement [23]; one study used essential amino acids plus tea catechins [24]; one study used branched-chain amino acids plus vitamin D [25]; one study used calcium β-hydroxy-β-methylbutyrate [27]; one study used soy- or milk-based essential amino acid supplementation [20]; and one study used a multicomponent oligopeptide preparation containing plant oligopeptides, casein peptide, branched-chain amino acids, and calcium β-hydroxy-β-methylbutyrate [28].

For daily supplementation, one study used β-hydroxy-β-methylbutyrate [30]; one study used whey protein plus vitamin D [31]; one study used whey protein isolate plus calcium β-hydroxy-β-methylbutyrate and vitamin D [32]; one study used whey protein plus essential amino acids and vitamin D_3 [33]; one study used vitamins C and E [34]; one study used a leucine-rich essential amino acid mixture [35]; one study used tea catechins [36]; and one study used fish oil [37]. The detailed intervention characteristics are presented in Supplementary Table S3.

3.4. Resistance Training Protocols

For post-exercise supplementation, the resistance training modalities included machine-based exercises [22,25], elastic band training [24,26], free-weight training [27,28], sit-to-stand exercises [23], training of the major muscle groups throughout the body [29], and a combination of free weights and machines [20].

For daily supplementation, the modalities included elastic band training [30,31,34], elastic band training combined with chair exercises [33], resistance cycling with chair-based exercises [32], chair-based exercises combined with resistance bands, ankle weights, and balance/gait training [35,36], and machine-based training [37]. The detailed intervention characteristics are presented in Supplementary Table S4.

3.5. Risk-of-Bias Summary

Figure 2 summarizes RoB 2 judgments for the effect of assignment to intervention [38]. Of the 17 trials, 4 trials were judged to be at low overall risk of bias, 9 trials raised some concerns, and 4 trials were judged to be at high risk of bias. The randomization process was the most frequent source of concern: 13 trials raised some concerns, whereas 4 trials were judged to be at low risk. For deviations from intended interventions, 11 trials were judged to be at low risk, 3 trials raised some concerns, and 3 trials were judged to be at high risk. For missing outcome data, 11 trials were judged to be at low risk, 3 trials raised some concerns, and 3 trials were judged to be at high risk. All trials were judged to be at low risk of bias in outcome measurement. For selection of the reported result, 11 trials were judged to be at low risk, and 6 trials raised some concerns. High overall risk was driven primarily by deviations from

intended interventions and/or missing outcome data. Pooled findings should therefore be interpreted cautiously, particularly when informed by trials at high risk of bias.

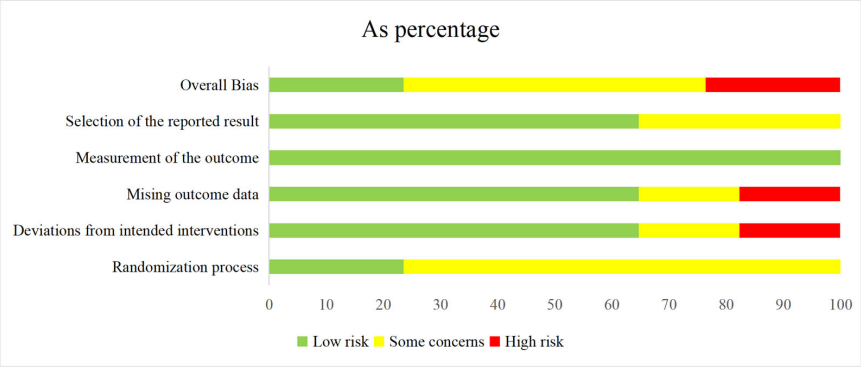


Figure 2. Risk-of-bias summary for the included trials, based on the effect of assignment to intervention.

3.6. Muscle Strength and Physical Performance

Muscle strength was assessed using HGS, and physical performance was assessed using gait speed. The detailed results are presented in Figures 3 and 4.

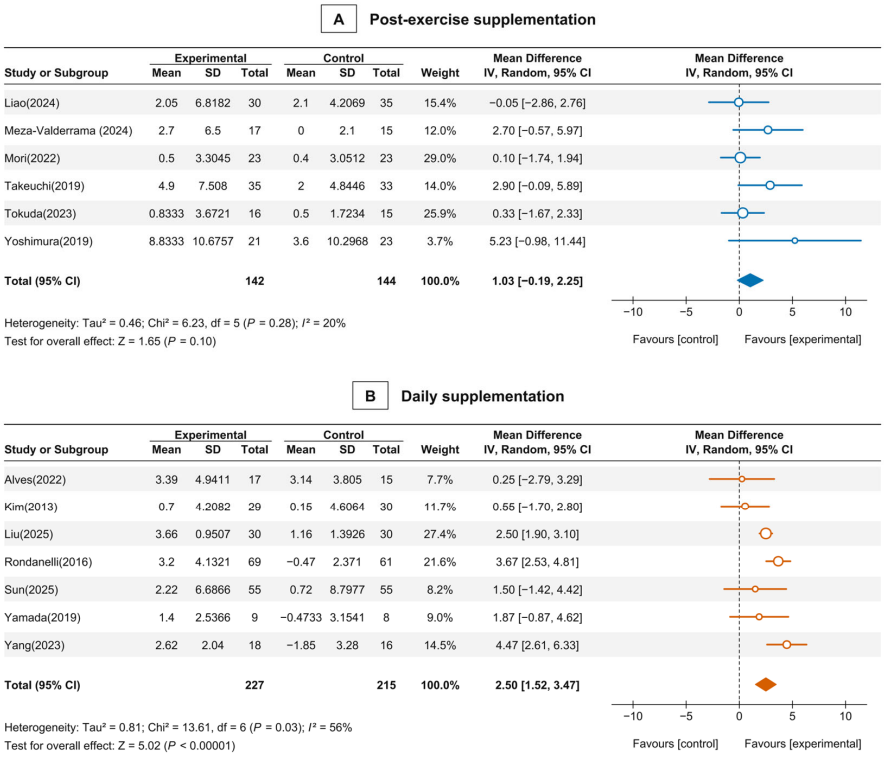


Figure 3. Forest plots of the effect of resistance training combined with nutritional supplementation on handgrip strength. (**A**) Post-exercise supplementation; (**B**) regular daily supplementation. Effect estimates are expressed as mean differences (MDs, kg) with 95% confidence intervals (CIs), calculated using inverse-variance random-effects models. Positive MDs indicate greater improvement in handgrip strength with the combined intervention relative to the study-specific comparator. Blue and orange symbols indicate post-exercise (**A**) and daily (**B**) supplementation, respectively. Open circles represent individual study estimates, with horizontal lines indicating 95% CIs; filled diamonds represent pooled estimates and their 95% CIs, and vertical dashed lines indicate no effect (MD = 0). CI, confidence interval; SD, standard deviation; IV, inverse variance; df, degrees of freedom. Studies included in the forest plots correspond to References [23–28,30–34,36,37].

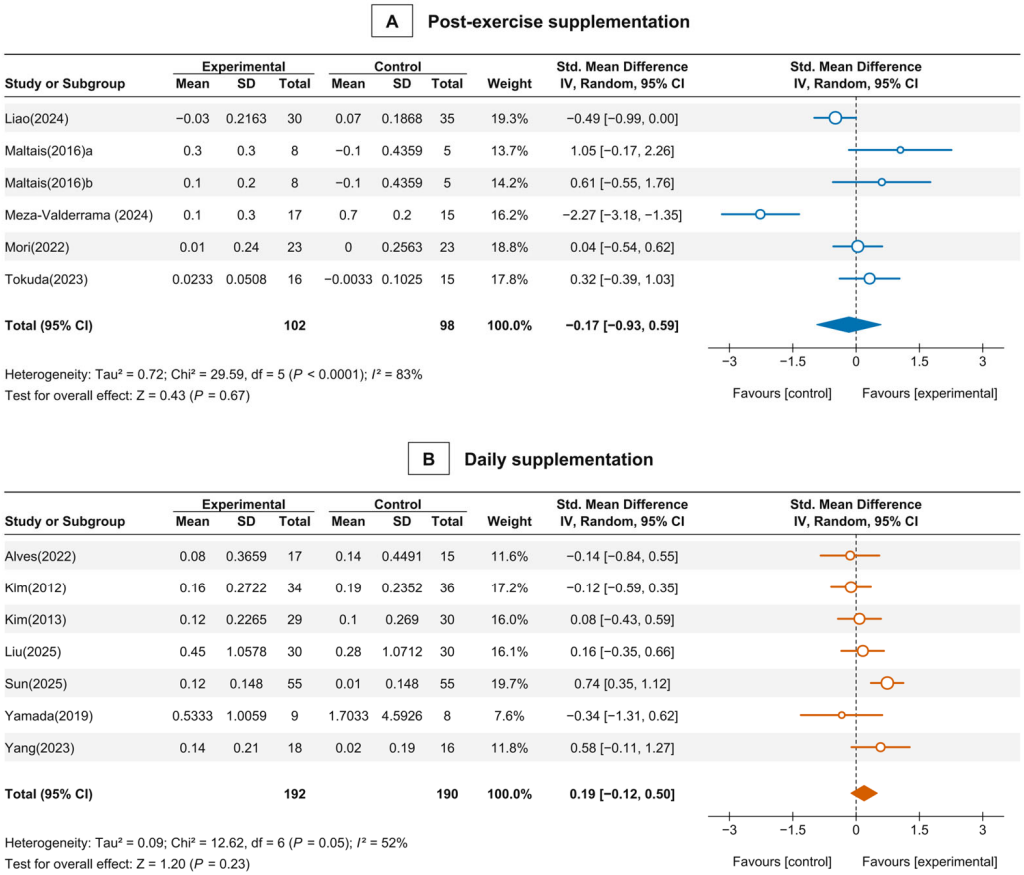


Figure 4. Forest plots of the effect of resistance training combined with nutritional supplementation on gait speed. (**A**) Post-exercise supplementation; (**B**) regular daily supplementation. Effect estimates are expressed as standardized mean differences (SMDs) with 95% confidence intervals (CIs) using inverse-variance random-effects models. Positive SMDs indicate greater improvement in gait speed with the combined intervention relative to the study-specific comparator. Blue and orange symbols indicate post-exercise (**A**) and daily (**B**) supplementation, respectively. Open circles represent individual study estimates, with horizontal lines indicating 95% CIs; filled diamonds represent pooled estimates and their 95% CIs, and vertical dashed lines indicate no effect (SMD = 0). SMD, standardized mean difference; CI, confidence interval; SD, standard deviation; IV, inverse variance; df, degrees of freedom. Studies included in the forest plots correspond to References [20,24,26–28,30–32,34–37].

3.6.1. Handgrip Strength

Six trials of post-exercise supplementation reported HGS data for 142 participants in combined-intervention groups and 144 in comparator groups. The I^2 statistic was 19.8%, and a random-effects model was used. The pooled effect was positive but not statistically significant (MD = 1.03 kg, 95% CI [−0.19, 2.25]; $p = 0.098$).

Seven trials of daily supplementation reported HGS data for 227 participants in combined-intervention groups and 215 in comparator groups. The I^2 statistic was 55.9%, and a random-effects model was used. The pooled effect favored the combined intervention (MD = 2.50 kg, 95% CI [1.52, 3.47]; $p < 0.001$).

Across 13 independent trials, involving 369 participants in the combined-intervention groups and 359 in the comparator groups, resistance training combined with nutritional supplementation was associated with a significant improvement in handgrip strength (MD = 1.97 kg, 95% CI [1.10, 2.84]; $p < 0.00001$). Between-study heterogeneity was observed ($I^2 = 58\%$; $\tau^2 = 1.18$). The corresponding forest plot is provided in Supplementary Figure S2.

3.6.2. Gait Speed

Five trials comprising six intervention arms investigated post-exercise supplementation and gait speed, including 102 participants in combined-intervention groups and 98 in comparator groups. The I^2 statistic was 83.1%, and a random-effects model was used. The pooled effect was negative but not statistically significant (SMD = −0.17, 95% CI [−0.93, 0.59]; $p = 0.667$).

Seven trials investigated daily supplementation and gait speed, including 192 participants in combined-intervention groups and 190 in comparator groups. The I^2 statistic was 52.5%, and a random-effects model was used. The pooled effect was not statistically significant (SMD = 0.19, 95% CI [−0.12, 0.50]; $p = 0.229$).

3.7. Body Composition

Body-composition outcomes included BMI, heterogeneous muscle-mass-related measures, and LM/FFM. The detailed results are presented in Figures 5–7.

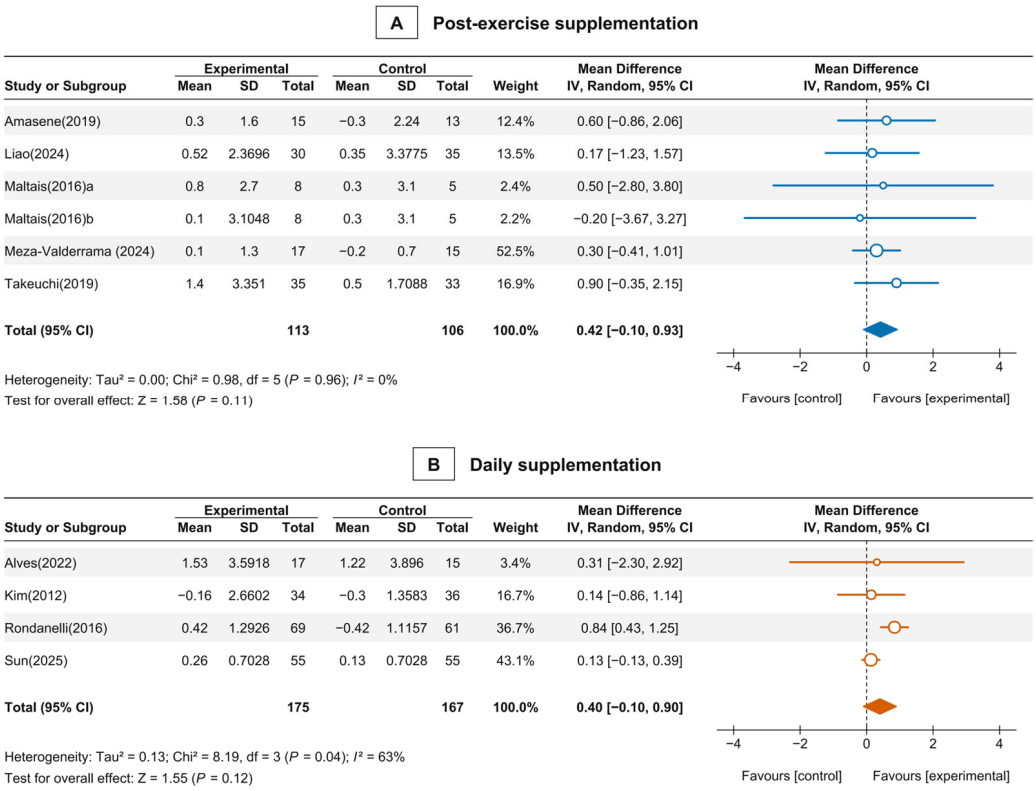


Figure 5. Forest plots of the effect of resistance training combined with nutritional supplementation on body mass index. (**A**) Post-exercise supplementation; (**B**) regular daily supplementation. Effect estimates are expressed as mean differences (MDs, kg/m^2) with 95% confidence intervals (CIs) using inverse-variance random-effects models. Positive MDs indicate a greater increase in BMI in the combined-intervention group relative to the study-specific comparator. Blue and orange symbols indicate post-exercise (**A**) and daily (**B**) supplementation, respectively. Open circles represent individual study estimates, with horizontal lines indicating 95% CIs; filled diamonds represent pooled estimates and their 95% CIs, and vertical dashed lines indicate no effect (MD = 0). BMI, body mass index; CI, confidence interval; SD, standard deviation; IV, inverse variance; df, degrees of freedom. Studies included in the forest plots correspond to References [20,25,27–29,32,33,35,37].

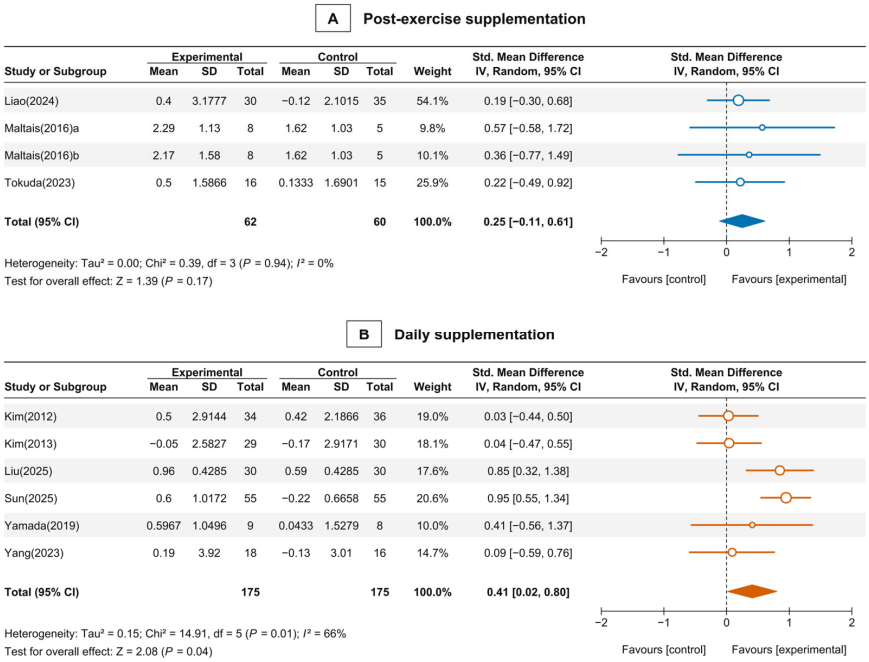


Figure 6. Forest plots of the exploratory synthesis of heterogeneous muscle-mass-related measures following resistance training combined with nutritional supplementation. (**A**) Post-exercise supplementation; (**B**) regular daily supplementation. Effect estimates are expressed as standardized mean differences (SMDs) with 95% confidence intervals (CIs) using inverse-variance random-effects models. The exploratory synthesis combined heterogeneous, non-equivalent measures of skeletal muscle mass, muscle mass, appendicular muscle mass, and arm lean mass. Positive SMDs indicate greater increases in muscle-mass-related measures with the combined intervention relative to the study-specific comparator. Blue and orange symbols indicate post-exercise (**A**) and daily (**B**) supplementation, respectively. Open circles represent individual study estimates, with horizontal lines indicating 95% CIs; filled diamonds represent pooled estimates and their 95% CIs, and vertical dashed lines indicate no effect (SMD = 0). SMD, standardized mean difference; CI, confidence interval; SD, standard deviation; IV, inverse variance; df, degrees of freedom. Studies included in the forest plots correspond to References [20,24,28,30–32,34–36].

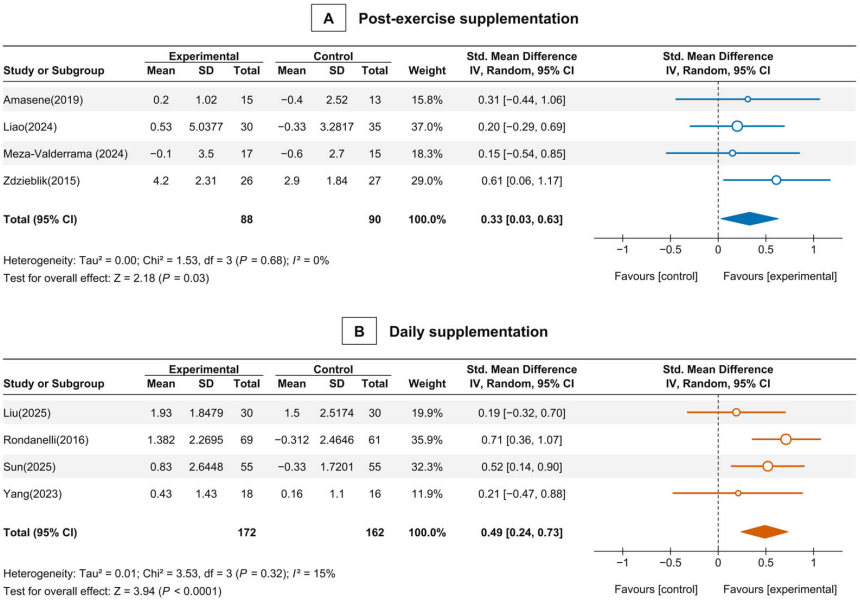


Figure 7. Forest plots of the effect of resistance training combined with nutritional supplementation on lean mass or fat-free mass. (**A**) Post-exercise supplementation; (**B**) regular daily supplementation.

Effect estimates are expressed as standardized mean differences (SMDs) with 95% confidence intervals (CIs) using inverse-variance random-effects models. Positive SMDs indicate greater increases in lean mass or fat-free mass with the combined intervention relative to the study-specific comparator. Blue and orange symbols indicate post-exercise (**A**) and daily (**B**) supplementation, respectively. Open circles represent individual study estimates, with horizontal lines indicating 95% CIs; filled diamonds represent pooled estimates and their 95% CIs, and vertical dashed lines indicate no effect (SMD = 0). LM, lean mass; FFM, fat-free mass; SMD, standardized mean difference; CI, confidence interval; SD, standard deviation; IV, inverse variance; df, degrees of freedom. Studies included in the forest plots correspond to References [22,27–30,32–34].

3.7.1. Body Mass Index

Five trials comprising six intervention arms evaluated post-exercise supplementation and BMI, including 113 participants in combined-intervention groups and 106 in comparator groups. The I^2 statistic was 0%, and a random-effects model was used. The pooled MD was not statistically significant (MD = 0.42 kg/m^2, 95% CI [−0.10, 0.93]; $p = 0.11$).

Four trials of daily supplementation reported BMI data for 175 participants in combined-intervention groups and 167 in comparator groups. The I^2 statistic was 63.4%, and a random-effects model was used. The pooled MD was not statistically significant (MD = 0.40 kg/m^2, 95% CI [−0.10, 0.90]; $p = 0.120$).

3.7.2. Exploratory Synthesis of Heterogeneous Muscle-Mass-Related Measures

Three trials comprising four intervention arms reported post-exercise supplementation effects on skeletal muscle mass or generically labeled muscle mass. These analyses included 62 participants in combined-intervention groups and 60 in comparator groups. The I^2 statistic was 0%, and a random-effects model was used. The pooled SMD was positive but not statistically significant (SMD = 0.25, 95% CI [−0.11, 0.61]; $p = 0.166$).

Six trials reported daily-supplementation effects on heterogeneous measures labeled skeletal muscle mass, muscle mass, appendicular muscle mass, or arm lean mass. These analyses included 175 participants in each group. The I^2 statistic was 66.5%, and a random-effects model was used. The pooled SMD was positive and statistically significant (SMD = 0.41, 95% CI [0.02, 0.80]; $p = 0.037$). Because these measures differ in anatomical scope and tissue construct, this pooled estimate should not be interpreted as a single well-defined skeletal-muscle outcome.

3.7.3. Lean Mass and Fat-Free Mass

Four trials reported post-exercise supplementation effects on LM or FFM, including 88 participants in combined-intervention groups and 90 in comparator groups. The I^2 statistic was 0%, and a random-effects model was used. The pooled SMD was positive and statistically significant (SMD = 0.33, 95% CI [0.03, 0.63]; $p = 0.029$).

Four trials reported daily-supplementation effects on LM or FFM, including 172 participants in combined-intervention groups and 162 in comparator groups. The I^2 statistic was 15%, and a random-effects model was used. The pooled SMD was positive and statistically significant (SMD = 0.49, 95% CI [0.24, 0.73]; $p < 0.001$).

3.8. Exploratory Subgroup Analysis of Handgrip Strength

Exploratory subgroup analyses examined whether HGS effects varied by intervention duration. Post-exercise trials were categorized as < 12 weeks, 12 weeks, or > 12 weeks; daily-supplementation trials were categorized as 12 weeks or > 12 weeks because none lasted < 12 weeks. Tests for subgroup differences did not reach statistical significance for

either post-exercise supplementation ($p = 0.057$) or daily supplementation ($p = 0.132$). The results of the analyses are shown in Supplementary Figure S3.

3.9. Sensitivity Analyses

Changing from random-effects to fixed-effect models while retaining the same studies, outcome data, and effect measures changed whether the 95% CI excluded zero in two of the 11 pooled analyses (gait speed and BMI with daily supplementation). The overall HGS estimate also remained positive under the fixed-effect model (MD = 2.35 kg, 95% CI [1.91, 2.78]; Table S5). After exclusion of four trials with overlapping supplementation schedules [22,27,28,34], the daily-supplementation HGS estimate remained positive (MD = 2.34 kg, 95% CI [0.92, 3.76]). The muscle-mass-related confidence intervals included zero in both the post-exercise (SMD = 0.33, 95% CI [−0.21, 0.86]) and daily (SMD = 0.32, 95% CI [−0.12, 0.76]) categories. Only one trial remained for post-exercise LM/FFM, while daily LM/FFM remained positive (SMD = 0.57, 95% CI [0.33, 0.81]). Following the additional exclusion of two unclear-timing trials [35,36], daily HGS remained positive (MD = 2.79 kg, 95% CI [1.40, 4.17]), while gait speed, BMI and the exploratory muscle-mass-related measure were not statistically significant. In the separate analysis excluding the trial by Sun et al. [32] from the primary daily-supplementation analyses, HGS (MD = 2.57 kg, 95% CI [1.52, 3.63]), BMI (MD = 0.73 kg/m^2, 95% CI [0.35, 1.11]), and LM/FFM (SMD = 0.43, 95% CI [0.05, 0.81]) remained positive; the gait-speed and heterogeneous muscle-mass-related CI included zero (Table S6). Leave-one-out analyses were conducted for all five outcomes in both supplementation-schedule categories (Table S7). Notably, excluding Rondanelli et al. [33] attenuated the daily HGS estimate (MD: 2.50 to 2.17 kg) and reduced the daily BMI estimate (MD: 0.40 to 0.13 kg/m^2), with BMI heterogeneity decreasing from 63.4% to 0% (Table S7).

When analyses were restricted to trials using protein-, amino acid-, or HMB-containing supplements, daily HGS remained statistically significant, and LM/FFM estimates remained significant in both schedule categories (Table S8). Analyses restricted to trials explicitly reporting EWGSOP or AWGS diagnostic criteria yielded statistically significant estimates for daily HGS and daily muscle-mass-related measures, as well as LM/FFM in both schedule categories (Table S9). After excluding trials at high overall risk of bias, HGS estimates were statistically significant in both schedule categories; daily muscle-mass-related measures and daily LM/FFM also remained significant (Table S10). Formal between-schedule tests showed no statistically significant differences for any outcome (all $p \geq 0.066$; Table S11). In the HKSJ analyses, daily HGS (MD = 2.50 kg, 95% CI [1.16, 3.84]) and daily LM/FFM (SMD = 0.49, 95% CI [0.09, 0.88]) were the only two comparisons with 95% CI excluding zero. All 95% prediction intervals included zero (Table S12).

3.10. Certainty of Evidence

Certainty was low for the overall HGS synthesis and low or very low for most schedule-specific comparisons. For overall HGS, certainty was downgraded for risk of bias and inconsistency. Imprecision contributed to downgrading across all schedule-specific comparisons, largely because of limited information size and confidence intervals compatible with materially different effect magnitudes. Risk of bias also reduced certainty for several schedule-specific comparisons, particularly in the post-exercise supplementation subgroup. Inconsistency contributed to downgrading for the overall HGS synthesis and for schedule-specific outcomes with substantial unexplained heterogeneity or instability across sensitivity analyses, whereas indirectness mainly reflected the pooling of related but non-equivalent body-composition measures. Formal assessment of small-study effects was not performed for the schedule-specific syntheses because fewer than 10 independent RCTs contributed

to each. For the overall HGS synthesis (13 independent RCTs), Egger's regression test did not indicate statistically significant funnel-plot asymmetry ($t(11) = -1.057$, $p = 0.313$; Supplementary Figure S4). This exploratory result does not rule out publication bias. Among schedule-specific comparisons, certainty was moderate for HGS and BMI with daily supplementation and low or very low for the remaining outcomes. Detailed certainty ratings and reasons for downgrading are presented in Supplementary Table S13.

4. Discussion

Across all 13 independent trials, the overall pooled estimate favored resistance training combined with nutritional supplementation for HGS (MD = 1.97 kg, 95% CI [1.10, 2.84]), although heterogeneity was moderate ($I^2 = 58\%$). In the schedule-specific syntheses, the pooled HGS estimate for daily supplementation was positive and supported by moderate-certainty evidence relative to study-specific comparators, whereas the post-exercise estimate was positive but inconclusive. This moderate-certainty rating reflects confidence in the daily-supplementation HGS effect estimate relative to study-specific comparators, rather than evidence of superiority over post-exercise supplementation. Exploratory between-schedule tests did not identify statistically significant differences for any of the five outcomes (all $p \geq 0.066$; Table S11). All 95% prediction intervals included zero (Table S12), and the certainty of evidence was moderate for BMI with daily supplementation and low or very low for the remaining schedule-specific comparisons. These findings provide descriptive, hypothesis-generating evidence and do not establish the relative effectiveness of the two schedules.

Previous meta-analyses have reported positive HGS estimates for whey protein supplementation combined with resistance training [13], resistance and balance training combined with protein-based supplementation [43], and exercise combined with nutritional supplementation more broadly [44]. These findings provide context for the positive daily-supplementation estimate in this review, although differences in eligibility criteria, intervention content, and comparator conditions limit direct comparisons of effect magnitude. The daily HGS estimate remained positive across the specified sensitivity analyses. However, excluding Rondanelli et al. [33] reduced the daily estimate from MD = 2.50 kg (95% CI [1.52, 3.47]; $I^2 = 55.9\%$) to MD = 2.17 kg (95% CI [1.04, 3.29]; $I^2 = 49.3\%$), representing an approximately 13.2% attenuation in the point estimate; heterogeneity decreased but was not eliminated (Table S7). Thus, while the positive direction of the effect remained unchanged, the estimated magnitude was somewhat sensitive to the inclusion of individual studies, warranting caution when interpreting the potential clinical benefit. The post-exercise HGS estimate was inconclusive in the primary analysis but became statistically significant after excluding trials at high overall risk of bias (MD = 3.08 kg, 95% CI); this result should be interpreted cautiously because only three trials remained. The between-schedule test for HGS was not statistically significant ($p = 0.066$; Table S11), so the larger point estimate in the daily-supplementation subgroup cannot be interpreted as evidence of superiority. Reference values of 5.0–6.5 kg for meaningful grip-strength change have been proposed in other clinical populations [45]. These values have not been validated for interpreting the pooled between-group MD in older adults with sarcopenia, and a well-established threshold directly applicable to this population and effect measure is not available. Therefore, the clinical importance of the approximately 2 kg average HGS difference observed after excluding Rondanelli et al. [33] remains uncertain.

Improvements in muscle strength may not be accompanied by equivalent gains in physical performance, highlighting the multidimensional nature of functional recovery in sarcopenia. Despite the positive HGS findings, neither supplementation subgroup demonstrated a statistically significant pooled effect on gait speed. This pattern is broadly

consistent with the network meta-analysis by Shen et al. [6], which found that adding nutritional interventions to exercise provided greater additional benefits for HGS than for physical performance outcomes, including gait speed. Notably, excluding trials with overlapping supplementation schedules shifted the post-exercise gait-speed estimate from negative to positive (SMD: −0.17 to 0.30) and reduced heterogeneity (I^2: 83.1% to 0%), although the effect was still not statistically significant. Physiologically, muscle strength reflects not only muscle size but also neural activation and contractile function [46], whereas walking performance is associated with multiple physical, cognitive, and behavioral factors [47]. Sayer et al. [2] emphasized that muscle strength and physical function represent related but distinct dimensions of sarcopenia. Evidence from a systematic review of brief, intermittent exercise interventions further suggests that different exercise approaches may influence functional outcomes, although these findings are not specific to older adults with sarcopenia [48]. Thus, improvements in HGS cannot be assumed to produce corresponding changes in mobility, and the absence of a statistically significant gait-speed effect does not negate the observed strength response.

Changes in BMI and lean-tissue measures require separate interpretation because they do not represent the same biological outcome. BMI describes body weight relative to height, so a higher value alone does not establish a gain in skeletal muscle or a health benefit [49]. Skeletal muscle mass, appendicular muscle mass, arm lean mass, and whole-body lean or fat-free mass also represent related but non-equivalent constructs [2]. Differences in assessment methods and anatomical measurement sites further complicate comparisons of muscle-mass estimates across studies [50]. A systematic review and meta-analysis of resistance training in older adults reported increases in muscle size and muscle fiber area without a corresponding clear increase in leg lean mass, illustrating the dependence of findings on the measurement construct [51]. In the present review, the CIs for the heterogeneous muscle-mass-related outcome included no effect in both schedule-based syntheses after trials with overlapping schedules were excluded. These exploratory estimates should therefore not be interpreted as convergent evidence of skeletal muscle accretion. Although the pooled LM/FFM estimates were positive in both supplementation subgroups, these separate estimates do not establish a difference in effectiveness between schedules, as no within-trial randomized comparison between schedules was conducted.

The effects of combining resistance training with nutritional supplementation may also depend on how the interventions are implemented, rather than on administration timing alone. The included trials differed substantially in supplement composition, dosage, frequency, training protocols, and comparator conditions. Moreover, the supplementation categories were not entirely distinct: four trials provided nutrients in relation to exercise as well as at additional times or on nontraining days [22,27,28,34]. A network meta-analysis by Zhou et al. [52] reported that post-exercise protein supplementation was associated with improvements in muscle-mass outcomes, whereas nighttime supplementation showed favorable effects on certain measures of muscle strength. However, no clear benefit was observed for physical performance. These findings suggest that the effects of supplementation timing may vary across different outcomes, although differences in study populations, nutritional interventions, and supplementation schedules should be considered when interpreting the evidence. In the present analysis, the positive daily HGS finding persisted after the exclusion of overlapping or insufficiently reported schedules, suggesting that it was not solely dependent on those trials. Nevertheless, the available evidence cannot determine whether this response was associated with supplementation timing, nutritional composition, administration frequency, baseline dietary intake, or interactions with the resistance-training program. A sustained-exposure hypothesis may help frame future research. However, the present meta-analysis did not measure total daily nutrient exposure consistently and

therefore cannot test this mechanism. The results therefore support further investigation of nutritional strategies that accompany resistance training, without identifying a single optimal supplementation schedule.

A key strength of this review is its focus on supplementation schedules in older adults with sarcopenia undergoing resistance training combined with nutritional supplementation. By separately synthesizing post-exercise and daily supplementation patterns, this study provides a more detailed perspective than previous reviews primarily examining the overall effects of combined interventions. Comprehensive sensitivity analyses further assessed the robustness of the findings across different study classifications and comparator conditions. Together, these approaches help clarify the available evidence and identify outcomes with relatively consistent effects.

5. Limitations

This review has several limitations. Although 17 trials were included, outcome-specific analyses often contained few small studies, limiting precision; an exploratory Egger's test for the overall HGS synthesis did not indicate statistically significant small-study effects ($p = 0.313$), but the test had limited power with 13 trials and publication bias could not be excluded. Supplementation schedules were classified at the study level, and no included trial directly randomized participants to the two schedules. Differences in supplement composition, dose, frequency, resistance-training protocols, comparator conditions, participant characteristics, and clinical settings, including imbalances in sex distribution and hospital-based versus community settings, therefore prevent isolation of timing effects. Four trials involved overlapping supplementation schedules, and residual confounding could not be excluded despite sensitivity analyses. BMI was retained as an exploratory anthropometric outcome but cannot distinguish lean mass from fat mass and should not be interpreted as evidence of improved muscle quantity or sarcopenia. The exploratory muscle-mass-related outcome combined non-equivalent measures; pooling LM and FFM also introduced indirectness, and several body-composition findings depended on study inclusion. Only four trials had low overall risk of bias, whereas four had high risk, reducing confidence in the pooled estimates. GRADE certainty was low for the overall HGS synthesis, moderate for HGS and BMI with daily supplementation, and low or very low for all remaining schedule-specific comparisons. These limitations constrain confidence in effect magnitude and the basis for schedule-specific clinical recommendations. Trial registries and gray-literature sources were not searched, which may have resulted in the omission of ongoing or unpublished studies.

Future research should prioritize adequately powered head-to-head trials of clearly defined schedules while matching supplement composition, total supplemental intake, resistance-training exposure, and comparator conditions. Trials should prespecify clinically relevant outcomes and distinguish muscle strength, physical performance, skeletal muscle mass, appendicular lean tissue, and fat-free mass. Adherence, habitual diet, energy intake, vitamin D status, background physical activity, and adverse events should be reported consistently. More precise body-composition methods, such as dual-energy X-ray absorptiometry, magnetic resonance imaging, or validated standardized bioelectrical impedance analysis, should be selected according to the intended tissue construct.

6. Conclusions

This review found a positive overall HGS estimate for resistance training combined with nutritional supplementation, although the certainty of this evidence was low. Daily supplementation showed a positive effect, whereas the evidence for post-exercise supplementation remained inconclusive. Neither schedule-specific synthesis provided clear

evidence of improved gait speed, and body-composition findings were limited by heterogeneous measurement constructs and sensitivity to study inclusion. Because supplement composition, dose, frequency, comparator conditions, and training protocols differed between trials, the observed effects cannot be attributed to supplementation timing alone. The schedule-based findings are therefore hypothesis-generating and do not establish the relative effectiveness of either supplementation schedule. Head-to-head trials with matched co-interventions are needed to determine whether supplementation schedules independently influence outcomes.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/nu18223826/s1. Methods S1: Detailed Statistical Calculations and Analytical Assumptions. Figure S1: Risk-of-bias judgments for individual trials. Figure S2: Overall HGS forest plot. Figure S3: Exploratory HGS subgroup analyses by intervention duration. Figure S4: Funnel plot for the overall HGS analysis. Figure S5: PRISMA 2020 checklist. Table S1: Database search strategy. Table S2: Measurement constructs and assessment methods of muscle-related outcomes. Table S3: Nutritional supplementation protocols. Table S4: Resistance training protocols. Table S5: Random-effects versus fixed-effect models. Table S6: Sensitivity analyses of supplementation timing and comparator consistency. Table S7: Leave-one-out sensitivity analyses. Table S8: Protein-, amino acid-, or HMB-containing supplement restrictions. Table S9: Restriction to explicitly reported EWGSOP/AWGS criteria. Table S10: Exclusion of trials at high overall risk of bias. Table S11: Exploratory between-schedule differences. Table S12: Hartung–Knapp robustness analyses and prediction intervals. Table S13: Summary of findings and GRADE certainty.

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Abbreviations

The following abbreviations are used in this manuscript:

AWGS	Asian Working Group for Sarcopenia
BMI	Body mass index

CI	Confidence interval
EWGSOP	European Working Group on Sarcopenia in Older People
EWGSOP2	Revised European Working Group on Sarcopenia in Older People consensus
FFM	Fat-free mass
HGS	Handgrip strength
LM	Lean mass
MD	Mean difference
PICOS	Population, intervention, comparator, outcomes, and study design
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PROSPERO	International Prospective Register of Systematic Reviews
RoB 2	Version 2 of the Cochrane risk-of-bias tool for randomized trials
SMD	Standardized mean difference

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