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SYSTEMATIC REVIEW

The Effect of Resistance Training in Women on Dynamic Strength and Muscular Hypertrophy: A Systematic Review with Meta-analysis

Amanda D. Hagstrom[1] · **Paul W. Marshall**[2] · **Mark Halaki**[3] · **Daniel A. Hackett**[3]

Abstract

Background The effect of resistance training (RT) on adaptations in muscular strength and hypertrophy has never been examined in an exclusively female synthesis of the literature.

Objective The objectives of this study were threefold: (1) to systematically review the literature on female adaptations to RT, characterising the effect in terms of muscular strength and hypertrophy; (2) to distinguish the individual effects of intervention duration, frequency, and intensity on these adaptations via sub-analysis; (3) to draw evidence-based conclusions regarding training expectations in female populations.

Methods Three electronic databases were searched using terms related to RT combined with females or women. Random-effects meta-analyses were undertaken to estimate the effect of RT on muscular strength and hypertrophy in females. Possible predictors that may have influenced training-related effects (e.g., training intensity and volume) were explored using univariate analyses.

Results The systematic search identified 14,067 articles of which a total of 24 studies met the inclusion criteria and were eligible. Upper body strength was assessed in 15 studies, lower body strength in 19 studies, and muscular hypertrophy in 15 studies. Study duration lasted between 4 weeks and 12 months. Large-effect sizes were found for upper body strength (Hedges' $g = 1.70$; $p < 0.001$) and lower body strength (Hedges' $g = 1.40$; $p < 0.001$). Following use of the Trim and Fill method (due to presence of publication bias), a large effect still remained for upper body strength (Hedges' $g = 1.07$), although a medium effect was found for lower body strength (Hedges' $g = 0.52$). A medium effect was found for muscular hypertrophy ($g = 0.52$, $p = 0.002$). Sub-analyses revealed that the moderating variables "training frequency" and "training volume" significantly influenced lower body muscular strength ($p < 0.001$). "Training frequency" and "sets per exercise" moderated the RT effects on upper body strength ($p < 0.01$). No moderating variables were found to significantly influence muscular hypertrophy. A trend for a moderating effect on upper body strength was found for "age of participants" ($p = 0.08$), whereby younger participants experienced a greater effect. A moderating effect was also observed where supervised training had a larger influence on the adaptation of lower body strength ($p = 0.05$) compared with unsupervised training. Methodological quality for the studies included in the review was found to be moderate.

Conclusions RT elicits large improvements in muscular strength and hypertrophy in healthy adult females. Training volume and frequency appear to be important variables that influence muscular strength.

1 Introduction

Over recent years, the popularity of resistance training (RT) as an exercise modality has been increasing, particularly among women. The nature of RT means that many of the physiological adaptations following a period of RT are distinct to this modality of exercise. RT is considered the gold standard exercise modality in terms of accrual of lean muscle mass [1]. RT also plays a role in the preservation and maintenance of bone mineral density [2], treatment of sarcopenia [3, 4], reduction of blood pressure [5], and the treatment and risk reduction for multiple chronic diseases including

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✉ Amanda D. Hagstrom
m.hagstrom@unsw.edu.au

[1] School of Medical Sciences, University of New South Wales, Sydney, NSW, Australia

[2] School of Science and Health, Western Sydney University, Sydney, NSW, Australia

[3] Physical Activity, Lifestyle, Ageing and Wellbeing Faculty Research Group, Faculty of Health Sciences, The University of Sydney, Lidcombe, NSW, Australia

Key Points

RT elicits a large effect in improvements in muscular strength and hypertrophy in healthy adult females.

Average gains of 1.45 kg of muscle mass and 25% in muscular strength were observed following periods of RT lasting an average of 15 weeks in females.

Training volume and frequency appear to be important variables that influence muscular strength.

Researchers are encouraged to be clear and thorough in their reporting of exercise prescription training parameters, including explicitly stating if RT is performed until 'concentric failure'.

metabolic syndrome, fibromyalgia, and rheumatoid arthritis [6, 7]. While it has been suggested that women can perform almost identical RT programs to men due to a few sex-based differences in the acute and chronic response to RT [8], an emerging body of evidence challenges that notion [9]. A few noteworthy sex differences in response to exercise include disparities in fatigability [9, 10], muscle perfusion [11], and the time course of recovery [12]. Sex differences in muscle fibre size and composition are also apparent [13, 14]. These physiological differences could potentially influence best practice program design, and the subsequent adaptations experienced. Currently, the majority of systematic reviews undertaken on the variables of RT have been conducted in male only or mixed sex samples [15–18]. To the authors' knowledge, no similar reviews have been conducted solely in females. When systematic reviews relating to RT have been conducted with female only cohorts, they have related to clinical outcomes such as breast cancer lymphoedema [15] or bone mineral density [19]. Recently, a systematic review and meta-analysis on the efficacy of RT in female youth has been published [20] showing that the magnitude in which female youth responded to RT (effect size (ES) = 0.54, 95% confidence interval (CI) [0.23–0.85]) was much lower than the effect previously observed in male youth (0.98 [0.70–1.27]) [21]. While additional maturational and developmental factors may affect these differences, these data add to the evidence that sex-based differences in adaptations to RT may be present. Part of the reason that it is still unclear how many, and to what extent, differences exist in terms of sex-specific adaptations to RT, is the dearth of literature specific to females. At present, females are significantly underrepresented in the sports and exercise science literature, with only 39% of all participants in the published data in this field being female [22]. The percentage is likely even lower in RT intervention based studies. Therefore, the purpose of this study was: (1) to systematically review the literature on female adaptations to RT, characterising the effect in terms of muscular strength and hypertrophy; (2) to distinguish the individual effects of intervention duration, frequency, and intensity on these adaptations via sub-analysis; (3) to draw evidence-based conclusions regarding training expectations in female populations. The synthesis of the literature specifically examining adaptation to RT in females will provide researchers and clinicians the knowledge of expected or usual adaptations and will provide a baseline against which the efficacy of future sex-specific training programs may be compared.

2 Methods

2.1 Search Strategy

A search from the earliest record up to and including April 2019 was carried out using the following electronic databases: PubMed, SPORTDiscus, and CINAHL. The search strategy employed combined the terms 'resistance exercise' OR 'resistance training' OR 'strength training' OR 'strength exercise' OR 'weightlifting' AND 'female' OR 'women'. Titles and abstracts of retrieved articles were individually evaluated by two reviewers (A. H. and D. H.) to assess their eligibility for review and meta-analysis. Any disagreements were solved by consensus by a third reviewer (M. H.). Additionally, forward citation tracking of the included articles was undertaken through Google Scholar. The reviewers were not blinded to the studies' authors, institutions, or journals of publication. Study abstracts that did not provide sufficient information according to the inclusion criteria were retrieved for full-text evaluation. Corresponding authors of articles that were potentially eligible were contacted for any missing data or clarification on data presented. This systematic review and meta-analysis was conducted in accordance with the recommendations outlined in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement [23].

2.2 Eligibility Criteria

Articles were eligible for inclusion if they met the following criteria: (1) involved females only or included female data presented separately if both sexes were involved; (2) were randomised controlled trials; (3) recruited participants with no known medical condition or injury; (4) involved adult participants with a mean age 18–50 years for intervention and control groups; (5) included an isotonic RT intervention and a non-exercise control group; (6) used interventions ≥ 4 week duration; (7) assessed muscular strength pre and post-intervention via a one-repetition maximum (RM);

and/or (8) measured changes in lean body mass (LBM) or fat-free mass (FFM) (via dual-energy X-ray absorptiometry, hydrodensitometry, whole-body air plethysmography), or muscle thickness (via ultrasound), muscle fibre cross-sectional area (CSA) (via biopsy), or whole-muscle CSA (via magnetic resonance imaging or computerized tomography); (9) original research (not review or conference abstract) published in English. Articles were ineligible if (1) there was a concurrent nutritional intervention; (2) the exercise intervention group performed other types of exercise such as aerobic exercise in addition to RT.

2.3 Data Extraction

Two reviewers (A. H. and D. H.) separately and independently evaluated full-text articles and conducted data extraction, using a standardised Excel template/spreadsheet. Data extracted were participant characteristics (age and training status), study characteristics (training frequency, exercises prescribed, sets, repetitions, rest between sets, intensity, failure or RM, number of exercises, intervention duration, training supervision, muscle strength, and/or hypertrophy measurement), and muscular strength and hypertrophy testing method. All studies that assessed muscular strength of the upper body used the chest/bench press, and therefore, only these results were extracted. For lower body muscular strength studies used the leg press, squat, leg extension, and calf raise either alone or in combination; therefore, results for these exercises were extracted. If mean and standard errors were reported, these values were converted to mean and standard deviation. Data that were reported in different units (e.g., pounds versus kilograms) were converted to metric units. Data presented in graphs were extracted using a web-based software (Graph Data Extractor, version 0.0.0.1, Dr. A. J. Matthews). Shortly after extractions were performed, the reviewers crosschecked the data to confirm their accuracy. Any discrepancies were discussed until a consensus was reached with any disagreements being resolved by consultation with a third reviewer (M. H.).

2.4 Quality Analysis

A modified version of the Downs and Black checklist was used to evaluate the studies' quality [24, 25]. The scoring of Item 27 (Power) was modified as "1" if studies had performed a power calculation to determine the sample size required for the study and as "0" if this was not performed. Studies were independently rated by two reviewers (A.H. and D.H.) and checked for internal (intra-rater) consistency across items before the scores were combined into an Excel spreadsheet for discussion. Scores range from 0 to 29 points, with higher scores reflecting higher quality research. Scores above 20 were considered good; scores of 11–20 were considered moderate; and scores below 11 were considered poor methodological quality [26]. Disagreements between ratings were resolved by discussion or consensus was reached through the assistance of a third reviewer (M. H.).

2.5 Statistical Analysis

The mean effect size (ES), expressed as Hedges' g, and 95% confidence interval for strength and hypertrophy outcomes of RT compared to the control condition were calculated using Comprehensive Meta-Analysis version 3 software (Biostat Inc., Englewood, NJ, USA). Hedges' g was selected to report the standardised mean difference, because it (1) corrects for parameter bias due to small sample sizes, and (2) uses pooled pre-SD which is thought to better reflect population SD and is comparable across studies [27, 28].

Imputed study-level correlation coefficient for change from pre-intervention SD was set at a conservative estimate of 0.5 across all studies. If a study had multiple time points where the outcomes of interest were assessed, only the pre- and post-interventions were used for analyses. However, for one study that extended up to 2 years [29], the 1 year assessment was chosen as the final-time point, since all of the other interventions included in the analyses were all completed in <1 year. For studies that included two intervention groups to a single control group, separate ES were calculated for each intervention group, but for the pooled ES, the sample size of the control group was halved to avoid double counting [30]. When studies had multiple outcomes (e.g., tested muscular strength of a body region with multiple exercises or muscular hypertrophy using different measures), ESs were selected based on a hierarchical model whereby the top-ranking exercise was chosen to input the effect size. For the lower body, the hierarchy was (1) leg press; (2) squat; (3) leg extension (bilateral given priority to unilateral); (4) calf raise. For the upper body, the hierarchy was (1) chest press; (2) bench press. These rankings were chosen as they prioritised compound non skill-based movements first. When studies presented multiple outcomes for muscle size, the hierarchy of inclusion was based on the relationship to the training intervention, i.e., if a study focused solely on the lower limb and provided a quadriceps thickness measurement, this was deemed superior to a full-body LBM measurement. Additionally, LBM of the upper or lower limbs was deemed superior to muscle thickness of a specific muscle. The variance (r) of ESs was calculated as described by Borenstein et al. [27]. The computed ES was assessed as small (ES = 0.20), medium (ES = 0.50), or large (ES = 0.80) [31]. The study heterogeneity was assessed using Q and I^2 statistics ($p < 0.05$). The heterogeneity thresholds using the I^2 were 25% (low), $I^2 = 50\%$ (moderate), and $I^2 = 75\%$ (high) [32]. Due to study heterogeneity, a random-effects model of meta-analysis was applied to the pooled data with significance set at $\alpha < 0.05$ and trends were declared at α 0.05 to < 0.10. Publication bias was examined visually via funnel plots and statistically ($p < 0.10$) using Egger's test [33]. The Trim and Fill procedure [34] was applied if evidence of publication bias was noted.

To examine possible variables that may affect training effectiveness, categories were created and analysed individually using univariate analyses. These categories were: (1) age of participants (18–30 vs. ≥ 31 years)[35]; (2) prescription method (failure/RM vs. non-failure/RM); (3) intervention duration (4–11 vs. 12–23 vs. ≥ 24 weeks); (4) load (< 70% vs. ≥ 70% 1RM) [36]; (5) frequency (1–2 vs. ≥ 3 days/week); (6) sets per exercise (1–2 vs. 3–4); (7) supervised training (without vs. with); (8) training volume per week (< 120 vs. ≥ 120 repetitions—upper body strength, < 250 vs. ≥ 250 repetitions—lower body strength, < 600 vs. ≥ 600 repetitions—muscular hypertrophy). This cut-point for training volume was determined by identifying a point at which the number of studies was most evenly distributed. Training volume was calculated for exercises targeting the upper body or lower body for strength of these respective regions (e.g., training volume of all exercises involving the upper body such as chest press, seated rows, bicep curls, and shoulder press were used to calculate 'regional' training volume to assess changes in the upper body strength outcome, e.g., chest press 1RM), and the whole body for muscular hypertrophy. When a range was provided for any RT variable, the median number was used (e.g. 8–12 repetitions = 10 repetitions). For studies that prescribed training intensities (i.e., loads) based on RM, the relative loads (% 1RM) used for training were calculated according to an estimated repetitions at %1RM chart [37] (e.g., 8RM corresponds to 80% 1RM).

3 Results

3.1 Study Characteristics

The database search yielded 14,067 potential studies, and following screening, a total of 24 [29, 38–60] studies met the eligibility criteria. The literature search results are presented in Fig. 1. There were a total of 912 participants, with the mean age of 565 participants between 18 and 30 years and for 347 participants between > 30 and 50 years. A detailed description of study characteristics is provided in Table 1.

3.2 Quality of the Studies

The mean quality rating score was 16.2 ± 2.2 out of a possible score of 29 (Table 2), which was considered moderate-study quality. All studies reported aims or purpose, main outcomes, overall findings, and estimates of random variability, whereas no studies reported information about adverse events (e.g., a list of possible adverse events is provided). All studies showed no evidence of data dredging, used appropriate statistical tests, and used accurate (valid and reliable) outcome measures. Six studies performed a power calculation to determine the sample size required for the study. Exercise adherence was reported in ten studies and was ≥ 74%.

3.3 Risk for Publication Bias and Heterogeneity

When estimated ES were plotted against standard error, there was publication bias risk detected for upper body strength (Egger's intercept = 3.12, $p < 0.001$) and lower body strength (Egger's intercept = 3.15, $p < 0.001$). However, no evidence of publication bias risk was detected for muscular hypertrophy (Egger's intercept = − 0.73, $p = 0.76$) (see Fig. 2). The heterogeneity using the random-effects model was low for upper body strength ($I^2 = 16.93\%$) and muscular hypertrophy ($I^2 = 0\%$), and moderate for lower body strength ($I^2 = 32.89\%$).

3.4 Effects of Resistance Training on Muscular Strength and Hypertrophy

RT resulted in significant increases in upper body strength ($g = 1.70$, $p < 0.001$, 95% CI 1.28–2.13), lower body strength ($g = 1.40$, $p < 0.001$, 95% CI 1.03–1.76), and muscular hypertrophy ($g = 0.52$, $p = 0.002$, 95% CI 0.25–0.78) (Fig. 3). Imputed estimated ES for upper and lower body strength, and adjusted for missing studies ($n = 8$ and $n = 11$, respectively) using the Trim and Fill method which showed a slight reduction in ES magnitude for upper body strength ($g = 1.07$, 95% CI 0.61–1.52) and lower body strength ($g = 0.69$, 95% CI 0.54–0.83). This suggests that the asymmetrical funnel plot for upper and upper body muscular strength was influenced by publication bias.

3.5 Influence of Different Moderating Variables on Resistance Training Effectiveness for Muscular Strength and Hypertrophy

3.5.1 Upper Body Strength

Subgroup analyses revealed a statistically significant effect of the moderator variable "frequency" on upper body strength ($Q = 7.23$; $p = 0.007$). For upper body strength, RT induced larger effects with frequencies of ≥ 3 days/week ($g = 1.95$; 95% CI 1.57–2.80; $p < 0.001$) compared to 1–2 days/week ($g = 1.08$; 95% CI 0.57–1.59; $p < 0.001$). The moderating variable "sets per exercise" showed a significant effect on upper body muscular strength ($Q = 5.44$; $p = 0.02$).

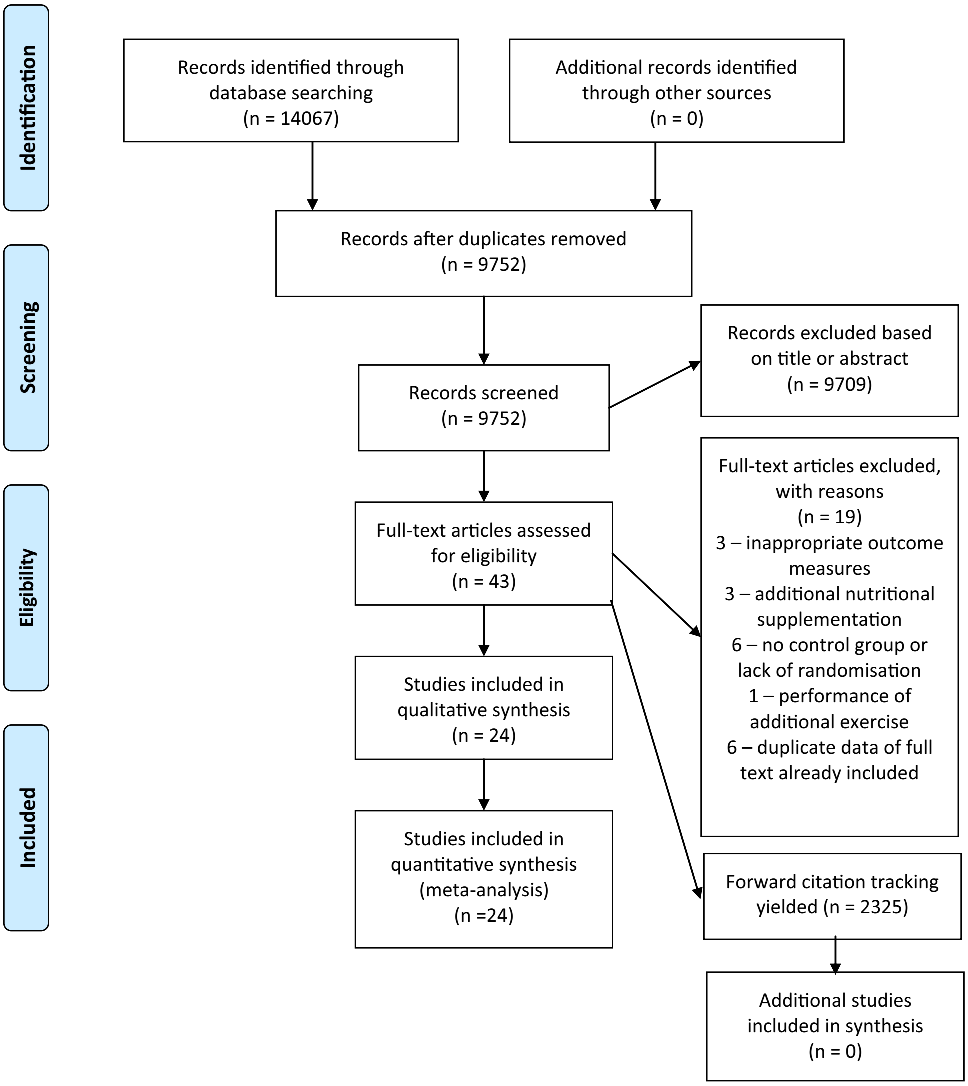


Fig. 1 Flowchart for inclusion and exclusion of studies

Larger effects were found with 3–4 sets per exercise ($g = 1.96$; 95% CI 1.40–2.49; $p < 0.001$) compared to 1–2 sets per exercise ($g = 1.13$; 95% CI 0.72–1.55; $p < 0.001$). There was a trend for a significant effect of the moderator variable "age" on upper body strength ($Q = 3.06$; $p = 0.08$). Slightly larger effects were found for participants aged 18–30 years ($g = 1.95$; 95% CI 1.39–2.50; $p < 0.001$) compared to ≥ 31 years ($g = 1.23$; 95% CI 0.67–1.80; $p < 0.001$). No other notable differences between groups were found for any other moderating variable (Table 3).

3.5.2 Lower Body Strength

There was a statistically significant effect of the moderator variable "frequency" on lower body strength ($Q = 13.92$; $p < 0.001$). For lower body strength, RT induced larger effects with frequencies of ≥ 3 days/week ($g = 1.69$; 95% CI 1.26–2.12; $p < 0.001$) compared to 1–2 days/week ($g = 0.62$; 95% CI 0.27–0.98; $p = 0.001$). Also, there was a statistically significant effect of the moderator variable "training volume" on lower body strength ($Q = 9.82$; $p = 0.002$). Larger effects were found with ≥ 250 repetitions per week ($g = 2.03$; 95% CI 1.39–2.67; $p < 0.001$) compared to < 250 repetitions per week ($g = 0.88$; 95% CI 0.55–1.21; $p < 0.001$). There was a trend for a significant effect of the moderator variable "supervised training" on lower body muscular strength ($Q = 3.86$; $p = 0.05$). Slightly larger effects were found with supervised sessions ($g = 1.71$; 95% CI 0.15–2.26; $p < 0.001$) compared to without supervision ($g = 1.01$; 95% CI 0.59–1.43; $p < 0.001$). No other moderating variable resulted in notable differences between groups (Table 4).

3.5.3 Muscular Hypertrophy

No notable differences between groups in muscular hypertrophy were found for any moderating variable (Table 5).

Table 1 Descriptive analysis of the included studies

Study	Group	*n*	Age (years)	Training status	Weeks	Session per week	% 1RM	No. of exercises	No. of sets	No. of reps	1RM test	Muscle hypertrophy measure
Abe et al. 2000 [38]	RT	20	41.0 ± 4.1	UT	12	3	60–70	6	1 or 3	8–12 (to fatigue)	LE	DXA (LBM)—whole body, US (MT—biceps, triceps, quadriceps, hamstring)
	CON	7	44.6 ± 5.7	UT								
Bell et al. 2000 [39]	RT	4	22.3 ± 3.3	UT	12	3	72–84	8	2–6	4–12	LP, LE	Not assessed
	CON	5	22.3 ± 3.3	UT								
Botton et al. 2016 [40]	RT (unilateral LE)	15	24.8 ± 1.4	UT	12	2		9	2–4	5–15 RM	LE	US (MT—quadriceps)
	RT (bilateral LE)	14	24.3 ± 3.7	UT	12	2		9	2–4	5–15 RM		
	CON	14	22.7 ± 2.8	UT	12							
Brown et al. 1986 [41]	RT (young)	25	21.5 ± NR	NR	12	3	60–75	10	3	6–12	BP, LP	Not assessed
	RT (mature)	25	44.4 ± NR	NR	12	3	60–75	10	3	6–12		
	CON (young)	25	21.5 ± NR	NR	12							
	CON (mature)	25	44.4 ± NR	NR	12							
Cesar et al. 2009 [42]	RT	9	21.0 ± 2.9	UT	12	3		8	3	15 RM	BP, LP, LE	Not assessed
	CON	10	20.3 ± 1.3	UT	12	3		8	3	15 RM		
DeLima et al. 2012 [43]	RT (linear)	10	25.2 ± 4.4	UT	12	4		8	3	15–30 RM	BP, LP	Not assessed
	RT (undulating)	10	27.4 ± 2.8	UT	12	4		8	3	15–30 RM		
	CON	8	23.4 ± 1.3	UT	12							
Hendrickson et al. 2010 [44]	RT	18	21.0 ± 0.5	NR	8	3		7	3	3–12 RM	SQ, BP	DXA (LBM)—whole body
	CON	10	20.0 ± 0.5	NR	8							
Kim et al. 2011 [45]	RT (slow)	14	19.5 ± 0.3	UT	4	2	50	5	1	Reps to failure	CP, LP	Not assessed
	RT (traditional)	13	20.8 ± 0.8	UT	4	3	80	5	3	8		
	CON	8	21.5 ± 0.8	UT	4							
LeMura et al. 2000 [46]	RT	11	20.0 ± 1.0	UT	16	3	60–70	11	2–3	8–10	Not assessed	UWW (FFM)—whole body
	CON	12	20.0 ± 1.0	UT	16	3						
Malin et al. 2013 [47]	RT (normal BF)	8	21.9 ± 0.8	UT	7	3	60	10	3	8–12	CP, LP	DXA (FFM)—whole body
	RT (high BF)	12	21.0 ± 0.8	UT	7	3	60	10	3	8–12		
	CON	7	20.9 ± 0.6	UT	7							
Marx et al. 2001 [48]	RT	12	23.2 ± 4.5	UT	24	3		10	1	8–12 (to failure)	BP, LP	UWW (FFM)—whole body

Table 1 (continued)

Study	Group	*n*	Age (years)	Training status	Weeks	Session per week	% 1RM	No. of exercises	No. of sets	No. of reps	1RM test	Muscle hypertrophy measure
Moghadasi et al. 2013 [49]	RT	12	22.6 ± 3.7	UT	24	4		7–12	3	3–15 RM		
	CON	10	22.2 ± 5.7	UT	24							
Mosti et al. 2014 [50]	RT	9	25.3 ± 3.2	UT	12	3	65–80	8	2–4	8–12	CP, LP, LE	Not assessed
	CON	10	25.3 ± 3.2	UT	12							
	RT	15	22.7 ± 2.2	UT	12	3	85–90	1	4	3–5	SQ	DXA (LBM)—whole body and lower extremity
	CON	15	21.5 ± 2.2	UT	12							
Olson et al. 2007 [51]	RT	16	39.0 ± 5.0	UT	52	2	NR	9	3	8–10	BP, LP	DXA—LBM (whole body)
	CON	12	38.0 ± 6.0	UT	52							
Poehelman et al. 2002 [52]	RT	16	28.0 ± 3.0	UT	26	3	80	9	3	8–10	Not assessed	DXA (FFM)—whole body
	CON	19	28.0 ± 4.0	UT	26							
Rana et al. 2008 [53]	RT (slow)	10	19.4 ± 1.3	UT	8	2–3		3	3	6–10 RM	LP, SQ, LE	BOD POD (FFM)—whole body
	RT (traditional)	9	20.6 ± 1.9	UT	8	2–3		3	3	6–10 RM		
	RT (endurance)	7	22.3 ± 3.9	UT	8	2–3		3	3	20–30 RM		
	CON	8	22.9 ± 2.4	UT	8	3						
Santos et al. 2010 [54]	RT (upper/lower	8	26.8 ± 1.6	UT	8	3		8	3	10–12	BP	Not assessed
	RT (agonist/antagonist	8	24.0 ± 2.3	UT	8	3		8	3	10–12		
	CON	8	25.4 ± 2.4	UT								
Sarsan et al. 2006 [55]	RT	20	42.5 ± 10.1	UT	12	3	40–80	6	1–3	10	CP, LE	Not assessed
	CON	20	43.6 ± 6.5	UT	12							
Schlumberger et al. 2001 [56]	RT	9	29.1 ± 9.2	T	6	2		7	1	6–9 RM	CP, LE	Not assessed
	RT	9	24.4 ± 2.9	T	6	2		7	3	6–9 RM		
	CON	9	25.3 ± 3.1	T	6							
Singh et al. 2009 [57]	RT	26	40.8 ± 6.3	UT	39	2		9	3	8–10 RM	BP, LP	DXA (LBM)—whole body
	CON	28	41.6 ± 6.6	UT	39							

Table 1 (continued)

Study	Group	*n*	Age (years)	Training status	Weeks	Session per week	% 1RM	No. of exercises	No. of sets	No. of reps	1RM test	Muscle hypertrophy measure
Stock et al. 2016 [58]	RT	15	21.0 ± 3.0	UT	4	2	NR	2	2	5	Not assessed	DXA (LBM)—lower extremity US (MT)—vastus lateralis
	RT	16	21.0 ± 3.0	UT	4	2	NR	2	4	5		
	CON	16	21.0 ± 3.0	UT	4							
Ucan et al. 2014 [59]	RT	13	23.1 ± 2.1	UT	12	3	50–60	15	3	12–14	Not assessed	DXA (FFM)—whole body
	CON	12	22.5 ± 1.7	UT	12							
Warren et al. 2008 [29]	RT	72	36.4 ± 5.5	UT	52	2	NR	8–10	3	8–10	BP, LP	DXA (FFM)—whole body
	CON	76	36.2 ± 5.6	UT	52							
Weiss et al. 1988 [60]	RT	14	20.8 ± 1.8	UT	8	3		1	4	9–13 RM	CR	US (MT)—triceps surae
	CON	14	20.8 ± 1.8	UT	8							

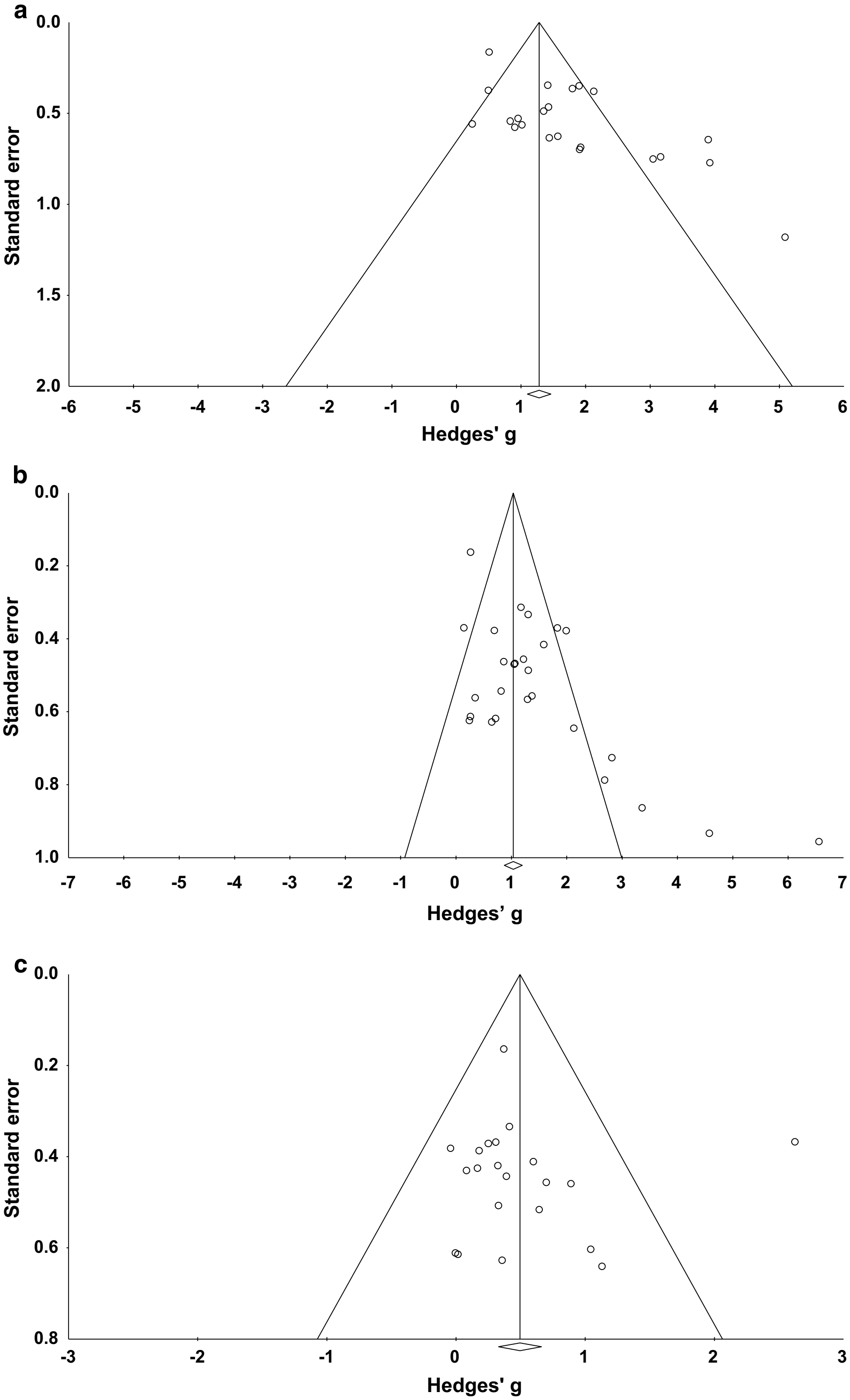
UT is considered to be no-resistance training for at least the previous 3 months, reported to be not currently training or having no formal training

RT resistance training, *CON* control, *UT* untrained, *T* trained, *NR* not reported, *RM* repetition maximum, *LE* leg extension, *CP* chest press, *BP* bench press, *LP* leg press, *SQ* squat, *CR* calve raise, *BF* body fat, *DXA* dual-energy X-ray absorptiometry, *LBM* lean body mass, *FFM* fat-free mass, *US* ultrasound, *MT* muscle thickness, *UWW* underwater weighing

Table 2 Quality of study assessment

Study	Reporting (/10)	External validity (/3)	Internal validity—bias (/7)	Internal validity—selection bias (/6)	Power (/1)	Adherence (/1)	Supervision (/1)	Rating score (/29)
Abe et al. 2000 [38]	6	1	3	3	0	0	1	14
Bell et al. 2000 [39]	6	1	3	2	0	0	0	12
Botton et al. 2016 [40]	7	1	3	2	1	1	1	16
Brown et al. 1986 [41]	5	2	3	3	0	0	0	13
Cesar et al. 2009 [42]	7	1	3	3	0	0	0	14
DeLima et al. 2012 [43]	7	1	3	2	0	0	1	14
Hendrickson et al. 2010 [44]	7	1	3	3	0	1	1	16
Kim et al. 2011[45]	8	1	3	2	1	0	1	16
LeMura et al. 2000 [46]	8	1	3	4	1	0	1	18
Malin et al. 2013 [47]	7	1	4	2	0	1	1	16
Marx et al. 2001 [48]	6	1	3	2	1	0	1	14
Moghadasi et al. 2013 [49]	8	1	3	2	0	0	0	14
Mosti et al. 2014 [50]	8	2	3	3	1	1	1	19
Olson et al. 2007 [51]	7	2	3	3	1	0	1	17
Poehelman et al. 2002 [52]	7	3	4	3	0	1	1	19
Rana et al. 2008 [53]	7	1	3	2	0	1	1	15
Santos et al. 2010 [54]	7	2	4	2	0	1	1	17
Sarsan et al. 2006 [55]	8	2	3	3	0	0	1	17
Schlumberger et al. 2001 [56]	6	1	4	3	0	1	1	16
Singh et al. 2009 [57]	9	1	3	5	0	1	1	20
Stock et al. 2016 [58]	8	1	4	3	0	0	1	17
Ucan et al. 2014 [59]	9	1	3	2	0	0	0	15
Warren et al. 2008 [29]	8	3	4	5	1	1	1	23
Weiss et al. 1988 [60]	8	1	4	2	0	0	0	15
Mean	7.3 ± 1.0	1.4 ± 0.6	3.3 ± 4.6	2.8 ± 0.9	0.3 ± 0.5	0.4 ± 0.5	0.8 ± 0.4	16.2 ± 2.5

Fig. 2 Funnel plots showing risk of publication bias for studies included in the analysis of: **a** upper body strength; **b** lower body strength; **c** muscular hypertrophy

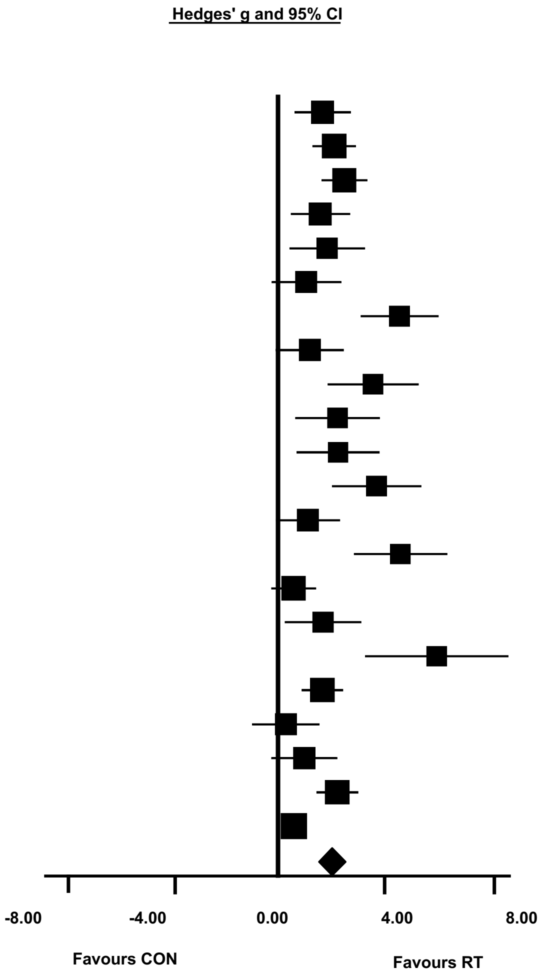


4 Discussion

The primary objective of this review was to quantify the effects of RT in females. To the authors' knowledge, this is the first review to synthesise the available literature in a sex-specific manner. Unsurprisingly, the main findings of this review were that RT had a significant effect on muscular strength and hypertrophy in untrained healthy adult females. Overall, the quality of the literature included in the meta-analyses was moderate. The analyses indicate that prescription variables related to both training frequency and volume, but not load, are significant contributors to the magnitude of

a

Study name	Hedges' g	Lower limit	Upper limit	p-Value	RT	CON
Abe et al. (2000) [38]	1.43	0.52	2.35	<0.001	20	7
Brown et al. (2000)(mature) [41]	1.81	1.09	2.53	<0.001	23	18
Brown et al. (2000) (young) [41]	2.13	1.39	2.88	<0.001	21	21
Cesar et al. (2009) [42]	1.36	0.40	2.32	0.01	9	10
DeLima el al. (2012) (linear) [43]	1.58	0.35	2.81	0.01	10	4
DeLima et al. (2012) (undulating) [43]	0.91	-0.22	2.05	0.12	10	4
Hendrickson et al. (2010) [44]	3.91	2.64	5.18	<0.001	18	10
Kim et al. (2011) (slow) [45]	1.02	-0.09	2.13	0.07	14	4
Kim et al. (2011) (traditional) [45]	3.05	1.58	4.53	<0.001	13	4
Malin et al. (2013) (high BF) [47]	1.92	0.54	3.29	0.01	12	3
Malin et al. (2013) (normal BF) [47]	1.93	0.58	3.28	0.01	8	4
Marx et al. (2001) (3 set) [48]	3.17	1.72	4.62	<0.001	12	5
Marx et al. (2001) (1 set) [48]	0.96	-0.08	2.00	0.07	12	5
Moghadasi et al. (2013) [49]	3.93	2.41	5.45	<0.001	9	10
Olson et al. (2006) [51]	0.50	-0.23	1.24	0.18	16	12
Santos et al. (2010) (agonist/antagonist) [54]	1.45	0.20	2.70	0.02	8	4
Santos et al. (2010) (upper/lower) [54]	5.10	2.78	7.42	<0.001	8	4
Sarsan et al. (2006) [55]	1.42	0.74	2.11	<0.001	20	20
Schlumberger et al. (2001) (1 set) [56]	0.25	-0.85	1.35	0.65	9	4
Schlumberger et al. (2001) (3 set) [56]	0.84	-0.23	1.91	0.12	9	5
Singh et al. (2009) [57]	1.91	1.22	2.60	<0.001	22	24
Warren et al. (2008) [61]	0.52	0.19	0.84	<0.001	72	76
Total	**1.70**	**1.28**	**2.13**	**<0.001**	**355**	**258**



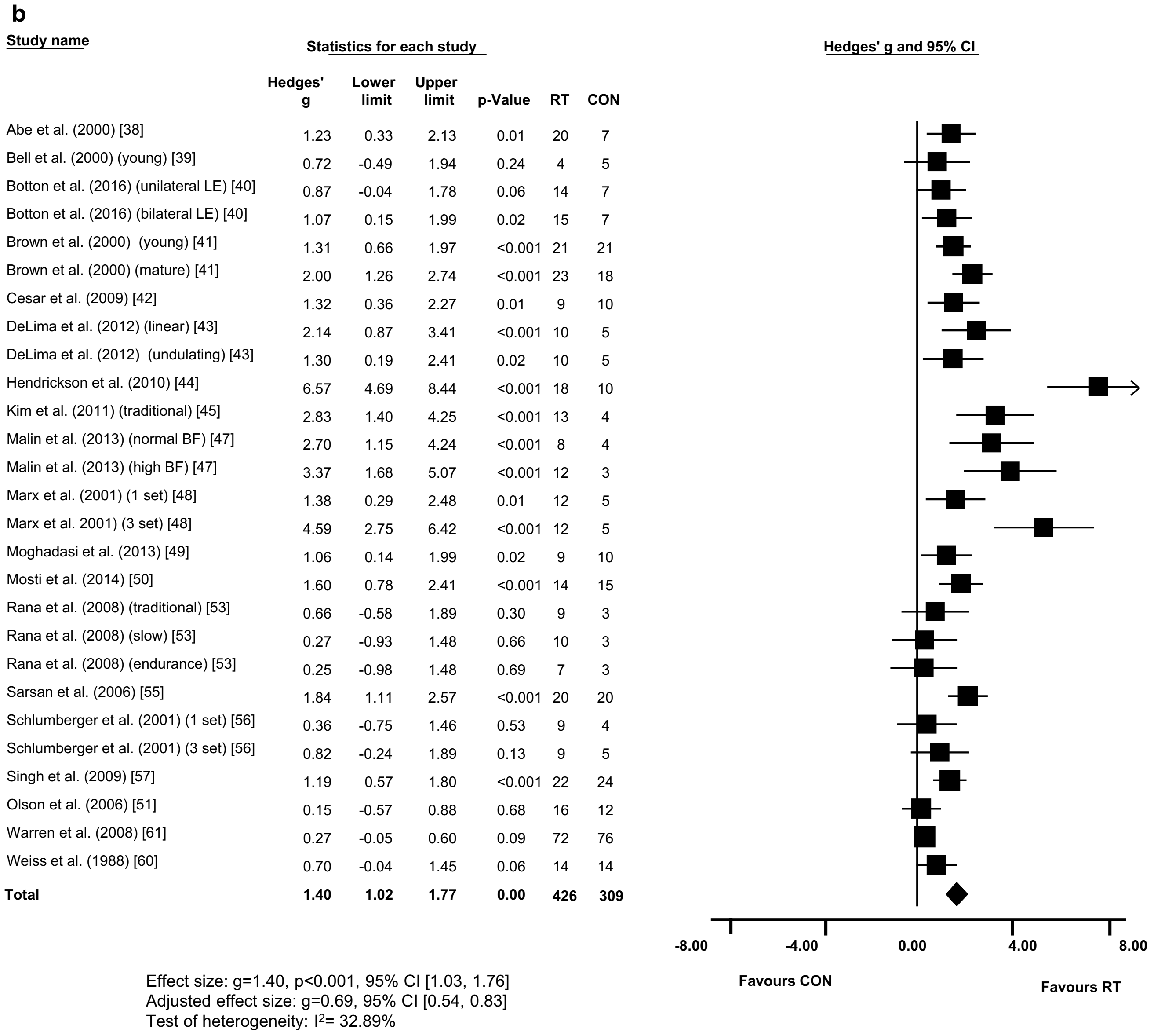
Effect size: g=1.70, p<0001, 95% CI [1.28, 2.13]
Adjusted effect size: g=1.07, 95% CI [0.61, 1.52]
Test of heterogeneity: I^2= 16.93%

Fig. 3 Forest plots of effect sizes with 95% confidence intervals for the effects of resistance training on: **a** upper body strength; **b** lower body strength; **c** muscular hypertrophy

upper and lower body strength gains in females. Although significant muscular hypertrophy occurred following RT, there was no difference within the different moderators (i.e., light vs heavy load; low vs high volume) for the magnitude of gains. Thus, manipulation of different training variables (i.e., load, volume, and sets per exercise) to elicit a greater hypertrophic response in females is not supported by the current literature.

This review can provide evidence-based estimations regarding the magnitude of adaptation to RT in females. In this review, average gains of 3.3% in lean mass, equating to approximately 1.45 kg (range 0.4–3.3 kg) following a full-body program were observed. Gains in muscular strength were approximately 25% (range 4–40%) in the upper body and 27% (range 6.5–54%) in the lower body. These adaptations occurred following participation in programs that were an average duration of 15 weeks. Typical prescriptive parameters included a frequency of three sessions per week, and the performance of three sets of each exercise for approximately ten repetitions. When intensity was reported as a percentage of 1RM, the mean training intensity was 70%. To the authors' knowledge, this is the first time an expected sex-specific adaptation to RT has been determined through a thorough synthesis of the literature. In an applied setting, these estimates provide clinicians and trainers guidelines for expectations of adaptation following periods of RT in female populations.

For the upper body, the analysis of the literature indicates that women should perform 3–4 sets per exercise, on 2–4 training days per week for the best strength gains. Moreover, this volume can be accrued across the range of training loads (i.e., light and heavy weights), and prescription methods (i.e., failure or non-failure sets), because neither of these variables moderated the magnitude of upper body strength



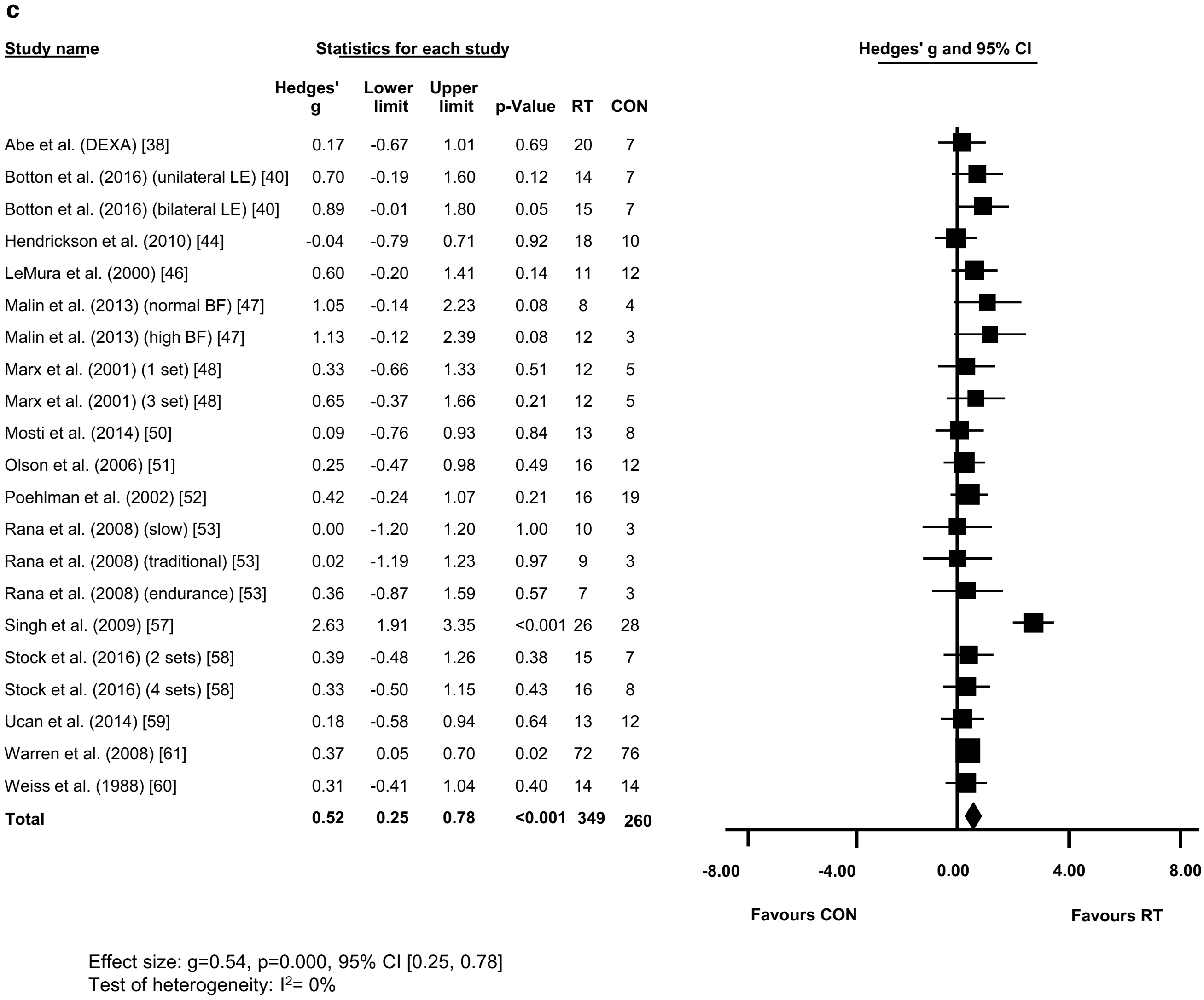
Study name	Hedges' g	Lower limit	Upper limit	p-Value	RT	CON
Abe et al. (2000) [38]	1.23	0.33	2.13	0.01	20	7
Bell et al. (2000) (young) [39]	0.72	-0.49	1.94	0.24	4	5
Botton et al. (2016) (unilateral LE) [40]	0.87	-0.04	1.78	0.06	14	7
Botton et al. (2016) (bilateral LE) [40]	1.07	0.15	1.99	0.02	15	7
Brown et al. (2000) (young) [41]	1.31	0.66	1.97	<0.001	21	21
Brown et al. (2000) (mature) [41]	2.00	1.26	2.74	<0.001	23	18
Cesar et al. (2009) [42]	1.32	0.36	2.27	0.01	9	10
DeLima et al. (2012) (linear) [43]	2.14	0.87	3.41	<0.001	10	5
DeLima et al. (2012) (undulating) [43]	1.30	0.19	2.41	0.02	10	5
Hendrickson et al. (2010) [44]	6.57	4.69	8.44	<0.001	18	10
Kim et al. (2011) (traditional) [45]	2.83	1.40	4.25	<0.001	13	4
Malin et al. (2013) (normal BF) [47]	2.70	1.15	4.24	<0.001	8	4
Malin et al. (2013) (high BF) [47]	3.37	1.68	5.07	<0.001	12	3
Marx et al. (2001) (1 set) [48]	1.38	0.29	2.48	0.01	12	5
Marx et al. 2001) (3 set) [48]	4.59	2.75	6.42	<0.001	12	5
Moghadasi et al. (2013) [49]	1.06	0.14	1.99	0.02	9	10
Mosti et al. (2014) [50]	1.60	0.78	2.41	<0.001	14	15
Rana et al. (2008) (traditional) [53]	0.66	-0.58	1.89	0.30	9	3
Rana et al. (2008) (slow) [53]	0.27	-0.93	1.48	0.66	10	3
Rana et al. (2008) (endurance) [53]	0.25	-0.98	1.48	0.69	7	3
Sarsan et al. (2006) [55]	1.84	1.11	2.57	<0.001	20	20
Schlumberger et al. (2001) (1 set) [56]	0.36	-0.75	1.46	0.53	9	4
Schlumberger et al. (2001) (3 set) [56]	0.82	-0.24	1.89	0.13	9	5
Singh et al. (2009) [57]	1.19	0.57	1.80	<0.001	22	24
Olson et al. (2006) [51]	0.15	-0.57	0.88	0.68	16	12
Warren et al. (2008) [61]	0.27	-0.05	0.60	0.09	72	76
Weiss et al. (1988) [60]	0.70	-0.04	1.45	0.06	14	14
Total	**1.40**	**1.02**	**1.77**	**0.00**	**426**	**309**

Effect size: g=1.40, p<0.001, 95% CI [1.03, 1.76]
Adjusted effect size: g=0.69, 95% CI [0.54, 0.83]
Test of heterogeneity: I^2= 32.89%

Fig. 3 (continued)

gains. Similarly, for the lower body, this review of the literature indicates that women should perform lower body exercise on 2–4 training days per week, with a goal of high-volume accrual across the week for the best strength gains (> 250 repetitions). Within-session prescription variables such as sets per exercise, load, and prescription method (failure vs non-failure) did not influence strength gains. Thus, the available evidence would suggest that lower body strength gains in women can be achieved with a variety of prescription combinations, although frequency and total weekly volume must be emphasized. A continuing dose response above four sessions per week may be present; however, due to the lack of high-frequency studies (4 +), we cannot draw conclusions as to the upper limit of this relationship.

The results of this review indicate that the manipulation of different training variables such as frequency, volume, and load does not influence the magnitude of hypertrophic gains reported in the literature for women. While it is likely that differing prescriptions of these variables, either in isolation or in conjunction, may influence hypertrophic adaptations, it was not possible to determine which factors are most pertinent. This is likely due to the design of the current review where inclusion was limited to RCTs, and as such, the individual studies were not designed to assess the influence of differing prescriptive parameters. Furthermore, while the interventions utilised were somewhat varied, many were relatively heterogeneous, and thus, there were insufficient data utilising vastly different exercise prescriptions.



Study name	Hedges' g	Lower limit	Upper limit	p-Value	RT	CON
Abe et al. (DEXA) [38]	0.17	-0.67	1.01	0.69	20	7
Botton et al. (2016) (unilateral LE) [40]	0.70	-0.19	1.60	0.12	14	7
Botton et al. (2016) (bilateral LE) [40]	0.89	-0.01	1.80	0.05	15	7
Hendrickson et al. (2010) [44]	-0.04	-0.79	0.71	0.92	18	10
LeMura et al. (2000) [46]	0.60	-0.20	1.41	0.14	11	12
Malin et al. (2013) (normal BF) [47]	1.05	-0.14	2.23	0.08	8	4
Malin et al. (2013) (high BF) [47]	1.13	-0.12	2.39	0.08	12	3
Marx et al. (2001) (1 set) [48]	0.33	-0.66	1.33	0.51	12	5
Marx et al. (2001) (3 set) [48]	0.65	-0.37	1.66	0.21	12	5
Mosti et al. (2014) [50]	0.09	-0.76	0.93	0.84	13	8
Olson et al. (2006) [51]	0.25	-0.47	0.98	0.49	16	12
Poehlman et al. (2002) [52]	0.42	-0.24	1.07	0.21	16	19
Rana et al. (2008) (slow) [53]	0.00	-1.20	1.20	1.00	10	3
Rana et al. (2008) (traditional) [53]	0.02	-1.19	1.23	0.97	9	3
Rana et al. (2008) (endurance) [53]	0.36	-0.87	1.59	0.57	7	3
Singh et al. (2009) [57]	2.63	1.91	3.35	<0.001	26	28
Stock et al. (2016) (2 sets) [58]	0.39	-0.48	1.26	0.38	15	7
Stock et al. (2016) (4 sets) [58]	0.33	-0.50	1.15	0.43	16	8
Ucan et al. (2014) [59]	0.18	-0.58	0.94	0.64	13	12
Warren et al. (2008) [61]	0.37	0.05	0.70	0.02	72	76
Weiss et al. (1988) [60]	0.31	-0.41	1.04	0.40	14	14
Total	**0.52**	**0.25**	**0.78**	**<0.001**	**349**	**260**

Effect size: g=0.54, p=0.000, 95% CI [0.25, 0.78]
Test of heterogeneity: I^2= 0%

Fig. 3 (continued)

Although these findings perhaps challenge historical notions regarding the importance of specific prescriptive requirements for eliciting muscular hypertrophy (i.e., the 8–10 repetition 'hypertrophy' zone), they show that hypertrophy can be achieved through a variety of exercise prescriptions and are in line with the previous research in females. Studies examining the individual prescriptive parameters in females have demonstrated that while consistent improvements in muscular strength and hypertrophy occur following RT in this cohort, there appears to be no difference in levels of adaptation between high volume and low volume [61, 62], high and low loads [63, 64], or in differing levels of frequency [65, 66]. In addition, these findings are supported by both the mechanistic studies examining acute changes in the protein signalling pathways that drive hypertrophy [67] and recent systematic reviews examining hypertrophic outcomes in men [68]. Mechanistic studies suggest that protein signalling responses occur in a dose–response manner, whereby three sets performed to failure with heavy loading (i.e., 70% 1-RM) elicit a larger response than a single set [69]. While acute signalling responses are further increased with volumes in excess of three sets [70], there is a dearth of training studies in women examining a similar prescription volume. Even though higher loading elicits greater signalling responses at matched volumes [71], when the volume of exercise is increased with multiple sets to failure, lighter loads (such as 30–50% 1-RM) elicit similar upregulation of pathways involved in hypertrophy [72]. Schoenfeld et al [68] recently conducted a meta-analysis examining low (≤ 60% 1RM) versus high (> 60% 1RM) load RT, showing no difference between low- and high-intensity RT in eliciting muscular hypertrophy. However, these authors did find a larger gain

Table 3 Effects of resistance training on upper body strength considering different moderating variables

Independent variables	Hedges' *g*	SE	95% CI	*P*	I^2 (%)	*df*	*Q* value and (*p*) between groups
Age of participants							
18–30 years	1.95	0.29	1.39–2.50	< 0.001	17.90	15	
≥ 31 years	1.23	0.29	0.67–1.80	< 0.001	0	5	3.06 (0.08)
Prescription method							
Failure/RM	1.70	0.31	1.08–2.31	< 0.001	26.70	11	
Non-failure/RM	1.71	0.31	1.11–2.32	< 0.001	3.21	9	0.01 (0.97)
Intervention duration							
4–11 weeks	2.01	0.46	1.11–2.90	< 0.001	13.7	8	
12–23 weeks	1.72	0.23	1.27–2.17	< 0.001	21.0	7	
≥ 24 weeks	1.27	0.41	0.47–2.06	0.002	24.8	4	1.58 (0.45)
Load							
< 70% 1RM	1.56	0.19	1.18–1.93	< 0.001	0	5	
≥ 70% 1RM	2.25	0.37	1.52–2.99	< 0.001	25.1	10	2.74 (0.10)
Frequency							
1–2 days per week	1.08	0.26	0.57–1.59	< 0.001	0	6	
≥ 3 days per week	2.18	0.31	1.57–2.80	< 0.001	5.58	14	7.23 (0.007)
Sets per exercise							
1–2	1.13	0.21	0.72–1.55	< 0.001	0	4	
3–4	1.96	0.28	1.40–2.49	< 0.001	9.65	16	5.44 (0.02)
Supervised training							
Without	1.61	0.37	0.88–2.34	< 0.001	16.82	6	
With	1.76	0.27	1.23–2.28	< 0.001	21.73	14	0.10 (0.75)
Training volumes (total repetitions) for upper body per week							
< 120 repetitions	2.10	0.35	1.42–2.78	< 0.001	41.87	8	
≥ 120 repetitions	1.57	0.29	1.00–2.13	< 0.001	5.54	11	1.38 (0.24)

in maximal strength with high- versus low-intensity training [68], although they noted that training with lower loads still elicited substantial gains in muscular strength in the magnitude of 28% [68]. In addition, they noted that the effect of intensity was larger with trained individuals, suggesting that higher intensities may be more beneficial in gaining muscular strength in this population [68]. While this analysis did not find an effect of intensity in isolation on muscular strength and hypertrophy, it is pertinent to note the range of intensities in reviewed studies was broad (40–90% of 1RM), and the other prescriptive parameters were not controlled.

These findings indicated no effect of training duration. Training interventions included in this review ranged from 4 to 52 weeks in length, with an average duration of just under 15 weeks. However, only six studies (seven intervention groups) utilised interventions longer than 12 weeks, while the remainder utilised interventions ≤ 12 weeks. As part of a systematic review, including both sexes, on volume and muscle mass, Schoenfeld and colleagues conducted a meta-regression [35] that also showed no influence of program duration. In their review, only three studies used longer durations of > 12 weeks. The lack of long-duration studies in the present literature mean that the findings regarding ‘no effect’ of duration should be interpreted with caution until more literature is accumulated utilising longer term interventions with muscular strength and hypertrophy outcomes. Furthermore, from the six studies that utilised long-duration programs in the analysis, only one was a periodised program [48], with the other five programs providing minimal progression recommendations such as increasing the weight by the smallest possible increment when a desired number of repetitions were achieved [29, 51, 52, 57]. As such, further research is not only needed utilising longer duration programs, but also in programs applying appropriate or best practice models of periodisation that include both progressions in weight lifted alongside manipulation of prescriptive parameters over the time course of the intervention, as occurs in real-world exercise programs.

The results of this review showed no effect of training to muscular failure in terms of adaptations to lower body strength, upper body strength, and muscular hypertrophy. However, this should be interpreted with caution due to the low number of ‘non-failure’ studies, and the difficulty in determining whether true failure was achieved in the ‘failure’-based studies. In the studies included in the present review, a variety of terms were used to imply failure-based

Table 4 Effects of resistance training on lower body strength considering different moderating variables

Independent variables	Hedges' *g*	SE	95% CI	*P*	I^2 (%)	*df*	*Q* value and (*p*) between groups
Age of participants							
18–30 years	1.52	0.22	1.08–1.95	< 0.001	37.8	21	
≥ 31 years	1.09	0.34	0.43–1.75	0.001	0	5	1.13 (0.29)
Prescription method							
Failure/RM	1.37	0.27	0.85–1.89	< 0.001	44.59	15	
Non-failure/RM	1.45	0.28	0.91–1.99	< 0.001	0	11	0.04 (0.85)
Intervention duration							
4–11 weeks	1.68	0.45	0.80–2.55	< 0.001	34.1	10	
12–23 weeks	1.41	0.14	1.16–1.67	< 0.001	0	11	
≥ 24 weeks	1.18	0.44	0.31–2.05	0.008	57.08	4	0.63 (0.73)
Load							
< 70% 1RM	1.62	0.24	1.14–2.09	< 0.001	12.83	8	
≥ 70% 1RM	1.45	0.24	0.98–1.92	< 0.001	46.49	16	0.11 (0.63)
Frequency							
1–2 days per week	0.62	0.22	0.27–0.98	0.001	0	6	
≥ 3 days per week	1.69	0.22	1.26–2.12	< 0.001	38.28	20	13.92 (< 0.001)
Sets per exercise							
1–2	1.34	0.25	0.86–1.83	< 0.001	0	4	
3–4	1.44	0.23	1.01–1.87	< 0.001	38.42	22	0.09 (0.77)
Supervised training							
Without	1.01	0.22	0.59–1.43	< 0.001	0	9	
With	1.71	0.28	0.15–2.26	< 0.001	35.34	17	3.86 (0.05)
Training volumes (total repetitions) for upper body per week							
< 250 repetitions	0.88	0.17	0.55–1.21	< 0.001	0	13	
≥ 250 repetitions	2.03	0.33	1.39–2.67	< 0.001	43.39	12	9.82 (0.002)

training including 'maximally fatigued', 'momentary fatigue', 'momentary failure', 'fatigue', 'RM', and 'concentric failure'. The exact interpretation of what constituted fatigue and failure may have differed between these studies, and as such, it is recommended that authors explicitly state that an exercise is performed until 'concentric failure' when reporting the prescriptive parameters of interventions conducted in this manner. The findings regarding a lack of influence of failure-based training are not unique, with Davies and colleagues' [73] meta-analysis on the effect of repetition failure on muscular strength finding little influence of failure-based training.

Many of the studies included in this review insufficiently reported numerous exercise prescription parameters. For example, rest period was only reported in just over half of the studies [42, 43, 45–50, 52, 54–58, 60], and ranged from 30 s to 3 min. Six studies failed to report if the exercise was supervised [29, 40–42, 49, 59], with the remainder of the studies providing supervision for either the entire program, or the first 15–16 weeks. While the analyses showed differential influences of supervision on adaptation to strength and hypertrophy, many studies were unable to be included in this analysis. Time under tension was only reported in six studies [43, 45, 46, 48, 53, 58]. Manipulation of these training variables may influence exercise adaptation [74, 75], and as such, this is a limitation of the current study as it is not possible to exclude a confounding influence of these training parameters. Another limitation of this study is that the findings are not generalisable across the lifespan. The authors decided to include only healthy adults (18–50 years) in this review to reduce the potential confounds of the hormonal changes and associated loss of muscle quality, mass, and strength that occurs with menopause and ageing [76, 77]. Furthermore, although the inclusion criteria were limited to 18–50 years, the average age of participants in this study was 27 years, with most participants being in their 20s. As such, further research is likely required to elucidate whether the effect of training observed in this review is standard in women aged between 30 and 50 years. In addition, since cut-offs for moderating variables, including age, were determined via different methods (e.g., classifications based on previous studies, or to evenly distribute studies into groups), the introduction of residual confounding cannot be excluded. Additionally, a limitation of the current design was that only isotonic 1RM strength assessments were included. Isometric assessments or interventions that were conducted with therabands or via

Table 5 Effects of resistance training on muscle hypertrophy considering different moderating variables

Independent variables	Hedges' *g*	SE	95% CI	*P*	I^2 (%)	*df*	*Q* value and (*p*) between groups
Age of participants							
18–30 years	0.40	0.11	0.18 to 0.62	< 0.001	0	16	
≥ 31 years	0.85	0.53	− 0.19 to 1.89	0.11	18.34	3	0.69 (0.41)
Prescription method							
Failure/RM	0.62	0.10	0.04 to 1.21	< 0.001	0	9	
Non-failure/RM	0.38	0.30	0.18 to 0.58	< 0.001	0	10	0.60 (0.44)
Intervention duration							
4–11 weeks	0.33	0.16	0.01 to 0.65	< 0.001	0	8	
12–23 weeks	0.43	0.16	0.12 to 0.74	< 0.001	0	7	
≥ 24 weeks	0.90	0.49	− 0.07 to 1.87	0.002	23.64	3	1.25 (0.53)
Load							
< 70% 1RM	0.48	0.20	0.09 to 0.86	0.016	0	5	
≥70% 1RM	0.58	0.26	0.07 to 1.09	0.027	0	10	0.09 (0.76)
Frequency							
1–2 days per week	0.79	0.26	0.57 to 1.59	0.013	82.30	6	
≥ 3 days per week	0.33	0.31	1.57 to 2.80	0.007	0	13	1.84 (0.18)
Sets per exercise							
1–2	0.24	0.33	− 0.40 to 0.88	0.47	0	1	
3–4	0.54	0.15	0.26 to 0.83	< 0.001	0	18	0.73 (0.39)
Supervised training							
Without	0.74	0.41	− 0.07 to 1.55	0.07	21.0	4	
With	0.41	0.12	0.18 to 0.64	< 0.001	0	15	0.59 (0.44)
Training volumes (total repetitions) week							
< 600 repetitions	0.54	0.20	0.14 to 0.94	0.008	72.02	11	
≥ 600 repetitions	0.46	0.16	0.14 to 0.78	0.005	0	8	0.10 (0.75)

isometric training were excluded. This approach was taken to attempt to focus on athletic strength training in which the prescriptive parameters (i.e., sets, reps, and intensity) could be accurately quantified.

As the literature to date is equivocal on whether differences in adaptation exist between males and females in response to RT, it is important for additional research to grow the limited data collected on female only participants. Future research should examine the effect of the manipulation of the training variables, in exclusively female populations, and should directly contrast male and female adaptations to the same training intervention, rather than group males and females together for analysis. Until further research is conducted, it will not be possible to definitively answer the question as to how many, and what extent, sex-based differences exist in the adaptation to RT.

5 Conclusion

Resistance training is an efficacious method of increasing muscular strength and hypertrophy in adult females. In a practical sense, the data provide values for expected adaptations following average RT programs in untrained females. With respect to the prescriptive parameters, for the upper body, our analysis indicates that women should perform 3–4 sets per exercise, on 2–4 training days per week for the best strength gains. The data also suggest that lower body strength gains in women can be achieved with a variety of prescription combinations, although frequency and total weekly volume should be a priority. While this review was able to show that significant muscular hypertrophy occurs following RT in females, it was unable to elucidate which individual prescriptive parameters have the most influence on this outcome.

Compliance with Ethical Standards

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Conflict of interest Amanda D. Hagstrom, Paul W Marshall, Mark Halaki, and Daniel A. Hackett declare that they have no conflicts of interest related to the content of this review.

Data availability All data sets generated and analysed during the current study are available as supplementary material. See Electronic Supplementary Material Appendix S1.

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