



Review

The influence of resistance exercise training prescription variables on skeletal muscle mass, strength, and physical function in healthy adults: An umbrella review

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Abstract

Purpose: The aim of this umbrella review was to determine the impact of resistance training (RT) and individual RT prescription variables on muscle mass, strength, and physical function in healthy adults.

Methods: Following Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, we systematically searched and screened eligible systematic reviews reporting the effects of differing RT prescription variables on muscle mass (or its proxies), strength, and/or physical function in healthy adults aged >18 years.

Results: We identified 44 systematic reviews that met our inclusion criteria. The methodological quality of these reviews was assessed using A Measurement Tool to Assess Systematic Reviews; standardized effectiveness statements were generated. We found that RT was consistently a potent stimulus for increasing skeletal muscle mass (4/4 reviews provide some or sufficient evidence), strength (4/6 reviews provided some or sufficient evidence), and physical function (1/1 review provided some evidence). RT load (6/8 reviews provided some or sufficient evidence), weekly frequency (2/4 reviews provided some or sufficient evidence), volume (3/7 reviews provided some or sufficient evidence), and exercise order (1/1 review provided some evidence) impacted RT-induced increases in muscular strength. We discovered that 2/3 reviews provided some or sufficient evidence that RT volume and contraction velocity influenced skeletal muscle mass, while 4/7 reviews provided insufficient evidence in favor of RT load impacting skeletal muscle mass. There was insufficient evidence to conclude that time of day, periodization, inter-set rest, set configuration, set end point, contraction velocity/time under tension, or exercise order (only pertaining to hypertrophy) influenced skeletal muscle adaptations. A paucity of data limited insights into the impact of RT prescription variables on physical function.

Conclusion: Overall, RT increased muscle mass, strength, and physical function compared to no exercise. RT intensity (load) and weekly frequency impacted RT-induced increases in muscular strength but not muscle hypertrophy. RT volume (number of sets) influenced muscular strength and hypertrophy.

Keywords: Hypertrophy; Resistance training; Resistance training prescription variables; Strength; Umbrella review

1. Introduction

Skeletal muscle is integral to many locomotive and metabolic processes critical for good health. Performing regular resistance training (RT)—muscle contraction against external resistance—improves muscular health;¹ in particular, RT increases skeletal muscle mass (i.e., hypertrophy), strength, and physical function (gait speed, timed up-and-go, chair sit-to-stand, etc.). RT prescription (RTx) involves multiple

programming variables, such as load, sets, frequency, rest intervals, muscle action type, and velocity.² Understanding how RTx variables impact muscular adaptations to RT is critical for effective exercise programming.

RTx has been a longstanding focus of exercise science; however, the contribution of many manipulatable RTx variables to muscular adaptations remains to be established. Systematic reviews have aimed to determine how individual RTx variables influence the development of strength and hypertrophy. These reports contributed to the development of advice by the World Health Organization for healthy adults to engage in moderate-to-vigorous RT at least twice weekly.³ Furthermore, the American College of Sports Medicine and National Strength and

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Conditioning Association have offered prescriptive position statements that advise adults to consider few (load and frequency^{3,4}) or several RTx variables (load, frequency, sets, muscle action type/velocity, and rest intervals^{5,6}). Systematic reviews provide high-quality evidence by collating and evaluating data with replicable search strategies and synthesis methods;⁷ however, a synthesis of systematic reviews integrating multiple RTx variables is lacking.

Umbrella reviews extend upon systematic reviews by identifying, synthesizing, and evaluating evidence from multiple systematic reviews and meta-analyses on a common topic. We sought to summarize the evidence from existing systematic reviews and meta-analyses investigating RTx variables and muscular adaptations to aid RT programming and guideline development for healthy adults. Thus, the purpose of the current umbrella review was two-fold: (a) to determine the influence of RT on skeletal muscle mass, strength, and physical function, compared with a non-exercise control group, and (b) to determine the impact individual RTx variables may have on RT-induced increases in muscle mass, muscle strength, and physical function.

2. Methods

2.1. Protocol and registration

This review was prospectively registered on the International Platform of Registered Systematic Review and

Meta-analysis Protocols (INPLASY202220028; <https://inplasy.com/>) and conducted under the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA).⁸

2.2. Information sources

A systematic search of Ovid MEDLINE, SPORTDiscus, and Web of Science was conducted from inception to December 9, 2021. No publication status, language, nor study design limits were used when conducting each search, and references from relevant systematic reviews were screened manually. The complete search strategy for Ovid MEDLINE is provided in [Supplementary Table 1](#).

2.3. Eligibility criteria

Eligibility was assessed by the predetermined Population, Intervention, Comparator, Outcomes, and Study Design (PICOS) criteria detailed in [Table 1](#). Eligible reviews were published in English and investigated how muscle mass, strength, and/or physical function were impacted by RT, compared to a non-exercising control, and/or the manipulation of individual RTx variables in healthy adults.

2.4. Study selection and data extraction

Per PICOS criteria, 2 reviewers (SMP and BSC) independently screened records at the title/abstract and full text

Table 1
Population, intervention, comparator, outcomes, and study design (PICOS) criteria

	Criteria	Description
Population	Does the review involve healthy adults?	<p>Included</p> <ul style="list-style-type: none"> - Adults aged >18 years who are generally healthy (no disease condition indicated other than sarcopenia) and community-dwelling adults <p>Excluded</p> <ul style="list-style-type: none"> - Athletes/military persons - Persons with or at risk for comorbidities (e.g., cardiovascular disease, type II diabetes, type I diabetes, cancer, peripheral artery disease, osteoarthritis, etc.) - Persons who are injured (e.g., musculoskeletal-related fracture and/or repair) - Explicitly mentions obese and/or overweight participants - Individuals who are hospitalized (inpatient/outpatient/rehabilitation, etc.) - Individuals living in long-term care homes - Animal studies (e.g., murine models)
Intervention	Does the review involve resistance training prescription?	<p>Included</p> <ul style="list-style-type: none"> - Resistance training programs (defined as the contraction of skeletal muscle against an external load/resistance, which can be provided by body mass, free-weights, guided motion machines, and elastic bands)
Comparator	Does the review include a different resistance training prescription or non-exercise control?	<p>Included</p> <ul style="list-style-type: none"> - A different resistance training prescription is when at least 1 programming variable is differentially prescribed for the duration of the intervention - A non-exercise control group continues a habitual lifestyle with no additional interventions
Outcomes	Does the review report on muscle-related outcomes?	<p>Included</p> <ul style="list-style-type: none"> - Muscle hypertrophy - Strength - Physical function (e.g., timed up and go test, chair rise, sit to stand test, gait speed test(s), walking test(s), short-performance physical battery test, Berg balance test, etc.)
Study design	Is the review secondary research?	<p>Included</p> <ul style="list-style-type: none"> - Only systematic reviews, meta-analyses, meta-regressions, network meta-analyses, and/or umbrella reviews are included <p>Excluded</p> <ul style="list-style-type: none"> - Non-systematic reviews (e.g., narrative review) or primary research (e.g., randomized controlled trial, case report, case-control, cohort study)

stages, and any discrepancies were resolved by consensus with a third reviewer (JCM). Two reviewers (BSC and CVL) independently extracted information regarding the methods, results, and quality of all included articles, and any discrepancies were resolved by consensus with a third reviewer (JCM). Article screening and data extraction was completed using the Covidence systematic review software (Veritas Health Innovation, Melbourne, VIC, Australia; available at www.covidence.org).

2.5. Methodological quality assessment and evidence synthesis

The methodological quality of all included reviews was determined in duplicate using A Measurement Tool to Assess Systematic Reviews (AMSTAR),⁹ as previously described,^{10,11} to yield a score ranging from 1 to 11. Three authors (BSC, CVL, and JCM) systematically synthesized the evidence from each review to produce a standardized effectiveness statement (sufficient evidence, some evidence, insufficient evidence, insufficient evidence to determine; see *Supplementary Table 2*) for each outcome.^{10,11} Two authors (BSC and JCM) then considered each standardized effectiveness statement to generate a bottom-line statement for the impact of each RTx variable on muscle mass, strength, and function. The quality of evidence (QoE) derived from each article was determined by a method based on the Grading of Recommendations Assessment, Development and Evaluation¹² approach for primary evidence (1 = *very low*, 2 = *low*, 3 = *moderate*, or 4 = *high*). This method incorporates the review design (meta-analysis: yes/no) and methodological quality (AMSTAR score) of included reviews^{10,11} (*Supplementary Table 3*). RT and RTx variables were judged on the strength of evidence and number of participants with increased muscle mass, strength, and/or function.¹³

3. Results

3.1. Included reviews

The literature search identified 837 records, and 362 were removed as duplicates. There were 407 records removed on title/abstract screening, 2 records could not be retrieved, and 23 records were excluded on full-text screening. Forty-four^{14–57} reviews (5 systematic reviews, 2 meta-regressions, 35 meta-analyses, 1 network meta-analysis, and 1 umbrella review) met the eligibility criteria and were included (*Fig. 1*). The AMSTAR scores and QoE for the included systematic reviews range from 2 to 10 and 1 to 4, respectively (*Supplementary Fig. 1, Table 2*). The average RT duration within the included reviews ranged from 6 weeks to 24 weeks. For details of the 44 systematic reviews included in the umbrella review, see *Supplementary Table 4*.

3.2. Muscle hypertrophy

3.2.1. RT vs. non-exercising control

Four reviews^{15,16,18,31} ranging from low QoE (Level 2) to high QoE (Level 4) provided some^{16,18} or sufficient^{15,31}

evidence that RT increases skeletal muscle mass compared to non-exercising controls (*Table 3*). In a high-quality meta-analysis (QoE: Level 4) comprising 15 original studies, Hagstrom and colleagues³¹ found that RT resulted in a significant increase in skeletal muscle mass (standardized mean difference (SMD) = 0.52; 95% confidence interval (95%CI): 0.20–0.78; $p = 0.002$) compared with non-exercising controls in young women. Csapo and colleagues¹⁸ conducted a meta-analysis including 5 original studies and found that, compared to non-exercising controls, gains in muscle size were small following higher-intensity RT (SMD = 0.199; 95%CI: 0.046–0.343; $p = 0.011$), and lower-intensity RT (SMD = 0.108; 95%CI: −0.050 to 0.261; $p = 0.179$) in healthy older adults.

3.2.2. Load

One low-quality review (QoE: Level 2),³⁶ 2 moderate-quality reviews (QoE: Level 3),^{44,48} and 1 high-quality review (QoE: Level 4)³⁷ provided evidence that RT load does not impact RT-induced skeletal muscle hypertrophy (*Table 3*). In a high-quality network meta-analysis (QoE: Level 4; 24 studies and $n = 747$ participants), Lopez and colleagues³⁷ compared 3 load prescriptions (high load, ≥80% of 1-repetition maximum (1RM) or ≤8 RM; moderate load, 60%–79% of 1RM or 9–15 RM; low load, <60% of 1RM or >15 RM) and found no significant difference in muscle hypertrophy between high-load RT and low-load RT (SMD = 0.12; 95%CI: −0.06 to 0.29; $p = 0.241$); moderate-load RT and low-load RT (SMD = 0.20; 95%CI: −0.04 to 0.44; $p = 0.113$); high-load RT and moderate-load RT (SMD = −0.09; 95%CI: −0.33 to 0.16; $p = 0.469$). A moderate-quality meta-analysis (QoE: Level 3) conducted by Schoenfeld et al.⁴⁸ reported similar hypertrophic adaptations between high-load RT (>60% 1RM or <15 RM) and low-load RT (\leq 60% 1RM or ≥15 RM; SMD = 0.03; 95%CI: −0.08 to 0.14; $p = 0.56$). Lacio et al.³⁶ highlighted that 14/16 randomized studies included in their review found no differences across low-load RT (<67% 1RM or >12RM), moderate-load RT (67%–85% 1RM or 6–12 RM), and high-load RT (>85% 1RM or <6 RM) performed to volitional fatigue in muscle cross-sectional area or muscle thickness (QoE: Level 2) in young adults.

In contrast, a meta-analysis of moderate-quality (QoE: Level 3; 7 studies and $n = 213$ participants)¹⁸ provided some evidence suggesting that high-load RT (\geq 80% 1RM) provoked larger gains in muscle size than low-load RT (\leq 60% 1RM), although the difference in hypertrophy was trivial (SMD = 0.136; 95%CI: 0.009–0.259; $p = 0.036$). Three reviews^{16,22,53} provided insufficient evidence to form a conclusion on the effects of RT load on skeletal muscle hypertrophy due to a limited number of studies^{16,53} and imprecise effect estimates.²²

3.2.3. Set end point (momentary muscular failure)

One high-quality meta-analysis (QoE: Level 4; comprising 7 studies ($n = 219$ participants)²⁸) concluded that performing

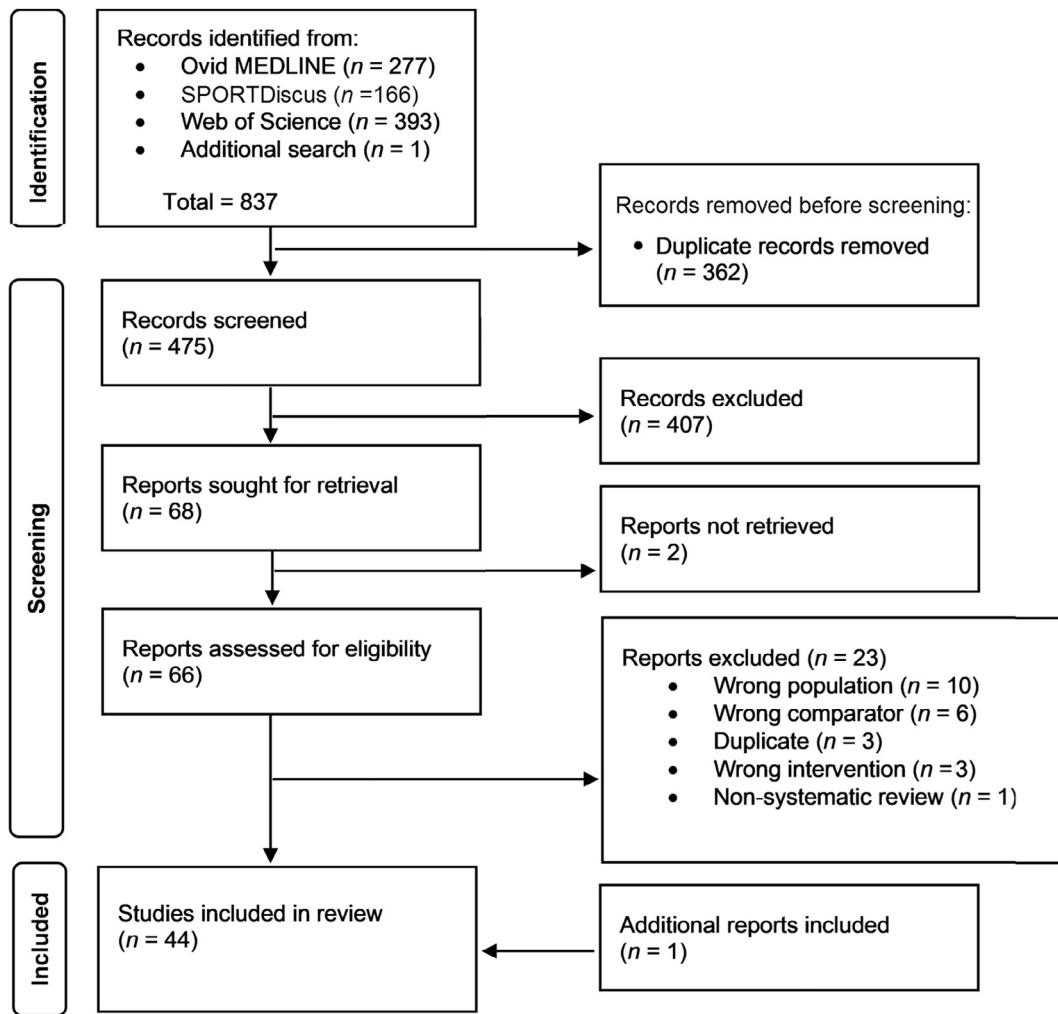


Fig. 1. PRISMA flowchart of reviews identified, screened, removed, and included in the review. PRISMA = Preferred Reporting Items for Systematic Reviews and Meta-Analyses.

RT to volitional fatigue had no impact on skeletal muscle hypertrophy ($SMD = 0.22$; 95%CI: -0.11 to 0.55 ; $p = 0.152$) (Table 3).

3.2.4. Contraction velocity/time under tension

A moderate-quality meta-analysis (QoE: Level 3)⁵¹ found no significant differences ($p = 0.94$) when training with repetition durations ranging from 0.5 s to 8.0 s (Table 3). One review¹⁶ contained insufficient evidence to determine the effect of time under tension on muscle hypertrophy in older adults.

3.2.5. Volume (number of sets)

A moderate-quality meta-analysis (QoE: Level 3; 15 studies) by Schoenfeld and colleagues⁵⁰ found that RT with a higher number of weekly sets promoted greater skeletal muscle mass gains than RT with a lower number of weekly sets ($SMD = 0.241 \pm 0.100$; 95%CI: 0.026 – 0.457 ; $p = 0.03$). Using meta-regression, the authors found there was a significant effect of the number of weekly sets on changes in skeletal muscle mass such that performing RT with 10+ sets per

muscle group per week ($SMD = 0.520 \pm 0.130$; 95%CI: 0.226 – 0.813 ; equivalent percent gain: 9.8%) elicited larger increases in skeletal muscle hypertrophy than performing RT with <5 sets per muscle group per week ($SMD = 0.307 \pm 0.07$; 95%CI: 0.152 – 0.462 ; equivalent percent gain = 5.4%). Krieger and colleagues³⁵ found that performing RT with multiple sets per exercise were associated with significantly larger increases in skeletal muscle than performing RT with a single set per exercise ($SMD = 0.11 \pm 0.40$; 95%CI: 0.02 – 0.19 ; $p = 0.016$), with no difference in performing 4–6 sets per exercise vs. 2–3 sets per exercise ($SMD = 0.10 \pm 0.10$; 95%CI: -0.09 to 0.30 ; $p = 0.29$). One meta-regression¹⁶ provided insufficient evidence to form a conclusion on the effect of RT volume on skeletal muscle hypertrophy in older adults (QoE: Level 3).

3.2.6. Set configuration

Davies and colleagues²⁰ found similar improvements in skeletal muscle hypertrophy between cluster-set RT and traditional-set RT ($SMD = -0.05 \pm 0.14$; 95%CI: -0.32 to 0.23 ; $p = 0.73$). Another meta-analysis³² investigating cluster sets

Table 2
Summary of included studies.

Study	AMSTAR	Standardized effectiveness statements			QoE (/4)
		Hypertrophy	Strength	Physical function	
RT vs. CTRL					
Beckwée et al. (2019) ¹⁵	5	Sufficient evidence in favor of RT variable	Sufficient evidence in favor of RT variable	Some evidence in favor of RT variable	2
Borde et al. (2015) ¹⁶	7	Some evidence in favor of RT variable	Insufficient evidence to determine	ND	3
Csapo et al. (2016) ¹⁸	6	Some evidence in favor of RT variable	Some evidence in favor of RT variable	ND	3
Guizelini et al. (2018) ³⁰	4	ND	Sufficient evidence in favor of RT variable	ND	3
Hagstrom et al. (2020) ³¹	8	Sufficient evidence in favor of RT variable	Sufficient evidence in favor of RT variable	ND	4
Silva et al. (2014) ⁵⁴	5	ND	Insufficient evidence to determine	ND	3
Load					
Csapo et al. (2016) ¹⁸	6	Some evidence in favor of RT variable	Some evidence in favor of RT variable	ND	3
Grgic et al. (2020) ²²	4	Insufficient evidence to determine	ND	ND	3
Lacio et al. (2021) ³⁶	6	Insufficient evidence in favor of RT variable	Some evidence in favor of RT variable	ND	2
Lopez et al. (2021) ³⁷	8	Insufficient evidence in favor of RT variable	Sufficient evidence in favor of RT variable	ND	4
Refalo et al. (2021) ⁴⁴	7	Insufficient evidence in favor of RT variable	Sufficient evidence in favor of RT variable	ND	3
Schoenfeld et al. (2017) ⁴⁸	6	Insufficient evidence in favor of RT variable	Sufficient evidence in favor of RT variable	ND	3
Schoenfeld et al. (2016) ⁵³	3	Insufficient evidence to determine	Insufficient evidence to determine	ND	2
Steib et al. (2010) ⁵⁵	7	ND	Some evidence in favor of RT variable	Insufficient evidence to determine	3
Borde et al. (2015) ¹⁶	7	Insufficient evidence to determine	Insufficient evidence to determine	ND	3
Set end point (momentary muscular failure)					
Davies et al. (2016) ¹⁹	8	ND	Insufficient evidence in favor of RT variable	ND	4
Grgic et al. (2022) ²⁸	6	Insufficient evidence in favor of RT variable	Insufficient evidence in favor of RT variable	ND	3
Contraction velocity/time under tension/power training					
Orssatto et al. (2019) ⁴⁰	8	ND	ND	Insufficient evidence to determine	4
Schoenfeld et al. (2015) ⁵¹	4	Insufficient evidence in favor of RT variable	ND	ND	3
Steib et al. (2010) ⁵⁵	7	ND	Insufficient evidence to determine	Insufficient evidence to determine	3
Borde et al. (2015) ¹⁶	7	Insufficient evidence to determine	Insufficient evidence to determine	ND	3
Volume (number of sets)					
Krieger et al. (2010) ³⁵	5	Some evidence in favor of RT variable	ND	ND	3
Ralston et al. (2017) ⁴¹	5	ND	Some evidence in favor of RT variable	ND	3
Schoenfeld et al. (2017) ⁵⁰	4	Sufficient evidence in favor of RT variable	ND	ND	3
Wolfe et al. (2004) ⁵⁷	5	ND	Some evidence in favor of RT variable	ND	3
Steib et al. (2010) ⁵⁵	7	ND	Insufficient evidence to determine	ND	3
Androulakis-Korakakis et al. (2020) ¹⁴	5	ND	Insufficient evidence to determine	ND	2
Borde et al. (2015) ¹⁶	7	Insufficient evidence to determine	Insufficient evidence to determine	ND	3
Ralston et al. (2019) ⁴³	7	ND	Insufficient evidence to determine	ND	3
Krieger et al. (2009) ³⁴	6	ND	Some evidence in favor of RT variable	ND	3
Set configuration					
Davies et al. (2021) ²⁰	8	Insufficient evidence in favor of RT variable	Insufficient evidence in favor of RT variable	ND	4
Jukic et al. (2021) ³²	9	Insufficient evidence to determine	Insufficient evidence in favor of RT variable	ND	4
Inter-set rest					
Grgic et al. (2017) ²⁴	6	Insufficient evidence to determine	ND	ND	2
Grgic et al. (2018) ²⁹	7	ND	Insufficient evidence in favor of RT variable	ND	2
Borde et al. (2015) ¹⁶	7	Insufficient evidence to determine	Insufficient evidence to determine	ND	3
Periodization					
Grgic et al. (2018) ²⁵	5	Insufficient evidence in favor of RT variable	ND	ND	2
Grgic et al. (2017) ²⁶	8	Insufficient evidence in favor of RT variable	ND	ND	4
Rhea et al. (2004) ⁴⁵	2	ND	Some evidence in favor of RT variable	ND	2
Williams et al. (2017) ⁵⁶	7	ND	Insufficient evidence to determine	ND	3
Weekly frequency					
Grgic et al. (2018) ²⁷	7	ND	Sufficient evidence in favor of RT variable	ND	3
Kneffel et al. (2021) ³³	6	Insufficient evidence in favor of RT variable	Some evidence in favor of RT variable	ND	2
Ralston et al. (2018) ⁴²	9	ND	Insufficient evidence in favor of RT variable	ND	4
Schoenfeld et al. (2019) ⁴⁷	5	Insufficient evidence in favor of RT variable	ND	ND	3
Schoenfeld et al. (2016) ⁴⁹	4	Some evidence in favor of RT variable	ND	ND	3
Steib et al. (2010) ⁵⁵	7	ND	Insufficient evidence to determine	ND	3
Borde et al. (2015) ¹⁶	7	Insufficient evidence to determine	Insufficient evidence to determine	ND	3

(continued on next page)

Table 2 (Continued)

Study	AMSTAR	Standardized effectiveness statements			QoE (/4)
		Hypertrophy	Strength	Physical function	
Muscle action type					
Buskard et al. (2018) ¹⁷	3	ND	Insufficient evidence to determine	ND	2
Douglas et al. (2017) ²¹	2	Some evidence in favor of RT variable	Some evidence in favor of RT variable	ND	1
Molinari et al. (2019) ³⁸	7	ND	Insufficient evidence to determine	ND	3
Roig et al. (2009) ⁴⁶	7	Insufficient evidence to determine	Insufficient evidence in favor of RT variable	ND	3
Schoenfeld et al. (2017) ⁵²	5	Some evidence in favor of RT variable	ND	ND	3
Time of day					
Grgic et al. (2019) ²³	8	Insufficient evidence in favor of RT variable	Insufficient evidence in favor of RT variable	ND	4
Exercise order					
Nunes et al. (2021) ³⁹	10	Insufficient evidence in favor of RT variable	Some evidence in favor of RT variable	ND	4

Abbreviations: AMSTAR = A Measurement Tool to Assess Systematic Reviews; CTRL = non-exercising control; ND = not determined; QoE = quality of evidence (/4); see Online [Supplementary Table 3](#) for details); RT = resistance training.

contained insufficient information to determine the impact of set configuration on skeletal muscle hypertrophy due to high heterogeneity (I^2 : 52%–87%) and a small number of studies synthesized for analysis (<3 studies).

3.2.7. Inter-set rest

Two reviews, 1 of moderate quality (QoE: Level 3)¹⁶ and 1 of low quality (QoE: Level 2),²⁴ contained insufficient evidence to determine the impact of inter-set rest on muscle hypertrophy due to the limited number of studies synthesized for analysis (<6 studies) ([Table 3](#)).

3.2.8. Periodization

A high-quality meta-analysis (QoE: Level 4) by Grgic and colleagues²⁶ found no significant differences between linear periodization and undulating periodization on measures of hypertrophy (SMD = 0.02; 95%CI: –0.25 to 0.21; p = 0.848). Similarly, a low-quality systematic review (QoE: Level 2)²⁵ concluded that periodized and non-periodized RT programs may yield similar hypertrophic adaptations ([Table 3](#)).

3.2.9. Weekly frequency

Two moderate-quality reviews (QoE: Level 3)^{33,47} provided evidence that weekly RT frequency does not impact skeletal muscle hypertrophy ([Table 3](#)). In a meta-analysis comprising 13 primary studies, Schoenfeld and colleagues⁴⁷ found that when RT volume was matched, there was no difference between higher- and lower-RT frequency (SMD = 0.07 ± 0.06; 95%CI: –0.08 to 0.21; p = 0.32). Similarly, in healthy older adults, Kneffel et al.³³ found there to be no significant difference of RT frequency for muscle hypertrophy (p = 0.51), with an estimate of 0.02 (95%CI: –0.04 to 0.07) for each day increase in frequency (QoE: Level 2). In contrast, Schoenfeld et al.⁴⁹ conducted a moderate-quality meta-analysis (QoE: Level 3) and found that higher-frequency RT was associated with a greater effect size than lower-frequency RT (SMD = 0.19 ± 0.03; 95%CI: 0.11–0.20; p = 0.003) (QoE: Level 3). One meta-regression¹⁶ provided insufficient evidence

to form a conclusion on the effect of RT frequency on skeletal muscle hypertrophy in older adults.

3.2.10. Muscle action type

Two reviews provided some evidence^{21,52} that muscle action type might influence skeletal muscle hypertrophy ([Table 3](#)). In a moderate-quality meta-analysis (QoE: Level 3; 15 studies), Schoenfeld and colleagues⁵² reported that, compared with concentric RT, eccentric RT modestly increased skeletal muscle hypertrophy (SMD = 0.25; 95%CI: –0.03 to 0.52; p = 0.076). One very low-quality systematic review (QoE: Level 1) concluded that “Eccentric training appears to elicit greater increases in muscle CSA (cross-sectional area) than concentric or traditional RT. . . Selective increases in fast-twitch fiber size have been reported and there is evidence to suggest that a shift towards a fast phenotype can occur as a result of chronic eccentric training”.²¹ One moderate-quality meta-analysis (3 studies and n = 73 participants)⁴⁶ provided insufficient evidence to determine the effect of muscle action type on skeletal muscle hypertrophy.

3.2.11. Time of day

One high-quality meta-analysis (QoE: Level 4; 6 primary studies (n = 112 participants))²³ found no significant difference between morning-RT and evening-RT (SMD = 0.20, 95%CI: –0.40 to 0.40; p = 0.958).

3.2.12. Exercise order

One high-quality meta-analysis (QoE: Level 4; 7 primary studies; n = 177 participants)³⁹ found no significant influence of exercise order on skeletal muscle hypertrophy (SMD = –0.02; 95%CI: –0.45 to 0.41; p = 0.937; I^2 = 0%).

3.3. Strength

3.3.1. RT vs. non-exercising control

One low-quality review (QoE: Level 2),¹⁵ 2 moderate-quality reviews (QoE: Level 3),^{18,30} and 1 high-quality review (QoE: Level 4)³¹ provided sufficient evidence^{15,30,31} or some

Table 3

Effects of resistance training and resistance training prescription variables on muscle hypertrophy, strength, and physical function.

	Hypertrophy	Strength	Physical function
RT vs. non-exercising control	Overall: ✓ 2 reviews ($n = 2651$) ↑↑ 2 reviews ($n = 304$) ↑	Overall: ✓ 3 reviews ($n = 3929$) ↑↑ 1 review ($n = \text{NR}$) ↑ 2 reviews ($n = 991$) ?	Overall: ✓ 1 review ($n = 404$) ↑
Load	Overall: ✗ 1 review ($n = 213$) ↑ 4 reviews ($n = 1895$) ↔ 3 reviews ($n = 470$) ?	Overall: ✓ 3 reviews ($n = 2431$) ↑↑ 3 reviews ($n = 1111$) ↑ 2 reviews ($n = 251$) ?	Overall: ? 1 review ($n = 168$) ?
Set end point (momentary muscular failure)	Overall: ✗ 1 review ($n = 219$) ↔	Overall: ✗ 2 reviews ($n = 593$) ↔	
Contraction velocity/time under tension	Overall: ✗ 1 review ($n = 204$) ↔ 1 review ($n = 159$) ?	Overall: ? 2 reviews ($n = 140$) ?	Overall: ? 2 reviews ($n = 692$) ?
Volume (number of sets)	Overall: ✓ 1 review ($n = 418$) ↑↑ 1 review ($n = 235$) ↑ 1 review ($n = 159$) ?	Overall: ✓ 3 reviews ($n = 1284$) ↑ 4 reviews ($n = 1074$) ?	
Set configuration	Overall: ✗ 1 review ($n = 195$) ↔ 1 review ($n = \text{NR}$) ?	Overall: ✗ 2 reviews ($n = 764$) ↔	
Inter-set rest	Overall: ? 2 reviews ($n = 115$) ?	Overall: ✗ 1 review ($n = 491$) ↔ 1 review ($n = \text{NA}$) ?	
Periodization	Overall: ✗ 2 reviews ($n = 417$) ↔	Overall: ? 1 review ($n = \text{NR}$) ↑ 1 review ($n = 612$) ?	
Weekly frequency	Overall: ✗ 1 review ($n = 200$) ↑ 2 reviews ($n = 711$) ↔ 1 review ($n = 159$) ?	Overall: ✓ 1 review ($n = 912$) ↑↑ 1 review ($n = 314$) ↑ 1 review ($n = 271$) ↔ 2 reviews ($n = 504$) ?	
Muscle action type	Overall: ✓ 2 reviews ($n = 795$) ↑ 1 review ($n = 73$) ?	Overall: ✗ 1 review ($n = \text{NR}$) ↑ 2 reviews ($n = 738$) ↔ 2 reviews ($n = 313$) ?	
Time of day	Overall: ✗ 1 review ($n = 112$) ↔	Overall: ✗ 1 review ($n = 221$) ↔	
Exercise order	Overall: ✗ 1 review ($n = 177$) ↔	Overall: ✓ 1 review ($n = 207$) ↑	

Notes: Resistance training and resistance training prescription variables important (✓), not important (✗), or unable to determine (?) for each outcome. The decision whether resistance training or a resistance training prescription variable was important or not was based on the total number of participants affected positively across the relevant trials (i.e., one trial ($n = 200$) showed an increase (↑); two trials ($n = 711$) showed no effects (↔); overall decision ✗). ↑↑ sufficient effect; ↑ some effect; ↔ no effect; ? cannot determine effect.

Abbreviations: NA = not available; NR = not reported; RT = resistance training.

evidence¹⁸ that RT increases skeletal muscle strength compared to non-exercising controls (Table 3).

In a high-quality meta-analysis (QoE: Level 4), Hagstrom and colleagues³¹ found that compared to non-exercising controls, RT resulted in significant increases in upper body strength ($SMD = 1.70$; 95%CI: 1.28–2.13; $p < 0.001$) and lower body strength ($SMD = 1.40$; 95%CI: 1.03–1.76; $p < 0.001$) in young women. Similarly, 2 other moderate-quality meta-analyses (QoE: Level 3)^{18,30} demonstrated similar benefits in muscular strength with RT, compared to non-exercising control groups, in healthy older adults. A low-quality umbrella review (QoE: Level 2; 7 reviews and $n = 2869$ participants) concluded there is a high QoE in support of RT for increasing muscle strength in older

adults.¹⁵ Csapo and colleagues¹⁸ provided some evidence that high-load RT ($SMD = 0.778$; 95%CI: 0.447–0.921; $p < 0.001$) or low-load RT ($SMD = 0.663$; 95%CI: 0.396–0.826; $p < 0.001$) provoked greater increases in muscle strength, compared with non-exercising controls, in healthy older adults. Two moderate-quality reviews (QoE: Level 3)^{16,54} provided insufficient evidence due to high heterogeneity ($I^2 > 80\%$).

3.3.2. Load

One high-quality review (QoE: Level 4),³⁷ 4 moderate-quality reviews,^{18,44,53,55} and 1 low-quality review (QoE: Level 2)³⁶ provided some^{18,36,55} or sufficient^{37,44,53} evidence that RT load impacts RT-induced muscular strength gains

(Table 3). In a high-quality network meta-analysis (QoE: Level 4), Lopez and colleagues³⁷ found that compared with low-load RT (<60% of 1RM or >15 RM), high-load RT ($\geq 80\%$ 1RM or ≤ 8 RM; SMD = 0.60; 95%CI: 0.38–0.82) and moderate-load RT (60%–79% 1RM or 9–15 RM; SMD = 0.34; 95%CI: 0.05–0.62) resulted in larger muscular strength improvements ($p < 0.001$ and < 0.003 , respectively). Refalo and colleagues⁴⁴ found that higher-load RT is superior to lower-load RT for increasing 1RM (QoE: Level 3; 36 studies, 1187 participants; SMD = 0.34; 95%CI: 0.15–0.52; $p = 0.0003$; favors high-load) and isometric maximal voluntary contraction (MVC; 14 studies, 302 participants; SMD = 0.41; 95%CI: 0.07–0.76; $p = 0.02$) but not isokinetic MVC (10 studies, 264 participants; SMD = 0.19; 95%CI: −0.10 to 0.49; $p = 0.20$). In a systematic review, Lacio and colleagues³⁶ demonstrated that most studies (11/18 studies for 1RM strength; 6/9 studies for isometric MVC) concluded that moderate- and high-load RT were superior to low-load RT for increasing 1RM strength and isometric MVC (QoE: Level 2) in young adults. Meta-analyses by Steib and colleagues⁵⁵ and Csapo and colleagues¹⁸ provided some evidence that RT with heavier loads may be required to maximize RT-induced skeletal muscle strength gains in older adults. Two reviews^{16,53} provided inconclusive evidence regarding the impact of RT load on muscle strength due to a small number of studies being synthesized for analysis⁵³ or high heterogeneity ($I^2 > 80\%$).¹⁶

3.3.3. Set end point (momentary muscular failure)

In a meta-analysis of 15 reviews, Grgic and colleagues²⁸ showed no significant difference between failure RT or non-failure RT on skeletal muscle strength (SMD = −0.09; 95%CI: −0.22 to 0.05; $p = 0.198$). Similarly, a high-quality meta-analysis (QoE: Level 4; 8 studies)¹⁹ found similar increases in muscle strength between failure RT (effect size = 0.33; 95%CI: 0.06–0.61) and non-failure RT (effect size = 0.34; 95%CI: 0.06–0.62) (Table 3).

3.3.4. Contraction velocity/time under tension

Two moderate-quality reviews (QoE: Level 3)^{16,55} provided insufficient evidence to determine an effect in older adults due to highly heterogenous effects ($I^2 > 80\%$; Table 3).

3.3.5. Volume (number of sets)

A moderate-quality meta-analysis (QoE: Level 3; 14 studies and $n = 440$ participants)³⁴ found that performing multiple sets/exercise was associated with significantly greater strength gains compared with performing a single set/exercise (SMD = 0.26 ± 0.05 ; 95%CI: 0.15–0.37; $p = 0.0001$). The same review³⁴ found that performing 2–3 sets/exercise was associated with a significantly greater effect size than performing 1 set/exercise (SMD = 0.25 ± 0.06 ; 95%CI: 0.14–0.37; $p = 0.0001$), but performing 4–6 sets/exercise was not superior to performing 1 set/exercise (SMD = 0.35 ± 0.25 ; 95%CI: −0.05 to 0.74; $p = 0.17$) or 2–3 sets/exercise (0.09 ± 0.20; 95%CI: −0.31 to 0.50; $p = 0.64$). In a moderate-quality meta-analysis (QoE: Level 3; 16 studies and $n = 621$

participants), Wolfe and colleagues⁵⁷ found that multiple sets were superior to single sets for trained individuals ($p < 0.001$) and RT programs with an extended duration ($p < 0.05$).

Four additional reviews, ranging from low quality (QoE: Level 2)¹⁴ to moderate quality (QoE: Level 3)^{16,43,55} provided insufficient evidence to determine an effect due to systematic reviews containing high heterogeneity ($I^2 > 80\%$),^{16,43} a low number of studies synthesized for review,⁵⁵ and 1 review¹⁴ reporting inconclusive results with no effect present in 3 of the 6 studies included (Table 3).

3.3.6. Set configuration

In a high-quality meta-analysis (QoE: Level 4), Davies and colleagues²⁰ showed no difference in muscular strength gains between cluster-set RT and traditional-set RT (SMD = -0.05 ± 0.08 ; 95%CI: −0.21 to 0.11; $p = 0.56$). Similarly, Jukic and colleagues³² found that neither cluster (SMD = −0.07; 95%CI: −0.21 to 0.07; $p = 0.300$; $I^2 = 0\%$) nor rest redistribution (SMD = −0.04; 95%CI: −0.20 to 0.12; $p = 0.641$; $I^2 = 51\%$) set structures were more effective than traditional set structures in promoting muscular strength adaptations.

3.3.7. Inter-set rest

One low-quality systematic review (QoE: Level 2; 23 studies; $n = 491$ participants)²⁹ concluded that rest interval duration does not impact skeletal muscle strength. Another review¹⁶ provided insufficient evidence to determine an effect in older adults due to considerably large heterogeneity ($I^2 > 80\%$; Table 3).

3.3.8. Periodization

In a low-quality meta-analysis (QoE: Level 2), Rhea and colleagues⁴⁵ found that periodized RT programs improved muscle strength over non-periodized RT programs. A moderate-quality review (QoE: Level 3)⁵⁶ provided insufficient evidence to determine an effect due to highly heterogeneous effects ($Q = 213.56$; $p < 0.001$; $I^2 = 62.5\%$; Table 3).

3.3.9. Weekly frequency

In a moderate-quality meta-analysis (QoE: Level 3; 22 studies; $n = 912$ participants), Grgic et al.²⁷ found a significant ($p = 0.003$) effect of weekly training frequency on muscular strength gains. Specifically, the authors concluded that higher RT frequencies (e.g., 4 days/week) resulted in larger strength gains than lower RT frequencies (e.g., 1 day/week). Similarly, a low-quality meta-regression (QoE: Level 2; 9 studies and $n = 314$ participants)³³ found a significant impact of weekly training frequency, such that for every daily increase in training frequency there was an 0.14 increase in effect size for muscular strength (Table 3).

In contrast, a high-quality meta-analysis (QoE: Level 4; 12 studies; $n = 299$ participants) done by Ralston and colleagues⁴² concluded there was no significant impact of weekly frequency on muscular strength, regardless of whether RT volume was equated or not. Two moderate-quality reviews (QoE: Level 3) provided insufficient evidence to determine the impact of RT frequency on muscular strength gains in older adults.^{16,55}

3.3.10. Muscle action type

In a very low-quality systematic review (QoE: Level 1), Douglas and colleagues²¹ concluded that “Eccentric training may improve overall strength to a greater extent than concentric and traditional modalities, although there is a mode-specificity (i.e., muscle action type and velocity) of improvements”. In contrast, a moderate-quality meta-analysis (QoE: Level 3)⁴⁶ found no differences between eccentric- or concentric-RT for improvement in peak torque (weighted mean difference: 3.71 N·m; 95%CI: -0.27 to 7.70; $p = 0.07$; $n = 333$) or 1RM (weighted mean difference: 1.07 kg; 95%CI: -0.22 to 2.37; $p = 0.10$; $n = 72$). Two moderate-quality reviews (QoE: Level 3)^{17,38} provided insufficient evidence to determine an effect due to the low number of studies synthesized for the analysis (<5 studies) (Table 3).

3.3.11. Time of day

One high-quality meta-analysis (QoE: Level 4; 11 primary studies; $n = 221$ participants)²³ found no significant differences between morning-RT and evening-RT, regardless of whether strength was assessed in the morning ($SMD = -0.08$; 95%CI: -0.40 to 0.25; $I^2 = 1\%$; $p = 0.643$) or in the evening ($SMD = -0.19$, 95%CI: -0.11 to -0.50; $I^2 = 0\%$; $p = 0.220$) (Table 3).

3.3.12. Exercise order

One high-quality meta-analysis (QoE: Level 4; 8 primary studies; $n = 207$ participants)³⁹ found no significant influence of exercise order on dynamic strength ($SMD = -0.02$; 95%CI: -0.45 to 0.41; $p = 0.937$; $I^2 = 0\%$) when all performed strength tests were considered (i.e., multi-joint (MJ) and single-joint (SJ)). However, exercise order did influence MJ dynamic strength ($SMD = 0.32$; 95%CI: 0.02–0.62; $p = 0.034$; $I^2 = 0\%$; favors performing MJ exercises first) and SJ dynamic strength ($SMD = -0.58$; 95%CI: -1.11 to -0.05; $p = 0.032$; $I^2 = 0\%$; favors performing SJ exercises first).

3.4. Physical function

Evidence was available for the influence of RT compared to no exercise and for the impact of RTx variables “load” and “contraction velocity/time under tension”. No evidence was available for the influence of other RTx variables on physical function.

3.4.1. RT vs. non-exercising control

A low-quality systematic review (QoE: Level 2; 3 studies and $n = 404$ participants)¹⁵ concluded that there is high-quality evidence to support the role of RT in improving physical function in older adults compared to non-exercising controls (Table 3).

3.4.2. Load

One moderate-quality meta-analysis (QoE: Level 3)⁵⁵ contained insufficient evidence to determine an effect due to the low number of studies synthesized for analysis (<2 studies).

3.4.3. Contraction velocity/time under tension

One moderate-quality review (QoE: Level 3)⁵⁵ and 1 high-quality review (QoE: Level 4)⁴⁰ contained insufficient evidence to determine an effect in older adults due to the limited number of studies synthesized for analysis (<3 studies)⁵⁵ or due to high heterogeneity and small-study publication bias.⁴⁰

4. Discussion

This umbrella review incorporated evidence from 44 systematic reviews and meta-analyses to determine the impact of RT and individual RTx variables on skeletal muscle mass, strength, and physical function in healthy adults. RT was consistently found to be a potent stimulus for increasing skeletal muscle mass, strength, and physical function compared to non-exercising controls. RT load, weekly frequency, volume (number of sets), and muscle action type were the most studied RTx variables. Load, weekly frequency, and exercise order impacted RT-induced increases in muscular strength but not muscle hypertrophy. RT volume (number of sets) influenced muscular strength and hypertrophy. Muscle action type also impacted skeletal muscle hypertrophy (eccentric favored). In contrast, several other RTx variables—including inter-set rest, periodization, set end point, contraction velocity/time under tension, and set configuration—did not appear to affect muscle hypertrophy and strength gains. In many cases, a paucity of data limited our ability to shed insight into the impact of several RTx variables on physical function.

RT load was the most investigated RTx variable (17/44 systematic reviews) across all outcomes. Traditionally, training with higher loads has been a key strategy to optimize neuromuscular adaptations. Six out of 8 systematic reviews contained some^{18,36,55} or sufficient^{37,44,48} evidence supporting the notion that higher-load RT is pertinent for maximizing muscular strength gains. The superiority of higher-load RT for muscular strength gains can be attributed to the principle of specificity (i.e., participants in higher-load groups regularly train using loads that are closer to the test of maximal (1RM) strength)⁴⁸ and neural adaptations that come with exercising at higher relative loads.⁵⁸ In contrast to muscular strength gains, muscle hypertrophy occurred independent of RT load (Table 3). Only 1 review examined the impact of RT load on physical function, and the low number of studies synthesized (<3 studies) prevented critical appraisal. However, the authors reported no differences between higher- and lower-load RT for improving stair climbing, timed up-and-go, chair rise, and walking speed in healthy older adults.⁵⁵ Further work is needed to clarify the impact—or lack thereof—of RT load on physical function. While the reviews included in our umbrella review provided important insight into the effects of RT load on skeletal muscle adaptations, RT load is primarily classified in binary terms (e.g., heavy load vs. light load), yet during an RT program, individuals may employ a spectrum of RT loading zones. It has been hypothesized that the amalgamation of a variety of RT loading zones may have synergistic effects on skeletal muscle adaptions;⁵⁹ however, future studies are needed to draw stronger inferences.

RT volume is the total amount of work performed in a resistance exercise session (or sometimes summed per week), and it is often defined by the number of sets performed. Our results herein suggest that RT volume impacts skeletal muscular strength and hypertrophic gains (Table 3). It has been suggested that the dose-response relationship between RT volume and skeletal muscle hypertrophy follows an inverted-U shape.⁵⁹ Krieger³⁴ showed that performing 2–3 sets/exercise and 4–6 sets/exercise was superior to performing 1 set/exercise, but there was no difference in hypertrophy adaptations when comparing 2–3 sets/exercise and 4–6 sets/exercise. The results from Krieger³⁴ suggest that higher volume RT confers an increasingly additive hypertrophic advantage but then plateaus, after which there are diminishing returns (less gain per volume increase) for hypertrophy and possibly detrimental outcomes.⁵⁹ A recent umbrella review by Bernárdez-Vázquez et al.⁶⁰ also observed a dose-response relationship between RT volume and hypertrophy and suggested that at least 10 sets per muscle group is optimal to increase muscle mass. Without considering blood flow restriction (excluded herein), our review strengthens this observation by including 32 (as opposed to 12⁶⁰) systematic reviews on RTx variables and hypertrophy. Bernárdez-Vázquez et al.⁶⁰ included 1 review not captured by our search strategy that showed exercise order might influence strength (favoring exercises performed at the beginning of a training session) but not hypertrophy.⁶⁰ Overall, our finding that RT volume is critical for hypertrophy supports and expands upon the findings from Bernárdez-Vázquez et al.⁶⁰

RT frequency was found to have a negligible impact on muscle hypertrophy but a potential influence on muscle strength. The discrepancy between muscle mass and strength outcomes might be attributed to including systematic reviews regardless of whether volume-equated studies were included. For instance, a meta-analysis of 22 studies²⁷ found a dose-response relationship between RT frequency and muscular strength gains; however, a subgroup analysis of volume-equated studies suggested that RT frequency negligibly impacted muscular strength gains. Furthermore, Schoenfeld et al.⁴⁹ demonstrated that when RT volume was *not* equated across protocols, higher training frequencies (e.g., 3 days per week) were consistently superior to lower training frequencies (e.g., 1 day per week). The same group conducted another meta-analysis⁴⁷ on only volume-equated studies and found no effect of RT frequency on muscular hypertrophy. The effect of weekly training frequency is difficult to discern because training frequency is related to RT volume. Therefore, we propose that weekly training frequency does not independently influence skeletal muscle adaptations, but that increasing training frequency can be manipulated to permit higher total weekly volume (with equal, or even reduced, within-session volume) and subsequent muscle mass and strength accrual. We also propose that, as with RT volume, at some point frequency becomes redundant and increases in strength and hypertrophy plateau. However, future studies are needed to determine whether splitting weekly RT volume across

additional weekly training sessions can maximize skeletal muscle adaptations.

Muscle action type (eccentric RT vs. concentric RT) was an impactful RT variable for muscle hypertrophy (Table 3). However, a limitation of the current umbrella review is that we did not consider limiting our inclusion to reviews that matched muscle action type for total work or maximum load, an oversight that could lead to divergent effects. Greater forces can be generated with eccentric contractions than concentric contractions, so utilizing eccentric loads (greater than concentric 1RM) could yield different workloads and subsequent adaptations;²¹ on the other hand, adaptations are similar when the 2 muscle action types are matched for total work or maximum load.⁶¹ Performing isolated, supra-maximal, eccentric contractions is pragmatically complex and may require special equipment (e.g., isokinetic dynamometers, iso-inertial devices) or external assistance (e.g., a spotter).^{52,62} However, flywheel training has emerged as a RT modality that is particularly effective for implementing high eccentric loads, which are difficult to achieve with traditional RT equipment.⁶³ Nonetheless, combining eccentric and concentric contractions (i.e., conventional RT) is more practical for practitioners.

There was either no impact or insufficient evidence to determine the impact of contraction-velocity/time-under tension on muscle hypertrophy, strength, and physical function. Diverse ranges of repetition durations are practical for promoting skeletal muscle adaptations, though very slow repetition durations (~10 s) appear to be detrimental. Considering that preserving muscle power appears to be important for maintaining physical function and the activities of daily living,^{6,64} older adults may benefit from high concentric-velocity RT (i.e., power training). High-quality studies must be conducted to provide more evidence clarifying the role of contraction velocity on skeletal muscle adaptations.

Non-periodized RT programs with adequate volume and progressive overload are sufficient to elicit muscular adaptations.⁵⁹ However, per session (or weekly) volume does not have to remain consistent throughout a training program, and periodizing volume has been hypothesized as a viable strategy for maximizing the dose-response relationship between volume and muscular adaptations. An RT program may be periodized using 1 or more conventional methods, such as linear periodization, daily undulating periodization, or block periodization. Overall, periodized and non-periodized RT programs elicit similar increases in hypertrophy. Furthermore, linear and undulating periodization approaches will yield similar skeletal muscle adaptations.²⁶ Early work from Rhea and colleagues⁴⁵ suggested that periodized RT is superior to non-periodized RT for strength development. The mechanisms behind augmented strength gains with periodized RT remain unclear, but periodization may aid with augmenting recovery and preventing overtraining.^{6,59} It has been suggested that superior strength gains with periodized RT are not due to the systematic variation of training, but could be attributed to the principle of specificity; participants may be training with heavier loads in the last mesocycle (i.e., near post-testing).⁶⁵ In the current study, none of the included reviews controlled

for the principle of specificity, and future studies should attempt to control for this phenomenon to properly determine whether periodized RT is an important variable to consider for maximizing strength gains.

Set configuration methods (traditional set distribution, rest redistribution, cluster sets) and rest intervals represent advanced techniques to disperse training volume within a resistance exercise session. However, we found less evidence supporting these variables than volume for optimizing skeletal muscle adaptations. Therefore, periodized or non-periodized training approaches, including various set configurations and rest intervals, appear to induce similar adaptations, provided adequate volume is employed.

Performing resistance exercises to momentary muscular failure has been posited as important for increasing muscular strength and mass. In contrast to this hypothesis, the current umbrella review suggests that RT-induced increases in muscle mass can be achieved without going to a set end point of momentary muscular failure. Training to muscular failure does not appear to have detrimental effects on training-induced adaptations *per se*, but studies on the chronic (i.e., >3 months) impact of momentary failure training are lacking. Training to momentary muscular failure may also elicit discomfort, pose safety risks, and lead to neuromuscular fatigue, particularly for older adults.⁶ Indeed, training to muscular fatigue is not required for older adults to observe training-induced neuromuscular adaptations.^{66,67} Training to momentary muscular failure may become increasingly important for trained individuals,^{28,59} but the findings here should be translated to athletic populations with caution and diligence to avoid excess fatigue and overtraining.

Human exercise performance⁶⁸ and strength⁶⁹ appear to peak in the evening (~18:00 h), and preclinical studies suggest the timing of exercise over the day can influence the beneficial effects of training.⁷⁰ However, the results presented herein demonstrate that morning or evening produces similar increases in muscle strength and mass (Table 3). Only 2 systematic reviews were identified on this topic; so, additional research is needed to determine whether there are differences between morning and evening training. Time of day for training does not appear to impact muscular adaptations and is best selected by personal preference.

We found that exercise order impacted RT-induced increases in muscular strength. Specifically, Nunes and colleagues³⁹ found that increases in dynamic strength were greater in exercises performed at the beginning of a resistance exercise session, which relates back to the principle of specificity. When exercises are performed at the beginning of a resistance exercise session, individuals are less fatigued and able to utilize higher relative loads and effort. To augment RT-induced increases in skeletal muscle hypertrophy, it has been hypothesized that individuals should prioritize performing MJ as opposed to SJ exercises at the beginning of a resistance exercise session as this allows for the accumulation of greater training volume.⁷¹ In contrast, to augment site-specific skeletal muscle hypertrophy (e.g., triceps) others have suggested that it is better to perform SJ exercises (e.g., triceps extension) prior to MJ exercises (e.g., bench press).⁷² The

results of the current umbrella review suggest that RT-induced increases in skeletal muscle hypertrophy are similar regardless of exercise order. Therefore, exercise order impacted RT-induced increases in muscular strength but not muscle hypertrophy. Individuals wanting to improve their maximal strength for a given exercise should perform that exercise at the beginning of the resistance exercise session.³⁹

The strengths of this umbrella review include the comprehensive search strategy utilized and the large number of systematic reviews included. Several limitations require acknowledgement and consideration when interpreting the results of this umbrella review. Potentially relevant reviews published since the last search (December 9, 2021 to current)^{60,73–77} were not captured by our search strategy, which prevented us from determining the impact of additional RT-variables, such as exercise selection,^{73,76} exercise variation,⁷⁴ and range of motion.^{75,77} Future work should be aimed at characterizing the influence of the aforementioned RTx variables on hypertrophy, strength, and physical function. We identified limited evidence from which we could draw conclusions on the impact of different RT variables on physical function, which may be attributed to including systematic reviews with only healthy older adults (e.g., not frail). Additionally, well-trained elite athletes/military persons were excluded because these populations commonly perform RT in addition to their sport-specific training, which would make it difficult to discern the influence of RTx variables from alternative modalities of exercise training. The current study also excluded individuals with chronic disease. To provide additional insight, future work is required to determine the impact of different RTx variables on these populations. The average range for RT duration was 6–24 weeks, and any interpretations of the results for longer durations should be viewed with caution. About 1/3 of the systematic reviews in the current study contained either high levels of heterogeneity or included a limited number of studies; thus, we were unable to draw satisfactory conclusions from these reviews. We also acknowledge that additional RT program variables not investigated in the current review (e.g., blood flow restriction) may influence outcomes. Nonetheless, based on observations from the current review, we propose that the impact of these other variables is likely limited in terms of effects on strength and hypertrophy. Directions for future research are apparent when we note the limited data for physical function and specific RTx variables (e.g., time of day, set configurations, and inter-set rest intervals). Additionally, not presenting a list of included and excluded studies (40 reviews), not including *a priori* design (38 reviews), and the use of publication status as an inclusion criterion (if the search included grey literature; 33 reviews) were the most common factors detracting from the quality of included reviews. Researchers may wish to consider these points before embarking on future systematic reviews.

5. Conclusion

This umbrella review found that RT promotes increased muscle hypertrophy, strength, and physical function in healthy

adults compared to no exercise. RT volume appears to be important for both muscular strength and hypertrophic gains. RT load and weekly frequency appeared to be important for muscle strength. Muscle action type seems to be important for hypertrophy but not strength. Inter-set rest, periodization, set end point, contraction velocity/time under tension, and set configuration were not important to RT-induced adaptations. Less is known regarding which RT variables are important for optimizing improvements in physical function. We conclude that RT largely increases muscle hypertrophy, strength, and physical function compared to no exercise, and that very few RTx variables impact muscular adaptations.

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Authors' contributions

JCM and BSC contributed equally to this paper, designed and executed the systematic search, with the assistance of CVL screened articles, extracted data, evaluated articles using standardized effectiveness statements and AMSTAR and, along with SMP, conceived the review and drafted the manuscript. All authors critically revised the manuscript. All authors have read and approved the final version of the manuscript, and agree with the order of presentation of the authors.

Competing interests

SMP reports grants or research contracts from the U.S. National Dairy Council, Canadian Institutes for Health Research, Dairy Farmers of Canada, Roquette Freres, Ontario Centre of Innovation, Nestle Health Sciences, Myos, National Science and Engineering Research Council, and the U.S. NIH during the conduct of the study; personal fees from Nestle Health Sciences and non-financial support from Enhanced Recovery, outside the submitted work. SMP has patents licensed to Exerkine, but reports no financial gains from any patent or related work. All the support had no involvement in the study design and writing of the manuscript or the decision to submit it for publication. The remaining authors report no competing interests.

Supplementary materials

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