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Comparison Between Eccentric vs. Concentric Muscle Actions On Hypertrophy: A Systematic Review and Meta-analysis

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Abstract

da Silva, LSL, Gonçalves, LdS, Alves Campos, PH, Benjamim, CJR, Tasinafo Júnior, MF, de Lima, LCR, Bueno Júnior, CR, and Alves, CPdL. Comparison between eccentric vs. concentric muscle actions on hypertrophy: a systematic review and meta-analysis. *J Strength Cond Res* 39(1): 115–134, 2025—Different physiological mechanisms of sarcomere activity during eccentric (ECC) and concentric (CON) muscle actions led to investigations into muscle hypertrophy outcomes, but conclusions remain elusive. We aimed to investigate the effects of ECC vs. CON muscle actions on muscle hypertrophy in apparently healthy adults through a systematic review with meta-analysis. The searches were conducted on EMBASE, MEDLINE, Cochrane Library, Web of Science, Scopus, and SPORTDiscus databases. To be eligible for inclusion, studies had to: (a) be randomized/controlled trials; (b) investigate the effects of CON vs. ECC resistance training programs in apparently healthy adults; (c) assess hypertrophy outcomes using direct imaging for cross-sectional area, muscle thickness, or muscle volume. A total of 15,778 studies were identified, and 26 (682 subjects included in the meta-analysis) met the inclusion criteria. The main findings indicated no statistical difference between ECC vs. CON on hypertrophy measurements (0.285 [95% CI: −0.131 to 0.701]; $p = 0.179$; I^2: 84.4%; GRADE: very low). Subgroup meta-analysis analyzing possible hypertrophy outcome moderators as age (18–59 years old and ≥60 years old) and weeks of intervention duration (>8 weeks) did not reveal differences between ECC vs. CON. Subgroup analysis revealed an effect favoring the ECC for the upper limb muscles ($p = 0.018$), ≤8 weeks of intervention ($p = 0.046$), muscle thickness assessment ($p = 0.0352$), and isokinetic contraction ($p = 0.0251$). Our findings suggest similar hypertrophy between ECC and CON muscle actions in apparently healthy adults. However, it appears that the muscles of the upper limbs, shorter interventions, hypertrophy assessment method, and the contraction type may favor ECC muscle actions.

Key Words: muscle growth, strength training, lengthening, shortening

Introduction

Eccentric (ECC) and concentric (CON) are 2 types of muscle actions that are prioritized in resistance training aiming to promote muscle hypertrophy (50). Eccentric muscle actions involve the active lengthening of sarcomeres, while CON muscle actions involve the shortening of sarcomeres to overcome external resistance (23,28). These distinct biomechanical and physiological characteristics of ECC and CON muscle actions have motivated researchers to investigate and compare their acute and chronic impact on muscle properties, especially in muscle hypertrophy (51,54).

The load used during both traditional and CON-based resistance training depends on the maximal CON strength (i.e., based on one repetition maximum [1RM]) (13). On the other hand, ECC-based training allows for the use of supramaximal loads (i.e., greater than CON 1RM), thus altering the mechanical stimuli applied to the muscle (37). Furthermore, ECC muscle actions demand less energy and muscle activation for similar torque production, making their application possible for individuals with various age and medical-related conditions (muscle atrophy, weakness, and physical dysfunction) (10,34,50). Therefore, it is speculated that the effects of ECC training are superior to CON training for hypertrophy (16,31).

Despite decades of research dedicated to elucidating the effects of ECC vs. CON muscle actions on muscle hypertrophy, conclusions remain elusive. For instance, a previous meta-analysis from Schoenfeld et al. (55) showed a very small but superior muscle growth effect for ECC- compared with CON-based resistance training. However, a small effect, methodological limitations (without certainty of evidence analysis), and variability in subject characteristics (young and older adults), training protocols, and hypertrophy measures (biopsy, DXA, ultrasound, etc.) in their meta-analysis limit the interpretation of the real-world application of ECC muscle actions to promote muscle growth. Therefore, we aimed to investigate the effects of

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ECC vs. CON muscle actions on muscle hypertrophy in apparently healthy adults through a systematic review with meta-analysis.

Methods

Experimental Approach to the Problem

This systematic review was included in the PROSPERO database (registration number: CRD42023452583). This systematic review was reported according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) (43) with an extension for Exercise, Rehabilitation, Sports Medicine, and Sports Science (PERSiST) (see Table 1, Supplemental Digital Content, http://links.lww.com/JSCR/A552) (1). The research questions were defined by the population, intervention, comparator, outcomes, and study design (PICOS) model following PRISMA guidelines, as follows: *Population:* Healthy adults; *Intervention:* Resistance training; *Comparator:* ECC vs. CON muscle actions; *Outcome:* Hypertrophy; *Study design:* longitudinal randomized trials employing either parallel or within-subject designs. The search was conducted in MEDLINE (through PubMed), EMBASE, Cochrane Library, Web of Science, SCOPUS, and SPORTDiscus. The meta-analysis compared ECC vs. CON muscle actions, using pre-post changes in hypertrophy, with subgroup analyses performed based on age, muscle location, training duration, regional hypertrophy, hypertrophy assessment, and contraction type, calculating effect size through the difference in pre-posttest changes divided by the pooled *SD*. We utilized robust variance estimation for the meta-analysis. The working model based on the correlated effects was selected for the variance weights.

Search Strategy and Study Selection

The search was conducted in 6 databases: MEDLINE (through PubMed), EMBASE, Cochrane Library, Web of Science, SCOPUS, and SPORTDiscus. We performed the searches on November 4, 2023, and an updated search on January 29, 2024. The search strategy was composed of the following keywords: "resistance training" or "resistance exercise" or "strength training" or "strength exercise" or "weightlifting" or "weight exercise" or "weight training" and "muscle action" or "concentric" or "eccentric" or "contraction" or "contractile properties" or "shortening" or "lengthening" and "muscle tissue" or "hypertrophy" or "muscle thickness" or "cross-sectional area" or "csa" or "fascicle length" or "pennation angle" or "muscle strength" or "strength." Detailed searches in each database are presented in Supplemental Digital Content (see Table 2, http://links.lww.com/JSCR/A552).

All obtained articles were exported to the Rayyan QCRI program (Qatar Computing Research Institute, Qatar) to exclude duplicates. The studies were screened in the Rayyan program by 2 independent reviewers (L.S.G. and L.S.L.S.), who read the titles and abstracts (phase 1). The eligibility stage (phase 2) was carried out by the same reviewers through reading the articles in full. The reviewers discussed the issue to find a consensus when disagreements occurred. Furthermore, the lists of references cited in the selected studies in phase 2 were analyzed to identify other eligible studies that could also be included in this review (snowball method).

Inclusion Criteria

To be included, the studies had to meet the following inclusion criteria: (a) population: apparently healthy adults (≥18 years); (b) training status: trained and untrained subjects; (c) study design: randomized clinical trial with different settings and at least 4 weeks of intervention. The following designs were considered: between-subject or crossover clinical trials and direct comparison between ECC vs. CON muscle actions; (d) hypertrophy measurements: cross-sectional area, muscle thickness, or muscle volume assessed by imaging methods (i.e., magnetic resonance imaging, computed tomography, or ultrasonography).

Data Extraction

The following information was extracted: authors (last name), year of publication, study design, sample size in each group, sex, age, intervention characteristics, hypertrophy assessment method, and main results. The data extraction performed by one reviewer was cross-validated by another (L.S.L.S. and L.S.G.).

We extracted the reporting of muscle hypertrophy presented in tables or graphs at baseline and the end of the resistance training intervention. The Web Plot Digitizer application was used to extract data presented in graphs. We adopted the criteria of extracting the delta (%) data and their respective *SD*. We also extracted the raw pre-post data to perform the delta change calculation. Values accessible with "standard error" or "confidence intervals" (CI) in the studies were converted to mean and *SD* for later calculation of the delta. To enhance the transparency of the meta-analysis, Supplemental Digital Content (see Table 3, http://links.lww.com/JSCR/A552) presents the information on where the data were extracted from each selected article.

Assessment of the Methodological Quality of the Studies

The methodological quality of the studies was assessed with the Tool for the assEssment of Study qualiTy and reporting in EXercise (TESTEX), a 15-point scale (5 points for study quality and 10 points for reporting) (60). The process was conducted by 2 authors (L.S.L.S. and L.S.G.). The Grades of Recommendation, Assessment, Development, and Evaluation (GRADE) Working Group was used to evaluate the level of evidence, study quality, and its limitations (39).

Qualitative Analysis

We performed a narrative synthesis to provide experimental detail for each included study. These results were plotted in tabular and graph form.

Meta-Analysis

The meta-analysis was calculated based on comparing ECC vs. CON muscle actions. The comparison of hypertrophy was assessed based on pre-post changes, considering the mean and *SD*s. We used the formula established by the Cochrane Handbook Chapter 6.5.2.8 (27) to calculate the *SD*. This formula comprises the *SD* of the change from pre- to posttest and the correlations between the pre- and post-measurements. Specifically, the formula follows:

$$SDchange = \sqrt{SDbaseline^2 + SDpost^2 - (2 \times Corr \times SDbaseline \times SDpost)}$$

We chose this formula because it provides a comprehensive approach to estimating the variability in change scores by incorporating both the individual variances at baseline and posttest, as well as the correlation between these measurements (49).

When the included studies did not report information about pre-posttest correlation, we fixed the correlation value at 0.5, to provide a conservative estimate of our outcomes (49). This assumption is commonly used in meta-analysis when the exact correlation is unknown, as it represents a moderate correlation between the pre- and posttest measurements, balancing the risk of over- or underestimating the variance.

In addition to calculating the *SD* change, we also calculated the pooled *SD*, which combines the *SD* changes of each group. The pooled *SD* was calculated using the following formula:

$$Pooled\,SD = \sqrt{\frac{(n_1 - 1) \times SD_1^2 + (n_2 - 1) \times SD_2^2}{n_1 + n_2 - 2}}$$

where n_1 and n_2 are the sample sizes of the 2 groups, and SD_1 and SD_2 are the *SD*s of the changes in each group. This method ensures that the pooled *SD* accurately reflects the variability within each group while accounting for the different sample sizes (35).

Critical targeted subgroup analyses were performed when a specific group was represented by at least 2 of the included studies. We performed subgroup analyses by considering: (a) different ages from studies, in this line, subgroup analyses were performed with young (18–59 years old) and older adults ($\geq$60 years old); (b) anatomic location of the muscles analyzed, where we subgroup analyzed lower and upper limb muscles; (c) training duration, where subgroups were defined for studies with $\leq$8 weeks of intervention and $>$8 weeks of intervention; (d) regional hypertrophy, where we subgroup analyzed proximal, middle, and distal sites; (e) hypertrophy assessment, where subgroups were defined for muscle thickness and cross-sectional area; (f) contraction type, where subgroups were defined for isokinetic, isotonic, isotonic with same load schemes, and isotonic with accentuated ECC (ECC actions with supramaximal [$>$1RM] loads).

We calculated the effect size by taking the difference in pre-posttest changes between the ECC and CON groups and dividing it by the pooled *SD* (27). The standard error of the effect size was calculated using the formula proposed by the What Works Clearinghouse Handbook version 4.1 (67).

We utilized robust variance estimation for the meta-analysis. The working model based on the correlated effects was selected for the variance weights. We applied Egger's test with a visual inspection of funnel plots to assess the potential risk of publication bias. This meta-analysis considered random models. Sensitivity analyses and subgroup analyses were conducted when heterogeneity was present. All analyses were performed using R (v. 4.4.1) with the "robumeta" and "metafor" packages, and the forest and funnel plots were generated using the "ggplot2" package.

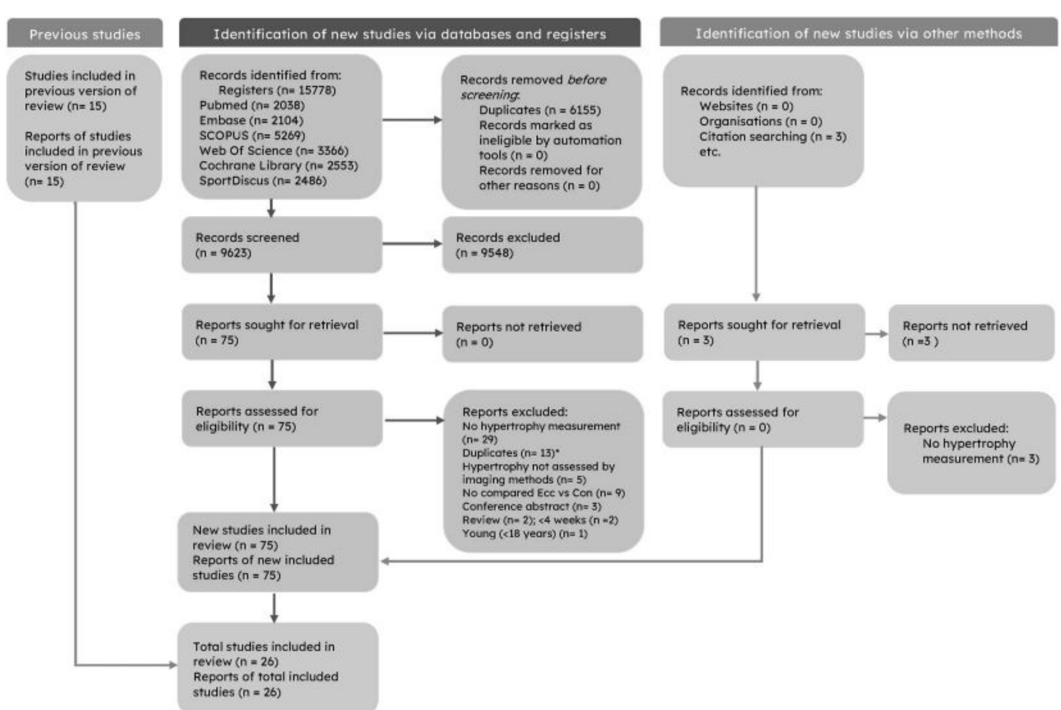

Figure 1. jPRISMA flowchart. PRISMA = Preferred Reporting Items for Systematic Reviews and Meta-Analyses.

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Table 1

Description of the characteristics of included studies by author and year, subjects, training status, study design, resistance training duration, training mode, hypertrophy measurement, and main findings.*

Study	Subjects	Training status	Study design	RT duration (wk)	Training mode	Hypertrophy measurement	Main findings
Baptista et al. (2)	23 older male subjects	n.i	Intrasubject	12	The training was carried out unilaterally in a knee extensor machine twice a week. In the ECC leg, they performed 2 sets of 10 eccentrical repetitions with 80% of 5RM within 3 s, while in the CON leg, they performed the same number of sets, repetitions, and cadence. The range of motion was 90° of knee flexion to full extension. The rest interval between sets was 1 min. Assistants move the arm machine for subjects only performing the specific contraction.	Muscle thickness by ultrasound method on *vastus lateralis* at 50% distance between the anterior superior iliac spine and the lateral femur epicondyle.	Both training regiments promote similar changes in MT.
Benford et al. (3)	16 healthy men	Physically active (>60 min per day, minimum 3 d per week)	Intrasubject	5	Training was carried out unilaterally in an isokinetic dynamometer for knee extension twice weekly. Both legs performed 4 sets of 8 continuous maximal knee extension repetitions at $30°\cdot s^{-1}$. The range of motion was maximal for each subject. The rest interval between sets is 1 min and a minimum of 48 h between sessions. The return of the machine arm was performed passively for specific contractions.	Muscle volume and regional ACSA by ultrasound method of vastus lateralis. The measures of ACSA were performed at 50 and 70% of muscle length as mid-point and distal point, respectively.	Both training regimens showed gains in muscle volume without differences between them, while they improved the measures of ACSA, but the CON leg showed better changes than the ECC leg at the mid-point, while the ECC leg showed greater changes at the distal point.
Blazevich et al. (4)	33 adults	Recreationally active, had not performed RT	Randomized trial	10	Training was carried out in an isokinetic dynamometer for knee extension 3 times per week. The number of sets increased from 4 to 6 sets across the intervention, and the intensity ranged from 50 to 100% of the maximum. The subjects were instructed to move the machine arm "as fast as hard possible," despite the machine was set to move at $30°\cdot s^{-1}$. CON group initiated your sets from maximal knee flexion to maximal knee extension followed by a small knee flexion for the next repetition, while the ECC group initiated the sets with a small knee extension before	Muscle volume and anatomic regional (proximal and distal) and physiological CSA by MRI of whole quadriceps and your muscles. Muscle thickness of vastus lateralis and vastus medialis by ultrasound.	Both training regimen improves increases in muscle volume of the quadriceps and vastus lateralis and medialis. Muscle thickness of vastus lateralis and medialis increases similarly between the training programs.

Table 1

Description of the characteristics of included studies by author and year, subjects, training status, study design, resistance training duration, training mode, hypertrophy measurement, and main findings.* *(Continued)*

Study	Subjects	Training status	Study design	RT duration (wk)	Training mode	Hypertrophy measurement	Main findings
					maximally extending the joint resisting to the arm machine downward. Rest between sets was 1 min, and the sessions were separated at least 1 d.		
Buker et al. (7)	60 men	Inactive	RCT	8	Training was performed with unilateral squat exercises 7 days per week. They performed 3 sets of 10 repetitions in moderate intensity. In addition, groups performed exercises on a 25° decline board. The CON group initiated the sets with the knee in 70° flexion and performed an effort to fully extend this joint, returning to the start point with the nondominant limb, while the ECC group initiated the sets with the knee fully extended and performed an effort to break the move of the joint to achieve 70° of flexion, returning to the initial point with a nondominant limb. The rest interval between sets was 2 min.	Quadriceps, rectus femoris, and vastus lateralis muscle thickness by ultrasound. Rectus femoris and vastus lateralis measures were obtained at the mid-point of tight (lateral condyle of the femur to the central palpable point of the greater trochanter). Quadriceps measure was obtained between the proximal musculotendinous part and the most proximal part of the patellar insertion.	Both interventions improved the muscle measures, but the ECC group showed a greater effect of percentage changes.
Cadore et al. (8)	22 healthy adults	Physically active, with RT experience but without engagement in training in the last year	RCT	6	Training was carried out in an isokinetic from knee extension or flexion twice weekly. They performed 2–5 sets of 10–12 repetitions along the intervention. The angular velocity was $60°\cdot s^{-1}$, and the range of motion traveled from 0° to 90°. The subjects were advised to perform maximal effort during all of the sets.	Muscle thickness by ultrasound method on vastus lateralis was taken midway between the lateral condyle of the femur and the greater trochanter.	Both groups improve muscle size, without differences between them.
Coratella et al. (12)	60 healthy women of a university-based population	Not engaged in the RT program in the last 6 mo, but practiced 1–3 sports	RCT	8	Training was carried out in a knee extension machine unilaterally, with 1 session in the first week and 2 in the remaining weeks. Volume load was matched between groups. The CON group performed 6 sets of 7 repetitions at 85% of 1RM, while the ECC group performed 5 sets of 6 repetitions at 120% of 1RM. Each set was	Muscle thickness by ultrasound method on vastus lateralis at the mid-point between the greater trochanter and the lateral condyle of the femur.	Both groups improve muscle size, without differences between them.

Table 1

Description of the characteristics of included studies by author and year, subjects, training status, study design, resistance training duration, training mode, hypertrophy measurement, and main findings.* *(Continued)*

Study	Subjects	Training status	Study design	RT duration (wk)	Training mode	Hypertrophy measurement	Main findings
					separated by 3 min of rest and the sessions by at least 3 d. Assistants move the arm machine for subjects only performing the specific contraction.		
Duhig et al. (15)	30 men	Recreationally active	Randomized trial	5	The CON group performed the prone leg curl machine within 3 s with only the concentric phase, starting at knee extension and finishing with knee flexion (90°), and the ECC group performed the Nordic hamstring exercise with only the lowering phase (eccentric phase) with their arms at the chest, initiating the set with the hip extended lowered your body slowly as possible into a prone position. In the ECC group, overload occurs initiating with only body mass and adding external load when the subjects were able to stop the movement at 10° from knee extension. The frequency was 2 sessions per week for the first 4 wk, but only 1 session in the last week. The groups performed 2–5 sets of 6 repetitions. The sessions were separated by 48 h.	Muscle thickness by ultrasound method on biceps femoris long head at distance between the superficial and intermediate aponeuroses of the muscle.	Both groups improve muscle size, without differences between them.
Farthing et al. (17)	34 young adults	Little strength training experience	RCT	8	Groups performed elbow flexion in an isokinetic dynamometer 3 times per week. The program consisted of 2–6 sets of 8 maximal repetitions. Groups were different in cadence. The CON and ECC group who trained with fast velocity performed the repetitions in a [180 s^{-1} (3.14 rad s^{-1})]. On the other hand, the CON and ECC group who trained with slow velocity performed the repetitions in a [30 s^{-1}(0.52 rad s^{-1})].	Muscle thickness by ultrasound method on elbow flexors. The mid-point was measured at two-thirds of the distance down from the acromion process to the olecranon process, with the proximal and distal point 3 cm above and below, respectively.	The ECC arm showed greater proximal changes than the CON arm, despite the velocity. The ECC showed greater changes in the mid-site and distal site compared with CON, despite the velocity. The ECC promoted better changes than the CON in the combined site.
Farup et al. (18)	22 healthy young men	Recreationally active	Intrasubject	12	Training was carried out on a leg-extension machine 3 times per week. The volume and intensity were	Quadriceps CSA by MRI in distal, middle, and proximal points by MRI in 1/3, 1/2, and 2/3 of the femur length,	Both training regiments promote similar changes in muscle size.

Table 1

Description of the characteristics of included studies by author and year, subjects, training status, study design, resistance training duration, training mode, hypertrophy measurement, and main findings.* *(Continued)*

Study	Subjects	Training status	Study design	RT duration (wk)	Training mode	Hypertrophy measurement	Main findings
					progressively increased and ranged, respectively, from 6 to 12 sets and 6 to 15 RM. The load of the ECC leg was 120% of the CON leg load. Each repetition was performed in 2 s of duration, and the recovery time between sets was 2 min. The CON leg extended performed the concentric phase lifting a load and the eccentric phase without a load. The ECC leg performed the eccentric phase against a load after performing the concentric phase without a load.	respectively. But, they analyzed only the mid-point and ∑CSA (the sum between proximal, middle, and distal points).	
Franchi et al. (19)	12 young men	Not engaged in the RT program	Randomized trial	10	Training was carried out 3 times per week unilaterally in a leg-press machine modified to enable only ECC or CON contraction. The intensity was 80% of 1RMcon for the CON group and 80%1RMecc for the ECC group. They performed 4 sets of 8–10 repetitions. The CON group performed the contraction in 2 s, while the ECC group held it for 3 s on each repetition. The rest interval was 1 min.	They used MRI to assess the regionally vastus lateralis CSA (proximal, middle, and distal) and VL volume. Proximal sites were when the muscle was visible starting from the hip/knee joint. Mid-point around the peak of CSA.	The vastus lateralis change in the mid-point was greater for the CON group, while in the distal the site was greater for the ECC group. Both training regimens lead to similar increases in vastus lateralis volume.
Higbie et al. (26)	60 women in good health and free of right knee pathology	Unfamiliar with the Kin-Com dynamometer and without engagement in the RT program in the last 6 mo	RCT	10	Training was carried out in a Kin-Com dynamometer for knee extension according to the group that was assigned 3 times per week. They performed 3 sets of 10 repetitions with 3 min of rest between sets. The speed was controlled by a Kin-Com dynamometer.	CSA of quadriceps at 20, 30, 40, 50, 60, 70, and 80% of the femur length by MRI.	Both groups changed the quadriceps CSA in all sites and the sum of them. At the 40, 50, 60, and 70% levels and in the sum of the 7 levels, the changes were greater in the ECC group.
Jones et al. (29)	12 healthy adults	Without previous participation in the RT program	RCT	12	Training was carried out in a variable-resistance leg-extension machine 3 times per week with 4 sets of 6 repetitions. The weight was ~80% 1RM, and the weight of the ECC leg was ~145% of the CON leg weight. The knee angle ranges from 45° to 180°. The duration of contraction was 2–3 s,	Quadriceps CSA was measured by CT midway between the greater trochanter and tibial femoral joint.	Both training regiments increase muscle size, without differences between them.

Table 1

Description of the characteristics of included studies by author and year, subjects, training status, study design, resistance training duration, training mode, hypertrophy measurement, and main findings.* *(Continued)*

Study	Subjects	Training status	Study design	RT duration (wk)	Training mode	Hypertrophy measurement	Main findings
					and the 6 repetitions were carried out within 30 s. One minute of rest was given between sets. The repetition was performed with the help of a researcher.		
Häkkinen et al. (21)	23 young women	Some experience in strength training, especially the bench press exercise for only their own recreational (but not for competitive or athletic purposes)	Randomized trial	10	Training was carried out in an isokinetic bench press twice weekly. The number of sets ranged from 2 to 4 sets, and the reps ranged from 3 to 4. At the start of each set, subjects first produced their maximal isometric force. Depending on their group, they continued to produce their maximal force throughout the following ECC or CON action depending on their group. The velocity used in 2 groups is 0.2 $m\cdot s^{-1}$. The rest between repetitions was 2 s. After isokinetics, they performed under supervision exercises at moderate load and low volume training for the legs and trunk muscles to maintain the strength and mass of these muscle groups.	Anatomical CSA of triceps brachii (long and lateral head) and muscle thickness of pectoralis major by ultrasound. The triceps measure the mid-point between the medial epicondyle and the acromion. The sum of the triceps and pectoralis also was calculated.	The CSA of the triceps brachii long head increased in both groups with greater changes for the ECC group, while for the lateral head, the increase was similar for both groups. The size of the pectoralis major increases for both groups. The sum of muscles increases similarly between groups, without difference between groups.
Kidgel et al. (30)	27 young adults	Had not participated in strength training for at least 12 mo	RCT	4	Training was performed in an isokinetic dynamometer 3 times per week on nonconsecutive days, performed by wrist flexors. Volume was 4 sets of 6–8 maximal repetitions with 3 min of rest. Repetitions were performed at $20^{\circ}\cdot s^{-1}$.	Muscle thickness of wrist flexors was measured by ultrasound at 5 cm distal to the olecranon.	The interventions did not promote effects on muscle size.
Kim et al. (32)	14 adults	Recreationally active	Randomized trial	8	Training was carried out in an isokinetic dynamometer performing shoulder abduction in a scapular plane with the right arm. Volume and intensity ranged along the training, varying to 4–6 sets and 6–8 repetitions at $60^{\circ}\cdot s^{-1}$ in a maximal effort. One minute of rest was provided between sets for both training regiments. Each subject was securely strapped to	Three different images of supraspinatus were obtained by ultrasound: relaxed 0° abduction, relaxed 60° abduction (arm supported by a pillow), and contracted (isometric) 60° abduction. Sagittal scans taken at the mid-point of the muscle belly were used to capture muscle thickness.	Both groups increase muscle thickness, without difference between them.

Table 1

Description of the characteristics of included studies by author and year, subjects, training status, study design, resistance training duration, training mode, hypertrophy measurement, and main findings.* *(Continued)*

Study	Subjects	Training status	Study design	RT duration (wk)	Training mode	Hypertrophy measurement	Main findings
					avoid compensatory movements.		
Maeo et al. (36)	12 healthy men	Physically active, but not competitive athletes or engaged in an RT program in the past 12 mo	Intrasubject	10	Training was carried out in an isokinetic dynamometer for knee extension twice weekly. The volume increases from 3 to 6 sets of 10 repetitions at 180°·s^{-1}. Eight-second rests were taken in between repetitions, during which the leg was passively (automatically) returned to the start position by the dynamometer at 20°·s^{-1} (~5 s) followed by a static rest (~3 s). Two minutes of rest were taken in between sets, during which subjects rested statically with the knee joint angle at approximately the middle of the range. The leg that initiated the training session was switched between sessions, and the total work volume per set and leg was matched.	The ACSA and whole muscle volume of the quadriceps were assessed by MRI.	They observed a tendency of increases in ACSA for ECC compared with CON from pre- to posttraining. The muscle volume increases only in ECC training and the %Δ muscle volume was greater for this contraction mode.
Moore et al. (40)	9 healthy young men	Recreationally active, without no more than 4 h per week of engagement on physical active or RT for the upper body in the past 6 mo	Intrasubject	9	Training was performed in an isokinetic dynamometer twice weekly with elbow flexion. The ECC arm resisted the machine at an angular velocity of 0.79 rad·s^{-1}, while the elbow angle progressed from 100° to 10°. The CON arm performed an equivalent volume of external work—the number of repetitions was greater because of the difference in strength between contraction modes. The volume increases from 2 to 6 sets along the intervention from the ECC arm with 10 repetitions. In the final week, the ECC arm performed only 2 sets to avoid residual fatigue for the study measures. Sessions were separated for at least 2 d.	CSA of biceps brachii at half the distance between the antecubital and axilla areas of the upper arm by hQCT.	Both training regiments increase muscle size, without differences between them.
Ünlu et al. (65)	42 male college students	Recreationally active, with previous experience in RT, but no engagement in the last 12 mo	Randomized trial	12	Subjects performed the exercise in a knee extension machine in 3 high-intensity RT sessions	Muscle volume of quadriceps by MRI and the images were obtained from the great trochanter	Both training regiments increase muscle size, without differences between them.

Table 1

Description of the characteristics of included studies by author and year, subjects, training status, study design, resistance training duration, training mode, hypertrophy measurement, and main findings.* *(Continued)*

Study	Subjects	Training status	Study design	RT duration (wk)	Training mode	Hypertrophy measurement	Main findings
					per week on nonconsecutive days. The volume was 3 sets to failure. The groups were different in the velocity of movement, with slow CON and ECC training with $30^{\circ}\cdot s^{-1}$ and fast CON and ECC with $180^{\circ}\cdot s^{-1}$. Assistants moved the arm machine, while subjects only performed the specific contraction.	to the proximal end of the patella.	
Quílan et al. (47)	37 healthy young and older men	Recreationally active	Randomized trial	8	The training was performed 3 times per week in a specialized leg-press machine. Each group trained with 60% 1RM of your maximal weight in their specific contraction mode. The program consisted of 4 sets of 15 repetitions, and the duration of each repetition was 3 s in the specific contraction mode. In week 5, the exercise became performed unilaterally, in the same training structure—the intensity was 60% of unilateral 1RM of the contraction mode assigned.	Quadriceps volume was assessed by MRI.	All training regiments increase muscle volume. In the older men, the ECC promoted greater responses in %Δ muscle volume to CON.
Ruas et al. (50)	40 healthy men	Participation in sports and recreational activities, but no engagement in RT or endurance training in the last 3 mo before the study intervention	RCT respectively to Q/H: CON/CON ECC/ECC CON/ECC	6	Training was performed with nondominant limb in a knee extension/flexion isokinetic dynamometer, twice weekly with 48 h of the interval between them. The CON/CON group started the first week of training by performing 1 set of 10 maximal repetitions at $210^{\circ}\cdot s^{-1}$ for quadriceps and hamstrings. The ECC/ECC group started the first week of training by performing 1 set of 10 maximal repetitions at $60^{\circ}\cdot s^{-1}$ for quadriceps and hamstrings. The CON/ECC group started the first week of training by performing 1 set of 10 maximal CON repetitions at $210^{\circ}\cdot s^{-1}$ for quadriceps and 1 set of 10 maximal ECC	Muscle thickness of rectus femoris, vastus lateralis, vastus intermedius, vastus medialis, biceps femoris long head, semitendinosus, and semimembranosus was assessed by ultrasound. The vastus lateralis MT was assessed in 30% of the distance between the greater trochanter and the lateral condyle of the femur, while the other muscles MT was assessed at 50% of the same distance. The MT of the quadriceps is the average of our muscles and for hamstrings the same.	All training group increases muscle size.

Table 1

Description of the characteristics of included studies by author and year, subjects, training status, study design, resistance training duration, training mode, hypertrophy measurement, and main findings.* *(Continued)*

Study	Subjects	Training status	Study design	RT duration (wk)	Training mode	Hypertrophy measurement	Main findings
					repetitions at 60°·s^{-1} for hamstrings. The training intensity was increased every week by increasing the isokinetic angular velocity for eccentric and decreasing it for concentric in 30°·s^{-1} increments. In addition, the training volume was increased by adding 1 set every week. They were verbally encouraged to perform the maximal effort within the range of motion predetermined (0° = full extension to 90° of knee flexion).		
Sato et al. (53)	31 healthy university students	Not performed RT or competitive sports in the past 6 mo	RCT	5	The training was carried out twice weekly in a preacher curl (45° of shoulder flexion). The number of sets was 6 in each session with 5 repetitions, and the load increased from 10 to 100% of the MVIC torque of the trained arm. In the ECC group, the ROM ranged from 90° of elbow flexion to 0°, while in the CON group, the move initiated in 5° of elbow flexion to 90°. The rest between repetitions was 15 s and 2 min between sets. When the subjects had difficulty controlling the dumbbell in higher loads (>80% MVIC torque), an assistant helped them in the hardest moments of the range.	Muscle thickness of biceps brachii plus brachial was assessed by ultrasound at 60% of the distance between the lateral epicondyle of the humerus from the acromion.	Only ECC intervention showed increases in muscle size.
Sato et al. (54)	53 healthy university students	Not performed RT in the past 6 mo	RCT	5	Training was performed by the dominant arm in a preacher curl, with the shoulder in 45° flexion and the forearm supinated to hold a dumbbell. The intensity was progressively increased along the intervention from 10 to 100% of MVC-ISO torque at 50°. Each session consisted of 3 sets of 10 repetitions of the specific contraction, with the repetition tempo controlled by a metronome (2 s for each	A total of biceps brachii and brachialis MT were assessed by ultrasound at 50, 60 and 70% of the distance between the lateral epicondyle of the humerus from the acromion.	Only ECC intervention showed increases in muscle size.

Table 1

Description of the characteristics of included studies by author and year, subjects, training status, study design, resistance training duration, training mode, hypertrophy measurement, and main findings.* *(Continued)*

Study	Subjects	Training status	Study design	RT duration (wk)	Training mode	Hypertrophy measurement	Main findings
					repetition). After each repetition, an assistant moved the weight to the initial position (0° for CON and 50° for ECC) and the range of motion was between 0° and 50° of elbow flexion. When the subjects had difficulty controlling the dumbbell at higher loads (>80% MVIC torque), an assistant helped them during the hardest moments of the range. The rest interval between sets was 3 min.		
Seger et al. (56)	10 male students of physical education	Moderately trained. None of them participated in the RT program before	RCT	20	Training was carried out in an isokinetic dynamometer 3 times per week. During the first 10 wk, the left leg was trained, and in the remaining weeks, the right leg was trained. Each session consisted of 4 sets of 10 maximal knee extensor contractions. Subjects were instructed to exert maximally across the whole range of motion (85°). The velocity was $90°\cdot s^{-1}$, so each contraction lasted 1 s with 1 s of passive recovery positioning for the next contraction. The rest interval between sets was 2 min.	CSA of quadriceps was obtained by MRI in half femur length (mid-point) and the other 12 cm distally from that point (distal point).	Increases were found to the ECC leg only in the distal point.
Shibata et al. (58)	22 university male soccer player	Not engaged in RT program after intervention	Randomized trial CON2s/ECC2s CON2s/ECC4s	6	They performed parallel back-squat with intensity of 75% 1RM in 3 sets until momentary failure. The duration tempo of repetition in each group was controlled by a metronome, with one group performing each phase in 2 s, and another group with CON in 2 s and ECC in 4 s. The rest interval was 3 min.	CSA of the right thigh (dominant for all subjects) was measured by MRI at 30, 50 and 70% of the distance between the greater trochanter upper end and the lateral condyle of the femur.	An increase in all regions was observed, with the greatest changes in CSA70% than other regions. No differences were observed between groups.
Timmins et al. (63)	28 men	Recreationally active	Randomized trial	6	Training was carried out in an isokinetic dynamometer with maximal unilateral knee flexion exercise. The sessions were initially twice weekly and increased to 3 times per week from the second week. Training volume	Muscle thickness of the biceps femoris long head was determined by ultrasound at the halfway point between the ischial tuberosity and the popliteal crease, along the line of the muscle.	No changes in muscle size were observed.

Table 1

Description of the characteristics of included studies by author and year, subjects, training status, study design, resistance training duration, training mode, hypertrophy measurement, and main findings.* *(Continued)*

Study	Subjects	Training status	Study design	RT duration (wk)	Training mode	Hypertrophy measurement	Main findings
					increased from 4 to 6 sets and the repetitions per set from 6 to 8 across interventions. The velocity of repetitions was $180^\circ \cdot s^{-1}$. The CON group initiated each set with the knee fully extended, making a maximal effort to flex it to 90°. The ECC group, however, started with the knee flexed at 90° and aimed to extend it fully. The rest interval between sets was 30 s, and the sessions were separated by 48 h. The assistants move the isokinetic arm to the initial position in each group for the subjects only performing their assigned contraction mode.		
Vikne et al. (66)	17 healthy men	Resistance-trained (within the sample some were recreationally RT practitioners and others were athletes on track and field or powerlifting)	Randomized trial	12	Training was carried out 2–3 times per week with a flexion elbow exercise with the shoulder flexed. The volume ranged from 3 to 5, and the load ranged from maximal (4–8 RM) or medium loads (85% of maximal loads). The CON group started the set at an angle of 160° with an end position of approximately 70° in the elbow joint, while the ECC group started at 70° and ended at 160° of this joint's range. The rest intervals range from 3 to 6 min. Assistants move the weight to ensure that subjects perform only their assigned contraction mode.	ACSA of elbow flexors was assessed by CT. Four images of these muscles were obtained at 1, 2, 3, and four-eighths of the humerus length, and the mean of them was taken to mean flexor area.	Only ECC intervention showed increases in muscle size for all site measures and in the mean flexor area.

*RCT = randomized controlled trial; CSA = cross-sectional area; ACSA = anatomical cross-sectional area; MT = muscle thickness; CT = computerized tomography; hQCT = high-resolution peripheral quantitative computerized tomography; RT = resistance training; MVIC = maximal voluntary isometric contraction; RM = repetition maximum.

Results

Figure 1 presents details of the search process and selection of articles in the PRISMA flowchart. Our initial search identified 15,778 articles, and after the removal of duplicates ($n = 6{,}155$), 9,623 articles were screened by title and abstract. For phase 2, the studies included in the meta-analysis of Schoenfeld et al. (55) ($n = 15$) were included. In this sense, 93 articles were considered eligible for full-text reading, and 26 (2–4,7,8,12,15,17–19,21,26,29,30,32,36,40,47,49,52,53,55,57,62,64,65) were included in the systematic review and meta-analysis.

Narrative Synthesis of the Studies

Table 1 shows the data (subjects, training status, study design, resistance training duration, training mode, hypertrophy measurement, and findings) extracted from each of the included articles. The total number of subjects included in the studies was 749. Fifteen of the studies included only men (57.7%) (2,3,7,15,18,19,36,40,47,49,55,57,62,64,65), 3 studies (11.5%) included only women (12,21,26) and 8 (30.7%) included both sexes (4,8,30,32,52,53). Only 2 studies (7.7%) included older adults (2,47). Regarding training status, one study (3.8%) did not provide information (2) and another (3.8%) used inactive subjects (7). Vikne et al. (66) studied a resistance-trained sample that included recreational resistance training practitioners and athletes in track and field or powerlifting. The other studies included recreationally active subjects without previous practice in resistance training before the intervention or in the previous few months.

Regarding training protocols, 13 studies (50%) used an isokinetic dynamometer (3,4,8,17,21,26,30,32,36,40,49,55,62), 10 used machines and exercises common in clinical settings (e.g., leg-extension machine, squat, etc.) (2,7,12,15,18,52,53,57,64,65), and 3 studies used specific machines or variable-resistance training (19,29,47). Eighteen (69.2%) studies involved lower-limb training (2–4,7,8,12,15,18,19,26,29,36,47,49,55,57,62,64) and the others upper limb (17,21,30,32,40,52,53,65). Eight studies (30.7%) performed the training of lower limbs in an isokinetic dynamometer (3,4,8,26,36,49,55,62). Seven studies used exercises/machines common in clinical settings, such as knee extensor chair and leg press 45° (2,7,12,15,18,57,64). Three studies used specialized ECC machines (19,29,47).

Training frequency ranged from 1 to 7 sessions per week between studies and the duration of the interventions ranged from 4 to 20 weeks, while the volume ranged from 2 to 12 sets per session. The intensity in studies using an isokinetic dynamometer was determined by angular velocities of $30°\cdot s^{-1}$ to $180°\cdot s^{-1}$, while other studies prescribed this variable by repetition zone, percentage of maximal repetition, or MVIC. Two studies equated training by work volume on the isokinetic dynamometer, one investigating elbow extension (36) and the other, elbow flexion (40).

Fifteen studies used ultrasound to assess muscle size (2–4,7,8,12,15,17,21,30,32,49,52,53,62) of which 12 studies evaluated muscle thickness and 3 cross-sectional area (CSA). Nine studies used magnetic resonance imaging (4,18,19,26,36,47,55,57,64) and 3 used computerized tomography (29,40,65). One study used ultrasound and magnetic resonance imaging to assess lower-limb hypertrophy (4). The most frequently assessed body segment was the lower limbs (2–4,7,8,12,15,18,19,26,29,36,47,49,55,57,62,64). Ten included studies performed regional measurements of muscle size (3,4,17–19,26,54,56,58,66), with 7 performing regional measures of lower limbs (3,4,18,19,26,56,58) and 3 in upper limbs (specifically elbow flexors) (17,54,66).

Regarding the training outcomes, 13 studies found no statistical difference between muscle actions (2,4,8,12,15,18,29,32,40,47,50,58,65), 4 reported regional differences between muscle actions (3,19,21,26), 8 showed greater responses for ECC (7,17,36,47,53,54,56,66), and 2 did not find any training effects (30,63). Among the studies that found advantages for ECC training, the study of Quílan et al. (47) found no difference between muscle actions in male adults, but greater effects of ECC training in older men.

Studies noted different regional changes in muscle size between eccentric and concentric muscle actions in both lower and upper limbs. The studies of Benford et al. (3) and Franchi et al. (19) analyzed lower limbs and reported no difference between the efficacy of different muscle actions in increasing muscle volume, with CON showing a greater effect than ECC at mid-distance, while ECC showed greater changes at the distal region of *vastus lateralis* anatomical CSA. Higbie et al. (26) found that both muscle actions promoted increases in muscle size, with greater increases in all measure sites and the sum of them for ECC. On the other hand, Häkkinen et al. (21) showed similar changes in muscle size of the pectoralis major and the lateral head of the triceps brachii for both contraction modes, while the long head of the triceps brachii showed a greater increase following ECC training.

Analysis of the Methodological Quality

The TESTEX analysis is reported in Table 2. Within these studies, 1 scored 11 points (8), 6 scored 10 points (2,12,15,21,63,66), 7 scored 9 points (18,19,32,36,40,58,65), while 11 studies obtained 8 points (3,4,17,26,29,30,47,50,53,54,56) and 1 study scored 5 points (7). None of the studies scored in *Randomization specified* and in *Activity monitoring in control groups*. Conversely, all studies scored in the *Relative exercise intensity remained constant,* and *Exercise volume and energy expenditure* criteria referring to training protocols.

Comparison Between Eccentric vs. Concentric Training for Hypertrophy

Figure 2 shows the meta-analysis comparing ECC vs. CON for hypertrophy. The main analysis suggests no statistical difference between muscle actions, with large heterogeneity (ES: 0.471 [95% CI: −0.000979 to 0.944]; $p = 0.051$; I^2: 83.2%; GRADE: ⊕⊕○○ Low). In the subgroup analysis (Table 3), the upper limb muscles ($p = 0.018$), ≤8 weeks of intervention ($p = 0.046$), muscle thickness assessment ($p = 0.0352$), and isokinetic contraction ($p = 0.0251$) favored the ECC training, with low certainty of evidence (GRADE: ⊕⊕○○ Low).

The sensitivity analysis is reported in the Supplemental Digital Content (see Table 3, http://links.lww.com/JSCR/A552). The statistical differences for hypertrophy occurred when removing the studies of Blazevich et al. (4), Coratella et al. (12), Farup et al. (18), Franchi et al. (19), Jones et al. (29), Shibata et al. (58), Timmins et al. (63), and Ünlu et al. (65) ($p < 0.05$), which favors ECC training. The other analysis remained without a statistical difference ($p > 0.05$).

Publication Bias

Figure 3 shows the funnel plot regarding the risk of publication bias. Egger's test reveals funnel-plot asymmetry ($z = 2.841$; $p = 0.005$), meaning there was a tendency for bias in the results provided by the meta-analysis.

Discussion

We investigated the effects of ECC vs. CON muscle actions on muscle hypertrophy in apparently healthy adults. Our main findings are as follows: (a) There was similar hypertrophy between ECC vs. CON; (b) Subgroup analyses revealed that upper limb muscles, ≤8 weeks of intervention, muscle thickness assessment, and isokinetic contraction benefit from an advantage conferred by ECC training; (c) Other subgroups (age, lower-limb muscles, >12 weeks of intervention, cross-sectional area

Table 2

Tool for the assEssment of Study qualiTy and reporting in EXercise (TESTEX) methodological quality of the studies included.

Study	Eligibility criteria specified	Randomization specified	Allocation concealment	Groups similar at baseline	Blinding of assessor (for at least one key outcome)	Outcome measures assessed in 85% of patients	Intention-to-treat analysis	Between-group statistical comparisons reported	Point measures and measures of variability for all reported outcome measures	Activity monitoring in control groups	Relative exercise intensity remained constant	Exercise volume and energy expenditure	Overall TESTEX score
Baptista et al. (2)	Yes	Unclear	Unclear	Yes	Yes	Yes (1)	Yes	Yes	Yes	No	Yes	Yes	10/15
Benford et al. (3)	Yes	Unclear	Unclear	Yes	No	Yes (1)	Yes	Yes	Yes	No	Yes	Yes	8/15
Blazevich et al. (4)	Yes	Unclear	Unclear	Yes	Unclear	Yes (1)	Yes	Yes	Yes	No	Yes	Yes	8/15
Buker et al. (7)	Yes	Unclear	Unclear	No	No	No	No	Yes	Yes	Unclear	Yes	Yes	5/15
Cadore et al. (8)	Yes	Unclear	Yes	Yes	Yes	Yes (2)	Yes	Yes	Yes	Unclear	Yes	Yes	11/15
Coratella et al. (12)	Yes	Unclear	Unclear	Yes	Unclear	Yes (2)	Yes	Yes	Yes	Unclear	Yes	Yes	10/15
Duhig et al. (15)	Yes	Unclear	Unclear	Yes	Yes	Yes (2)	Yes	Yes	Yes	No	Yes	Yes	10/15
Farthing et al. (17)	Yes	Unclear	Unclear	Yes	Unclear	Yes (1)	Yes	Yes	Yes	Unclear	Yes	Yes	8/15
Farup et al. (18)	Yes	Unclear	Unclear	Yes	Yes	Yes (1)	Yes	Yes	Yes	No	Yes	Yes	9/15
Franchi et al. (19)	Yes	Unclear	Yes	Yes	Unclear	Yes (1)	Yes	Yes	Yes	No	Yes	Yes	9/15
Higbie et al. (26)	Yes	Unclear	Unclear	Yes	Unclear	Yes (1)	Yes	Yes	Yes	No	Yes	Yes	8/15
Jones et al. (29)	Yes	Unclear	Unclear	Yes	Unclear	Yes (1)	Yes	Yes	Yes	Unclear	Yes	Yes	8/15
Häkkinen et al. (21)	Yes	Unclear	Yes	Yes	Yes	Yes (1)	Yes	Yes	Yes	No	Yes	Yes	10/15
Kidgel et al. (30)	Yes	Unclear	Unclear	Yes	Unclear	Yes (1)	Yes	Yes	Yes	No	Yes	Yes	8/15
Kim et al. (32)	Yes	Unclear	Unclear	Yes	Yes	Yes (1)	Yes	Yes	Yes	No	Yes	Yes	9/15
Maeo et al. (36)	Yes	Unclear	No	Yes	Yes	Yes (1)	Yes	Yes	Yes	No	Yes	Yes	9/15
Moore et al. (40)	Yes	Unclear	Unclear	Yes	Yes	Yes (1)	Yes	Yes	Yes	No	Yes	Yes	9/15
Ünlu et al. (65)	Yes	Unclear	No	Yes	Yes	Yes (1)	Yes	Yes	Yes	Unclear	Yes	Yes	9/15
Quílan et al. (47)	Yes	Unclear	No	Yes	Unclear	Yes (1)	Yes	Yes	Yes	No	Yes	Yes	8/15
Ruas et al. (50)	Yes	Unclear	No	Yes	Unclear	Yes (1)	Yes	Yes	Yes	No	Yes	Yes	8/15

Table 2

Tool for the assEssment of Study qualiTy and reporting in EXercise (TESTEX) methodological quality of the studies included. *(Continued)*

Study	Eligibility criteria specified	Randomization specified	Allocation concealment	Groups similar at baseline	Blinding of assessor (for at least one key outcome)	Outcome measures assessed in 85% of patients	Intention-to-treat analysis	Between-group statistical comparisons reported	Point measures and measures of variability for all reported outcome measures	Activity monitoring in control groups	Relative exercise intensity remained constant	Exercise volume and energy expenditure	Overall TESTEX score
Sato et al. (53)	Yes	Unclear	Unclear	Yes	Unclear	Yes (1)	Yes	Yes	Yes	Unclear	Yes	Yes	8/15
Sato et al. (54)	Yes	Unclear	Unclear	Yes	Unclear	Yes (1)	Yes	Yes	Yes	Unclear	Yes	Yes	8/15
Seger et al. (56)	Yes	Unclear	No	Yes	Unclear	Yes (1)	Yes	Yes	Yes	No	Yes	Yes	8/15
Shibata et al. (58)	Yes	Unclear	No	Yes	Unclear	Yes (2)	Yes	Yes	Yes	No	Yes	Yes	9/15
Timmins et al. (63)	Yes	Unclear	No	Yes	Yes	Yes (2)	Yes	Yes	Yes	No	Yes	Yes	10/15
Vikne et al. (66)	Yes	Unclear	No	Yes	Yes	Yes (2)	Yes	Yes	Yes	No	Yes	Yes	10/15

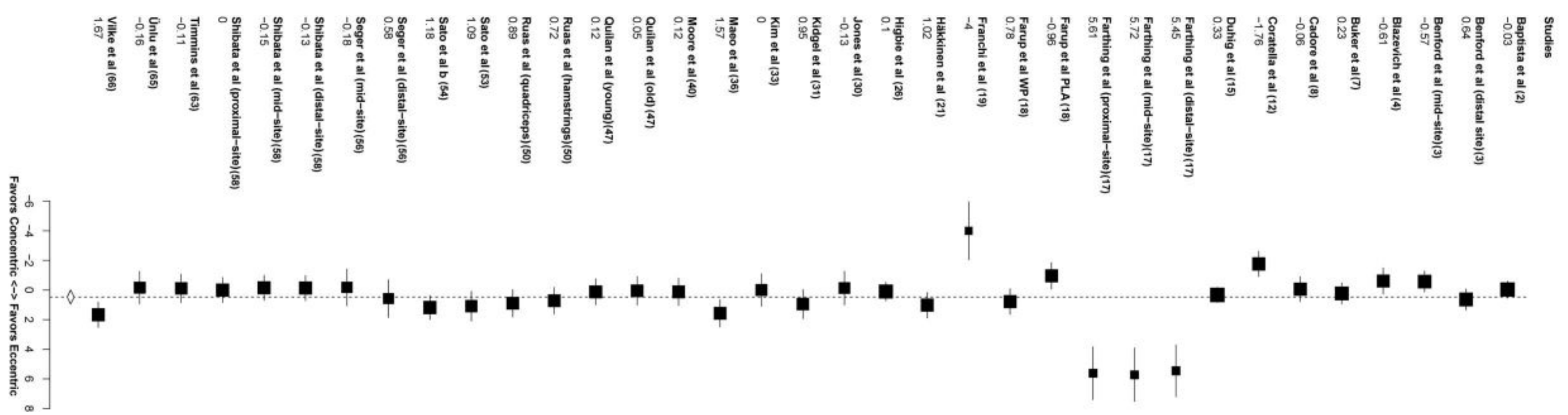

Figure 2. Forest plot results comparing concentric vs. eccentric muscle actions on muscle hypertrophy.

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Table 3
Subgroup analysis regarding the comparison of concentric (CON) vs. eccentric (ECC) training on muscle hypertrophy.

Subgroup analysis	Studies (*n*)	Size (*n*) (CON/ECC)	Effect size (95% CI)	I^2 (%)	*p*	Certainty of evidence
Age						
Adults (18–59 y)	33	381/372	0.508 (−0.0044 to 1.02)	84	0.052	⊕○○○ (very low)
Older adults (≥60 y)	2	31/32	−0.01 (−0.455 to 0.436)	0	0.836	⊕○○○ (very low)
Muscles analyzed						
Upper limb muscles	9	103/97	2.24 (0.498 to 3.98)	89	**0.018**	⊕⊕○○ (low)
Lower-limb muscles	26	309/307	−0.014 (−0.288 to 0.317)	65	0.922	⊕○○○ (very low)
Training duration						
≤8 wk of intervention	21	263/254	0.749 (0.0463 to 1.48)	86	**0.046**	⊕⊕○○ (low)
>8 wk of intervention	14	149/150	0.124 (−0.474 to 0.723)	76	0.661	⊕○○○ (very low)
Hypertrophy assessment						
Cross-sectional area	13	148/149	0.089 (−0.385 to 0.564)	69	0.693	⊕○○○ (very low)
Muscle thickness	19	264/255	0.868 (0.0352 to 1.7)	88	**0.0352**	⊕⊕○○ (low)
Regional Hypertrophy						
Proximal	2	24/22	2.75 (−32.9 to 38.4)	96	0.507	⊕○○○ (very low)
Middle	29	343/339	0.26 (−0.152 to 0.671)	78	0.206	⊕○○○ (very low)
Distal	4	45/43	1.47 (−2.24 to 5.18)	90	0.295	⊕○○○ (very low)
Contraction type						
Isokinetic	19	203/200	0.947 (0.133 to 1.76)	85	**0.0251**	⊕⊕○○ (low)
Isotonic	16	209/204	0.02 (−0.508 to 0.548)	78	0.808	⊕○○○ (very low)
Isotonic (same load schemes)	12	166/161	0.224 (−0.302 to 0.749)	72	0.368	⊕○○○ (very low)
Isotonic (accentuated eccentric load)	4	43/43	−0.529 (−2.32 to 1.26)	83	0.416	⊕○○○ (very low)

Bold values indicates the significance of the p values < 0.05.

assessment, regional, and isotonic contraction) showed similar hypertrophy in ECC training. In this sense, our study contrasts with the previous meta-analysis of Schoenfeld et al. (55), which differs in the number of studies included ($n = 15$), inclusion criteria (especially regarding hypertrophy measures), number of subgroup/sensitivity analysis, and the main effects (ES: −0.27 [95% CI: −0.57 to −0.01]; $p < 0.05$). Therefore, our review adds some interesting aspects to be discussed with the literature.

Both ECC and CON muscle actions promote distinct muscular morphological adaptations. Prioritizing one type of contraction during a resistance training program can make these adaptations, more evident. During CON muscle actions, the muscle fascicle length decreases as the muscle contracts (32). This decrease results from the sliding of cross-bridges formed between actin and myosin filaments, shortening the sarcomere and consequently the entire muscle (4,15,63). In addition, CON training tends to add sarcomeres in parallel (68). This characteristic is common in muscles that perform short amplitude and high-speed movements, favoring increased force generation capacity and improvement in muscle power (9). Therefore, hypertrophic changes appear to be achieved through specific adaptations with CON training, providing distinct structural adaptations compared with ECC (68).

On the other hand, during ECC muscle actions, the muscle length increases as it elongates (4). This occurs because the cross-bridges between actin and myosin filaments stretch while controlling the downward movement or deceleration, promoting this type of adaptation during interventions that prioritize this action. The pennation angle tends to increase during ECC contraction, as muscle fibers move away from each other during muscle stretching, which generates adaptations to muscular architecture (33,57). Furthermore, ECC muscle actions appear to induce unique adaptations compared with traditional CON-ECC resistance training protocols. Brandenburg and Docherty (5) showed that when using ECC loads greater than maximal concentric force (i.e., > 1RM), exclusively ECC training seems to promote greater increases in overall strength (i.e., combined CON, isometric, and CON strength) compared with CON-based and traditional training (i.e., alternating CON-ECC muscle actions). Therefore, ECC muscle actions are particularly effective for overall and specific strength gains.

The distinct mechanisms of muscular force production during ECC and CON muscle actions result in significant differences in force/power generation capacity, energy cost, and fatigue (50,61,64). A recent meta-analysis estimated that the maximal ECC force is approximately 40% greater than the maximal CON force (41). Furthermore, Souron et al. (61) demonstrated that to achieve the same level of fatigue observed in CON muscle actions (i.e., 40% reduction in maximal isometric force), a 28.8% greater volume of contractions (134 vs. 104) was required when the exercise was performed eccentrically. When the same external resistances are used (i.e., 70–95%RM), CON-ECC muscle action protocols to failure resulted in substantially greater volume (64–152%) (59).

One of the adaptations of ECC contraction stems from the protein titin, which regulates muscle contraction (24). Its filamentous structure spans the half-sarcomere, connecting the Z lines to the myosin filaments at the sarcomere's center. This central position allows titin to regulate sarcomere length during muscle contraction, enabling elongation while maintaining structural integrity and elasticity. Its primary function is to provide passive elasticity to muscles, enabling them to return to their resting length after contraction or stretching. In addition, titin interacts directly with contractile filaments, acting as a sort of "molecular spring" that influences contraction force and relaxation speed (25). Storing potential elastic energy during the muscle stretching process amplifies the muscle's capacity to generate force when this energy is released in the subsequent contraction (6,24). Finally, the interaction with titin implies that the enhanced residual force could result in specific adaptations, such as longitudinal muscle hypertrophy after ECC exercise, driven by the peak fascicle force during muscle-tendon unity stretch and the muscle's final stretched length (62).

In our subgroup analysis, some findings are highlighted. First, studies examining the upper limb muscles found that ECC muscle

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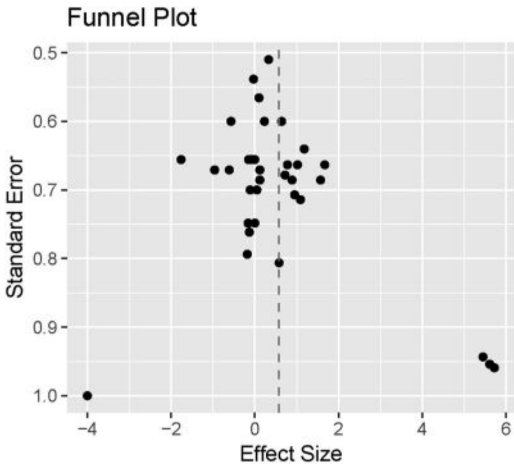

Figure 3. Funnel plot of the meta-analysis.

actions induce greater hypertrophy than CON actions. These results suggest a potential difference in hypertrophy between limbs (20), possibly attributed to morphological differences (44) or different fiber-type expressions between upper and lower-limb muscles. Short-term interventions (≤8 weeks) and muscle thickness assessment also favored ECC muscle actions, but the mechanisms that explain this difference are still unclear in the literature and require future investigations. Finally, our study showed a difference in the ECC vs. CON hypertrophy for the isokinetic subgroup, but not for the isotonic subgroups. This is likely due to the different forms of mechanical stress, where conventional machines involve a constant load and different amounts of resistive torque based on the moment arm of the machine axis, whereas isokinetic dynamometers adjust the load to maintain a constant velocity, requiring the muscle to produce approximately maximal voluntary levels of torque throughout the range of motion (48). The findings therefore suggest that perhaps these 2 training modes may promote different degrees of hypertrophy in ECC training.

Despite the strengths of a meta-analysis, our review has several limitations. First, most of the analyzed studies employed isokinetic dynamometry for training. While isokinetic dynamometry provides precise control over ECC contraction (42), enhancing experimental rigor, it may limit the ecological validity of the findings. The nearly isolated principle of isokinetic exercises may not fully replicate the dynamic and multifaceted conditions encountered in real-world resistance training settings. Consequently, the outcomes of our analysis may not be entirely representative of the diverse stimuli encountered during more conventional forms of resistance training, potentially limiting the generalizability of our findings to practical applications. Future research should incorporate a wide range of resistance training modalities to ensure a more comprehensive understanding of the eccentric-concentric dichotomy in muscle hypertrophy under ecologically valid conditions.

We included only regional imaging methods to measure muscle hypertrophy (i.e., MRI, ultrasound, and computed tomography). Muscle biopsies and skeletal muscle estimation (through equations) are also adequate to measure muscle hypertrophy (22). However, analyzing studies with different methods of measuring muscular hypertrophy may introduce a bias and true differences in effects may be obscured (35).

Finally, another limitation is the heterogeneity in defining training status across studies. Most studies used a criterion to categorize training status, such as previous experience (in years) with resistance training. However, some studies defined the subjects as physically/recreationally active or did not inform the training status. Furthermore, previous experience with resistance training is not the only criterion to define training status (52). Other criteria include strength level, current uninterrupted training time, time of detraining, previous training experience, and exercise technique (52). While we acknowledge the limitation of training status, it is highlighted that most studies included in our analysis focus on untrained individuals. This is particularly relevant for ECC training, as untrained individuals experience heightened muscle damage compared with CON, which can significantly impact their adaptation process (11,46). Trained subjects have some protection against muscle damage due to repeated bout effects, potentially altering the time course of adaptations (38). Therefore, the training status should be considered when interpreting results, as it may limit the generalizability of findings to more trained populations.

Practical Applications

In practice, a typical training session involves exercises that naturally include both ECC and CON phases, such as squats, bench presses, and rows. Since our study showed similar hypertrophy of ECC compared with CON training, some practical applications should be considered. Integrating specific ECC-focused exercises periodically can target muscle groups that require more attention in the training program. For example, implementing higher loads during the ECC phase can promote adaptation. Furthermore, some ECC predominance exercises such as the Nordic hamstring curl also offer advantages in terms of skeletal muscle adaptations, including changes in pennation angle, fascicle length, and muscle thickness (45). Adding these exercises to resistance training regimens may benefit the training prescription, particularly for individuals aiming to optimize muscle growth. Athletes or individuals rehabilitating from injuries may also benefit from emphasizing ECC training to enhance muscle architecture parameters and promote joint stability (4,14). In addition, strength and conditioning coaches may design resistance training routines based on individual preferences and specific muscle goals. In summary, while ECC training offers unique advantages, it should be integrated thoughtfully into a comprehensive resistance training program that includes both ECC and CON muscle actions. Similar hypertrophy was evidenced between eccentric and concentric, in addition to greater heterogeneity and a low level of recommendations (GRADE) in the main analysis. On the other side, the subgroup analysis suggests that the muscles of the upper limbs, shorter interventions, hypertrophy assessment method, and the isokinetic contraction may favor eccentric muscle actions. Therefore, caution should be exercised when implementing eccentric muscle actions into resistance training programs.

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