# Sex Differences in Absolute and Relative Changes in Muscle Size following Resistance Training in Healthy Adults: A Systematic Review with Bayesian Meta-Analysis

Supplementary materials:
https://osf.io/trz3y

For correspondence:
mrefalo@deakin.edu.au

Martin C. Refalo[1], Greg Nuckols[2], Andrew J. Galpin[3], Iain J. Gallagher[4], D. Lee Hamilton[1], Jackson J. Fyfe[1]

[1]Institute for Physical Activity and Nutrition (IPAN), School of Exercise and Nutrition Sciences, Deakin University, Geelong, Australia
[2]Stronger by Science LLC, Raleigh, NC 27605, USA.
[3]Human Performance Center, Parker University, Dallas, TX.
[4]Centre for Biomedicine and Global Health, Edinburgh Napier University, Edinburgh, UK.

*Please cite as*: Refalo, M.C., Nuckols, G., Galpin, A.J., Gallagher, I.J., Hamilton, D.L., & Fyfe, J.J (2024). Sex Differences in Absolute and Relative Changes in Muscle Size following Resistance Training in Healthy Adults: A Systematic Review with Bayesian Meta-Analysis. *SportRχiv*.

All authors have read and approved this version of the manuscript. This article was last modified on Sep 7h, 2024.

Authors can be reached on X:
@MartinRefalo, @jacksonfyfe,
@dlhamilton82, @GregNuckols,
@DrAndyGalpin, @iainjgallagher

# ABSTRACT

**Purpose:** Muscle hypertrophy may be influenced by biological differences between males and females. This meta-analysis investigated absolute and relative changes in muscle size following resistance training (RT) between males and females and whether measures of muscle size, body region assessed, muscle fibre type, and RT experience moderate the results. **Methods:** Studies were included if male and female participants were healthy (18-50 years old) adults that completed the same RT intervention, and a measure of pre- to post-intervention changes in muscle size was included. Out of 2720 screened studies, 29 studies were included in the statistical analysis. Bayesian methods were used to estimate a standardised mean difference (SMD) and log response ratio (lnRR) with exponentiated percentage change (Exp. % Change of lnRR) for each outcome. **Results:** Absolute increases in muscle size slightly favoured males versus females [SMD = 0.19 (95% HDI: 0.11 to 0.28)], however, relative increases in muscle size were similar between sexes [Exp. % Change of lnRR = 0.69% (95% HDI: – 1.50% to 2.88%)]. Outcomes were minimally influenced by the measure of muscle size and not influenced by RT experience of participants. Absolute hypertrophy of upper-body but not lower-body regions was favoured in males. Type I muscle fibre hypertrophy slightly favoured males, but Type II muscle fibre hypertrophy was similar between sexes. **Conclusion:** Our findings indicate that females have a similar potential to induce muscle hypertrophy as males (particularly when considering relative increases in muscle size from baseline) and findings of our secondary analyses should inform future research investigations.

# 1. INTRODUCTION

Resistance training (RT) promotes increases in muscle fibre and ultimately whole-muscle cross-sectional area, known as skeletal muscle hypertrophy [1]. The magnitude of muscle hypertrophy with resistance training may vary between individuals [2], and importantly, may be influenced by biological differences between males and females arising after puberty [3]. For example, postpubescent males have approximately tenfold higher endogenous testosterone levels compared with typical postpubescent females [4]. This difference in basal testosterone is believed to be the primary factor explaining greater average muscle mass in adult males versus females. For example, in untrained and resistance-trained individuals, biceps brachii and quadriceps cross sectional area (CSA) of females is ~50-60% and ~70-80% of CSA in males, respectively [5]. The proportion of type II muscles fibres, which undergo greater hypertrophy than type I fibres [6], is also greater in males than females [7]. This difference in muscle mass and fibre type distribution may contribute to females having ~50-60% and ~60-70% of male upper-body and lower-body strength, respectively (at the group level) [5].

It has been postulated that males experience greater muscle hypertrophy following RT compared to females, potentially due to factors relating to gene expression [8] or the higher levels of testosterone in males versus females, on average [4]. A previous meta-analysis compared muscle hypertrophy outcomes between young to middle-aged males and females [9] and found no statistically significant differences in pre- to post-intervention changes in muscle size; however, this meta-analysis did not differentiate *absolute* (i.e., raw change in muscle size) and *relative* (i.e., percentage increase in muscle size from baseline) changes in muscle size. Considering the marked differences in baseline muscle size between males and females [5], exploring both absolute and relative changes in muscle size is important. For example, another meta-analysis [10] of studies in older adults (>50 years of age) found absolute increases in muscle size following RT favoured males versus females, with no statistically significant difference in relative muscle hypertrophy. Furthermore, other studies have noted the possibility for sex differences in fibre type-specific muscle hypertrophy [11, 12], but previous meta-analyses [9, 10] have not investigated muscle fibre cross sectional area (fCSA) as an outcome. It is also unclear if the RT experience of participants and the assessment of muscle size (e.g., body region assessed, type of measurement) used influence sex differences in muscle hypertrophy.

This Bayesian systematic review with meta-analysis aimed to extend previous meta-analytic findings by investigating i) differences in absolute and relative changes in muscle size following RT between *young to middle-aged* males and females, and ii) whether key variables (i.e., method of muscle size assessment and individual characteristics) moderate the influence of sex on muscle hypertrophy. We employed a Bayesian approach to data analysis to improve the interpretation of the effect estimate, directly model its uncertainty, and enable the results to be presented with posterior probabilities allowing for meaningful and intuitive inferences [13].

# 2. MATERIALS & METHODS

A systematic review and meta-analysis were performed in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [14]. The PRISMA checklist can be found in Online Resource 6. The original protocol was registered with Open Science Framework on the 1st of June 2023 (https://osf.io/trz3y/).

## 2.1 Research Question(s)

The research question(s) were defined using the participants, interventions, comparisons, outcomes, and study design (PICOS) framework, as follows. The primary research question was: *"What is the estimated difference in muscle hypertrophy following RT between young to middle-aged males and females*, *in both absolute and relative (%) terms?"*. To facilitate the interpretation of this research question, we also investigated whether the assessment of muscle size (i.e., body region assessed, type of measurement used, muscle fibre type) or participant RT experience (years) had a moderating effect on the overall outcome of the meta-analysis.

## 2.2 Literature Search Strategy

The literature search followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines [14]. Original literature searches of the PubMed, SCOPUS and SPORTDiscus databases were started in May 2023 and completed in June 2023. However, an updated systematic search was conducted in August 2024 returning two studies [15, 16]. The following search terms were used and adapted for each individual database: "resistance training" OR "resistance exercise" OR "strength training" AND "gender" OR "women" OR "woman" OR "female" OR "sex" OR "sex difference" AND "muscle hypertrophy" OR "muscle size" OR "muscle growth" OR "muscle mass" OR "muscle thickness" OR "cross-sectional area". Search terms were added using the NOT term to reduce the number of irrelevant studies according to exclusion criteria (e.g., older, elderly, sarcopenia, cancer). The reference list of previous meta-analyses [9, 10] and the retrieved articles were manually searched, and six additional studies [17-22] that met the inclusion criteria were identified and subject to the screening process, with full-text review confirming eligibility for inclusion (Fig 1). Only studies conducted in humans were included.

## 2.3 Study Selection

*Covidence software (*Veritas Health Innovations, Melbourne, Australia) *was used to manage and conduct the systematic study selection process, including the removal of duplicates and the exclusion of ineligible studies at each stage of the screening process*. An overview of the article identification process is shown in Fig 1. The article identification process was completed independently (to reduce any bias during this process) by two authors (MR and JF) with any disagreement resolved by discussion*. Finally, the authors* (MR and JF) *reviewed the full text to* *determine eligibility for inclusion based on the inclusion criteria.* If any studies were added through reference checking or manual searching, they were subjected to the same screening process as if they were found in the initial database search.

## 2.4 Inclusion Criteria

Studies were included if: 1) participants were apparently healthy young to middle-aged (18-50 years old) adults of any RT experience, 2) the experimental comparison involved male and female participants completing the same RT intervention (e.g., set volume, load, frequency, exercises, proximity-to-failure), and 3) one of the following measures of pre- to post-intervention changes in muscle size were included; a) muscle thickness, b) whole-limb or muscle CSA or volume, c) muscle fCSA, or d) lean body/fat free mass via dual x-ray absorptiometry (DXA) or bioelectrical impedance analysis (BIA). Only original research articles (English language) in peer reviewed journals were included. Articles that did not meet these criteria were excluded.

## 2.5 Data Extraction

Data extraction was carried out by the principal investigators (MR and JF) to capture key information in a table format (Table 1). The following participant characteristics were extracted: 1) RT status (i.e., untrained, or resistance-trained), 2) age, and 3) sex. The following article characteristics were also extracted: 1) first author, 2) sample size, 3) publication date, 4) intervention groups/protocol outlines and duration, and 5) key findings (i.e., percentage increase in muscle size from pre- to post-intervention and an indication of whether any muscle hypertrophy was statistically different between sexes). Raw data from pre- and post-intervention for muscle hypertrophy outcomes were extracted for meta-analysis [if figures were used instead of numerical data, those data were extracted using Web Plot Digitizer (Version 4.6, California, USA)]. Studies were classified as recruiting 'resistance-trained' participants if the participants had any level of RT experience immediately prior to study commencement, whereas studies that involved a RT prohibitory period (e.g., "no RT 6-months prior to study commencement") were classified as recruiting untrained participants. Considering the absence of detail regarding training status in some studies further classification of training status (e.g., "beginner", "intermediate", "advanced", "highly advanced") with multiple criteria [23] is difficult. Several studies prescribed loads based on repetition maximum (RM) rather than as a percentage of 1-RM, with adjustments made throughout the RT intervention. This variation made it challenging to determine an accurate load for data analysis. Similarly, in some studies, the number of sets per muscle group per week was adjusted across the RT intervention, and due to vague reporting, accurately extracting these values was difficult. Furthermore, set termination methods were often ambiguously described, and given the inconsistencies in the definitions of set failure within the RT literature [24], we refrained from classifying studies based on proximity-to-failure.

Consequently, and despite the methods stated in our pre-registration (https://osf.io/trz3y/), we decided to omit RT characteristics (i.e., load, set volume, proximity-to-failure) from our sub-group analyses to ensure our results were not confounded by inaccurate data extraction.

### 2.6 Methodological Quality Assessment

Evaluation of methodological study quality (including risk of bias) was conducted (by MR) using the tool for the assessment of study quality and reporting in exercise (TESTEX) scale [25]. Any ambiguities in methodological quality assessment were resolved by discussion between MR and JF. The TESTEX scale is an exercise science-specific scale used to assess the quality and reporting of exercise training trials. The scale contains 12 criteria that can either be scored a 'one' or not scored at all; 1, eligibility; 2, randomisation; 3, allocation concealment; 4, groups similar at baseline; 5, assessor blinding; 6, outcome measures assessed in 85% of patients (3 possible points); 7, intention-to-treat; 8, between-group statistical comparisons (2 possible points); 9, point-estimates of all measures included; 10, activity monitoring in control groups; 11, relative exercise intensity remained constant; 12, exercise parameters recorded. The best possible total score is 15 points.

### 2.7 Statistical Analysis

To provide a more flexible modelling approach and enable results to be interpreted intuitively through reporting of probabilities [13], we carried out a Bayesian meta-analysis using the "brms" (Bürkner, 2023) package in R (v 4.0.2; R Core Team, https://www.r-project.org/). Detailed statistical analysis procedures can be found on the Open Science Framework (https://osf.io/trz3y/). Posterior draws were extracted using "tidybayes" (Kay, 2023) and effect estimates calculated using "emmeans" (Lenth, 2023). The absolute (mean and standard deviation) changes in muscle size from pre- to post-intervention for both male and female participants were extracted from each study. Standardised mean differences were calculated using the pooled standard deviation of baseline values as the denominator [via the "escalc" function in the "metafor" (Viechtbauer, 2010) package] to provide a more balanced estimate of variability between males and females [26]. Pooling the standard deviations accounts for variability in both groups and avoids bias from using group-specific standard deviations. This method ensures a more robust comparison, especially when baseline variability differs between groups. Converting absolute values to relative changes for SMD calculation may not be statistically efficient [27] so we therefore calculated the log response ratio (lnRR) for an interaction effect of group x time factorial design [28]. To enhance practical interpretation, we exponentiated the lnRR values with a correction factor for transformation bias [29], thereby converting them to percentage change scores (Exp. % Change of lnRR). Positive values indicate greater muscle size increases in males, and negative values indicate greater increases in females. The Bayesian hierarchical analysis accounted for nested observations and used “shrinkage” to adjust study-level effects towards the overall mean [13]. Shrinkage-adjusted effect estimates are presented, with raw estimates available in Online Resource 4. Due to the lack of reported correlations between pre- and post-test measures, we assumed a correlation coefficient of $r = 0.87$ from a recent meta-analysis [10] and conducted sensitivity analyses using $r$ values from 0.7 to 0.99 (Online Resource 1). Non-informative priors were used, and inferences were drawn from posterior distributions via Hamiltonian MCMC and highest density intervals (HDI). Interpretations were based on the size of the mean effect estimate [30], HDI limits [30], and the posterior probability (ranging from 50% to 100%) that an effect estimate goes in a particular direction (*pd*) [31]. Publication bias was visually assessed using funnel plots.

# 3. RESULTS

## 3.1 Search Results and Study Characteristics

A total of 30 studies met the inclusion criteria. A PRISMA diagram of the systematic literature search and study selection process is displayed in Fig 1. Data from one study [32] could not be retrieved; the remaining 29 studies were systematically reviewed and meta-analysed. Visual inspection of funnel plots (Online Resource 2) identified no publication bias. A total of 1278 male and 1537 female data points were included in the meta-analysis, with the mean age of males being 26 ± 4 (range: 20 to 42) and females also 26 ± 4 (range: 19 to 41) years. Six [15, 16, 32-35] out of the 29 studies involved participants with some RT experience, with the remainder of the studies involving participants with either i) no RT experience (*n* = 4), or ii) no RT experience 5-years (n = 1), 1-year (n = 7), 8-months (n = 1), 6-months (n = 7), and 3-months (n = 2) prior to study commencement. However, in some cases the exact RT experience (years) of the 'resistance-trained' participants was vaguely described and therefore unclear (Table 1). In total, 68 muscle hypertrophy outcomes were extracted, with some studies reporting numerous *direct* outcomes: i) muscle CSA using magnetic resonance imaging (MRI) [2, 32, 36, 37], ultrasound [19, 21, 34, 38], or computed tomography (CT) [35, 39, 40], ii) muscle fCSA using biopsy samples [11, 12, 16, 20, 22, 38, 41], iii) muscle physiological CSA using ultrasound [42], iv) muscle volume using MRI [18, 36, 43], and v) muscle thickness using ultrasound [19, 33, 41, 44-47], and other studies using *indirect* outcomes: i) lean mass using DXA [15-17, 20, 44, 48], and ii) estimated skeletal muscle mass using bioelectrical impedance analysis (BIA) [49]. Most of the muscle hypertrophy outcomes were assessed in the lower body (69% of outcomes [11, 12, 16, 18-22, 32-34, 36, 38, 39, 41, 42, 44-46, 48]; quadriceps and hamstrings) versus the upper-body (22% of outcomes [2, 19, 33, 35, 37, 39, 40, 43, 44, 47]; biceps, triceps, and chest), with 9% of outcomes [15-17, 20, 44, 49] assessing lean mass of the upper- and lower-body combined (i.e., total body lean mass). In some instances, studies were excluded from sub-group analyses because i) outcome measures were only employed in one study (e.g., pCSA [42] and skeletal muscle mass via BIA [49]), and ii) measures of lean mass were not separated into upper- or lower-body [15-17, 20, 49]. The duration of the RT interventions ranged from six to 24 weeks, with a mean of 11 weeks. For a comprehensive summary of other RT characteristics, see Table 1.

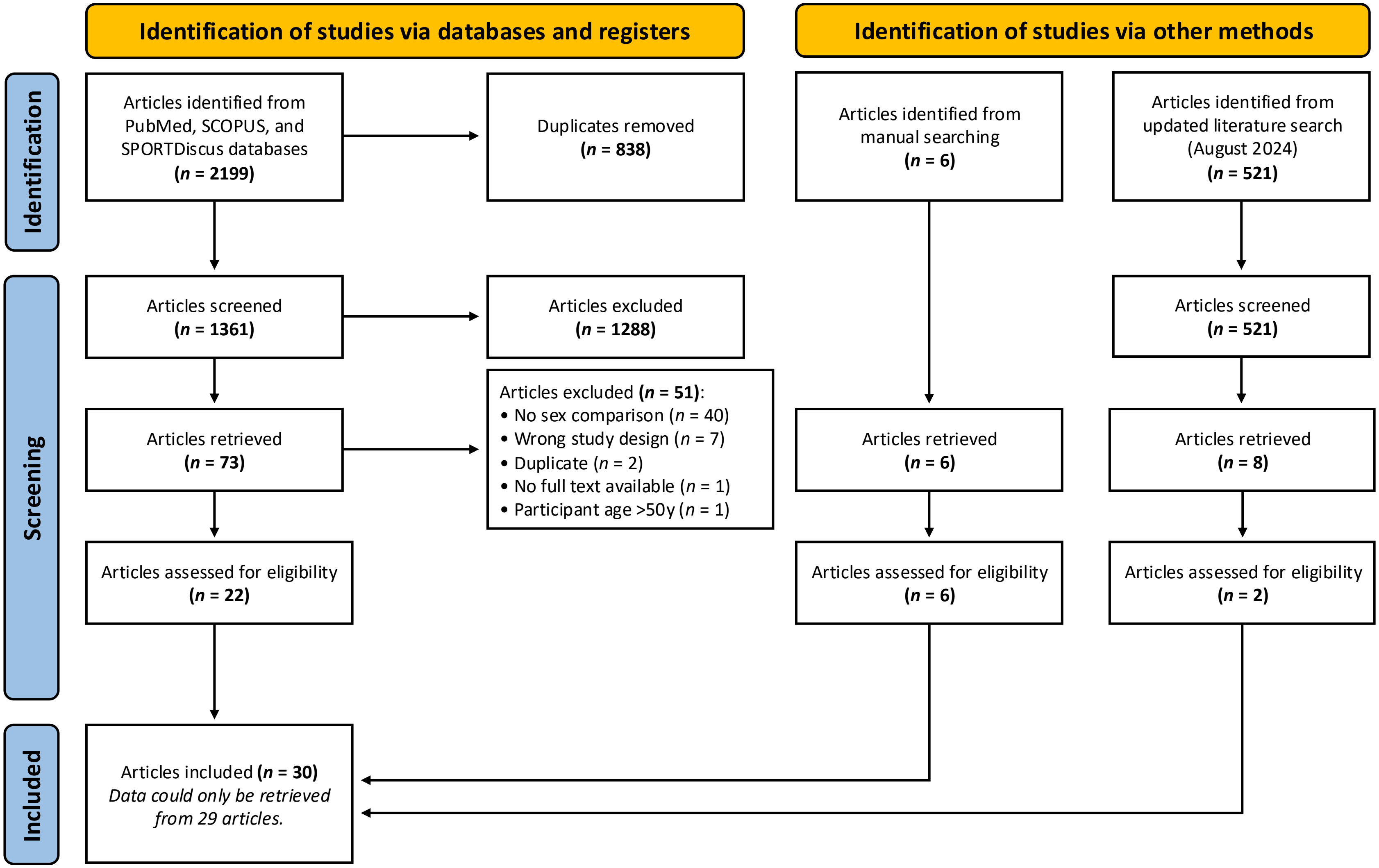

Figure 1. PRISMA flow chart. Summary of systematic literature search and article selection process.

**Table 1. Summary of data extraction.** Summary of studies included comparing changes in muscle size from pre-to post-intervention between males and females. Data presented as mean ± *SD*.

**Abbreviations:** BB, barbell; BFR, blood flow restriction; BIA, bioelectrical impedance analysis; CSA, cross-sectional area; CT, computed tomography; EF, elbow flexor; fCSA, fibre cross-sectional area; MRI, magnetic resonance imaging; pCSA, physiological cross-sectional area; RF, rectus femoris; Reps, repetitions; RM, repetition maximum; RT, resistance training; sessions/week, sessions per muscle group per week; VeL, velocity loss; VL, vastus lateralis; ↑ = increased; ↓ = decreased; ↔ = no difference between sexes; * = results of statistical comparison between sexes not reported; ^ = relative load estimated from repetitions at % of 1-RM chart; # = mean number of muscle fibres analysed for each participant across timepoints.

| Study | Participants | Age (years) | RT protocol | Duration (sessions /week) | Outcome measure (device; muscle) | Key findings |
|---|---|---|---|---|---|---|
| **Abe et al. 2000 [44]** | Males (*n* = 17)<br>Females (*n* = 20)<br>→ Untrained: No RT 1 year prior | 37.7 ± 7.2<br>41 ± 4.1 | 3 sets x 8-12 reps<br>→ 60-70% 1-RM<br>Exercises: Leg extension, leg curl, chest press, horizontal row, biceps curl, triceps extension | 12 weeks<br>(3/week) | Lean mass (DXA; total body)<br>Muscle thickness (ultrasound; biceps, triceps, chest, quadriceps, hamstrings) | ↔ Total body lean mass between males (+2.6%) and females (+1.7%)<br>↔ Muscle thickness between males (+10.3%) and females (+10.8%) for all muscle groups measured |
| **Abou Sawan et al. 2021 [12]** | Males (*n* = 10)<br>Females (*n* = 10)<br>→ Untrained: No RT 3-months prior | 23 ± 4<br>23 ± 5 | 4 sets x 10-12 reps<br>→ 75% 1-RM<br>Exercises: Leg press, leg extension | 8 weeks<br>(3/week) | Muscle fCSA (biopsy + histochemistry; VL)<br># Type 1 = 84<br># Type II = 92 | ↑ Type I VL fCSA observed in males (+21.1%) versus females (+5.6%) but ↔ Type II VL fCSA between males (+18%) and females (+27.5%) |
| **Abou Sawan et al. 2022 [45]** | Males (*n* = 10)<br>Females (*n* = 10)<br>→ Untrained: No RT 3-months prior | 23 ± 4<br>23 ± 5 | 4 sets x 10-12 reps<br>→ 75% 1-RM<br>Exercises: Leg press, leg extension | 8 weeks<br>(3/week) | Muscle thickness (ultrasound; VL) | ↔ VL thickness between males (+10.7%) and females (+8.2%) |
| **Alway et al. 1992 [35]** | Males (*n* = 5)<br>Females (*n* = 5)<br>→ Trained: ≥5 years of RT experience | 32.8 ± 4.5<br>34.8 ± 2.7 | 3-5 sets x 6-14 reps<br>→ 60-85% 1-RM^<br>Exercises: Biceps curl (multiple variations) | 24 weeks<br>(2/week) | Muscle CSA [CT; biceps, flexor (brachialis + biceps)] | Biceps and flexor CSA ↑ for both males (+5.6%) and females (+3.1%) * |
| **Coratella et al. 2018 [46]** | Males (*n* = 13)<br>Females (*n* = 13) | 21.2 ± 2.6<br>20.8 ± 3 | 4 sets x 10 reps<br>→ 120% 1-RM | 8 weeks<br>(2/week) | Muscle thickness (ultrasound; VL) | ↔ VL muscle thickness between males (+11.1%) and females (+13%) |

| | | | | | | |
|---|---|---|---|---|---|---|
| | → Untrained: No RT 6-months prior | | Exercise: Leg extensions (eccentric only) | | | |
| **Cureton et al. 1988 [39]** | Males (*n* = 7)<br>Females (*n* = 9)<br>→ Untrained: No RT 6-months prior | 24.7 ± 2.1<br>25.5 ± 2.3 | 1-3 sets x *n* reps<br>→ 70-90% 1-RM<br>Exercises: Multiple exercises targeting all primary muscle groups | 16 weeks (3/week) | Muscle CSA (CT; biceps, quadriceps) | ↔ Biceps and quadriceps CSA between males (+9.5%) and females (+13.1%) for both RT protocols |
| **Fernandez-Gonzalo et al. 2014 [48]** | Males (*n* = 16)<br>Females (*n* = 16)<br>→ Untrained: No RT 6-months prior | 23 ± 4.8<br>24 ± 4.9 | 4 sets x 7 reps<br>→ 83% 1-RM^<br>Exercise: Supine squat (flywheel) | 6 weeks (2-3/week) | Lean mass (DXA; thigh) | ↔ Thigh lean mass between males (+4.6%) and females (+5.4%) |
| **Grandperrin et al. 2024 [15]** | Males (*n* = 12)<br>Females (*n* = 12)<br>→ Trained: Unknown years of RT experience | 27.4 ± 4<br>29 ± 6 | 4 sets x 10 reps<br>→ 70% 1-RM<br>Exercises: Multiple exercises targeting all primary muscle groups | 16 weeks (3/week) | Lean mass (DXA; total body) | ↔ Total body lean mass between males (+1.9%) and females (+2%) |
| **Hakkinen et al. 1998 [21]** | Males (*n* = 10)<br>Females (*n* = 11)<br>→ Untrained: No RT experience | 42 ± 2<br>39 ± 3 | 3-6 sets x 3-15 reps<br>→ 50-80% 1-RM<br>Exercises: Leg press, leg extension | 24 weeks (2/week) | Muscle CSA (ultrasound; quadriceps) | Quadriceps CSA ↑ for both males (+5.4%) and females (+9.3%) * |
| **Hakkinen et al. 2001 [22]** | Males (*n* = 10)<br>Females (*n* = 11)<br>→ Untrained: No RT experience | 42 ± 2<br>39 ± 3 | 3-6 sets x 3-15 reps<br>→ 50-80% 1-RM<br>Exercises: Leg press, leg extension | 24 weeks (2/week) | Muscle fCSA (biopsy + histochemistry; VL)<br># Type I = 41<br># Type II = 37 | VL fCSA ↑ for both males (Type I = +18.9%, Type II = +3.3%) and females (Type I = +22.5%, Type II = +39.2%) * |
| **Hammarström et al. 2020 [32]** | Males (*n* = 16)<br>Females (*n* = 18)<br>→ Trained: Unknown years of RT experience | 23.6 ± 4.1<br>22 ± 1.3 | Group A: 1 set x 7-10 reps<br>→ 75-83% 1-RM^<br>Group B: 3 sets x 7-10 reps<br>→ 75-83% 1-RM^ | 12 weeks (2-3/week) | Muscle CSA (MRI; quadriceps) | Quadriceps CSA ↑ for both males (+4.4%) and females (+4.2%) * |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | Exercises: Leg press, leg extension, leg curl | | | |
| **Hubal et al. 2005 [2]** | Males (*n* = 243)<br>Females (*n* = 342)<br>→ Untrained: No RT 1 year prior | 24.8 ± 6.2<br>23.9 ± 5.5 | 3 sets x 6-12 reps<br>→ 70-85% 1-RM^<br>Exercises: Biceps curl (multiple variations) | 12 weeks (2/week) | Muscle CSA (MRI; biceps) | ↑ Biceps CSA observed in males (+19.7%) versus females (+17.6%) |
| **Hurlbut et al. 2002 [17]** | Males (*n* = 10)<br>Females (*n* = 9)<br>→ Untrained: No RT 6-months prior | 25 ± 3.2<br>26 ± 3 | 1-3 sets x 12-15 reps<br>→ 60-70% 1-RM^<br>Exercises: Multiple exercises targeting all primary muscle groups | 24 weeks (3/week) | Lean mass (DXA; total body) | ↔ Total body lean mass between males (+2.9%) and females (+3.5%) |
| **Ivey et al. 2000 [18]** | Males (*n* = 11)<br>Females (*n* = 11)<br>→ Untrained: No RT 6-months prior | 25 ± 1<br>26 ± 1 | 5 sets x 5-20 reps<br>→ ≤85% 1-RM^<br>Exercise: Leg extension | 9 weeks (3/week) | Muscle volume (MRI; quadriceps) | ↑ Quadriceps muscle volume observed in males (+12.1%) versus females (+6.3%) |
| **Kojic et al. 2021 [19]** | Males (*n* = 9)<br>Females (*n* = 9)<br>→ Untrained: No RT 8-months prior | 24.7 ± 2.1<br>23.3 ± 0.5 | 3-4 sets x *n* reps<br>→ 60-70% 1-RM<br>Exercises: Biceps curl, Back squat | 7 weeks (2/week) | Muscle thickness (ultrasound; biceps)<br>Muscle CSA (ultrasound; RF, VI, VM, VL) | ↔ Biceps muscle thickness between males (+13.7%) and females (+21.2%)<br>↔ Quadriceps CSA between males (+3.9%) and females (+5.9%) |
| **Kosek et al. 2006 [20]** | Males (*n* = 13)<br>Females (*n* = 11)<br>→ Untrained: No RT 5 years prior | 26.2 ± 5<br>27.9 ± 3.6 | 3 sets x 8-12 reps<br>→ 80% 1-RM<br>Exercises: Back squat, leg press, leg extension | 16 weeks (3/week) | Lean mass (DXA; total body)<br>Muscle fCSA (biopsy + histochemistry; VL)<br># Type I = 60<br># Type II = 63 | Lean mass ↑ for both males (+1.7%) and females (+1.7%) *<br>VL fCSA Both males (Type I = +25.6%, Type II = +31.5%) and females (Type I = +8.8%, Type II = +22.9%) ↑ VL fCSA * |
| **Lundberg et al. 2019 [36]** | Males (*n* = 8)<br>Females (*n* = 8)<br>→ Untrained: Recreationally active | ~26 ± 4 | Group A: 4 sets x 8-12 reps<br>→ 70-80% 1-RM^ | 8 weeks (2-3/week) | Muscle CSA (MRI; quadriceps) | Quadriceps CSA ↑ for both males (+6.9%) and females (+8.5%) for both RT protocols *<br>Quadriceps (proximal and distal) muscle |

|  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|
|  |  |  | Group B: 4 sets x 7 reps (flywheel)<br>Exercise: Leg extension |  | Muscle volume (MRI; Quadriceps) | volume ↑ for both males (+7.7%) and females (+7.9%) for both RT protocols * |
| **McMahon et al. 2018 [42]** | Males (*n* = 8)<br>Females (*n* = 8)<br>→ Untrained: No RT 1 year prior | 20 ± 2.8<br>19 ± 8.5 | 3-4 sets x 8-10 reps → 70% 1-RM<br>Exercises: Back squat, leg press, leg extension, lunge, split squat | 8 weeks (3/week) | Muscle pCSA (ultrasound; VL) | ↔ VL pCSA between males (+22.5%) and females (+30%) |
| **Moesgaard et al. 2022 [11]** | Males (*n* = 12)<br>Females (*n* = 12)<br>→ Untrained: No RT 1 year prior | 28 ± 7<br>27 ± 7 | 3 sets x 8-12 reps → 70-80% 1-RM^<br>Exercises: Leg press, leg extension | 8 weeks (3/week) | Muscle fCSA (biopsy + histochemistry; VL)<br># Type I = 191<br># Type II = 166 | ↑ Type I VL fCSA observed in males (+22.7%) versus females (+6.3%) but ↔ Type II VL fCSA between males (+29%) and females (+25.8%) |
| **Nunes et al. 2020 [47]** | Males (*n* = 25)<br>Females (*n* = 10)<br>→ Untrained: No RT 6-months prior | ~23.7 ± 5.3 | 3 sets x 8-12 reps → 70-80% 1-RM^<br>Exercises: Biceps preacher curl | 10 weeks (3/week) | Muscle thickness (ultrasound; biceps) | Biceps thickness ↑ for both males (+10.5%) and females (+8%) * |
| **O'Hagan 1995 [40]** | Males (*n* = 6)<br>Females (*n* = 6)<br>→ Untrained: No RT experience | 21.2 ± 1.2<br>20 ± 0.8 | 3-5 sets x 8-12 reps → 70-80% 1-RM^<br>Exercises: Biceps curl variations | 20 weeks (3/week) | Muscle CSA [CT; flexor (brachialis + biceps)] | ↔ Flexor CSA between males (+13.8%) and females (+26.9%) |
| **Peterson et al. 2010 [43]** | Males (*n* = 43)<br>Females (*n* = 40)<br>→ Untrained: No RT 1 year prior | ~25.1 ± 5.5 | 3 sets x 6-12 reps → 70-85% 1-RM^<br>Exercises: Biceps curl (multiple variations) | 12 weeks (2/week) | Muscle volume (MRI; biceps) | ↑ Biceps muscle volume observed in males (+15.2%) versus females (+12.1%) |
| **Psilander et al. 2019 [41]** | Males (*n* = 9)<br>Females (*n* = 10)<br>→ Untrained: No RT experience | ~25 ± 1 | 3 sets x 5-12 reps → 70-85% 1-RM<br>Exercises: Leg press, leg extension | 12 weeks (3/week) | Muscle thickness (ultrasound; VL)<br>Muscle fCSA (biopsy + histochemistry; VL)<br># Type I = 198<br># Type II = 374 | VL thickness ↑ for both males (+9.8%) and females (+9.5%) *<br>VL fCSA ↑ for both males (+15.1%) and females (+22.6%) * |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Reece et al. 2023 [38]** | Males (*n* = 14)<br>Females (*n* = 16)<br>→ Untrained: No RT 1 year prior | 21.5 ± 2.3<br>22.1 ± 3.6 | Group A: 3 sets x 8-12 reps<br>→ 80% 1-RM<br>Group B: 3 sets x *n* reps (BFR)<br>→ 30% 1-RM<br>Exercise: Leg extension | 6 weeks (3/week) | Muscle CSA (ultrasound; VL)<br>Muscle fCSA (biopsy + histochemistry; VL)<br># Type I = 38<br># Type II = 55 | VL CSA ↑ for both males (+5.3%) and females (+7.1%) for both RT protocols *<br>VL fCSA ↑ for both males (Type I = +18.9%, Type II = +17.3%) and females (Type I = +11.3%, Type II = +21.3%) for both RT protocols * |
| **Ribeiro et al. 2014 [49]** | Males (*n* = 30)<br>Females (*n* = 34)<br>→ Untrained: No RT 6-months prior | 22.7 ± 4.4<br>22.7 ± 4.1 | 3 sets x 8-12 reps<br>→ 70-80% 1-RM^<br>Exercises: Multiple exercises targeting all primary muscle groups | 16 weeks (3/week) | Skeletal muscle mass (BIA; total body) | ↔ Skeletal muscle mass between males (+4.2%) and females (+3.9%) |
| **Rissanen et al. 2022 [34]** | Males (*n* = 23)<br>Females (*n* = 22)<br>→ Trained: ≥1 year of RT experience | 26.4 ± 3.9<br>25.5 ± 3.8 | Group A: 2-5 sets x 20% VeL<br>→ 65-75% 1-RM<br>Group B: 2-5 sets x 40% VeL<br>→ 65-75% 1-RM<br>Exercise: Back squat | 8 weeks (2/week) | Muscle CSA (ultrasound; VL) | ↔ VL CSA between males (+17.1%) and females (+21.5%) for both RT protocols |
| **Schwanbeck et al. 2020 [33]** | Males (*n* = 15)<br>Females (*n* = 21)<br>→ Trained: >2 year of RT experience | ~22.5 ± 3.5 | Group A: 3-4 sets x 4-10 reps (free weights)<br>→ 75-90% 1-RM^<br>Group B: 3-4 sets x 4-10 reps (machines)<br>→ 75-90% 1-RM^<br>Exercises: Biceps curl variations, back squat, lunge | 8 weeks (1/week) | Muscle thickness (ultrasound; biceps, quadriceps) | ↔ Biceps and quadriceps muscle thickness between males (+5.4%) and females (+4.5%) for both RT protocols |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Sterczala et al. 2024 [16]** | Males (*n* = 19)<br>Females (*n* = 14)<br>→ Trained: Unknown years of RT experience | 28 ± 4<br>26 ± 5 | 3-5 sets x 3-10 reps → 64-88% 1-RM<br>Exercises: Multiple exercises targeting all primary muscle groups | 12 weeks (3/week) | Lean mass (DXA; total body)<br>Muscle fCSA (biopsy + histochemistry; VL)<br># Type I = N/A<br># Type II = N/A | Lean mass ↑ for both males (+3.5%) and females (+3.4%)<br>↑ VL fCSA in males (Type I = +14.2%, Type II = +7.9%) versus females (Type I = –6%, Type II = –4.2%) |
| **Walsh et al. 2009 [37]** | Males (*n* = 280)<br>Females (*n* = 412)<br>→ Untrained: No RT 1 year prior | ~24.8 ± 9<br>~24 ± 6 | 3 sets x 6-12 reps → 65-90% 1-RM<br>Exercises: Biceps curl (multiple variations) | 12 weeks (2/week) | Muscle CSA (MRI; biceps) | Biceps CSA ↑ for both males (+19.7%) and females (+17.7%) * |

### 3.2 Methodological Quality

A detailed overview of the methodological quality of included studies using the TESTEX scale [16] can be found in Online Resource 3. Study quality scores ranged from 9 to 12 (out of a possible 15), with mean and median scores of 10. Although each study had some risk of bias, many studies lost points due to i) no activity monitoring, ii) no 'intention-to-treat' analysis of participants who had withdrawn, and iii) no reporting of adverse incidents or compliance rate of participants. Overall, a total of 19 out of 29 (66%) studies scored highly (>10) on the TESTEX scale and visual inspection of methodological quality results revealed no impact of study quality on the effect size estimates generated. Considering that all included studies involved a comparison between males and females, no randomisation procedures were required, allocation concealment was not possible, and muscle size differed at baseline, thus, criterion '2' (i.e., "randomisation specified"), criterion '3' (i.e., "allocation concealment"), and criterion '4' (i.e., "groups similar at baseline") were given one point for every study. Although randomisation of participants into groups was not necessary in the studies included in this systematic review with meta-analysis, studies that involved different RT groups for each sex, and/or a control group, did employ appropriate randomisation procedures [33, 34, 36, 38, 40-42, 44, 47].

### 3.3 Meta-Analysis Results

Meta-analysis (including all 68 outcomes) of absolute changes in muscle size from pre- to post-intervention (Fig 2) estimated a 100% probability of superior absolute muscle hypertrophy in males versus females [SMD = 0.19 (95% HDI: 0.11 to 0.28)]. The HDI covers ESs that suggest a negligible to small effect (favouring males), with low to moderate between-study variance identified [$\tau$ = 0.09 (95% HDI: 0.01 to 0.20)]. Additionally, meta-analysis (including all 68 outcomes) of lnRR to assess relative changes in muscle size from pre- to post-intervention (Fig 3) estimated similar muscle hypertrophy in males and females [lnRR = 0.01 (95% HDI: – 0.01 to 0.03); *pd* = 74%]. The HDI covers ESs that suggest a negligible effect, with negligible between-study variance identified [$\tau$ = 0.01 (95% HDI: 0.00 to 0.03)]. Exponentiated percentage changes calculated from lnRR also showed similar muscle hypertrophy between males and females [Exp. % Change of lnRR = 0.69% (95% HDI: – 1.50% to 2.88%)]. Results of secondary sub-group analyses are displayed in Table 2 and Online Resource 5. Raw SMD and Exp. % Change of lnRR of meta-analysed studies are displayed in Online Resource 4.

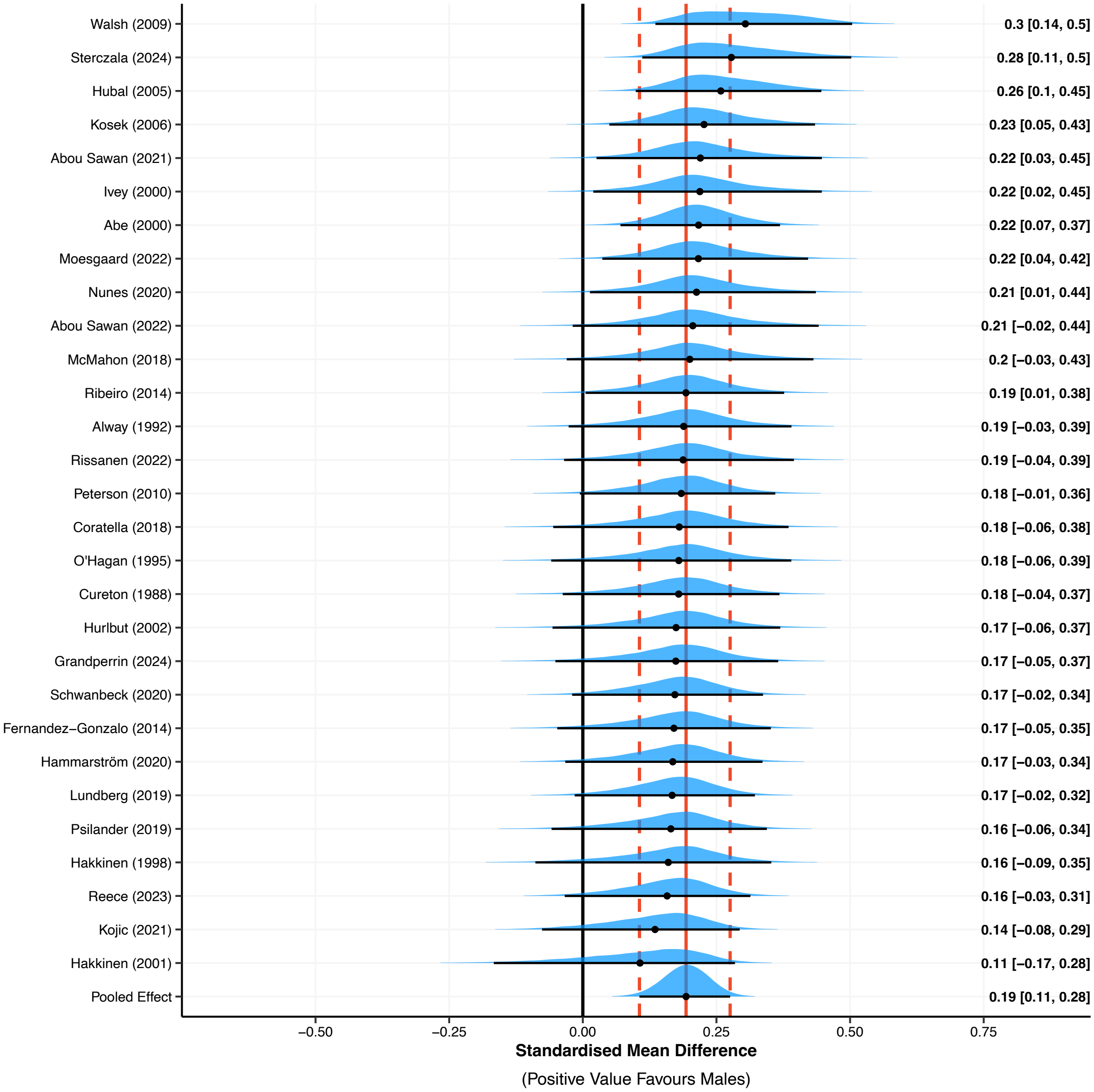

**Fig 2. Meta-analysis of standardised mean differences to assess absolute changes in muscle size from pre- to post-intervention between males and females.** Positive values favour greater increases in muscle size for male participants. Point (mean) estimates and 95% high density credible intervals are shown by the point and interval line below each posterior distribution. Red vertical lines represent the point estimate (solid) and width of the highest density credible interval (dotted) for the pooled effect size. Standardised mean differences shown are adjusted towards the overall mean, known as shrinkage.

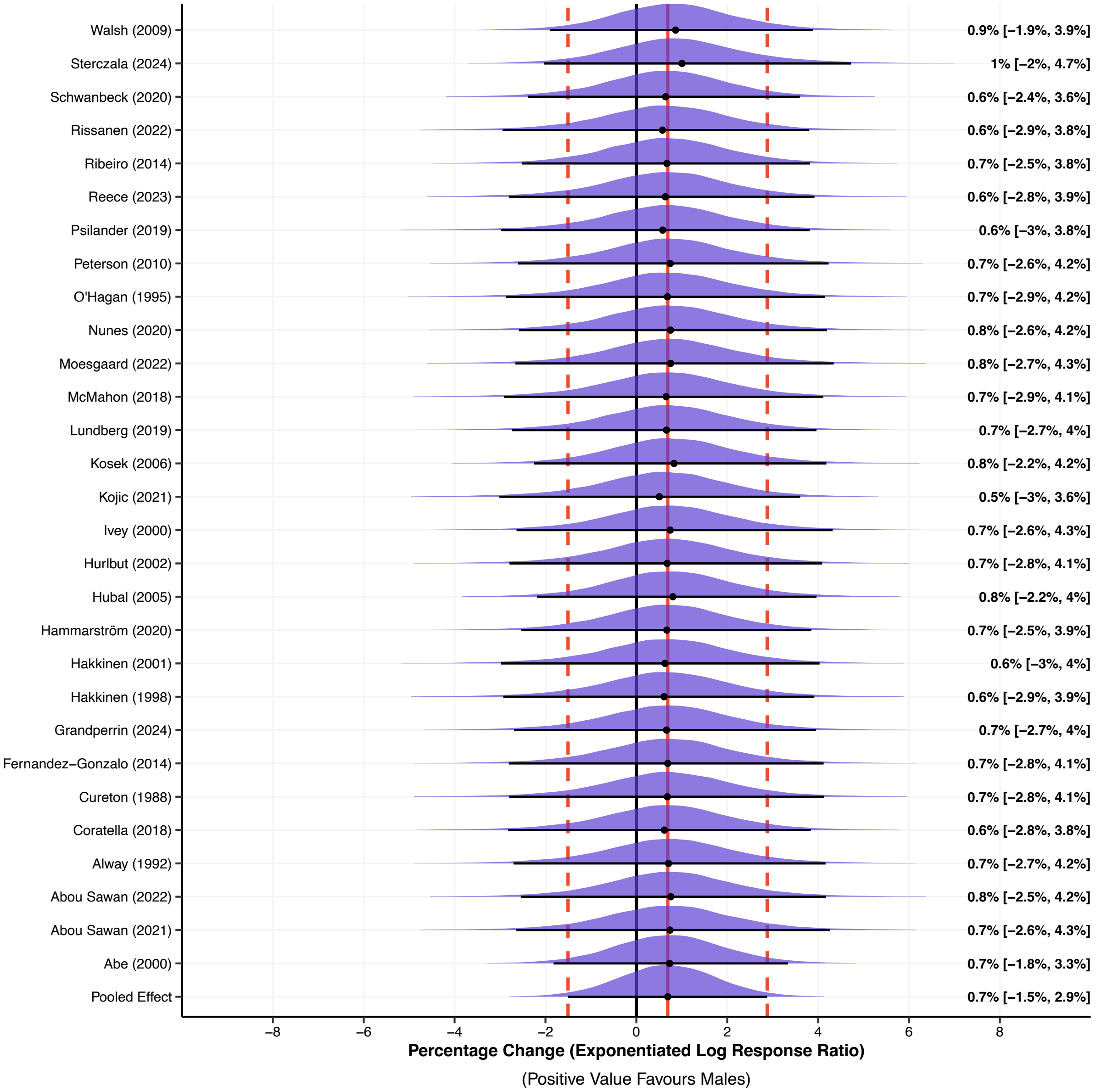

**Fig 3. Meta-analysis of log response ratios (converted to exponentiated percentage changes) to assess relative changes in muscle size from pre- to post-intervention between males and females.** Positive values favour greater increases in muscle size for male participants. Point (mean) estimates and 95% high density credible intervals are shown by the point and interval line below each posterior distribution. Red vertical lines represent the point estimate (solid) and width of the highest density credible interval (dotted) for the pooled effect size. Exponentiated log response ratios are adjusted towards the overall mean, known as shrinkage.

**Table 2. Secondary sub-group analyses of body region, assessment of muscle hypertrophy, and resistance training experience, and muscle fibre type.** Effect estimates displayed as standardised mean difference or exponentiated percentage change of log response ratio. Positive values indicate larger increases in muscle size for male participants. *HDI, highest density credible interval; Obs, observations; pd, probability of direction.*

| Categorical Variable | Effect Estimate | HDI | *pd* | Obs. |
|---|---|---|---|---|
| Absolute Change in Muscle Size (Standardised Mean Difference) | | | | |
| *Body Region* | | | | |
| Lower Body | 0.17 | 0.056 to 0.29 | 100% | 47 |
| Upper Body | 0.30 | 0.14 to 0.44 | 100% | 15 |
| *Assessment of Muscle Hypertrophy* | | | | |
| Lean Mass | 0.02 | – 0.19 to 0.23 | 60% | 6 |
| Muscle CSA | 0.19 | 0.04 to 0.34 | 99% | 21 |
| Muscle fCSA | 0.29 | 0.11 to 0.47 | 100% | 16 |
| Muscle Thickness | 0.19 | – 0.02 to 0.39 | 97% | 17 |
| Muscle Volume | 0.19 | – 0.08 to 0.45 | 92% | 6 |
| *Muscle Fibre Type* | | | | |
| Type I | 0.39 | – 0.03 to 0.81 | 97% | 8 |
| Type II | 0.10 | – 0.33 to 0.52 | 70% | 8 |
| *Resistance Training Experience* | | | | |
| Resistance-Trained | 0.20 | 0.01 to 0.38 | 98% | 13 |
| Untrained | 0.19 | 0.09 to 0.29 | 100% | 54 |
| Relative Change in Muscle Size (Exponentiated Percentage Change) | | | | |
| *Body Region* | | | | |
| Lower Body | 1.04% | – 2.03 to 4.2% | 75% | 47 |
| Upper Body | 0.60% | – 2.97 to 4.18% | 63% | 15 |
| *Assessment of Muscle Hypertrophy* | | | | |
| Lean Mass | 0.02% | – 5.12 to 5.32% | 50% | 6 |
| Muscle CSA | 0.45% | – 3.23 to 4.19% | 59% | 21 |
| Muscle fCSA | 6.03% | – 2.55 to 15.4% | 91% | 16 |
| Muscle Thickness | 0.35% | – 3.25 to 3.93% | 58% | 17 |
| Muscle Volume | 2.29% | – 8.58 to 14.5% | 64% | 6 |
| *Muscle Fibre Type* | | | | |
| Type I | 12.7% | – 6.84 to 34.9% | 90% | 8 |
| Type II | – 2.29% | – 19.2 to 16.7% | 62% | 8 |
| *Resistance Training Experience* | | | | |
| Resistance-Trained | 0.87% | – 3.46 to 5.4% | 65% | 13 |
| Untrained | 0.66% | – 1.79 to 3.07% | 71% | 54 |

### 3.4 Sensitivity Analysis

Sensitivity analysis of *r* values from 0.7 to 0.99 found SMDs between 0.17 and 0.22 (meta-analysis result = 0.19). The primary analysis was conducted with an *a priori* assumption that the correlation coefficient between pre-test and post-test measures was $r = 0.87$; this is a reasonable assumption that was obtained from previous literature [10], with sensitivity analyses indicating little impact of different correlation coefficient values on the pooled SMD. As such the results of our meta-analysis may be interpreted with increased confidence. Results of sensitivity analysis are displayed in Online Resource 1.

# 4. DISCUSSION

## 4.1 Absolute and Relative Changes in Muscle Size

This systematic review with meta-analysis extends previous findings with a total of 29 included studies (versus 10 in a previous meta-analysis [9]), providing an up to date synthesis of the current literature investigating biological sex differences in both absolute and relative muscle hypertrophy following RT. We found absolute increases in muscle size following RT slightly favoured males versus females (SMD = 0.19), however, the relative increase in muscle size (percentage increase from baseline) following RT was similar between sexes (Exp. % Change of lnRR = 0.69%). Inherent differences in testosterone levels between sexes [5] are known to be responsible for larger baseline muscle size in males versus females on average (e.g., out of 68 observations extracted from reviewed studies, only two showed larger baseline muscle size in females). Therefore, differences in absolute muscle hypertrophy observed between sexes are likely due to differences in baseline muscle size, whereas relative muscle hypertrophy is based on the proportional increase from baseline size. For example, since females state with less muscle mass on average, the absolute increase will be smaller even if the proportional change (i.e., relative muscle hypertrophy) is similar to that of males (Fig 6). Considering the similar relative increases in muscle size observed between sexes, physiological signals (e.g., mechanical tension mediated anabolic signalling, metabolic stress [50]) other than sex-specific hormonal balance may play the primary role in promoting muscle hypertrophy following RT [50]. Supportive of our findings is research highlighting i) the anabolic properties of estradiol that may contribute to muscle hypertrophy [51-53], ii) the positive association between androgen receptor content with muscle hypertrophy [54], iii) similarities in post-exercise protein synthesis and molecular signalling between sexes that triggers muscle hypertrophy [55, 56], and iv) the acute post-exercise elevation in anabolic hormones does not play a major role in stimulating muscle protein synthesis [57]. Taken as a whole, our data suggest RT is likely to induce slightly greater absolute increases in muscle size in males versus females, but similar relative increases in muscle size from baseline, which suggests comparable muscle hypertrophic potential between males and females following RT.

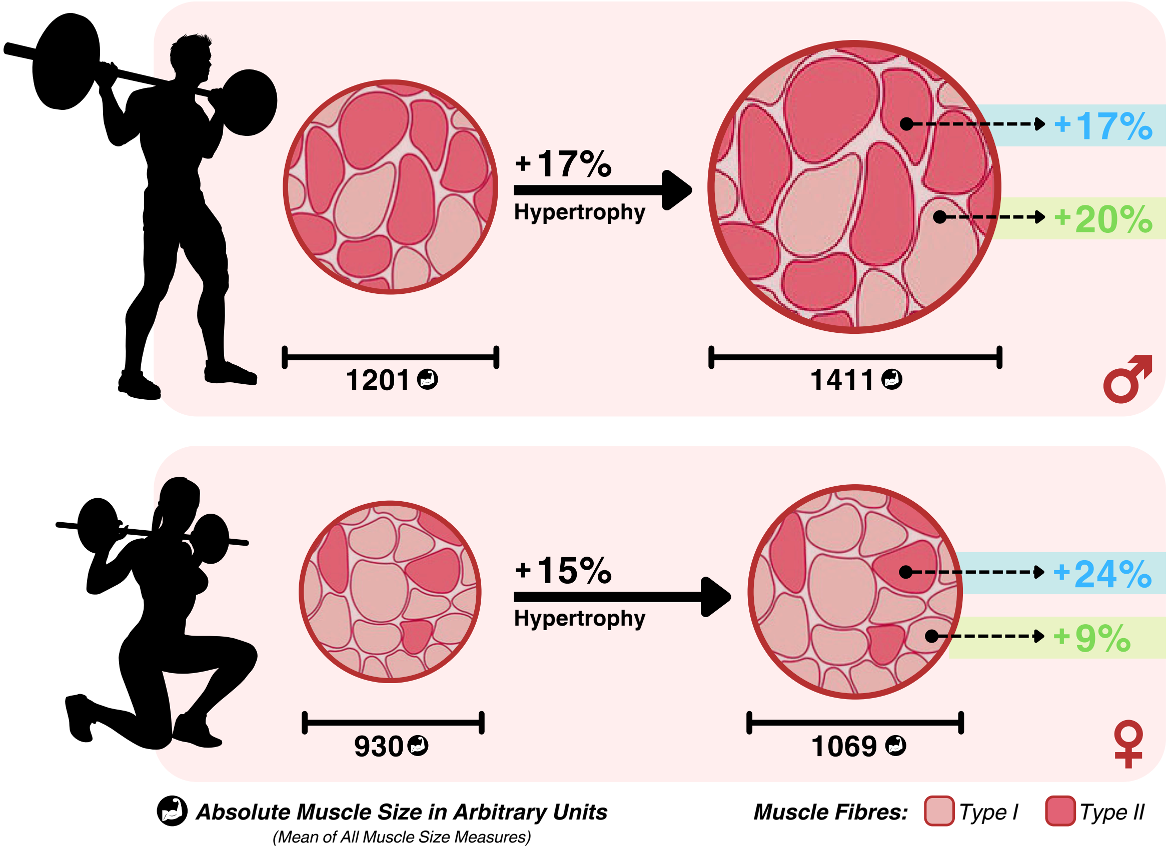

**Fig 6. Graphical overview of absolute and relative changes in muscle size (including muscle fibre cross sectional area) following resistance training for males and females.** To depict changes in absolute muscle size, the mean value of all muscle size outcomes (independent of the units of measurement) was calculated and described as "absolute muscle size in arbitrary units".

### 4.2 Moderators of Absolute and Relative Changes in Muscle Size

Sub-group analyses were conducted to assess possible variability in muscle hypertrophy outcomes across measures and body regions. Absolute differences in muscle hypertrophy between sexes were more evident with direct measures (i.e., muscle volume, muscle thickness, and muscle CSA and fCSA) versus indirect measures (i.e., lean mass). However, measures of lean mass should be interpreted with caution as they can be influenced by fluid alterations and may be less accurate versus other direct measures used [58]. Nonetheless, relative changes in muscle size between sexes were similar across all measures employed. Although sex differences in relative hypertrophy slightly favoured muscle fCSA versus other measures, the very wide HDIs suggests high variability in the response. We categorised body regions measured into either upper- or lower-body and found relative changes in muscle size between sexes were similar independent of the body region assessed. However, absolute changes in muscle size of the upper-body slightly favoured males (SMD = 0.30 versus 0.17), likely due to larger baseline differences in muscle size between sexes in the upper- versus lower-body [5]. Overall, these data suggest i) sex differences in absolute and relative muscle hypertrophy do not appear to depend on the measurement of muscle size, and ii) males experience slightly greater absolute muscle hypertrophy versus females in body regions where larger baseline differences are evident (i.e., in upper-body versus lower-body muscles).

A total of seven studies (*n* = 170) using histochemical analysis of skeletal muscle biopsies to determine fCSA [11, 12, 16, 20, 22, 38, 41] were meta-analysed. Similar to previous findings [11, 12], we observed a >90% probability of absolute (SMD = 0.39) and relative (Exp. % Change of lnRR = 12.7%) type I muscle fibre hypertrophy favouring males versus females, providing further support males have a greater capacity to hypertrophy type I muscle fibres than females. However, the 95% HDIs covered wide effect estimates for both absolute and relative type I muscle fibre hypertrophy, suggesting considerable uncertainty in outcomes. Conversely, we estimated a negligible difference in i) relative hypertrophy of type II muscle fibres favouring females versus males (Exp. % Change of lnRR = – 2.29 %; *pd* = 62%), and ii) absolute hypertrophy of type II muscle fibres between sexes, despite larger baseline mean muscle fCSA for males (4616 ± 713μm$^2$) versus females (3652 ± 621μm$^2$) across all studies included in our meta-analysis. These findings support the possibility for sex-specific differences in muscle fibre type hypertrophy. Nonetheless, despite all studies assessing muscle fCSA with histochemical analysis of skeletal muscle biopsies, variability in the number of muscle fibres chosen and subsequently analysed per participant (range = 37 to 374), and how studies reported type II muscle fCSA based on the combination of type IIa and IIx values (which differ in size at baseline and in their physiological response to chronic exercise [38]), may have influenced our findings. As such, due to the intricate nature of measuring muscle fCSA in research and the uncertainty and variability in responses observed (Online Resource 4), our findings should be interpreted with caution and used to inform future research that compares muscle fibre type-specific hypertrophy between males and females.

The RT experience of participants did not seem to influence sex differences in absolute and relative muscle hypertrophy following RT. Previous research has indicated that long-term RT experience alters the physiological response to RT [59] and may also cause muscle fibre type transitions that could influence sex-specific muscle hypertrophy [60]. For example, a study in high-level competitive weightlifters (i.e., World/Olympic and National level) found years competing in weightlifting influences the proportion of type II muscle fibres more than biological sex *per se*, with females having a higher abundance of type II muscle fibres than males [61]. Whether a higher proportion of type II muscle fibres in highly trained females would influence sex differences in whole muscle and muscle fibre type-specific hypertrophy remains to be explored. Given only six of the 29 studies included in the meta-analysis involved resistance-trained participants, further research investigating sex differences in muscle hypertrophy within resistance-trained samples is encouraged.

### 4.3 Limitations

Although most (66%) of the included studies were of 'high' quality, a brief overview of key findings in Table 1 suggests that results are consistent across both low and high quality studies. Our sub-group analysis investigating hypertrophy of type I and type II fibres only involved seven studies with a total of 170 participants, and the wide HDIs highlight the variability in outcomes. Although interpretations about muscle fibre type-specific hypertrophy were based on data from 170 participants, it is possible that a larger pool of evidence may strengthen or weaken the findings. Only six out of 29 studies were conducted in resistance-trained participants, however, in some cases the RT experience (years) of the 'resistance-trained' participants was vaguely described and therefore unclear (Table 1). Future research should investigate sex differences in muscle hypertrophy amongst resistance-trained samples and clearly report RT status of participants (e.g., years of experience). Finally, considering exact correlation coefficient values (between pre-test and post-test measures) could not be retrieved from individual studies, we used an *a priori* assumption of $r = 0.87$ to calculate SMDs. However, sensitivity analyses showed minimal impact of varying correlation coefficients on the pooled SMD, supporting the robustness of our meta-analysis results.

### 4.4 Practical Applications

Our findings suggest healthy adult males and females have comparable muscle hypertrophic potential following RT, and thus, may experience similar benefits associated with RT-induced muscle hypertrophy. For example, i) low skeletal muscle mass index is associated with an increased risk of all-cause mortality [62], and ii) some physiological characteristics important for athletic performance (e.g., force production, rate of force development, fatigue resistance) may be influenced by muscle size [63, 64]. Considering we found minimal evidence of a moderating effect of RT experience on sex differences in muscle hypertrophy, RT may be prescribed similarly between both untrained and resistance-trained males and females, with primary differences in RT prescription based on long-term goals (e.g., aesthetics or performance-based goals) and individual characteristics (e.g., enjoyment, perceptions of discomfort, preferences, stress tolerance, etc.). However, potential sex differences in short-term responses to RT, such as neuromuscular fatigue and muscle damage, may be greater in males versus females [65-67] and should be considered in RT prescription.

## 5. CONCLUSION

This systematic review with Bayesian meta-analysis investigated differences in muscle hypertrophy following RT between healthy adult males and females. The evidence suggests absolute increases in muscle size following RT slightly favour males, however, relative changes in muscle size are similar between sexes. These results were not influenced by different measures of muscle size or the RT experience (i.e., untrained or resistance-trained) of participants. Further, differences in absolute muscle hypertrophy favouring males over females were larger in the upper- versus lower-body regions. Although there were possible sex differences in muscle-fibre type specific hypertrophy, with greater type I muscle fibre hypertrophy in males versus females, our findings should be interpreted with caution due to the intricate nature of measuring muscle fCSA in research and the variability in responses observed. Our primary analyses strengthen the understanding that females have a similar potential to induce muscle hypertrophy as males (particularly when considering relative increases in muscle size from baseline) and findings of our secondary analyses should inform future research that investigates sex differences in highly trained participants and muscle fibre type-specific hypertrophy.

# 6. STATEMENTS AND DECLARATIONS

## Contributions

Article conceptualisation: MR, JJF; literature search: MR and JF; data extraction: MR and JF; statistical analysis: MR and IG; drafted manuscript: MR and JF; critically revised manuscript: all authors.

## Acknowledgements

N/A

## Funding information

No funding was used to directly support the preparation of this review.

## Data and Supplementary Material Accessibility

Data and code available on Open Science Framework (https://osf.io/trz3y/)

## Competing interests

Lee Hamilton, Jackson Fyfe, and Iain Gallagher declare that they have no conflicts of interest or competing interests. Martin Refalo, Greg Nuckols, and Andrew Galpin are all coaches and writers in the fitness industry. No known companies will benefit from the results of the present study.

# 7. REFERENCES

1. Haun CT, Vann CG, Roberts BM, Vigotsky AD, Schoenfeld BJ, Roberts MD. A Critical Evaluation of the Biological Construct Skeletal Muscle Hypertrophy: Size Matters but So Does the Measurement. Front Physiol. 2019;10:247.
2. Hubal MJ, Gordish-Dressman H, Thompson PD, Price TB, Hoffman EP, Angelopoulos TJ, et al. Variability in muscle size and strength gain after unilateral resistance training. Med Sci Sports Exerc. 2005;37(6):964-72.
3. Handelsman DJ. Sex differences in athletic performance emerge coinciding with the onset of male puberty. Clin Endocrinol (Oxf). 2017;87(1):68-72.
4. Vingren JL, Kraemer WJ, Ratamess NA, Anderson JM, Volek JS, Maresh CM. Testosterone physiology in resistance exercise and training: the up-stream regulatory elements. Sports Med. 2010;40(12):1037-53.
5. Nuzzo JL. Narrative Review of Sex Differences in Muscle Strength, Endurance, Activation, Size, Fiber Type, and Strength Training Participation Rates, Preferences, Motivations, Injuries, and Neuromuscular Adaptations. J Strength Cond Res. 2023;37(2):494-536.
6. Tesch PA. Skeletal muscle adaptations consequent to long-term heavy resistance exercise. Med Sci Sports Exerc. 1988;20(5 Suppl):S132-4.
7. Nuzzo JL. Sex differences in skeletal muscle fiber types: A meta-analysis. Clin Anat. 2023.
8. Liu D, Sartor MA, Nader GA, Gutmann L, Treutelaar MK, Pistilli EE, et al. Skeletal muscle gene expression in response to resistance exercise: sex specific regulation. BMC Genomics. 2010;11:659.
9. Roberts BM, Nuckols G, Krieger JW. Sex Differences in Resistance Training: A Systematic Review and Meta-Analysis. J Strength Cond Res. 2020;34(5):1448-60.
10. Jones MD, Wewege MA, Hackett DA, Keogh JWL, Hagstrom AD. Sex Differences in Adaptations in Muscle Strength and Size Following Resistance Training in Older Adults: A Systematic Review and Meta-analysis. Sports Med. 2021;51(3):503-17.
11. Moesgaard L, Jessen S, Mackey AL, Hostrup M. Myonuclear addition is associated with sex-specific fiber hypertrophy and occurs in relation to fiber perimeter not cross-sectional area. J Appl Physiol (1985). 2022;133(3):732-41.
12. Abou Sawan S, Hodson N, Babits P, Malowany JM, Kumbhare D, Moore DR. Satellite cell and myonuclear accretion is related to training-induced skeletal muscle fiber hypertrophy in young males and females. J Appl Physiol (1985). 2021;131(3):871-80.
13. Kruschke JK, Liddell TM. The Bayesian New Statistics: Hypothesis testing, estimation, meta-analysis, and power analysis from a Bayesian perspective. Psychon Bull Rev. 2018;25(1):178-206.
14. Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ. 2021;372:n71.
15. Grandperrin A, Ollive P, Kretel Y, Maufrais C, Nottin S. Impact of a 16-week strength training program on physical performance, body composition and cardiac remodeling in previously untrained women and men. Eur J Sport Sci. 2024;24(4):474-86.

16. Sterczala AJ, Rodriguez-Ortiz N, Feigel ED, Krajewski KT, Martin BJ, Sekel NM, et al. Skeletal muscle adaptations to high-intensity, low-volume concurrent resistance and interval training in recreationally active men and women. Physiol Rep. 2024;12(6):e15953.
17. Hurlbut DE, Lott ME, Ryan AS, Ferrell RE, Roth SM, Ivey FM, et al. Does age, sex, or ACE genotype affect glucose and insulin responses to strength training? J Appl Physiol (1985). 2002;92(2):643-50.
18. Ivey FM, Roth SM, Ferrell RE, Tracy BL, Lemmer JT, Hurlbut DE, et al. Effects of age, gender, and myostatin genotype on the hypertrophic response to heavy resistance strength training. J Gerontol A Biol Sci Med Sci. 2000;55(11):M641-8.
19. Kojic F, Mandic D, Ilic V. Resistance training induces similar adaptations of upper and lower-body muscles between sexes. Sci Rep. 2021;11(1):23449.
20. Kosek DJ, Kim JS, Petrella JK, Cross JM, Bamman MM. Efficacy of 3 days/wk resistance training on myofiber hypertrophy and myogenic mechanisms in young vs. older adults. J Appl Physiol (1985). 2006;101(2):531-44.
21. Hakkinen K, Kallinen M, Izquierdo M, Jokelainen K, Lassila H, Malkia E, et al. Changes in agonist-antagonist EMG, muscle CSA, and force during strength training in middle-aged and older people. J Appl Physiol (1985). 1998;84(4):1341-9.
22. Hakkinen K, Kraemer WJ, Newton RU, Alen M. Changes in electromyographic activity, muscle fibre and force production characteristics during heavy resistance/power strength training in middle-aged and older men and women. Acta Physiol Scand. 2001;171(1):51-62.
23. Santos Junior ERT, de Salles BF, Dias I, Ribeiro AS, Simão R, Willardson JM. Classification and Determination Model of Resistance Training Status. Strength & Conditioning Journal. 2021;Publish Ahead of Print.
24. Refalo MC, Helms ER, Hamilton DL, Fyfe JJ. Towards an improved understanding of proximity-to-failure in resistance training and its influence on skeletal muscle hypertrophy, neuromuscular fatigue, muscle damage, and perceived discomfort: A scoping review. J Sports Sci. 2022:1-23.
25. Smart NA, Waldron M, Ismail H, Giallauria F, Vigorito C, Cornelissen V, et al. Validation of a new tool for the assessment of study quality and reporting in exercise training studies: TESTEX. Int J Evid Based Healthc. 2015;13(1):9-18.
26. Morris SB. Estimating Effect Sizes From Pretest-Posttest-Control Group Designs. Organizational Research Methods. 2008;11(2).
27. Vickers AJ. The use of percentage change from baseline as an outcome in a controlled trial is statistically inefficient: a simulation study. BMC Med Res Methodol. 2001;1:6.
28. Lajeunesse MJ. Bias and correction for the log response ratio in ecological meta-analysis. Ecology. 2015;96(8):2056-63.
29. Spake R, Bowler DE, Callaghan CT, Blowes SA, Doncaster CP, Antao LH, et al. Understanding 'it depends' in ecology: a guide to hypothesising, visualising and interpreting statistical interactions. Biol Rev Camb Philos Soc. 2023;98(4):983-1002.
30. Swinton P, Murphy A. Comparative effect size distributions in strength and conditioning and implications for future research. SportRxiv. 2022;Preprint.
31. Kelter R. How to Choose between Different Bayesian Posterior Indices for Hypothesis Testing in Practice. Multivariate Behav Res. 2023;58(1):160-88.

32. Hammarstrom D, Ofsteng S, Koll L, Hanestadhaugen M, Hollan I, Apro W, et al. Benefits of higher resistance-training volume are related to ribosome biogenesis. J Physiol. 2020;598(3):543-65.
33. Schwanbeck SR, Cornish SM, Barss T, Chilibeck PD. Effects of Training With Free Weights Versus Machines on Muscle Mass, Strength, Free Testosterone, and Free Cortisol Levels. J Strength Cond Res. 2020;34(7):1851-9.
34. Rissanen J, Walker S, Pareja-Blanco F, Hakkinen K. Velocity-based resistance training: do women need greater velocity loss to maximize adaptations? Eur J Appl Physiol. 2022;122(5):1269-80.
35. Alway SE, Grumbt WH, Stray-Gundersen J, Gonyea WJ. Effects of resistance training on elbow flexors of highly competitive bodybuilders. J Appl Physiol (1985). 1992;72(4):1512-21.
36. Lundberg TR, Garcia-Gutierrez MT, Mandic M, Lilja M, Fernandez-Gonzalo R. Regional and muscle-specific adaptations in knee extensor hypertrophy using flywheel versus conventional weight-stack resistance exercise. Appl Physiol Nutr Metab. 2019;44(8):827-33.
37. Walsh S, Kelsey BK, Angelopoulos TJ, Clarkson PM, Gordon PM, Moyna NM, et al. CNTF 1357 G -> A polymorphism and the muscle strength response to resistance training. J Appl Physiol (1985). 2009;107(4):1235-40.
38. Reece TM, Godwin JS, Strube MJ, Ciccone AB, Stout KW, Pearson JR, et al. Myofiber hypertrophy adaptations following 6 weeks of low-load resistance training with blood flow restriction in untrained males and females. J Appl Physiol (1985). 2023;134(5):1240-55.
39. Cureton KJ, Collins MA, Hill DW, McElhannon FM, Jr. Muscle hypertrophy in men and women. Med Sci Sports Exerc. 1988;20(4):338-44.
40. O'Hagan FT, Sale DG, MacDougall JD, Garner SH. Response to resistance training in young women and men. Int J Sports Med. 1995;16(5):314-21.
41. Psilander N, Eftestol E, Cumming KT, Juvkam I, Ekblom MM, Sunding K, et al. Effects of training, detraining, and retraining on strength, hypertrophy, and myonuclear number in human skeletal muscle. J Appl Physiol (1985). 2019;126(6):1636-45.
42. McMahon G, Morse CI, Winwood K, Burden A, Onambele GL. Gender associated muscle-tendon adaptations to resistance training. PLoS One. 2018;13(5):e0197852.
43. Peterson MD, Pistilli E, Haff GG, Hoffman EP, Gordon PM. Progression of volume load and muscular adaptation during resistance exercise. Eur J Appl Physiol. 2011;111(6):1063-71.
44. Abe T, DeHoyos DV, Pollock ML, Garzarella L. Time course for strength and muscle thickness changes following upper and lower body resistance training in men and women. Eur J Appl Physiol. 2000;81(3):174-80.
45. Abou Sawan S, Hodson N, Malowany JM, West DWD, Tinline-Goodfellow C, Brook MS, et al. Trained Integrated Postexercise Myofibrillar Protein Synthesis Rates Correlate with Hypertrophy in Young Males and Females. Med Sci Sports Exerc. 2022;54(6):953-64.
46. Coratella G, Longo S, Ce E, Limonta E, Rampichini S, Bisconti AV, et al. Sex-Related Responses to Eccentric-Only Resistance Training in Knee-Extensors Muscle Strength and Architecture. Res Q Exerc Sport. 2018;89(3):347-53.
47. Nunes JP, Jacinto JL, Ribeiro AS, Mayhew JL, Nakamura M, Capel DMG, et al. Placing Greater Torque at Shorter or Longer Muscle Lengths? Effects of Cable vs. Barbell Preacher Curl

Training on Muscular Strength and Hypertrophy in Young Adults. Int J Environ Res Public Health. 2020;17(16).

48. Fernandez-Gonzalo R, Lundberg TR, Alvarez-Alvarez L, de Paz JA. Muscle damage responses and adaptations to eccentric-overload resistance exercise in men and women. Eur J Appl Physiol. 2014;114(5):1075-84.

49. Ribeiro AS, Avelar A, Schoenfeld BJ, Ritti Dias RM, Altimari LR, Cyrino ES. Resistance training promotes increase in intracellular hydration in men and women. Eur J Sport Sci. 2014;14(6):578-85.

50. Wackerhage H, Schoenfeld BJ, Hamilton DL, Lehti M, Hulmi JJ. Stimuli and sensors that initiate skeletal muscle hypertrophy following resistance exercise. J Appl Physiol (1985). 2019;126(1):30-43.

51. Hansen M, Kjaer M. Influence of sex and estrogen on musculotendinous protein turnover at rest and after exercise. Exerc Sport Sci Rev. 2014;42(4):183-92.

52. Haizlip KM, Harrison BC, Leinwand LA. Sex-based differences in skeletal muscle kinetics and fiber-type composition. Physiology (Bethesda). 2015;30(1):30-9.

53. Chidi-Ogbolu N, Baar K. Effect of Estrogen on Musculoskeletal Performance and Injury Risk. Front Physiol. 2018;9:1834.

54. Morton RW, Sato K, Gallaugher MPB, Oikawa SY, McNicholas PD, Fujita S, et al. Muscle Androgen Receptor Content but Not Systemic Hormones Is Associated With Resistance Training-Induced Skeletal Muscle Hypertrophy in Healthy, Young Men. Front Physiol. 2018;9:1373.

55. West DW, Burd NA, Churchward-Venne TA, Camera DM, Mitchell CJ, Baker SK, et al. Sex-based comparisons of myofibrillar protein synthesis after resistance exercise in the fed state. J Appl Physiol (1985). 2012;112(11):1805-13.

56. Dreyer HC, Fujita S, Glynn EL, Drummond MJ, Volpi E, Rasmussen BB. Resistance exercise increases leg muscle protein synthesis and mTOR signalling independent of sex. Acta Physiol (Oxf). 2010;199(1):71-81.

57. Van Every DW, D'Souza AC, Phillips SM. Hormones, Hypertrophy, and Hype: An Evidence-guided Primer on Endogenous Endocrine Influences on Exercise-Induced Muscle Hypertrophy. Exerc Sport Sci Rev. 2024.

58. Rodriguez C, Mota JD, Palmer TB, Heymsfield SB, Tinsley GM. Skeletal muscle estimation: A review of techniques and their applications. Clin Physiol Funct Imaging. 2024;44(4):261-84.

59. Damas F, Phillips S, Vechin FC, Ugrinowitsch C. A review of resistance training-induced changes in skeletal muscle protein synthesis and their contribution to hypertrophy. Sports Med. 2015;45(6):801-7.

60. Plotkin DL, Roberts MD, Haun CT, Schoenfeld BJ. Muscle Fiber Type Transitions with Exercise Training: Shifting Perspectives. Sports (Basel). 2021;9(9).

61. Serrano N, Colenso-Semple LM, Lazauskus KK, Siu JW, Bagley JR, Lockie RG, et al. Extraordinary fast-twitch fiber abundance in elite weightlifters. PLoS One. 2019;14(3):e0207975.

62. Wang Y, Luo D, Liu J, Song Y, Jiang B, Jiang H. Low skeletal muscle mass index and all-cause mortality risk in adults: A systematic review and meta-analysis of prospective cohort studies. PLoS One. 2023;18(6):e0286745.

63. Taber CB, Vigotsky A, Nuckols G, Haun CT. Exercise-Induced Myofibrillar Hypertrophy is a Contributory Cause of Gains in Muscle Strength. Sports Med. 2019;49(7):993-7.

64. Kavvoura A, Zaras N, Stasinaki AN, Arnaoutis G, Methenitis S, Terzis G. The Importance of Lean Body Mass for the Rate of Force Development in Taekwondo Athletes and Track and Field Throwers. J Funct Morphol Kinesiol. 2018;3(3).
65. Hunter SK. Sex differences in human fatigability: mechanisms and insight to physiological responses. Acta Physiol (Oxf). 2014;210(4):768-89.
66. Hunter SK. The Relevance of Sex Differences in Performance Fatigability. Med Sci Sports Exerc. 2016;48(11):2247-56.
67. Enns DL, Tiidus PM. The influence of estrogen on skeletal muscle: sex matters. Sports Med. 2010;40(1):41-58.