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Hypertrophic effects of concentric versus eccentric muscle actions: A systematic review and meta-analysis

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Abstract

Controversy exists as to whether different dynamic muscle actions produce divergent hypertrophic responses. The purpose of this paper was to conduct a systematic review and meta-analysis of randomized controlled trials comparing the hypertrophic effects of concentric versus eccentric training in healthy adults following regimented resistance training (RT). Studies were deemed eligible for inclusion if they met the following criteria: 1) were an experimental trial published in an English-language refereed journal; 2) directly compared concentric and eccentric actions without the use of external implements (i.e. blood pressure cuffs) and all other RT variables equivalent; 3) measured morphologic changes via biopsy, imaging (magnetic resonance imaging, computerized tomography, or ultrasound), bioelectrical impedance, and/or densitometry; 4) had a minimum duration of 6 weeks; and, 5) used human participants without musculoskeletal injury or any health condition that could directly, or through the medications associated with the management of said condition, be expected to impact the hypertrophic response to resistance exercise. A systematic literature search determined that 15 studies met inclusion criteria. Results showed that eccentric muscle actions resulted in a greater effect size (ES) compared to concentric actions, but results did not reach statistical significance (ES difference = 0.25 ± 0.13; CI_{95}: -0.03, 0.52; $P = 0.076$). The mean percent change in muscle growth across studies favored eccentric compared to concentric actions (10.0% vs 6.8, respectively). The findings indicate the importance of including eccentric and concentric actions in a hypertrophy-oriented RT program as both have shown to be effective in increasing muscle hypertrophy.

Keywords: lengthening actions, shortening actions, muscle cross sectional area, muscle mass

Introduction

Dynamic resistance training involves two basic types of muscle actions: concentric and eccentric. Concentric actions involve the dynamic shortening of sarcomeres while eccentric actions involve the active lengthening of sarcomeres (48). Research suggests that the two types of actions produce distinct neuromuscular stimuli leading to different post-exercise adaptive responses (47). This is consistent with the principle of specificity, which dictates that the body adapts to the specific demands that are placed upon it.

There is ongoing controversy as to whether differences exist in the hypertrophic response to concentric versus eccentric actions. There is some evidence that eccentrics promote superior increases in muscle mass (16, 21, 29, 45), and one study actually indicated that maximal hypertrophy is not attained without the inclusion of eccentric actions (24). These findings are consistent with acute research showing that eccentric actions promote a more rapid protein synthetic response and greater increases in anabolic signaling and gene expression when compared with other types of muscle actions (13, 19, 40, 52). However, eccentric strength is approximately 20-50% greater than concentric strength (3), and the greater absolute intensities of load often employed during eccentric training may be a confounding factor when comparing adaptations associated with the two actions.

It has been postulated that eccentric actions may produce greater hypertrophic gains as a result of increased muscle damage (49). While concentric exercise can cause damage in muscle tissue (10, 22), the performance of eccentric actions elicits the greatest disruptions to contractile, structural, and supportive elements (14). This phenomenon has been attributed to heightened force demands on fewer active fibers, which are susceptible to tear when resisting dynamic lengthening (48). Researchers speculate that exercise-induced damage to muscle mediates an anabolic response that ultimately strengthens the affected tissue, thereby helping to protect the muscle against future injury (4). Several mechanisms have been hypothesized to be involved in the process, including the release of myokines, satellite cell activation, and cell swelling (49). However, there is a dearth of studies directly investigating the relationship between myodamage and muscular adaptations, and its ultimate role in the growth response remains undetermined.

To the authors' knowledge, only one previous meta-analysis has attempted to investigate the impact of dynamic muscle actions on hypertrophic changes. Roig et al (47) found that eccentric actions elicited statistically greater increases in muscle girth compared to concentric actions. However, comparing pre- and post-study girth measures may mask changes in protein accretion because it does not specifically measure muscle tissue, and therefore the measure is not considered an accurate proxy for assessing exercise-induced hypertrophy (58). Roig et al (47) also noted that increases in muscle cross sectional area (CSA) favoring eccentric versus concentric actions as assessed by imaging modalities, although these findings were limited to only 3 studies available at the time and did not exceed the *a priori* alpha; a number of studies subsequently have been published that shed further insight on the topic. Moreover, the analysis did not assess fiber type specific growth, which may provide unique insight into potential divergent effects between dynamic muscle actions considering that eccentric exercise has been shown to elicit a preferential recruitment of high-threshold motor units (42). Given the gaps in our knowledge base, the purpose of this paper was to systematically review the current literature in an effort to elucidate the hypertrophic effects of concentric versus eccentric actions following consistent, regimented resistance training. Meta-regression was employed to quantify and compare the magnitude of effects between conditions, as well as to determine the potential influence of covariates on findings.

2. Methods

Inclusion Criteria

Studies were deemed eligible for inclusion if they met the following criteria: 1) were an experimental trial published in an English-language refereed journal; 2) directly compared concentric and eccentric actions without the use of external implements (i.e., pressure cuffs, hypoxic chamber, etc.) and all other RT variables equivalent; 3) measured morphologic changes via biopsy, imaging, bioelectrical impedance, and/or densitometry; 4) had a minimum duration of 6 weeks; and, 5) used human participants without musculoskeletal injury or any health condition that could directly, or through the medications associated with the management of said condition, be expected to impact the hypertrophic response to resistance exercise (e.g., coronary artery disease and angiotensin receptor blockers).

Search Strategy

The systematic literature search was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (37) using the online software Covidence (Veritas Health Innovation, Melbourne, Australia). To carry out this review, English-language literature searches of the PubMed, Sports Discus, and CINAHL databases were conducted from all time points up until December, 2016. Combinations of the following keywords were used as search terms: For training (Resistance training OR resistance exercise OR strength training OR weightlifting OR weight lifting OR weight-lifting); for hypertrophy (Hypertrophy OR CSA OR cross sectional area OR growth OR muscle growth OR lean body mass OR LBM); for mode (Eccentric OR Concentric OR contraction mode OR shortening OR lengthening).

A total of 1128 studies were evaluated based on search criteria. To reduce the potential for selection bias, each study was independently reviewed by three of the investigators (BJS, ADV, and DIO), and a mutual decision was made as to whether it met basic inclusion criteria. Any inter-reviewer disagreements were settled by consensus. The reference lists of articles retrieved were then screened for any additional articles that had relevance to the topic, as described by Greenhalgh and Peacock (23), and three additional studies were identified as possibly meeting inclusion criteria. Of the studies initially reviewed, 37 were determined to be potentially relevant to the paper based on information contained in the abstracts. Full texts of these articles were then screened and 19 were deemed suitable for inclusion in accordance with the criteria outlined. Of the studies meeting inclusion criteria, 4 had insufficient data to render an analysis (6, 32, 36, 53), thus leaving a total of 15 studies eligible to be analyzed (see Figure 1). Table 1 summarizes the studies analyzed.

Insert Figure 1 About Here

Insert Table 1 About Here

Coding of Studies

Studies were read and individually coded by two of the investigators (BJS and DIO) for the following variables: Descriptive information of subjects by group including sex, body mass index, training status (trained subjects were defined as those with at least one year regular RT experience), stratified subject age (classified as either young [18-29 years], middle-aged [30-49 years] or elderly [50+ years]); whether the study was a parallel or within-subject design; the number of subjects in each group; duration of the study; weekly training frequency; training mode (isotonic, isokinetic); training intensity as a percentage of 1 repetition maximum (RM); number of sets performed per session; repetition range; whether the study was work matched; whether the study was repetition matched; mode of morphologic measurement (magnetic resonance imaging [MRI], ultrasound, biopsy, dual energy x-ray absorptiometry [DXA], and/or air displacement plethysmography); type of morphological measurement (CSA, volume, thickness); region/muscle of body measured (upper, lower, or both); and whether hypertrophy measure was direct or indirect. Coding was cross-checked between coders, and any discrepancies were resolved by mutual consensus. To assess potential coder drift, 30% of the studies were randomly selected for recoding as described by Cooper et al. (11). Per case agreement was determined by dividing the number of variables coded the same by the total number of variables. Acceptance required a mean agreement of 0.90.

Calculation of Effect Size

For each hypertrophy outcome, an effect size (ES) was calculated as the pretest-posttest change, divided by the pooled pretest standard deviation (SD) (1). A percentage change from pretest to posttest was also calculated. A small sample bias adjustment was applied to each ES (41). The variance around each ES was calculated using the sample size in each study and mean ES across all studies (7).

Statistical Analyses

Meta-analyses were performed using robust variance meta-regression for multilevel data structures, with adjustments for small samples (28, 56). Study was used as the clustering variable to account for correlated effects within studies. Observations were weighted by the inverse of the sampling variance. Model parameters were estimated by the method of restricted maximum likelihood (REML) (54); an exception was during the model reduction process, in which parameters were estimated by the method of maximum likelihood (ML), as likelihood ratio tests cannot be used to compare nested models with REML estimates. Meta-regressions on ESs were performed with treatment group (concentric or eccentric) as the moderator variable. For studies with multiple ES outcomes within a treatment group (such as muscle thickness and fiber hypertrophy), an average within-study ES difference between concentric and eccentric groups was calculated to allow for the generation of a forest plot. To assess the practical significance of the outcomes, the equivalent percent change was calculated for each meta-regression outcome. To assess the potential confounding effects of study-level moderators on outcomes, an additional full meta-regression model was created with training mode (isokinetic or isotonic) and body half (upper or lower) as covariates. Other covariates could not be included due to the limited sample size of the data set, and due to some covariates not having factor levels in more than two studies. The full model was then reduced by removing predictors one at a time, starting with the most insignificant predictor (8). The final model represented the reduced model with the lowest Bayesian Information Criterion (BIC) (50) and that was not statistically different ($P > 0.05$) from the full model when compared using a likelihood ratio test. Treatment group (eccentric or concentric) was not removed during the model reduction process. To explore possible interactions between muscle action and other variables, separate regressions were performed on muscle action and its interaction with training duration, training mode, and body half.

In order to identify the presence of highly influential studies which might bias the analysis, a sensitivity analysis was carried out for each model by removing one study at a time, and then examining the muscle action predictor. Studies were identified as influential if removal resulted in a change of P value from $P \leq 0.10$ to $P > 0.10$, or vice versa, or if removal caused a large change in the magnitude of the coefficient.

To assess publication bias, fail-safe N (the number of additional null studies required to reduce the observed ES difference by half) was calculated according to the method described by Orwin (46). Analysis for publication bias was carried out using a rank correlation test described by Begg and Mazumdar (5).

All analyses were performed using package metafor in R version 3.3.1 (The R Foundation for Statistical Computing, Vienna, Austria). An *a priori* alpha for effects was 0.05. Data are reported as $\overline{x}$ ± standard error of the means (SEM) and 95% CIs.

Results

The final analysis comprised 30 treatment groups from 15 studies. The mean ES across all studies was 0.89 ± 0.17 (CI_{95}: 0.54, 1.25). The mean percent change was 8.4 ± 1.0% (CI_{95}: 6.2, 10.5).

Concentric vs. Eccentric Muscle Actions

Eccentric muscle actions resulted in a greater ES compared to concentric actions, but results did not rise to statistical significance (ES difference = 0.25 ± 0.13; CI_{95}: -0.03, 0.52; P = 0.076). The mean ES for concentric actions was 0.77 ± 0.17 (CI_{95}: 0.41, 1.13), while the mean ES for eccentric actions was 1.02 ± 0.20 (CI_{95}: 0.58, 1.45). The mean percent change for concentric actions was 6.8 ± 1.4% (CI_{95}: 3.8, 9.7), while the mean percent change for eccentric actions was 10.0 ± 1.7% (CI_{95}: 6.3, 13.6). Analysis of study level ESs revealed a similar difference between concentric and eccentric actions (ES difference = 0.27 ± 0.13; CI_{95}: -0.56, 0.01; P = 0.057) (Figure 2). In the final reduced regression model, only body half (upper versus lower) remained as a statistically predictive covariate (P = 0.037). The ES difference between concentric and eccentric actions remained at 0.25 ± 0.13 (CI_{95}: -0.04, 0.54; P = 0.089). There were no statistical interactions between muscle action and training mode (isokinetic versus isotonic) (P = 0.85), body half (P = 0.28), or training duration (P = 0.28).

Insert Figure 2 About Here

Sensitivity Analyses

Due to the limited sample size, sensitivity analyses revealed numerous influential studies (Table 2). Most studies decreased the difference between concentric and eccentric actions upon removal (Table 2). Removal of two influential studies (17, 51) magnified the difference between concentric and eccentric actions so that it exceeded the *a priori* alpha (Table 2).

Insert Table 2 About Here

Publication Bias

There was no evidence of publication bias according to the rank correlation test (P = 0.88). Fail-safe N revealed that 15 null studies would be needed to reduce the observed ES difference in half.

Discussion

Our primary analysis found that, on average, eccentric training produced greater increases in hypertrophy compared to concentric training (10.0% versus 6.8%, respectively). Based on the Hopkins et al (30) scale, these results were likely/probably not due to chance alone (p = 0.076). However, the effect size difference (0.25) indicates the hypertrophic advantage of eccentric training was relatively small. The findings support previous research showing a modest hypertrophic benefit with the use of eccentric actions (47).

Given that maximal strength in eccentric training is approximately 20-50% greater than that of concentric training (2), and considering that the vast majority of studies matched total repetitions as opposed to total work, it can be speculated that the greater amount of work performed during eccentric actions may be responsible for differences in muscle growth. Only two included studies matched total work between conditions. Hawkins et al (26) found only those trained with eccentric actions to have a statistically significant increase in thigh and whole leg lean mass due to training, whereas Moore et al (38) found a smaller difference in muscle growth favoring eccentrics (6.5% vs 4.6%) that was not statistically significant. There were not enough studies to perform a subanalysis on this covariate, thereby preventing quantification of data. Consequently, additional research is warranted to determine what, if any, growth-related effects of eccentric exercise are related to loading differences between muscle actions.

A statistically influential effect of body half was found, wherein upper body training decreased the ES predicted by the models by 0.62 and 0.59 for the full and reduced models, respectively, when contraction mode (concentric or eccentric) and resistance type (isotonic or isokinetic) were held constant. This finding is inconsistent with Abe et al. (1), who found larger mean increases for upper body muscle growth (12–21%) compared to lower body muscle growth (7–9%) over a 12-week period of resistance training, although no statistical difference was found. These inconsistent findings may be at least partially due to different types of measurement being mixed within the same analysis. For example, Nickols-Richardson et al. (44) utilized DXA to quantify upper- and lower-limb LBM, which was weighted heavily in the meta-analysis due to its large sample size ($N = 70$), while many other studies utilized imaging and/or biopsy. Moreover, Nickols-Richardson et al. (44) accounts for about 48% of the weight of upper-body ESs included; within the study itself, investigators reported a relative advantage for upper body training, which further conflicts with the findings of this covariate. Previous work suggests that imaging modalities such as MRI and CT are more sensitive than DXA for measuring subtle changes in CSA and thus more sensitive for detecting effects (12, 43). Therefore, observed differences between body halves from varying muscle actions should be taken with circumspection.

Although we investigated whole muscle growth, it is interesting to note that eccentric and concentric actions have been shown to produce regional-specific effects on muscle growth. Franchi et al. (19) found significantly greater hypertrophy in the mid-portion of the vastus lateralis from concentric exercise while eccentric training had a greater effect on distal growth of the muscle. Similar findings have been reported in other research (51). Although the reason for these differences remain to be elucidated, the phenomenon may be due to localized muscle damage along the length of the fiber that brings about non-uniform alterations in muscle activation (27). These findings also demonstrate the need for multiple sampling sites along the length of the measured muscle when comparing eccentric and concentric training, as uniform effects at an individual sampling site may not occur. Regardless of the mechanisms, these data, in combination with research showing diverse intracellular signaling responses between concentric and eccentric training (19), suggest that whole muscle growth is best achieved by a performing a combination of the two actions.

All three muscle biopsy studies included in this review found that eccentric training produces greater type II fiber hypertrophy than concentric training (17, 31, 57), with only one study suggesting that eccentric training also produces greater type I fiber hypertrophy (57). It can only be speculated as to why this is, but previous work suggests that eccentric loading preferentially recruits higher-threshold motor units (42). If higher threshold motor units contain more type II muscle fibers, then this may at least partially explain the findings, but at present, it is not clear as to whether or not this is the case (15). Notwithstanding murky neuromuscular physiological mechanisms, selective glycogen depletion of type II fibers has been documented following an 8-week eccentric training program, which suggests that type II fibers are preferentially utilized (20). While it would seem logical that differential loads may play a role, preferential type II fiber hypertrophy has also been demonstrated even with lighter loads (50–60% of maximum eccentric force) during combined concentric/eccentric training (24). Moreover, due to lateral force transmission, it is unclear as to whether or not different fibers truly 'experience' different loads *in vivo* (15, 25). At present, the interplay between fiber contraction/activation and force transmission is not clear, nor are the mechanisms by which preferential type II hypertrophy occurs with eccentric loading.

It is important to note that results were found to be sensitive to the removal of individual studies. In some cases, removal decreased the magnitude of difference between eccentric and concentric actions (16, 18, 31, 39, 44, 57), while in others, removal strengthened the relationship (17, 51). This highlights the need for additional research on the topic to enhance the robustness of findings and provide greater clarity for drawing evidence-based conclusions. Further, it should be noted that our analyses did not take into account measurement error, which would decrease all of the ESs; the extent to which this would occur is unclear and could not be calculated because not all of the included studies reported reliability measures. Thus, it is imperative that future studies include reliability measures so as to allow both readers and meta-analyses to take measurement error into account when attempting to draw conclusions.

Practical Applications

Given the modest ES difference between exclusively eccentric and concentric training, it appears that eccentric-only training likely provides a small advantage over concentric-only training for promoting a hypertrophic response; notwithstanding, both contraction modes can promote significant muscular hypertrophy. Further research is required to clarify whether the benefit of eccentric training is related to the higher forces produced and ultimately total work completed relative to concentric-only training (39). Practically, the risk/reward ratio of eccentric-only actions must be considered before being employed – eccentric actions may elicit a slightly larger hypertrophic response than concentric actions, but at the same time, they also require greater overload and induce greater delayed-onset muscle soreness. Traditionally, resistance training includes the completion of coupled eccentric and concentric actions, and special equipment or external assistance may be required to complete isolated eccentric actions. Many commercial solutions, such as flywheels, offer eccentric overload relative to the concentric range of motion, which differs from exclusively eccentric or concentric training. Therefore, the results of the present study must be considered in this specific context and cannot be used to justify the use of relative eccentric overload when completing coupled eccentric and concentric actions; however, the inclusion of such protocols may be justified according to recent work (35).

Conflict of Interest: The authors declare no conflicts of interest with this manuscript. We would like to thank Jonathan Farthing and Jean Farup for providing supplemental data necessary to carry out statistical analyses.

Table 1

Summary of Hypertrophy Training Studies Investigating Type of Muscle Action

Study	**Subjects**	**Design**	**Study duration**	**Mode**	**Hypertrophy measurement**	**Findings**
Cadore et al. (9)	22 recreation-ally trained young men and women	Random assignment to a resistance training protocol of either eccentric or concentric actions for the knee extensors. All subjects performed 2 to 5 sets of 8 to 10 maximal repetitions. Training was carried out twice weekly.	6 weeks	Isokinetic dynamometer	Ultrasound	No significant differences in muscle thickness between conditions
Farthing and Chilibeck (16)	36 untrained young men and women	Within-subject design in which subjects performed concentric actions of the elbow flexors with one arm and eccentric actions with the other arm. Subjects were randomly assign to perform the actions at either a fast or	8 weeks	Isokinetic dynamometer	Ultrasound	Greater increase in muscle thickness for the eccentric condition

		slow speed. All subjects performed 2 to 6 sets of 8 maximal repetitions. Training was carried out 3 days per week.				
Farup et al. (18)	22 untrained young men	Within-subject design in which subjects performed concentric actions of the knee extensors with one leg and eccentric actions with the other leg. All subjects performed 6 to 12 sets of 6- to 15RM. Eccentric actions were performed at 120% of concentric 1RM. Training was carried out 3 days per week.	12 weeks	Knee extension machine	MRI	No significant differences in quadriceps hypertrophy between conditions
Farup et al. (17)	22 untrained young men	Within-subject design in which subjects performed concentric actions of the knee extensors with one leg and eccentric actions with the other leg. All subjects performed 6 to 12 sets of 6- to 15RM. Eccentric actions were performed at 120% of concentric 1RM. Training was carried out 3 days per week.	12 weeks	Knee extension machine	Muscle biopsy	Significantly greater increases in Type II fiber CSA for the concentric condition
Franchi et al. (19)	12 untrained young men	Random assignment to a resistance training protocol of either eccentric or concentric actions of the lower-limb extensors. All subjects performed 4 sets of 8- to 10RM. Eccentric actions were performed at 120% of concentric 1RM. Concentric actions were performed for 2 seconds; eccentric actions, for 3 seconds. Training was carried out 3 days per week.	10 weeks	Leg press machine	MRI	No significant differences in thigh hypertrophy between conditions
Hawkins et al (26)	8 untrained young women	Within-subject design in which subjects performed concentric actions of the knee extensors with one leg and eccentric actions with the other leg. The concentric condition involved 3 sets of 4 maximal repetitions whereas the eccentric	18 weeks	Isokinetic dynamometer	DXA	Significantly greater increases in mid-thigh lean mass for the eccentric condition

		condition involved 3 sets of 3 maximal repetitions. Training was carried out 3 days per week.				
Higbie et al. (29)	54 untrained young women	Random assignment to a resistance training protocol of either eccentric or concentric actions for the knee extensors. All subjects performed 3 sets of 10 maximal repetitions. Training was carried out 3 days per week.	10 weeks	Isokinetic dynamometer	MRI	Significantly greater increases in quadriceps muscle hypertrophy for the eccentric condition
Hortobagyi et al. (31)	21 untrained young men	Random assignment to a resistance training protocol of either eccentric or concentric actions for the knee extensors. All subjects performed 4 to 6 sets of 8 to 12 maximal repetitions. Training was carried out 3 days per week.	12 weeks	Isokinetic dynamometer	Biopsy	Significantly greater increase in Type II fiber hypertrophy of the quadriceps for the eccentric condition
Jones and Rutherford (33)	12 untrained young men and women	Within-subject design in which subjects performed concentric actions of the knee extensors with one leg and eccentric actions with the other leg. All subjects performed 4 sets of 6 maximal repetitions. Eccentric actions were performed at 145% of concentric 1RM. Training was carried out 3 days per week.	12 weeks	Variable resistance knee extension machine	CT	No significant differences in thigh hypertrophy between conditions
Kim et al. (34)	13 young men and women (training status not disclosed)	Random assignment to a resistance training protocol of either eccentric or concentric actions for the shoulder abductors. All subjects performed 4 to 6 sets of 6 to 8 maximal repetitions. Training was carried out 3 days per week.	8 weeks	Isokinetic dynamometer	Ultrasound	No significant differences in hypertrophy of the supraspinatus between conditions
Moore et al. (39)	9 untrained young men	Within-subject design in which subjects performed concentric actions of the elbow flexors with one arm and eccentric actions with the other arm. All subjects performed 2 to 6 sets of 10 maximal repetitions. Training was carried out twice per week.	9 weeks	Isokinetic dynamometer	CT	No significant differences in hypertrophy of the elbow flexors between conditions.

Nickols-Richardson et al. (44)	70 untrained young women	Random assignment to a resistance training protocol of either eccentric or concentric actions for the limbs. All subjects performed 5 sets of 6 maximal repetitions. Training was carried out 3 days per week.	5 months	Isokinetic dynamometer	DXA	No significant differences in fat-free soft tissue mass between conditions
Seger et al. (51)	10 untrained young men	Within-subject design in which subjects performed concentric actions of the knee extensors with one leg and eccentric actions with the other leg. All subjects performed 4 sets of 10 maximal repetitions. Training was carried out 3 days per week.	10 weeks	Isokinetic dynamometer	MRI	Greater increases in whole quadriceps muscle hypertrophy distally for the eccentric condition
Timmins et al (55)	28 recreation-ally trained young men	Random assignment to concentric- or eccentric-only knee flexor resistance training. Subjects performed 4-6 sets of 6-8 repetitions. Training was carried out 2 or 3 days per week.	6 weeks	Isokinetic dynamometer	Ultrasound	No significant differences in muscle thickness between conditions
Vikne et al. (57)	17 resistance-trained young men	Random assignment to a resistance training protocol of either eccentric or concentric actions for the elbow flexors. Training was divided between maximum and medium days. Those in the maximum training group performed 3 to 5 sets of 4- to 8RM; those in the medium training group performed 3 or 4 sets of the same repetition scheme but with lighter loads. Concentric actions were performed explosively, whereas eccentric actions were performed in 3 to 4 sec. Training was carried out 2 or 3 days per week.	12 weeks	Specially designed cable pulley apparatus	CT scan and biopsy	Significantly greater increases in whole muscle CSA of the upper arm for the eccentric condition. Greater increases in Type I and Type II fiber area for the eccentric condition.

Abbreviations: RM = repetition maximum; CSA = cross-sectional area; CT = computerized tomography; MRI = magnetic resonance imaging; DXA = dual X-ray absorptiometry

Table 2

Influential Studies

Study Removed	**New ES Difference (CI)**	**New P-Value**
Farthing et al. (16)	0.22 ± 0.16 (-0.12, 0.56)	0.19
Farup et al. (18)	0.22 ± 0.13 (-0.07, 0.51)	0.12
Farup et al. (17)	0.33 ± 0.12 (0.08, 0.58)	0.015*
Hortobagyi et al. (31)	0.19 ± 0.12 (-0.07, 0.45)	0.13
Moore et al. (39)	0.22 ± 0.13 (-0.06, 0.50)	0.11
Nickols-Richardson et al. (44)	0.28 ± 0.16 (-0.07, 0.62)	0.11
Seger et al. (51)	0.29 ± 0.13 (0.01, 0.57)	0.04*
Vikne et al. (57)	0.20 ± 0.13 (-0.08, 0.47)	0.14

References

1. Abe, T, DeHoyos, DV, Pollock, ML, and 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.* 81: 174-180, 2000.

2. Bamman, MM, Shipp, JR, Jiang, J, Gower, BA, Hunter, GR, Goodman, A, McLafferty, CL,Jr, and Urban, RJ. Mechanical load increases muscle IGF-I and androgen receptor mRNA concentrations in humans. *Am. J. Physiol. Endocrinol. Metab.* 280: E383-90, 2001.

3. Bamman, MM, Shipp, JR, Jiang, J, Gower, BA, Hunter, GR, Goodman, A, McLafferty, CL,Jr, and Urban, RJ. Mechanical load increases muscle IGF-I and androgen receptor mRNA concentrations in humans. *Am. J. Physiol. Endocrinol. Metab.* 280: E383-90, 2001.

4. Barash, IA, Mathew, L, Ryan, AF, Chen, J, and Lieber, RL. Rapid muscle-specific gene expression changes after a single bout of eccentric contractions in the mouse. *Am. J. Physiol. Cell. Physiol.* 286: C355-64, 2004.

5. Begg, CB, and Mazumdar, M. Operating characteristics of a rank correlation test for publication bias. *Biometrics* 50: 1088-1101, 1994.

6. Blazevich, AJ, Cannavan, D, Coleman, DR, and Horne, S. Influence of concentric and eccentric resistance training on architectural adaptation in human quadriceps muscles. *J. Appl. Physiol.* 103: 1565-1575, 2007.

7. Borenstein, M, Hedges, LV, and Higgins, JPT. Effect sizes based on means. In: Introduction to Meta-Analysis. Anonymous United Kingdom: John Wiley and Sons, LTD, 2009. pp. 21-32.

8. Burnham, KP, and Anderson, DR. Model Selection and Inference: A Practical Information-Theoretic Approach. New York; Springer-Verlag, 2002.

9. Cadore, EL, Izquierdo, M, Pinto, SS, Alberton, CL, Pinto, RS, Baroni, BM, Vaz, MA, Lanferdini, FJ, Radaelli, R, Gonzalez-Izal, M, Bottaro, M, and Kruel, LF. Neuromuscular adaptations to concurrent training in the elderly: effects of intrasession exercise sequence. *Age (Dordr)* 35: 891-903, 2013.

10. Clarkson, PM, Byrnes, WC, McCormick, KM, Turcotte, LP, and White, JS. Muscle soreness and serum creatine kinase activity following isometric, eccentric, and concentric exercise. *Int. J. Sports Med.* 7: 152-155, 1986.

11. Cooper, H, Hedges, L, and Valentine, J. The Handbook of Research Synthesis and Meta-Analysis. . New York; Russell Sage Foundation, 2009.

12. Delmonico, MJ, Kostek, MC, Johns, J, Hurley, BF, and Conway, JM. Can dual energy X-ray absorptiometry provide a valid assessment of changes in thigh muscle mass with strength training in older adults? *Eur. J. Clin. Nutr.* 62: 1372-1378, 2008.

13. Eliasson, J, Elfegoun, T, Nilsson, J, Kohnke, R, Ekblom, B, and Blomstrand, E. Maximal lengthening contractions increase p70 S6 kinase phosphorylation in human skeletal muscle in the absence of nutritional supply. *Am. J. Physiol. Endocrinol. Metab.* 291: 1197-1205, 2006.

14. Enoka, RM. Eccentric contractions require unique activation strategies by the nervous system. *J. Appl. Physiol.* 81: 2339-2346, 1996.

15. Enoka, RM, and Duchateau, J. Inappropriate interpretation of surface EMG signals and muscle fiber characteristics impedes understanding of the control of neuromuscular function. *J. Appl. Physiol. (1985)* 119: 1516-1518, 2015.

16. Farthing, JP, and Chilibeck, PD. The effects of eccentric and concentric training at different velocities on muscle hypertrophy. *Eur. J. Appl. Physiol.* 89: 578-586, 2003.

17. Farup, J, Rahbek, SK, Riis, S, Vendelbo, MH, Paoli, F, and Vissing, K. Influence of exercise contraction mode and protein supplementation on human skeletal muscle satellite cell content and muscle fiber growth. *J. Appl. Physiol. (1985)* 117: 898-909, 2014.

18. Farup, J, Rahbek, SK, Vendelbo, MH, Matzon, A, Hindhede, J, Bejder, A, Ringgard, S, and Vissing, K. Whey protein hydrolysate augments tendon and muscle hypertrophy independent of resistance exercise contraction mode. *Scand. J. Med. Sci. Sports* 24: 788-798, 2014.

19. Franchi, MV, Atherton, PJ, Reeves, ND, Fluck, M, Williams, J, Mitchell, WK, Selby, A, Beltran Valls, RM, and Narici, MV. Architectural, functional and molecular responses to concentric and eccentric loading in human skeletal muscle. *Acta Physiol. (Oxf)* 210: 642-654, 2014.

20. Friden, J, Seger, J, Sjostrom, M, and Ekblom, B. Adaptive response in human skeletal muscle subjected to prolonged eccentric training. *Int. J. Sports Med.* 4: 177-183, 1983.

21. Friedmann, B, Kinscherf, R, Vorwald, S, Muller, H, Kucera, K, Borisch, S, Richter, G, Bartsch, P, and Billeter, R. Muscular adaptations to computer-guided strength training with eccentric overload. *Acta Physiol. Scand.* 182: 77-88, 2004.

22. Gibala, MJ, MacDougall, JD, Tarnopolsky, MA, Stauber, WT, and Elorriaga, A. Changes in human skeletal muscle ultrastructure and force production after acute resistance exercise. *J. Appl. Physiol.* 78: 702-708, 1995.

23. Greenhalgh, T, and Peacock, R. Effectiveness and efficiency of search methods in systematic reviews of complex evidence: audit of primary sources. *BMJ* 331: 1064-1065, 2005.

24. Hather, BM, Tesch, PA, Buchanan, P, and Dudley, GA. Influence of eccentric actions on skeletal muscle adaptations to resistance training. *Acta Physiol. Scand.* 143: 177-185, 1991.

25. Hatze, H. Fundamental issues, recent advances, and future directions in myodynamics. *J. Electromyogr. Kinesiol.* 12: 447-454, 2002.

26. Hawkins, SA, Schroeder, ET, Wiswell, RA, Jaque, SV, Marcell, TJ, and Costa, K. Eccentric muscle action increases site-specific osteogenic response. *Med. Sci. Sports Exerc.* 31: 1287-1292, 1999.

27. Hedayatpour, N, and Falla, D. Non-uniform muscle adaptations to eccentric exercise and the implications for training and sport. *J. Electromyogr. Kinesiol.* 22: 329-333, 2012.

28. Hedges, LV, Tipton, E, and Johnson, MC. Robust variance estimation in meta-regression with dependent effect size estimates. *Res. Synth. Methods* 1: 39-65, 2010.

29. Higbie, EJ, Cureton, KJ, Warren, GL,3rd, and Prior, BM. Effects of concentric and eccentric training on muscle strength, cross-sectional area, and neural activation. *J. Appl. Physiol. (1985)* 81: 2173-2181, 1996.

30. Hopkins, WG, Marshall, SW, Batterham, AM, and Hanin, J. Progressive statistics for studies in sports medicine and exercise science. *Med. Sci. Sports Exerc.* 41: 3-13, 2009.

31. Hortobagyi, T, Hill, JP, Houmard, JA, Fraser, DD, Lambert, NJ, and Israel, RG. Adaptive responses to muscle lengthening and shortening in humans. *J. Appl. Physiol. (1985)* 80: 765-772, 1996.

32. Hortobagyi, T, Dempsey, L, Fraser, D, Zheng, D, Hamilton, G, Lambert, J, and Dohm, L. Changes in muscle strength, muscle fibre size and myofibrillar gene expression after immobilization and retraining in humans. *J. Physiol.* 524 Pt 1: 293-304, 2000.

33. Jones, DA, and Rutherford, OM. Human muscle strength training: the effects of three different regimens and the nature of the resultant changes. *J. Physiol. (Lond.)* 391: 1-11, 1987.

34. Kim, SY, Ko, JB, Farthing, JP, and Butcher, SJ. Investigation of supraspinatus muscle architecture following concentric and eccentric training. *J. Sci. Med. Sport* , 2014.

35. Maroto-Izquierdo, S, García-López, D, Fernandez-Gonzalo, R, Moreira, OC, González-Gallego, J, and de Paz, JA. Skeletal muscle functional and structural adaptations after eccentric overload flywheel resistance training: a systematic review and meta-analysis. *Journal of Science and Medicine in Sport.* , 2017.

36. Miller, LE, Nickols-Richardson, SM, Wootten, DF, Ramp, WK, Steele, CR, Cotton, JR, Carneal, JP, and Herbert, WG. Isokinetic resistance training increases tibial bending stiffness in young women. *Calcif. Tissue Int.* 84: 446-452, 2009.

37. Moher, D, Liberati, A, Tetzlaff, J, Altman, DG, and PRISMA Group. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *PLoS Med.* 6: e1000097, 2009.

38. Moore, DR, Areta, J, Coffey, VG, Stellingwerff, T, Phillips, SM, Burke, LM, Cleroux, M, Godin, JP, and Hawley, JA. Daytime pattern of post-exercise protein intake affects whole-body protein turnover in resistance-trained males. *Nutr. Metab. (Lond)* 9: 91-7075-9-91, 2012.

39. Moore, DR, Young, M, and Phillips, SM. Similar increases in muscle size and strength in young men after training with maximal shortening or lengthening contractions when matched for total work. *Eur. J. Appl. Physiol.* 112: 1587-1592, 2012.

40. Moore, DR, Phillips, SM, Babraj, JA, Smith, K, and Rennie, MJ. Myofibrillar and collagen protein synthesis in human skeletal muscle in young men after maximal shortening and lengthening contractions. *Am. J. Physiol. Endocrinol. Metab.* 288: 1153-1159, 2005.

41. Morris, B. Estimating effect sizes from pretest-posttest-control group designs. *Organizational Research Methods* 11: 364-386, 2008.

42. Nardone, A, Romano, C, and Schieppati, M. Selective recruitment of high-threshold human motor units during voluntary isotonic lengthening of active muscles. *J. Physiol. (Lond.)* 409: 451-471, 1989.

43. Nelson, ME, Fiatarone, MA, Layne, JE, Trice, I, Economos, CD, Fielding, RA, Ma, R, Pierson, RN, and Evans, WJ. Analysis of body-composition techniques and models for detecting change in soft tissue with strength training. *Am. J. Clin. Nutr.* 63: 678-686, 1996.

44. Nickols-Richardson, SM, Miller, LE, Wootten, DF, Ramp, WK, and Herbert, WG. Concentric and eccentric isokinetic resistance training similarly increases muscular strength, fat-free soft tissue mass, and specific bone mineral measurements in young women. *Osteoporos. Int.* 18: 789-796, 2007.

45. Norrbrand, L, Fluckey, JD, Pozzo, M, and Tesch, PA. Resistance training using eccentric overload induces early adaptations in skeletal muscle size. *Eur. J. Appl. Physiol.* 102: 271-281, 2008.

46. Orwin, RG. A fail-safe N for effect size in meta-analysis. *Journal of Educational Statistics,* 8: 157-159, 1983.

47. Roig, M, O'Brien, K, Kirk, G, Murray, R, McKinnon, P, Shadgan, B, and Reid, WD. The effects of eccentric versus concentric resistance training on muscle strength and mass in healthy adults: a systematic review with meta-analysis. *Br. J. Sports Med.* 43: 556-568, 2009.

48. Schoenfeld, BJ. Science and Development of Muscle Hypertrophy. Champaign, IL; Human Kinetics, 2016.

49. Schoenfeld, BJ. Does exercise-induced muscle damage play a role in skeletal muscle hypertrophy? *J. Strength Cond Res.* 26: 1441-1453, 2012.

50. Schwarz, G. Estimating the dimension of a model. *Ann. Stat.* 6: 461-464, 1978.

51. Seger, JY, Arvidsson, B, and Thorstensson, A. Specific effects of eccentric and concentric training on muscle strength and morphology in humans. *Eur. J. Appl. Physiol. Occup. Physiol.* 79: 49-57, 1998.

52. Shepstone, TN, Tang, JE, Dallaire, S, Schuenke, MD, Staron, RS, and Phillips, SM. Short-term high- vs. low-velocity isokinetic lengthening training results in greater hypertrophy of the elbow flexors in young men. *J. Appl. Physiol. (1985)* 98: 1768-1776, 2005.

53. Smith, RC, and Rutherford, OM. The role of metabolites in strength training. I. A comparison of eccentric and concentric contractions. *Eur. J. Appl. Physiol. Occup. Physiol.* 71: 332-336, 1995.

54. Thompson, SG, and Sharp, SJ. Explaining heterogeneity in meta-analysis: a comparison of methods. *Stat. Med.* 18: 2693-2708, 1999.

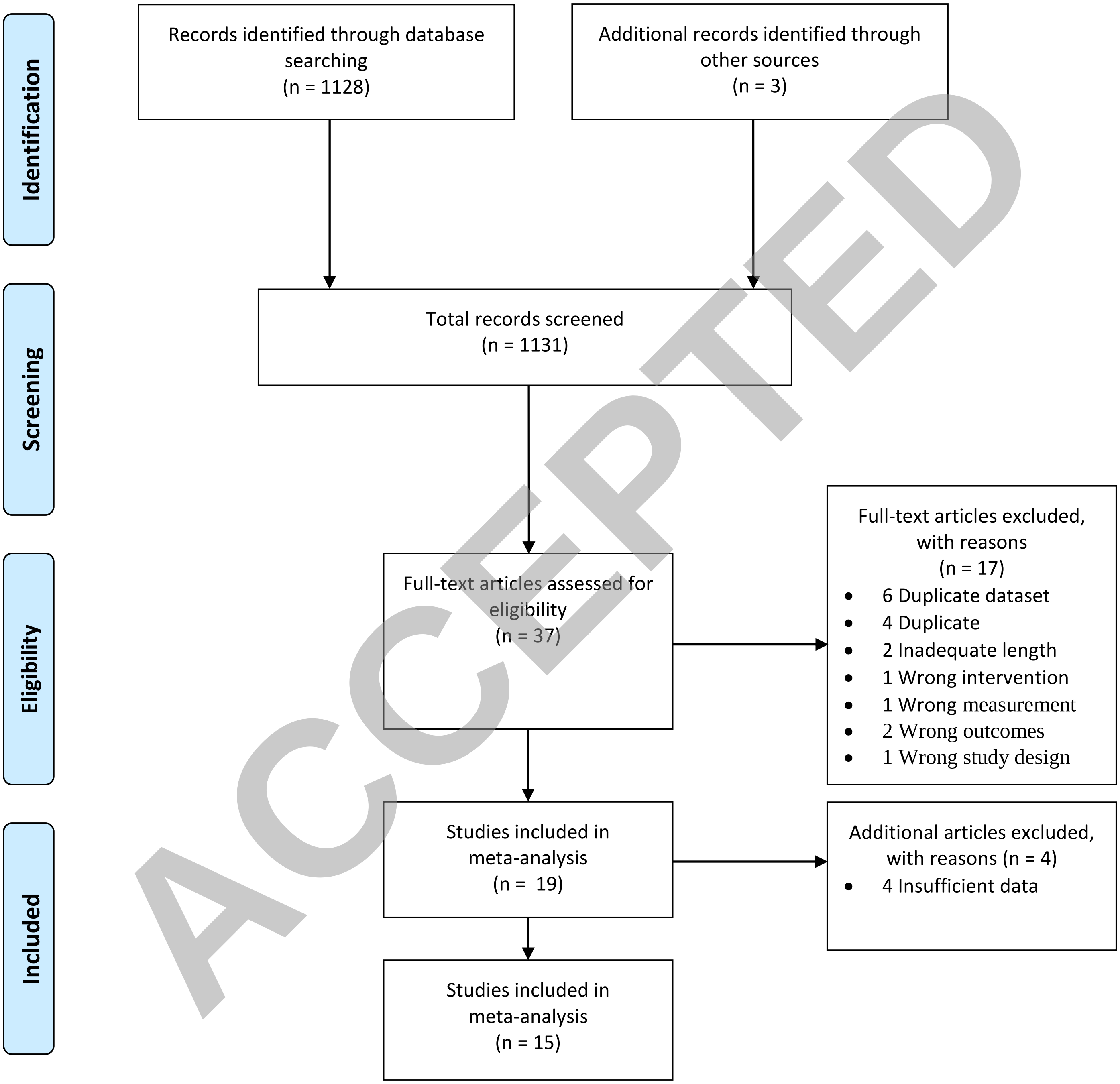
55. Timmins, RG, Ruddy, JD, Presland, J, Maniar, N, Shield, AJ, Williams, MD, and Opar, DA. Architectural Changes of the Biceps Femoris Long Head after Concentric or Eccentric Training. *Med. Sci. Sports Exerc.* 48: 499-508, 2016.

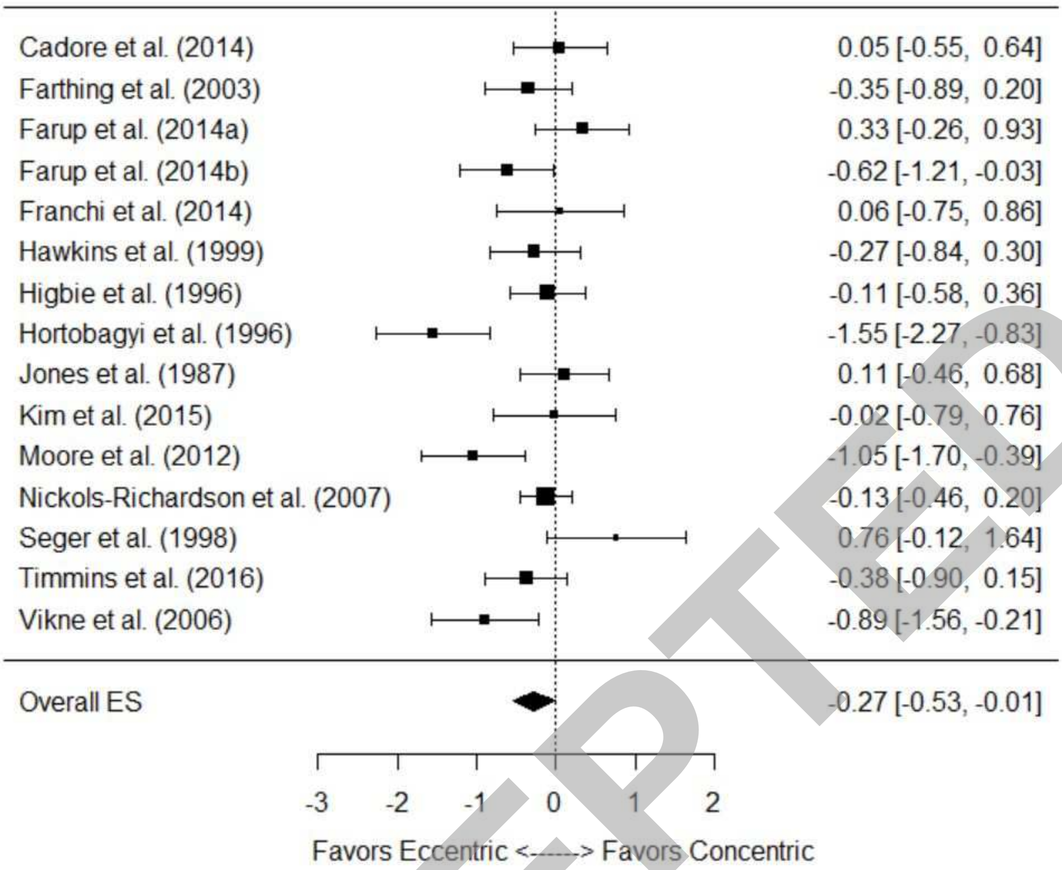
56. Tipton, E. Small sample adjustments for robust variance estimation with meta-regression. *Psychol. Methods* 20: 375-393, 2015.

57. Vikne, H, Refsnes, PE, Ekmark, M, Medbo, JI, Gundersen, V, and Gundersen, K. Muscular performance after concentric and eccentric exercise in trained men. *Med. Sci. Sports Exerc.* 38: 1770-1781, 2006.

58. Weiss, LW, Coney, HD, and Clark, FC. Gross measures of exercise-induced muscular hypertrophy. *J. Orthop. Sports Phys. Ther.* 30: 143-148, 2000.

Figure 1


Identification
Screening
Eligibility
Included
Records identified through database searching (n = 1128)
Additional records identified through other sources (n = 3)
Total records screened (n = 1131)
Full-text articles assessed for eligibility (n = 37)
Full-text articles excluded, with reasons (n = 17)
• 6 Duplicate dataset
• 4 Duplicate
• 2 Inadequate length
• 1 Wrong intervention
• 1 Wrong measurement
• 2 Wrong outcomes
• 1 Wrong study design
Studies included in meta-analysis (n = 19)
Additional articles excluded, with reasons (n = 4)
• 4 Insufficient data
Studies included in meta-analysis (n = 15)


Cadore et al. (2014) 0.05 [-0.55, 0.64]
Farthing et al. (2003) -0.35 [-0.89, 0.20]
Farup et al. (2014a) 0.33 [-0.26, 0.93]
Farup et al. (2014b) -0.62 [-1.21, -0.03]
Franchi et al. (2014) 0.06 [-0.75, 0.86]
Hawkins et al. (1999) -0.27 [-0.84, 0.30]
Higbie et al. (1996) -0.11 [-0.58, 0.36]
Hortobagyi et al. (1996) -1.55 [-2.27, -0.83]
Jones et al. (1987) 0.11 [-0.46, 0.68]
Kim et al. (2015) -0.02 [-0.79, 0.76]
Moore et al. (2012) -1.05 [-1.70, -0.39]
Nickols-Richardson et al. (2007) -0.13 [-0.46, 0.20]
Seger et al. (1998) 0.76 [-0.12, 1.64]
Timmins et al. (2016) -0.38 [-0.90, 0.15]
Vikne et al. (2006) -0.89 [-1.56, -0.21]
Overall ES -0.27 [-0.53, -0.01]
-3
-2
-1
0
1
2
Favors Eccentric <------> Favors Concentric