The effects of eccentric versus concentric resistance training on muscle strength and mass in healthy adults: a systematic review with meta-analysis

M Roig,[1,2] K O'Brien,[3] G Kirk,[1] R Murray,[1] P McKinnon,[1] B Shadgan,[2,4] W D Reid[1,2]

[1] Department of Physical Therapy, University of British Columbia, Vancouver, Canada; [2] Muscle Biophysics Laboratory, University of British Columbia, Vancouver, Canada; [3] Department of Physical Therapy, University of Toronto, Toronto, Canada; [4] Experimental Medicine, University of British Columbia, Vancouver, Canada

Correspondence to: Dr M Roig, Muscle Biophysics Laboratory, University of British Columbia, Vancouver, Canada V5Z 1L8; markredj@interchange.ubc.ca

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ABSTRACT

The aim of this systematic review was to determine if eccentric exercise is superior to concentric exercise in stimulating gains in muscle strength and mass. Meta-analyses were performed for comparisons between eccentric and concentric training as means to improve muscle strength and mass. In order to determine the importance of different parameters of training, subgroup analyses of intensity of exercise, velocity of movement and mode of contraction were also performed. Twenty randomised controlled trials studies met the inclusion criteria. Meta-analyses showed that when eccentric exercise was performed at higher intensities compared with concentric training, total strength and eccentric strength increased more significantly. However, compared with concentric training, strength gains after eccentric training appeared more specific in terms of velocity and mode of contraction. Eccentric training performed at high intensities was shown to be more effective in promoting increases in muscle mass measured as muscle girth. In addition, eccentric training also showed a trend towards increased muscle cross-sectional area measured with magnetic resonance imaging or computerised tomography. Subgroup analyses suggest that the superiority of eccentric training to increase muscle strength and mass appears to be related to the higher loads developed during eccentric contractions. The specialised neural pattern of eccentric actions possibly explains the high specificity of strength gains after eccentric training. Further research is required to investigate the underlying mechanisms of this specificity and its functional significance in terms of transferability of strength gains to more complex human movements.

Resistance training is widely utilised by many facets of the population as a method of inducing gains in muscular strength with the goal of enhancing athletic performance, preventing injuries and maintaining a healthy lifestyle. Resistance programmes incorporate the use of static and dynamic muscle actions under the tension of an external load. During static actions, muscle is actively held at a fixed fibre length. In contrast, dynamic muscle actions can be divided into concentric actions, involving the shortening of muscle fibres, and eccentric actions, consisting of the active lengthening of the muscle fibres. Based on the specificity principle of strength training,[1] it has been postulated that eccentric and concentric actions provide a different stimulus to the muscle and, therefore, could produce different adaptations.[2]

When performed in isolation, eccentric muscle actions have shown to possess several distinct physiological properties as compared with concentric actions. For example, different neurological patterns have been observed between these two types of muscle contractions.[3] Compared with concentric actions, eccentric actions are characterised by a broader and faster cortical activity as movements are being executed;[4] inversed motor unit activation pattern;[5] increased cross-education effect;[6] faster neural adaptations secondary to resistance training;[7] attenuated muscle sympathetic nerve activity;[8] reduced electromyography (EMG) amplitude at similar force levels;[9] and greater EMG signal prior to the onset of movement.[10]

From a mechanical perspective, muscles are capable of achieving higher absolute forces when contracting eccentrically as compared with concentrically.[11–13] As increases in muscular strength are thought to be proportional to the magnitude of force developed,[14] it has been postulated that resistance training including eccentric contractions could stimulate greater adaptations compared with focusing only on concentric training.[15] In addition, given the decreased fatigability,[16] lower cardiopulmonary responses[17–22] and increased metabolic efficiency[23–25] associated with eccentric contractions, one could also theoretically train at a given workload at a reduced metabolic expense and for an increased duration of time. For example, a protocol consisting of eccentric cycling has shown greater strength gains and muscle hypertrophy compared with concentric training at the same metabolic intensity.[26] The ability to provide equal or enhanced strengthening at a minimal energy cost could theoretically be of great benefit to those groups characterised by a low tolerance to exercise such as older adults[27 28] and patients with chronic health conditions.[29] However, because unaccustomed eccentric exercise tends to produce transient muscle damage, soreness and force impairments,[30] especially in older adults,[31] the application of this type of exercise in these groups requires extreme caution.

While a significant amount of research has been generated on the topic of comparing the effectiveness of eccentric and concentric resistance programmes, there has yet to be a systematic review performed to summarise the results of these studies and adequately assess their scientific rigor. Three main methodological barriers have limited comparisons of eccentric versus concentric training towards inducing gains in muscle strength and mass: eccentric and concentric actions are cyclically repeated during normal human movements, and so it is difficult to isolate one muscle contraction from the other;[32] muscles are capable of achieving higher absolute forces during eccentric contractions,[11–13] and so, even using the same loads, the relative intensity at which muscles are trained during each of these contractions can differ substantially; gains in strength tend to be specific to the velocity of movement and mode of contraction used during the training process.[1] To circumvent these limitations, we performed a systematic review including only training studies comparing concentric and eccentric contractions performed separately. In addition, the relative training intensity and the matching or mismatching of testing and training in terms of velocity of movement and mode of contraction were factorised into the meta-analysis.

The primary aim of this systematic review was to determine if eccentric training is superior to concentric training in stimulating gains in strength. Although initial gains of strength are mainly produced by neurological adaptations,[33] over longer durations, increases in strength are strongly correlated to adaptations in muscle mass.[34–36] Therefore, the secondary aim of this review was to determine if eccentric training is superior to concentric training in stimulating gains in muscle mass. The understanding of the distinct physiological properties and potential training adaptations inherent with either eccentric or concentric actions could be utilised to develop more effective training programmes in the fields of exercise science and rehabilitation.

METHODS

Search strategy

Two reviewers performed electronic searches on SPORTDiscus, EMBASE, MEDLINE, CINAHL, PEDro and the Cochrane Controlled Trial Register. The last search was performed in March 2008. The searches were language-restricted to English, and a search filter containing medical subject headings (MeSH) terms was applied. A primary search including the terms "eccentric training," "eccentric contraction," "excentric contraction," "eccentric exercise," "lengthening contraction," "negative work" and "concentric training," "concentric contraction," "concentric exercise," "shortening contraction," "positive work" was performed. These search terms were chosen because they have been traditionally used to describe eccentric and concentric exercise, respectively.[37] The results of this primary search were then combined with the following terms: "strength," "force," "hypertrophy" and "muscle mass." Additionally, reference lists of included articles were screened using the same criteria as applied to the initial citation search.

Selection

Studies were included in the systematic review if they: were randomised controlled trials (RCTs) or clinical controlled trials (CCTs) published in peer-reviewed journals; had study participants who were healthy adults aged 18–65 years; had comparison of eccentric and concentric training programmes performed separately (eg, isokinetic dynamometer); had training programmes that lasted at least 4 weeks with a minimum frequency of 2 days per week;[38] had incorporated one or more of the following outcome measures, muscle strength and muscle mass; and had full text available.

Studies were excluded if they: did not meet the minimum requirements of an experimental study design (eg, case reports); had participants with any pathology; did not compare eccentric and concentric training performed separately (eg, eccentric cycling or isotonic training involving both muscle actions); did not meet the minimum requirements regarding training design (eg, duration or frequency); did not include at least one of the above-mentioned outcomes; did not have a washout period greater than 1 month following training with alternate muscle actions or contralateral limbs (ie, studies with a potential crossover effect between limbs);[39] or were not written in English.

Based on the inclusion and exclusion criteria, two independent reviewers screened citations of potentially relevant publications. If the citation showed any potential relevance, it was screened at the abstract level. When abstracts indicated potential inclusion, full text articles were reviewed for inclusion using a standardised screening form to determine consensus. A third-party consensus meeting was held if two reviewers were not able to reach agreement on inclusion of an article.

Quality assessment

Two reviewers independently performed quality assessments of included studies, and disagreements were resolved during a consensus meeting. Methodological quality was assessed using the PEDro scale[40] because it had previously shown good reliability.[41 42] This scale is an adaptation of the Delphi list for quality assessment of RCTs for conducting systematic reviews,[43] and it is based on the following 11 items regarding scientific rigor: eligibility criteria, random allocation, concealed allocation, follow-up, baseline comparability, blinded subjects, blinded therapists, blinded assessors, intention-to-treat, between-group analysis, and both point and variability measures. All except one item (eligibility criteria) were used to calculate the final score (maximum 10 points). This item was excluded because it affects external but not internal or statistical validity.[40] Although PEDro does not provide specific instructions to classify studies according to the score obtained, the following criteria were established by consensus: a study was considered of high quality when the score was greater than 5, of moderate quality when the score was 5 or 4, and of low quality when the study was scored 3 or less. These criteria have been used elsewhere.[29] Inter-rater reliability was evaluated using the intraclass correlation coefficient (ICC,2)[44] calculated on the total score.

Data management and statistical analysis

When studies were similar in terms of parameters of training protocols and measurement of outcomes, meta-analyses were performed with RevMan 5.0 (free to download at http://www.cc-ims.net/RevMan/download.htm) to determine the effectiveness of eccentric versus concentric training in increasing muscle strength and mass. Data were pooled in different subgroups according to three main parameters: mode of contraction during testing (concentric, eccentric, isometric), intensity of training (eccentric training intensity was higher or comparable with intensity of concentric training) and velocities of movement during testing and training (velocity of testing and training were matched or mismatched).

Outcomes were analysed as continuous outcomes using a random effects model to calculate a weighted mean difference (WMD) and 95% CI. A p value less than 0.05 indicated a statistical significance for an overall effect, and a p value less than 0.1 indicated statistical significance for heterogeneity between studies.[45] When the articles selected did not provide sufficient data for the analysis, authors were contacted to obtain relevant data. Studies were not included in the meta-analyses if summary statistics of means, standard deviations and number of participants allocated in each group were not available.

RESULTS

Figure 1 shows a flow chart with the different phases of the search and selection of the studies included in the review. The initial search of electronic databases identified 1954 titles, of which 276 were suitable for abstract review. Screening the references of these articles yielded a further 18 citations eligible for abstract review, one of which met the inclusion criteria. Following a review of titles and abstracts, 66 full text articles were reviewed. When exclusion criteria were applied, only 20 studies satisfied the criteria to be included in the review.[2 7 46–63] The main reasons for exclusion were: eccentric and concentric exercises not performed separately (n = 26); potential crossover effect (n = 9); participants with clinical conditions enrolled (n = 4); not published in a peer-review journal (n = 1); age of the participants (n = 2); and insufficient or incomplete description of the parameters of training (n = 4).

Quality assessment

A detailed description of the PEDro scores obtained is shown in table 1. The mean methodological quality of the studies was 5.4 (SD 1.14) out of 10, with scores ranging from 4 to 7. Ten studies were categorised as high quality, and the remaining 10 studies had a moderate methodological quality. The most common flaws were the lack of blinding of participants, therapists and assessors. It should be taken into account, however, that

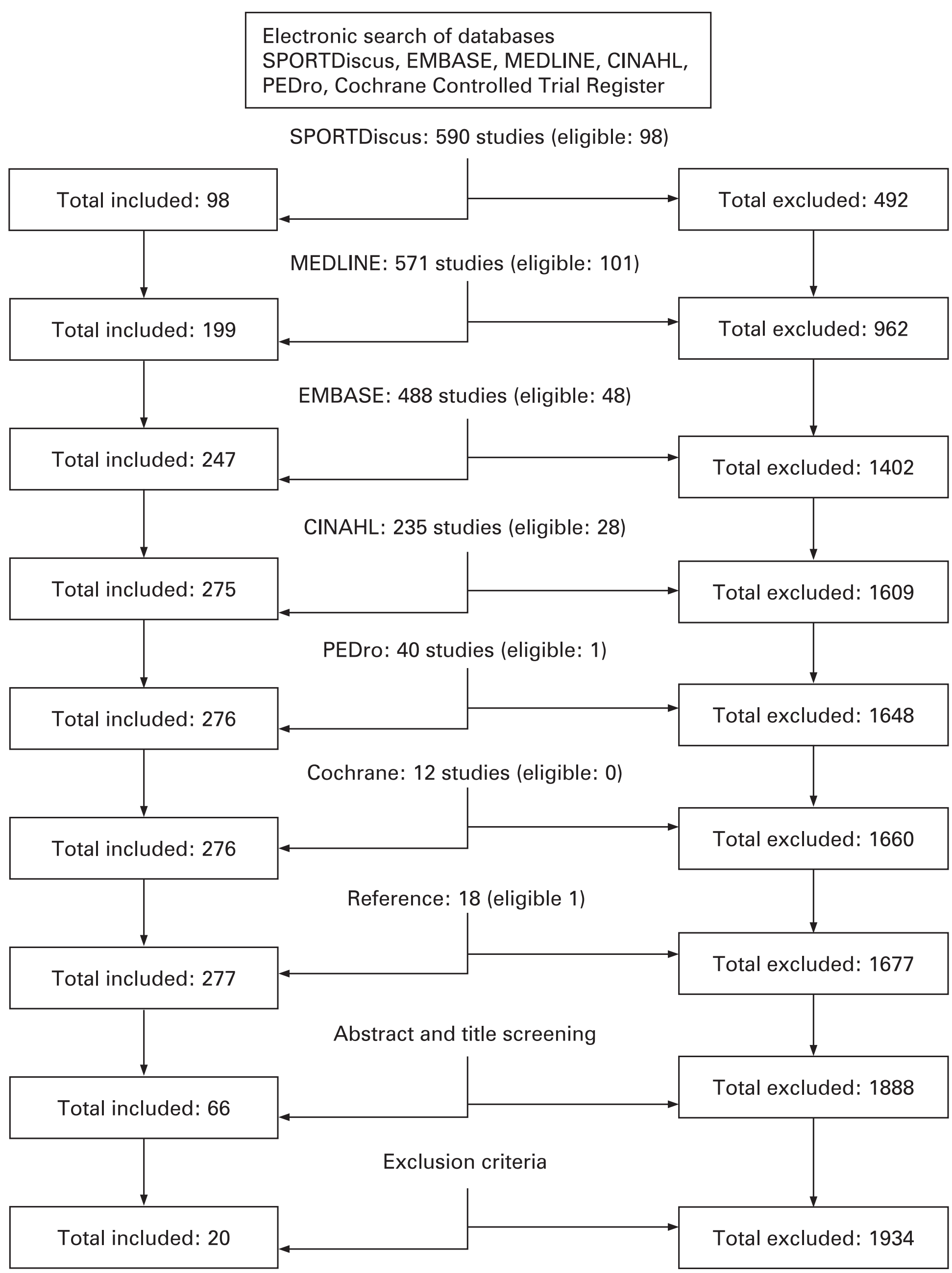

Figure 1 Flow chart illustrating the different phases of the search and selection of the studies included in the review.

Table 1 Detailed description of the PEDro scores

Study (year)	Random allocation	Concealed allocation	Baseline comparability	Assessors blinded	Participants blinded	Therapists blinded	Follow-up	Intention-to-treat analysis	Between group analysis	Points estimates and variability	Total score
Vikne *et al*[46]	√	√							√	√	4
Pavone and Moffat[63]			√				√		√	√	4
Nickols-Richardson *et al*[47]	√	√	√				√	√	√	√	7
Miller *et al*[48]	√		√				√	√	√	√	6
Komi and Buskirk[49]	√	√	√				√	√	√	√	7
Hortobagyi *et al*[7]		√	√				√	√	√	√	6
Hortobagyi *et al*[2]		√	√				√	√	√	√	6
Hortobagyi *et al*[50]	√		√				√	√	√	√	6
Higbie *et al*[51]	√		√				√		√	√	5
Ben-Sira *et al*[62]	√		√						√	√	4
Raue *et al*[52]	√	√	√				√	√	√	√	7
Mayhew *et al*[53]	√						√	√	√	√	5
Mont *et al*[54]			√				√		√	√	4
Duncan *et al*[55]							√	√	√	√	4
Ellenbecker *et al*[56]	√	√	√				√	√	√	√	7
Tomberlin *et al*[57]	√	√					√	√			4
Seger *et al*[58]	√		√				√	√	√	√	6
Seger and Thorstensson [59]	√		√				√	√	√	√	6
Blazevich *et al*[60]	√		√				√		√	√	5
Farthing and Chilibeck[61]	√		√				√		√	√	5

blinding of participants in these studies is a difficult requisite to satisfy. Furthermore, allocation was not concealed in 12 of the studies evaluated. Inter-rater reliability was significantly high (ICC, 2 = 0.91).

Characteristics of participants and interventions

The main characteristics of the studies included in the review regarding participants, interventions and results are illustrated in table 2. After adjusting for dropouts, the total number of participants in the studies included was 678. Of these 678 participants, 237 and 234 performed eccentric and concentric exercise respectively. In addition, a crossover design study included 24 subjects that performed both eccentric and concentric exercise.[61] The rest of participants (n = 183) served as controls or performed another type of exercise. Although demographic data were not provided for all studies, the estimated mean age of the eccentric and concentric groups was 23.51 (2.38) and 23.33 (2.28), respectively. The distribution of gender among studies was not proportional, with a total of 254 women and 179 men in both the eccentric and concentric groups. Gender was not provided for 60 participants in the eccentric and concentric training groups of two studies.[56 57]

Training interventions ranged from 4 to 25 weeks with a mean frequency of 2.97 (0.47) sessions per week. The total number of repetitions per session was variable (10 to 80) depending on the study. In 17 studies, exercise was performed with an isokinetic device that allowed for the control of angular velocity.[2 7 47–61] In two studies that used a dynamic device for training, spotters were used to isolate eccentric and concentric contractions (eg, the participant performed the eccentric part of the movement, and a spotter lifted the weight during the concentric part).[62 63] A third study used a custom-made device especially designed for the experiment.[46] The muscle groups trained were knee extensors,[2 7 47 48 50–53 55 57–60 62 63] elbow flexors[46 47 49 61] and extensors,[47] and the rotator cuff.[54 56] Given the fact that muscles are capable of achieving higher absolute forces when contracting eccentrically as compared with concentrically,[11–13] the intensity of training was estimated to be higher for eccentric groups in 15 studies, in which participants performed maximum voluntary contractions (MVC) or submaximal voluntary contractions.[2 46–51 54–61] In contrast, four studies equated the intensity of eccentric and concentric training by taking the percentage of one repetition maximum (1 RM) performed during a concentric muscle contraction.[7 52 53 62] One study calculated the intensity of training for each group (eccentric and concentric) as the percentage of eccentric and concentric 1 RM.[63]

META-ANALYSES

Strength

Ten meta-analyses were performed on the different outcomes of strength with a maximum of up to 11 studies per analysis. Studies were categorised depending on the mode of strength measures (total, eccentric, concentric, isometric), and then further divided based on how strength was measured (average peak torque or 1 RM). Subgroup analyses were performed according to: whether eccentric training intensity was higher or comparable with concentric training; and whether velocity of testing and training were matched or mismatched. Studies in which eccentric versus concentric training was performed at a higher intensity (MVC or submaximal) were allocated to the subgroup analyses of higher eccentric intensity. In contrast, studies that equated intensity of both types of training as a percentage of the concentric 1 RM were allocated into the subgroup of comparable training intensities. To determine whether gains in strength were velocity-specific, studies were

Table 2 Characteristics of the studies included

Study	Participants*	Muscle group	Interventions	Results†
Vikne *et al*[46]	Resistance trained men (n = 17); mean age 27	Elbow flexors	12 weeks (2.5 sessions×week) 24 repetitions×session Intensity = MVC	Ecc and con training improved con strength similarly; only ecc training improved ecc strength muscle CSA and Type I and II muscle fibre areas
Pavone and Moffat[63]	Women (n = 27); mean age 29	Knee extensors	6 weeks (3 sessions×week) 30 repetitions×session Intensity = % 1RM ecc and con	No differences in isometric strength after ecc and con training
Nickols-Richardson *et al*[47]	Women (n = 70); mean age 20	Knee extensors/flexors Elbow extensors/flexors	25 weeks (3 sessions×week) 15 repetitions×session Intensity = MVC	No differences in strength and muscle fat free mass after ecc and con training
Miller *et al*[48]	Women (n = 38); mean age 20	Knee extensors	20 weeks (3 sessions×week) 15 repetitions×session Intensity = MVC	Ecc training improved more ecc strength and similarly con strength compared with con training
Komi and Buskirk[49]	Men (n = 31); mean age 19	Elbow flexors	7 weeks (4 sessions×week) Intensity = MVC	Ecc training improved more ecc strength than con training; muscle girth increased only in the ecc group
Hortobagyi *et al*[7]	Women (n = 42); mean age 21	Knee extensors	6 weeks (4 sessions×week) 32 repetitions×session Intensity = % 1RM con	Ecc training increased ecc and isom strength more than con training; con training improved con strength more than ecc training
Hortobagyi *et al*[2]	Men (n = 21); mean age 21	Knee extensors	12 weeks (3 sessions×week) 50 repetitions×session Intensity = MVC	Ecc and con training improved ecc and con strength respectively; type II muscle fibre area increased only after ecc training
Hortobagyi *et al*[50]	Men (n = 24) and women (n = 24); mean age 22	Knee extensors	12 weeks (3 sessions×week) 50 repetitions×session Intensity = MVC	Ecc and con training improved ecc and con strength respectively; ecc training improved more isometric strength than con training; type II muscle fibre area increased more after ecc compared with con training
Higbie *et al*[51]	Women (n = 54); mean age 20	Knee extensors	10 weeks (3 sessions×week) 30 repetitions×session Intensity = MVC	Ecc and con training improved ecc and con strength respectively; ecc training improved CSA more than con
Ben-Sira *et al*[62]	Women (n = 48); mean age 21	Knee extensors	8 weeks (2 sessions×week) 30 repetitions×session Intensity = % 1RM con	No differences between con and ecc training in con strength or muscle mass
Raue *et al*[52]	Sedentary men (n = 15); mean age 23	Knee extensors	4 weeks (3 sessions×week) 32 repetitions×session Intensity = % 1RM con	Only con training improved con strength; MHC isoforms did not change significantly after ecc or con training
Mayhew *et al*[53]	Women (14); men (6); mean age 24	Knee extensors	4 weeks (3 sessions×week) 50 repetitions×session Intensity = % 1RM con	Con training improved more isometric strength than con training; type II muscle fibre area increased more after con compared with ecc training
Mont *et al*[54]	Men (n = 30); mean age 33	Rotator cuff	6 weeks (3 sessions×week) 80 repetitions×session Intensity = submaximal	No differences in con or ecc strength between ecc and con training
Duncan *et al*[55]	Men (n = 48); mean age 24	Knee extensors	6 weeks (3 sessions×week) 10 repetitions×session Intensity = MVC	Ecc and con training improved ecc and con strength respectively; gains after ecc training were more mode-specific
Ellenbecker *et al*[56]	Trained; gender and age not provided (n = 22)	Rotator cuff	6 weeks (2 sessions×week) 60 repetitions×session Intensity = submaximal	Ecc training only improved con strength; con training improved con and ecc strength

Continued

Table 2 Continued

Study	Participants*	Muscle group	Interventions	Results†
Tomberlin *et al*[57]	Gender not provided (n = 63); mean age 27	Knee extensors	6 weeks (3 sessions×week) 30 repetitions×session Intensity = MVC	Ecc and con groups improved ecc and con strength respectively
Seger *et al*[58]	Trained men (n = 10); mean age 25	Knee extensors	20 weeks (3 sessions×week) 40 repetitions×session Intensity = MVC	Ecc and con training increased ecc and con muscle strength respectively; CSA was improved only after ecc training; no differences in muscle fibre characteristics between groups
Seger and Thorstensson[59]	Men (n = 10); mean age 25	Knee extensors	10 weeks (3 sessions×week) 40 repetitions×session Intensity = MVC	Ecc and con training increased ecc and con muscle strength respectively; gains after ecc training were more mode- and velocity-specific
Blazevich *et al*[60]	Men (n = 14) and women (n = 16); mean age 23	Knee extensors	10 weeks (3 sessions×week) 30 repetitions×session Intensity = MVC	Con strength was improved more after con training; no differences in muscle thickness after either training groups was found
Farthing and Chilibeck[61]	Men (n = 12) and women (n = 22); mean age 21	Elbow flexors	16 weeks; (3 sessions×week) 32 repetitions×session Intensity = MVC	Fast ecc training was more effective to increase ecc and con strength than con or slow ecc training; fast ecc training was more effective to increase muscle thickness than con or slow ecc training

*Number of participants at the end of the studies.
†Only results for the outcomes of interest are provided.
% 1 RM: percentage repetition maximum; CSA, cross-sectional area; con, concentric; ecc, eccentric; MVC, maximal voluntary contraction.

allocated into subgroups that had matched or mismatched velocities of testing and training.

Total strength

Since human movements result from the combination of different muscle actions, total strength was calculated as the average of the strength gains (average peak torque or 1 RM) of the three different types of muscle contractions used while testing (average of concentric+eccentric+isometric torque). The meta-analyses of all participants in 15 studies, regardless of whether they trained at higher or equal eccentric than concentric training intensities, showed no difference in improved total strength as reflected by average peak torque (WMD 3.71 N.m; 95% CI −0.27 to 7.70; p = 0.07; n = 333) (fig 2) and 1 RM (WMD 1.07 kg; 95% CI −0.22 to 2.37; p = 0.10; n = 72) (table 3). However, a meta-analysis of a subgroup of participants who trained at higher eccentric than concentric intensity showed significantly greater increases in total strength of 4.24 N.m (95% CI 0.24 to 8.24; p = 0.04; n = 313) (fig 2) and 1.80 kg (95% CI 0.50 to 3.10; p = 0.007; n = 38) (table 3). In contrast, when the intensity of eccentric and concentric training was comparable, no significant differences in the improvement of total strength after training were observed (fig 2; table 3).

Meta-analyses of nine studies that used matched or mismatched testing and training velocities showed greater total strength gains after eccentric training with a WMD of 7.84 N.m (95% CI 3.14 to 12.54; p = 0.001; n = 257) (fig 3). In addition, subgroup analysis of studies that matched testing and training velocity demonstrated greater average peak torque gains after eccentric compared with concentric training (WMD 8.66 N.m 95% CI 3.95 to 13.37; p = 0.0003; n = 237) (fig 3). In contrast, subgroup analysis of studies that mismatched velocity of testing and training found no significant difference (p = 0.74) in total strength gains between the types of training (fig 3).

Eccentric strength

Meta-analyses of those training at a higher eccentric than concentric intensity showed significantly greater increases in eccentric peak torque of 13.71 N.m (95% CI 5.56 to 21.86; p = 0.001; n = 294) (fig 4) and 1 RM of 4.11 kg (95% CI 1.47 to 6.76; p = 0.002; n = 38) (table 3). No studies examined the outcome of eccentric torque after comparable intensities of eccentric and concentric training.

The meta-analyses of all participants in seven studies, regardless of matched or mismatched testing and training velocities, demonstrated a significantly greater increase in eccentric strength of 20.70 N.m (95% CI 10.56 to 30.85; p<0.0001; n = 257) (fig 5), after eccentric compared with concentric training. A subgroup meta-analysis of studies that matched velocities of testing and training showed a significantly greater increase in eccentric strength of 23.56 N.m (95% CI 12.22 to 34.91; p<0.0001; n = 237) (fig 5) after eccentric training compared with concentric training. Subgroup analysis of studies that mismatched velocities of testing and training found no significant difference (p = 0.54) in eccentric strength gains after the two types of training (fig 5).

Concentric strength

The meta-analyses showed no significant differences in concentric strength gains of participants training eccentrically compared with concentrically regardless of the overall or subgroup analyses. Subgroup analysis found no difference in change in concentric strength after training at higher eccentric versus concentric intensities as measured by average peak

Study or subgroup	Eccentric training Mean	Eccentric training SD	Eccentric training Total	Concentric training Mean	Concentric training SD	Concentric training Total
1.1.1 Subgroup: higher eccentric vs concentric training intensity						
Blazevich 2007	33.6	22.8	11	46.8	22.8	10
Ellenbecker 1988	3.6	7.2	12	7.2	6.8	10
Farthing 2003	6.8	5.1	24	1.4	5	24
Higbie 1996	19.7	5.4	19	13.4	8.5	16
Miller 2006	24	8	17	15	5.8	21
Nickols-Richardson 2007	25	10.6	33	15.8	5	37
Pavone 1985	3.4	1.8	11	4.3	1.9	8
Seger 1998	38.2	23.4	5	10.6	11.9	5
Seger 2005	21.2	11.2	5	20.4	10.6	5
Tomberlin 1991	30.3	37.8	21	21.2	25.6	19
Subtotal (95% CI)			158			155
Heterogeneity: Tau² = 25.09; χ²=52.37, df=9 (p<0.00001); I²=83%						
Test for overall effect: Z=2.08 (p=0.04)						
1.1.2 Subgroup: comparable eccentric and concentric training intensities						
Mayhew 1995	20	22.1	10	35	27.6	10
Subtotal (95% CI)			10			10
Heterogeneity: not applicable						
Test for overall effect: Z= 1.34 (p = 0.18)						
Total (95% CI)			168			165
Heterogeneity: Tau² = 25.74; χ² = 54.78, df=10 (p < 0.00001); I²=82%						
Test for overall effect: Z=1.83 (p=0.07)						
Test for subgroup differences: χ² = 2.40, df=1 (p = 0.12), I²=58.4%						

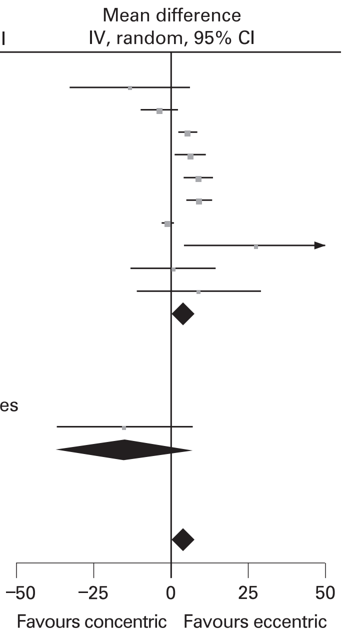

Figure 2 Forest plot of meta-analyses showing comparison of eccentric versus concentric training at different intensities on total strength measured as average peak torque (N.m). Total strength is calculated as the average of eccentric, concentric and isometric strength. Subgroup analyses were performed on studies with higher or comparable intensities of eccentric versus concentric training.

torque (WMD −3.34 N.m; 95% CI −8.30 to 1.62; p = 0.19; n = 294) (fig 6) or at comparable or different training intensities as reflected by concentric strength gains of 1 RM (WMD 0.10 kg; 95% CI −1.23 to 1.43; p = 0.88; n = 72) (table 3). The CIs of meta-analyses for concentric strength as measured by the average peak torque indicated a tendency towards a greater improvement among those training concentrically compared with eccentrically (fig 6).

Meta-analyses demonstrated no difference in concentric strength gains among participants who were exercising eccentrically compared with concentrically for all three subgroup analyses at matched or mismatched velocities of testing and training (WMD −3.81 N.m; 95% CI −9.31 to 1.69; p = 0.17; n = 257), matched velocities of testing and training only (WMD −3.97 N.m; 95% CI −10.00 to 2.07; p = 0.20; n = 237) and mismatched velocities of testing and training only (WMD −2.36 N.m; 95% CI −18.46 to 13.73; p = 0.77; n = 20) (fig 7). However, CIs indicated a trend towards greater improvements in concentric strength among those exercising concentrically compared with eccentrically for each of these analyses (fig 7).

Study or subgroup	Eccentric training Mean	Eccentric training SD	Eccentric training Total	Concentric training Mean	Concentric training SD	Concentric training Total
2.1.1 Subgroup: matched testing and training velocities						
Blazevich 2007	33.6	22.8	11	46.8	22.8	10
Farthing 2003	6.8	5.1	24	1.4	5	24
Miller 2006	24	8	17	15	5.8	21
Nickols-Richardson 2007	25	10.6	33	15.8	5	37
Seger 1998	61.5	24.4	5	16	17	5
Seger 2005	39.5	11.4	5	23.5	9.9	5
Tomberlin 1991	30.3	37.8	21	21.2	25.6	19
Subtotal (95% CI)			116			121
Heterogeneity: Tau² = 18.34; χ²=17.29, df=6 (p=0.008); I²=65%						
Test for overall effect: Z=3.61 (p=0.0003)						
2.1.2 Subgroup: mismatched testing and training velocities						
Seger 1998	26.5	23	5	8.2	12.6	5
Seger 2005	12.2	11.2	5	18.9	10.9	5
Subtotal (95% CI)			10			10
Heterogeneity: Tau² =219.30; χ² = 3.35, df=1 (p=0.07); I²=70%						
Test for overall effect: Z=0.33 (p = 0.74)						
Total (95% CI)			126			131
Heterogeneity: Tau² = 21.74; χ² = 22.18, df=8 (p = 0.005); I²=64%						
Test for overall effect: Z=3.27 (p=0.001)						
Test for subgroup differences: χ² = 1.54, df=1 (p=0.21), I²=35.1%						

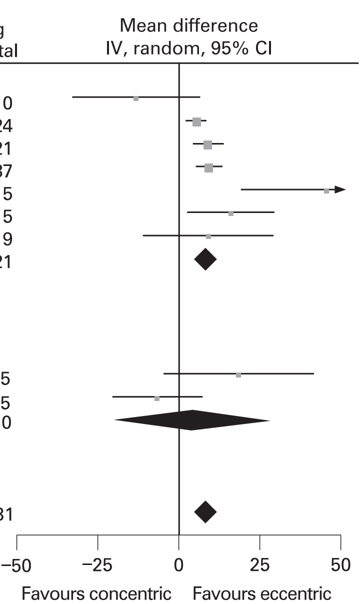

Figure 3 Forest plot of meta-analyses showing comparison of eccentric versus concentric training at matched or mismatched testing and training velocities on total strength measured as average peak torque (N.m). Total strength is calculated as the average of eccentric, concentric and isometric strength. Subgroup analyses were performed on studies categorised according to matched or mismatched testing and training velocities.

Study or subgroup	Eccentric training Mean	SD	Total	Concentric training Mean	SD	Total
1.2.1 Subgroup: higher eccentric vs concentric training intensity						
Blazevich 2007	45.4	24.8	11	50.1	26.9	10
Ellenbecker 1988	0.3	10.1	12	5.9	7.6	10
Farthing 2003	5.9	5.7	24	1.8	5.9	24
Higbie 1996	34	6.6	19	12.5	9.6	16
Miller 2006	34	10.6	17	14	7.5	21
Nickols-Richardson 2007	35.5	10.6	33	15.5	6.1	37
Seger 1998	47.3	25.9	5	4.3	13.5	5
Seger 2005	34.5	14.2	5	22.7	14	5
Tomberlin 1991	52.7	50.8	21	25.5	28.7	19
Subtotal (95% CI)			147			147

Heterogeneity: Tau^2 = 113.06; χ^2=85.76, df=8 (p<0.00001); I^2=91%
Test for overall effect: Z=3.30 (p=0.0010)

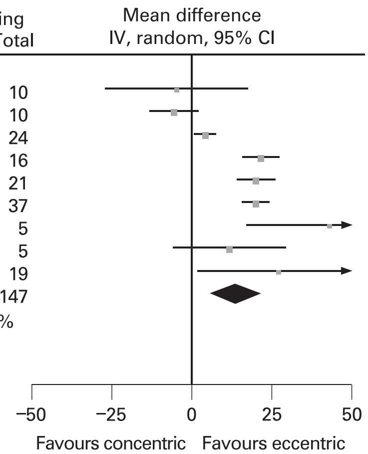

Figure 4 Forest plot of meta-analysis showing comparison of eccentric versus concentric exercise on eccentric strength measured as average peak torque (N.m). Since studies only included groups where eccentric training was performed at a higher intensity than concentric training, no subgroup analysis was performed on comparisons of eccentric and concentric training at equal intensities.

Isometric strength

Meta-analyses showed no difference in isometric strength gains between participants exercising eccentrically compared with those exercising concentrically at different or equal training intensities (WMD −3.54 N.m; 95% CI −14.33 to 7.24; p = 0.52; n = 39).

Muscle mass

Nine of the 20 included studies measured muscle mass.[46 47 49 51–53 58 60 62] Two meta-analyses were performed with a combination of up to five studies (table 4). Subgroup analyses were performed for training intensity on studies that used higher eccentric than concentric training intensity. Meta-analyses on all studies and the subgroup analysis demonstrated significantly greater increases in muscle mass as measured by girth by 0.46 and 0.49 cm, respectively, among participants exercising eccentrically compared with participants exercising concentrically (table 4). The CIs for cross-sectional area also indicated a modest trend towards a greater improvement in muscle mass among participants exercising eccentrically at higher levels of intensities compared with concentric training intensity (WMD 1.49 cm^2; 95% CI −1.32 to 4.31; p = 0.30; n = 73) (table 4).

DISCUSSION

Strength

Meta-analyses of strength outcomes indicate that regardless of velocity of testing and training, eccentric training performed at high intensities is associated with greater improvements in total and eccentric strength compared with concentric training. Furthermore, when velocity of testing and training were incorporated into the meta-analyses, strength gains from

Study or subgroup	Eccentric training Mean	SD	Total	Concentric training Mean	SD	Total
2.2.1 Subgroup: matched testing and training velocities						
Blazevich 2007	45.4	24.8	11	50.1	26.9	10
Farthing 2003	5.9	5.7	24	1.8	5.9	24
Miller 2006	34	10.6	17	14	7.5	21
Nickols-Richardson 2007	35.5	10.6	33	15.5	6.1	37
Seger 1998	90	30.3	5	0	21.1	5
Seger 2005	72	16	5	26	13.2	5
Tomberlin 1991	52.7	50.8	21	25.5	28.7	19
Subtotal (95% CI)			116			121
Heterogeneity: Tau^2 =168.15; χ^2=82.62, df=6 (p<0.00001); I^2=93%						
Test for overall effect: Z=4.07 (p<0.0001)						
2.2.2 Subgroup: mismatched testing and training velocities						
Seger 1998	26	23.8	5	−1.5	14.45	5
Seger 2005	15.8	13.4	5	21	14.4	5
Subtotal (95% CI)			10			10
Heterogeneity: Tau^2 =418.43; χ^2 = 4.60, df=1 (p=0.03), I^2=78%						
Test for overall effect: Z=0.61 (p = 0.54)						
Total (95% CI)			126			131

Heterogeneity: Tau^2 = 166.39; χ^2 = 88.15, df=8 (p < 0.00001); I^2=91%
Test for overall effect: Z=4.00 (p<0.0001)
Test for subgroup differences: χ^2 = 0.93, df=1 (p=0.34), I^2=0%

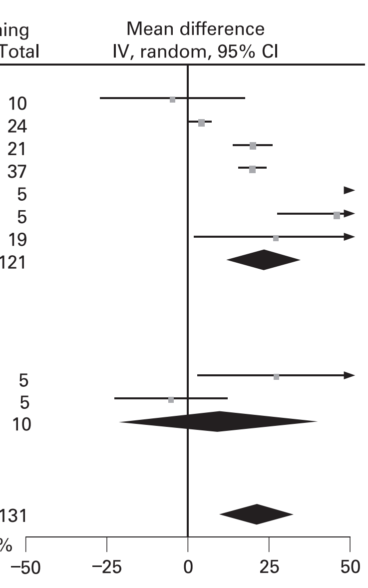

Figure 5 Forest plot of meta-analyses showing comparison of eccentric versus concentric training on eccentric strength measured as average peak torque (N.m). Subgroup analyses were performed on studies with matched or mismatched velocities of testing and training.

Study or subgroup	Eccentric training Mean	SD	Total	Concentric training Mean	SD	Total
1.3.1 Subgroup: higher eccentric vs concentric training intensity						
Blazevich 2007	21.7	20.8	11	43.5	18.7	10
Ellenbecker 1988	6.9	4.4	12	8.6	6	10
Farthing 2003	7.7	4.4	24	1	4.1	24
Higbie 1996	5.4	4.2	19	14.4	7.4	16
Miller 2006	14	5.4	17	16	4.2	21
Nickols-Richardson 2007	14.5	10.6	33	16	3.9	37
Seger 1998	29	20.9	5	17	10.3	5
Seger 2005	8	8.25	5	18.2	7.2	5
Tomberlin 1991	8	24.8	21	16.9	22.5	19
Subtotal (95% CI)			147			147

Heterogeneity: Tau^2 = 40.22; χ^2=64.58, df=8 (p<0.00001); I^2=88%
Test for overall effect: Z=1.32 (p=0.19)

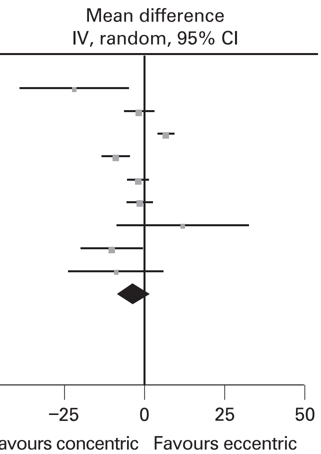

Figure 6 Forest plot with meta-analysis showing comparison of eccentric versus concentric exercise on concentric strength measured as average peak torque (N.m). A subgroup analysis could only be performed for studies with higher intensities of eccentric versus concentric training.

eccentric exercise tended to be more velocity-specific. In other words, compared with concentric exercise, strength gains after eccentric exercise were more pronounced when the velocity of testing and training was the same. Despite the difference not being significant, concentric training showed a trend towards a greater improvement of concentric strength compared with eccentric training. Taken together, these results suggest that eccentric is superior to concentric exercise in promoting strength gains but also that strength gains from eccentric exercise are highly specific to the mode of contraction and velocity of movement.

While previous studies have reported on the specificity of strength gains in relation to the mode of contraction,[64] our systematic review provides evidence that strength gains from eccentric training are also velocity-dependent. The high specificity of eccentric exercise has to be taken into account when gains in total strength are interpreted. The results of this review suggest that eccentric training increased more eccentric strength than concentric training increased concentric strength. Because total strength was calculated as the average of eccentric, concentric and isometric strength gains, we must consider that excessively weighted gains in eccentric strength could have influenced the measure of total strength.

Although in some studies the intensity of training was not specifically reported, we assumed that when participants were performing eccentric training at MVC, the absolute intensity was higher compared with concentric training. This estimation is based on our own experience with isokinetic training as well as previous studies showing that muscles can achieve higher absolute forces when contracting eccentrically compared with concentrically.[11–13] In contrast, when intensity between concentric and eccentric training was equated as a percentage of 1 RM during concentric training,[7 52 53 62] the intensity of eccentric training was assumed to be far below its maximum potential.

Study or subgroup	Eccentric training Mean	SD	Total	Concentric training Mean	SD	Total
2.3.1 Subgroup: matched testing and training velocities						
Blazevich 2007	21.7	20.8	11	43.5	18.7	10
Farthing 2003	7.7	4.4	24	1	4.1	24
Miller 2006	14	5.4	17	16	4.2	21
Nickols-Richardson 2007	14.5	10.6	33	16	3.9	37
Seger 1998	33	18.4	5	32	12.8	5
Seger 2005	7	6.8	5	21	6.6	5
Tomberlin 1991	8	24.8	21	16.9	22.5	19
Subtotal (95% CI)			116			121
Heterogeneity: Tau^2 = 44.23; χ^2=47.71, df=6 (p<0.00001); I^2=87%						
Test for overall effect: Z=1.29 (p=0.20)						
2.3.2 Subgroup: mismatched testing and training velocities						
Seger 1998	27	22.2	5	18	10.6	5
Seger 2005	8.5	9	5	16.8	7.4	5
Subtotal (95% CI)			10			10
Heterogeneity: Tau^2 =75.55; χ^2 = 2.02, df=1 (p =0.16); I^2=50%						
Test for overall effect: Z=0.29 (p = 0.77)						
Total (95% CI)			126			131

Heterogeneity: Tau^2 = 43.55; χ^2 = 51.62, df=8 (p < 0.00001); I^2=85%
Test for overall effect: Z=1.36 (p=0.17)
Test for subgroup differences: χ^2 = 1.89, df=1 (p=0.17), I^2=47.1%

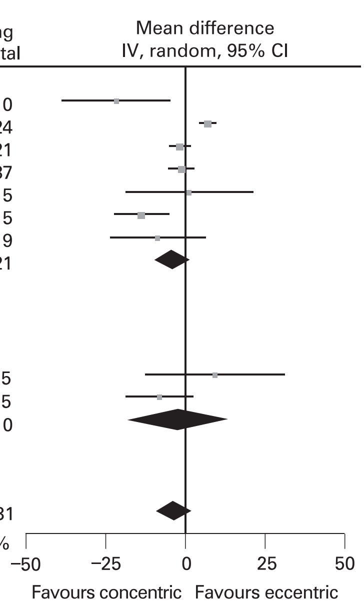

Figure 7 Forest plot with meta-analyses showing comparison of eccentric versus concentric exercise on concentric strength measured as average peak torque (N.m). Subgroup analyses were performed for studies with matched or mismatched velocities of testing and training.

Table 3 Results of meta-analyses of studies that measured strength using 1 repetition maximum (1 RM)

Outcomes	Subgroup analyses	Individual studies	N	Weighted mean difference (95% CI)	Overall effect (p value)	Heterogeneity (p value)	Interpretation
Total strength (1 RM kg)	All studies in this category: higher or comparable eccentric versus concentric training intensities	Komi and Buskirk[49] Vikne *et al*[46] Ben-Sira *et al*[62] Raue *et al*[52]	72	1.07 kg (−0.22 to 2.37)	0.10	0.07**	No difference in change in total strength among ecc compared with con trainers
	Subgroup: higher eccentric versus concentric training intensities	Komi and Buskirk[49] Vikne *et al*[46]	38	1.80 kg (0.50 to 3.10)	0.007*	0.50	Statistically significant greater increase in total strength in ecc compared with con trainers
	Subgroup: comparable eccentric and concentric training intensities	Ben-Sira *et al*[62] Raue *et al*[52]	34	−1.84 kg (−8.45 to 4.78)	0.59	0.03**	No difference in change in total strength among ecc compared with con trainers
Ecc strength (1 RM kg)	All studies in this category: higher eccentric versus concentric training intensities	Komi and Buskirk[49] Vikne *et al*[46]	38	4.11 kg (1.47 to 6.76)	0.002*	0.10	Statistically significant greater increase in ecc strength in ecc compared with con trainers
Con strength (1 RM kg)	All studies in this category: higher or comparable eccentric versus concentric training intensities	Komi and Buskirk[49] Vikne *et al*[46] Ben-Sira *et al*[62] Raue *et al*[52]	72	0.10 kg (−1.23 to 1.43)	0.88	0.04**	No difference in change in con strength among ecc compared with con trainers
	Subgroup: higher eccentric versus concentric training intensities	Komi and Buskirk[49] Vikne *et al*[46]	38	−0.07 kg (−1.44 to 1.30)	0.92	0.25	No difference in change in con strength among ecc compared with con trainers
	Subgroup: comparable eccentric and concentric training intensities	Ben-Sira *et al*[46] Raue *et al*[62]	34	−1.84 kg (−8.45 to 4.78)	0.59	0.03**	No difference in change in con strength among ecc compared with con trainers

con, concentric; ecc, eccentric; N, number of participants.
*Statistically significant for overall effect ($p<0.05$).
**Statistically significant for heterogeneity ($p<0.1$).

Subgroup analyses showed that the three studies [52 53 62] in which intensity was equated as a percentage of 1 RM during concentric training showed no major differences between eccentric and concentric training in promoting gains in strength. In contrast, strength gains were maximised in all studies in which eccentric training was performed at higher intensities except in three studies.[52 60 63] Noteworthy, two of these studies measured isometric strength only.[53 63] One study not included in the meta-analysis showed that although the intensity of eccentric exercise was equated to the concentric MVC, eccentric was superior to concentric exercise in promoting strength gains.[7] The main characteristic of this latter study [7] is that the training loads were matched at higher intensities (concentric MVC) compared with the rest of studies in which intensity was equated as a percentage of 1 RM during concentric exercise.[52 53 62] These results suggest that the higher forces developed during eccentric contractions might be a critical factor in contributing to greater strength gains after eccentric training.

Due to the lack of raw data, four studies included in the review were not incorporated in the meta-analysis for strength

Table 4 Results of meta-analyses: muscle mass

Outcomes	Subgroup analyses	Individual studies	N	Weighted mean difference (95% CI)	Overall effect (p value)	Heterogeneity (p value)	Interpretation
Muscle mass (CSA, cm^2)	Subgroup: higher eccentric versus concentric training intensity	Blazevich *et al*[60] Higbie *et al*[51] Vikne *et al*[46]	73	1.49 cm^2 (−1.32 to 4.31)	0.30	0.28	No difference in change in muscle CSA among ecc compared with con trainers; confidence interval indicates a positive trend towards a greater improvement in CSA among ecc trainers
Muscle mass (girth, cm)	All studies in this category: higher or comparable eccentric versus concentric training intensities	Duncan *et al*[55] Ben-Sira *et al*[62] Komi and Buskirk[49]	73	0.46 cm (0.11 to 0.81)	0.01	0.59	Statistically significant greater increase in muscle girth in ecc compared with con trainers
	Subgroup: higher eccentric versus concentric training intensity	Duncan *et al*[55] Komi and Buskirk[49]	51	0.49 cm (0.12 to 0.87)	0.01	0.84	Statistically significant greater increase in muscle girth in ecc compared with con trainers

con, concentric; CSA, cross-sectional area; ecc, eccentric.

What is already known on this topic

- Higher muscular forces can be produced during eccentric contractions compared with concentric.
- Eccentric contractions produce less fatigue and are more efficient at metabolic level compared with concentric contractions.
- Unaccustomed eccentric contractions produce transient muscle damage, soreness and force impairments.

What this study adds

- Eccentric training is more effective at increasing total and eccentric strength than concentric training.
- Eccentric training appears to be more effective at increasing muscle mass than concentric training.
- The superiority of eccentric training to produce adaptations in strength and muscle mass is possibly mediated by the higher forces developed during this type of exercise.
- Adaptations after eccentric training are highly specific to the velocity and type of contraction.

gains.[2 7 50 54] While three of these studies support the results of the meta-analyses,[2 7 50] one study did not find eccentric training superior to concentric in promoting strength gains.[54] However, in this study,[54] the intensity of training was submaximal, which could explain the discrepancies in the results.

It is noteworthy that 16 of 18 subgroup analyses performed for strength were positive for heterogeneity. Reasons for heterogeneity may include differences in the type of eccentric and concentric training interventions, intensities of training interventions, methods of strength testing and characteristics of participants. A potential source of heterogeneity that might limit the interpretation of these results is related to the different duration of the studies included in the meta-analyses. Training interventions lasted from 4 to 25 weeks, and so we cannot ignore the fact that, depending on the duration of the studies, improvements in strength were due to central or peripheral adaptations.

Muscle mass

The results of meta-analyses suggest that eccentric exercise is more effective than concentric exercise in increasing muscle girth. However, due to its low reproducibility, the use of muscle girth measurements to estimate muscle mass should be regarded with caution. We also observed a positive trend towards a greater improvement in muscle cross-sectional area among participants exercising eccentrically at higher levels of intensity. It is noteworthy that two[58 61] of the three studies[47 58 61] not included in the meta-analyses underscored the greater effect of eccentric exercise in promoting increases in muscle mass.

Conflicting results regarding muscle mass gains after eccentric versus concentric exercise could be partly explained by the different methods of evaluation used. While some studies used muscle girth,[49 55 62] dual *x* ray absorptiometry (DEXA)[47] and ultrasound,[61] four studies assessed increases in muscle cross-sectional area via MRI[51 58 60] or computerised tomography (CT),[46] which are regarded as the most reliable methods for muscle mass measurement. Three studies that used MRI[51 58] or CT[46] showed that eccentric training is superior to increase muscle mass compared with concentric training. In contrast, one study failed to show any difference between improvements of muscle cross-sectional area assessed with MRI after eccentric and concentric training.[60] Since these studies were quite similar with respect to populations and interventions,[46 51 58 60] the reasons for these discrepancies are unclear.

The results of this review indicate that either eccentric or concentric training performed separately can promote increases in muscle mass. However, given the higher absolute loads that are generated during eccentric contractions, greater hypertrophy after eccentric training could be expected.[65] Although our results indicate that eccentric training could maximise muscle hypertrophy, other factors such as nutritional or hormonal status can influence muscle growth.[66] Whether there are contraction-specific mechanisms of muscle hypertrophy is a matter that requires more investigation. In the future, more studies controlling for potential confounding factors and including measures of muscle architecture such as fascicle length and pennation angle should be performed.[60]

In summary, this systematic review suggests that compared with concentric training, eccentric training may be associated with greater improvements in both total and eccentric strength in healthy individuals. In addition, eccentric training appeared to be more effective in promoting overall increases in muscle mass. The effectiveness of eccentric training in promoting strength gains is possibly mediated by the capacity to achieve higher forces during eccentric muscle actions. However, strength gains after eccentric training are highly specific to the mode of contraction and velocity of movement. Even though the results of the present review support the effectiveness of eccentric training in promoting strength gains, whether the neural specificity of eccentric exercise[3] may compromise the transferability of strength gains to more functional movements requires further investigations.

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Competing interests: None.

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