TITLE

Effects of eccentric resistance training on lower-limb passive joint range of motion: A systematic review and meta-analysis

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RUNNING HEAD

Eccentric training induces large increases in joint ROM

ABSTRACT

Introduction: Substantial increases in joint range of motion (ROM) have been reported following eccentric resistance training, however between-study variability and sample size issues complicate the interpretation of the magnitude of effect. **Methods:** PubMed, Medline and SPORTDiscus databases were searched for studies examining the effects of eccentric training on lower-limb passive joint ROM in healthy human participants. Meta-analysis used an inverse-variance random-effects model to calculate the pooled standardised difference (Hedge's *g*) with 95% confidence intervals (CI). **Results:** Meta-analysis of 22 ROM outcomes (17 studies; 376 participants) revealed a large increase in lower-limb passive joint ROM (*g* = 0.86 [CI = 0.65, 1.08]). Subgroup analyses revealed a moderate increase after 4-5 weeks (*g* = 0.63 [0.27, 0.98]), large increase after 6-8 weeks (*g* = 0.98 [0.73,1.24]), and moderate increase after 9-14 weeks (g = 0.75 [0.03, 1.46]) of training. Large increases were found in dorsiflexion (*g* = 1.12 [0.78, 1.47]) and knee extension (*g* = 0.82 [0.48, 1.17]), but a small increase in knee flexion was observed (*g* = 0.41 [0.05, 0.77]). A large increase was found after isokinetic (*g* = 1.07 [0.59, 1.54]) and moderate increase after isotonic (*g* = 0.77 [0.56, 0.99] training. **Conclusions:** These findings demonstrate the potential of eccentric training as an effective flexibility training intervention and provide evidence for 'best practice' guidelines. The larger effect after isokinetic training despite <50% training sessions being performed is suggestive of a more effective exercise mode, although further research is needed to determine the influence of contraction intensity and to confirm the efficacy of eccentric training in clinical populations.

Key Words: Flexibility, muscle lengthening, muscle-tendon mechanics, passive and active stretching.

INTRODUCTION

Limited joint range of motion (ROM) compromises the capacity to perform activities of daily living (1, 2), negatively influences sporting performance (3), potentially increases muscle strain injury risk (4–6). Limited ROM is also evident in several clinical conditions including, but not limited to, stroke (7), cerebral palsy (8), cystic fibrosis (9), fibromyalgia (10), diabetes (11), and arthritis (12). Consequently, increasing ROM during pre-activity (warm-up) routines and through longitudinal training or therapeutic exercise programmes (13, 14) is a priority in both healthy and clinical populations. Increasing ROM in the lower limbs is especially important as muscle strain injuries are prevalent in the lower-limb muscle groups (6) and where restricted ROM decreases mobility and functional independence in a range of clinical populations (7, 8). For millennia, muscle stretching exercises have been used to increase ROM, with their efficacy confirmed in several comprehensive reviews (13–15). However, stretch-induced increases in ROM often occur without substantial changes to muscle-tendon unit (MTU) mechanical properties or structural characteristics (16–18), limiting the magnitude of change in ROM and potential reduction of muscle strain injury risk. Furthermore, muscle stretching exercises often fail to provide clinically meaningful improvements in ROM in a range of neurological conditions in which ROM is often compromised (19). These issues highlight the need to identify alternative therapies with the capacity to promote substantial mechanical and architectural MTU adaptations to induce greater increases in ROM.

Resistance training is commonly advocated as a strength training exercise employed primarily to increase muscle strength and mass (20). However, recent reviews have reported increased joint ROM following resistance training (17, 21), with meta-analysis (22) confirming comparable mean increases in lower-limb ROM in studies comparing resistance training (4.9°) and static stretching (4.0°) programmes. Resistance training usually combines concentric, isometric, and eccentric muscle actions, however eccentric contractions enable greater tissue loading (23, 24) to provide a greater adaptive stimulus. Furthermore, the use of dynamometers to force a maximally contracted muscle to lengthen (i.e., isokinetic eccentric contractions), enables a greater loading than isotonic muscle contractions (i.e., bodyweight or resistance machines) (25). Unsurprisingly, superior gains in strength and muscle mass have been reported following eccentric exercise (20). However, of greater interest to the present review are the large increases in ROM reported following isotonic and isokinetic eccentric training (10-15°) (26–28), which are substantially greater than those previously reported after muscle stretching exercises or traditional resistance training (22). Therefore, the greater increases in ROM achievable following eccentric exercise than with other contraction modes or (passive) muscle stretching exercises, highlight the potential for eccentric exercise to be an effective clinical flexibility training modality.

To our knowledge, three reviews (29–31) have examined the effects of eccentric resistance training on ROM. However, in the first review (30) only three studies were included that directly measured joint ROM, whilst the remaining three studies measured fascicle length, which is not a valid indicator of ROM or its temporal change (32, 33). Given the paucity of literature at the time, a meta-analysis was not performed, however that review was recently updated (31) with meta-analysis of 27 studies reporting a moderate pooled standardised effect size (Hedge's g = 0.54). Nonetheless, in the updated review only five studies included passive lower-limb ROM tests in healthy participants as an outcome measure with the remainder examining fascicle length, imposing upper body interventions, or including clinical populations (tendinopathy). A similar recently published review (29) included 18 studies, however many included studies examined fascicle length as an outcome measure, with only four studies measuring passive joint ROM and no meta-analysis performed. The inclusion of active ROM data, clinical populations, data from both the upper and lower body concurrently, and (importantly) fascicle length data as a proxy for ROM outcomes, are problematic.

Given these issues, the effect of eccentric exercise on lower-limb passive ROM remains unclear and, more importantly, the influence of study design remains untested. Therefore, the aims of this systematic review with meta-analysis were to document the chronic effects of eccentric exercise training on lower-limb passive joint ROM in healthy populations. Subgroup analyses were also performed to examine the impact of training duration and volume, muscle group tested, and method of eccentric training to better describe the potential effects of study design. These outcomes were examined as they should allow for 'best practice' guidelines for training implementation to be developed.

METHODS

Search strategy

This systematic review was conducted following the four-step (identification, screening, eligibility, and inclusion) PRISMA guidelines for conducting systematic reviews (34) and is registered (CRD42022338136) in the PROSPERO database. PubMed, Medline and SPORTDiscus databases were searched from inception with the final search performed on the 8th of August 2022 for articles that examined the chronic effects of eccentric exercise training on lower-limb joint ROM. Search terms included "eccentric" OR "active stretch*" OR "Nordic" within the title, combined with search terms "flexib*" OR "range of motion" OR "ROM" OR "range of movement" within the text; * enabled the search engine to use truncation to find various derivatives of the search term (i.e., 'stretch*' returned results for 'stretches', stretched, or 'stretching'). Recursive reference checking was performed on all included articles' bibliographies to identify further potential articles.

Study selection and inclusion criteria

Selection criteria included randomised or quasi-randomised controlled trials (RCT) and intervention-based trials that examined the chronic effects of eccentric exercise programmes on lower-limb passive joint ROM. Chronic eccentric resistance training was defined as an intervention in which isolated eccentric muscle actions (i.e., without inclusion of other contraction modes) were performed regularly for a minimum of four weeks of training (i.e., studies investigating acute and repeated bout effect were removed). Studies were limited to full original research articles published in peer reviewed journals that involved the testing of healthy human participants. Upon collation of the searched literature, two reviewers (BAB and ADK) excluded irrelevant articles based upon the title and screened the abstracts of included studies, with any disagreement resolved by discussion with a third reviewer (MWH). Full texts of the remaining articles were assessed by two reviewers (BAB and ADK), with any disagreement resolved by discussion with a third reviewer (AJB).

Assessment of study validity

The PEDro scale was used to assess methodological quality of the included studies, with the 10-point scale previously being confirmed to have very good reliability (35) and validity (36). Study quality was classified as 'poor' (<4/10), 'fair' (4-5), 'high' (6-8), or 'excellent' (9-10) (37).

Data extraction

Two reviewers (BAB and ADK) extracted data from the included studies, with any disagreement resolved by discussion with a third reviewer (AJB). The data included: sample size, pre- and post-training mean and standard deviation (SD) data of lower-limb joint ROM, muscle group trained, intervention contraction mode, weekly training frequency, and duration of training programme. All included studies measured joint ROM in degrees with measurements taken using isokinetic dynamometry or goniometry. To ensure that reporting bias was not introduced into the review, where multiple ROM measures were reported within a study (38–41), each relevant finding was included in the analysis. However, where a study included multiple groups for a single ROM measure (42), the data from each group (i.e., sample size, mean, and SD) were combined to produce a single data set (43). Five studies (26, 38, 44–46) did not report pre- and post-training group mean and SD data, however the corresponding authors were contacted and provided the data to enable their inclusion within the review and meta-analysis.

Meta-analysis

Pre- and post-training joint ROM mean and SD as well as study sample data were entered into Cochrane Review Manager software (RevMan v5.4.1 for Windows) with meta-analysis performed using an inverse variance random-effects model to calculate the pooled standardised mean difference (Hedge's g) and 95% confidence intervals (CI). After the studies were examined collectively to determine the overall effect on ROM, subgroup analyses were performed with studies pooled by training duration (i.e., 4-5, 6-8, 9-14 weeks) and number of exposures (i.e., 4-9, 11-20, 23-42 sessions) to determine temporal changes and dose-response effects, respectively. Studies were also pooled by muscle group trained (i.e., plantar flexors, knee flexors, and knee extensors) to determine the influence across different lower-limb joints. Studies that measured hip flexion or knee extension were pooled as they measured the effects of training the hamstrings group. Finally, studies were grouped by the eccentric contraction mode employed (i.e., isokinetic vs. isotonic) to determine whether the method of loading influenced ROM outcomes. Effect sizes have been described previously (47) with <0.20

representing a trivial, 0.20–0.49 as small, 0.50–0.79 as moderate, and ≥0.80 as large magnitude of change. As all studies used degrees, weighted mean differences (and CI) in ROM (°) from pre- to post-training were also calculated to better describe the magnitude of change.

RESULTS

Search results

Our searches identified 1724 articles (PubMed = 449, Medline = 497, SPORTDiscus = 778), with 944 articles remaining once duplicates were removed. Screening by title removed a further 829 articles with the remaining 115 articles screened by abstract; 34 articles failed to meet the inclusion criteria and were removed (20 acute studies, 5 upper body, 6 additional or non-eccentric interventions, 3 animal models). The full texts of the remaining 81 articles were examined, 64 articles failed to meet the inclusion criteria and were removed (44 studies where passive ROM was not an outcome measure, 13 combined or non-eccentric interventions, 4 acute, 1 upper body, 1 clinical population, 1 review article), resulting in 17 remaining articles. Recursive reference checking of the 17 included articles' bibliographies revealed 1 potential additional article, however upon abstract checking it was found not to meet eligibility criteria (acute study), resulting in 17 articles being finally included for review (see Figure 1).

Details of the eccentric exercise training programmes

Within the 17 studies included for review (see Table 1), 22 measures of lower-limb joint ROM were reported; 9 for dorsiflexion, 5 for knee flexion, 5 for knee extension, and 3 for hip extension. Sample size ranged from 8-40 subjects (mean ± SD = 16.1 ± 9.0, n = 274). Training load was implemented using isotonic eccentric contractions (i.e., bodyweight or resistance machines [12 studies, 14 measures]) or isokinetic eccentric contractions (i.e., dynamometers [5 studies, 8 measures]). The average training duration was 7.1 ± 2.7 weeks (range = 4-14 weeks), and weekly frequency was 2.6 ± 1.4 sessions/week (range 1-7/week), resulting in an average of 18.4 ± 10.5 sessions completed during the training programmes (range = 4-42 sessions). Training intensity in the isotonic studies included bodyweight exercises or free-weight and machine-based exercises that ranged from 40-100% of one-repetition maximum (1RM; i.e., 100% concentric maximum voluntary contraction [MVC]). All isokinetic studies used 100% of eccentric MVC (i.e., supramaximal equivalent to ~140% concentric MVC based on concentric-to-eccentric strength ratio).

Methodological quality of included studies

Not all of the PEDro criteria could be satisfied because the experimental design implemented by the majority of studies resulted in subject and therapist blinding not being possible. Given that therapist and assessor roles were normally performed by the same individuals, assessor blinding was also limited. Nonetheless, the average methodological quality of studies was found to be high (mean ± SD = 7.1 ± 1.2 with one study classified as 'fair', 14 studies as 'good', and two studies as 'excellent' (Table 2).

Main effects on lower-limb ROM

Twenty-two measures of lower-limb ROM were reported across the 17 studies in 376 participants (Figure 2). Meta-analysis of the 22 outcomes revealed a large increase in ROM ($g = 0.86$ [0.65, 1.08], 5.7° [3.9°, 7.4°]; Test for overall effect: $Z = 7.82$ [$P < 0.00001$]). The study by Geremia et al. (40) reported a very large effect ($g = 2.09$), however when this study was excluded during a sensitivity analysis a large standardised effect size was still calculated for the group ($g = 0.81$ [0.61, 1.01], 5.3° [3.6°, 7.0°]; Test for overall effect: $Z = 8.05$ [$P < 0.00001$]). As RevMan software does not provide a statistical test for small study sample bias, the data were entered into SPSS (v.28) to conduct Egger's test, which revealed no conclusive evidence of small sample bias between trials (Egger's test = 1.244 [CI = -0.056, 2.544], t = 1.997, P = 0.06).

Subgroup analyses

Where studies were grouped by training duration (Figure 3), a moderate increase was found after 4-5 weeks (g = 0.63 [0.27, 0.98], 3.4° [0.8°, 5.9°]), large increase after 6-8 weeks (g = 0.98 [0.73, 1.24], 7.2° [4.7°, 9.6°]), and moderate increase after 9-14 weeks (g = 0.75 [0.03, 1.46], 4.2° [-0.4°, 8.7°]). There were no differences between subgroups when eccentric programmes were compared by weekly duration (Test for subgroup differences: $\text{Chi}^2 = 2.62$, df = 2 [P = 0.27], $I^2 = 23.8\%$).

Given the large variation in weekly training dose (1-7 sessions/week), and moderate, then large, then moderate effect sizes calculated as weekly training duration increased, further dose-response analysis was conducted using the total number of exposures (Figure 4). Where studies were grouped by exposure number, a moderate increase was found after 4-9 sessions (g = 0.66 [0.27, 1.05], 1.9° [0.3°, 3.5°]), large increase after 11-20 sessions (g = 0.80 [0.46, 1.15], 7.6° [4.4°, 10.7°]), and large increase after 23-42 sessions (g = 1.04 [0.67, 1.41], 6.4° [4.4°, 8.4°]). There were no significant differences between subgroups when eccentric programmes were compared by total number of exposures (Test for subgroup differences: $\text{Chi}^2 = 2.02$, df = 2 (P = 0.36), $I^2 = 1.0\%$).

Where studies were grouped by the muscle group trained (Figure 5), a large increase was found in dorsiflexion (g = 1.12 [0.78, 1.47], 6.8° [4.8°, 8.8°]), large increase in hip flexion and knee extension (i.e. hamstrings flexibility) (g = 0.82 [0.48, 1.17], 7.7° [4.7°, 10.8°]), and small increase in knee flexion (g = 0.41 [0.05, 0.77], 1.3° [0.2°, 2.5°]). There was a significant difference between subgroups with a greater increase in dorsiflexion than knee flexion (Test for subgroup differences: $Chi^2 = 7.78$, $df = 2$ ($P = 0.02$), $I^2 = 74.3\%$).

Where studies were grouped by eccentric contraction mode (Figure 6), a large increase was found after isokinetic (g = 1.07 [0.59, 1.54], 5.6° [2.6°, 8.7°]) and moderate increase was found after isotonic training (g = 0.77 [0.56, 0.99], 5.8° [4.0°, 7.5°]). There was no difference between subgroups when eccentric programmes were compared by eccentric contraction mode (Test for subgroup differences: $Chi^2 = 1.23$, $df = 1$ ($P = 0.27$), $I^2 = 18.8\%$).

DISCUSSION

Main findings

The current meta-analysis examined 22 measures of lower-limb ROM from 17 studies in 274 participants and provides high-quality evidence of a large (g = 0.86 [0.65, 1.08]) increase in lower-limb ROM following eccentric training. These data expand upon, and clarify the findings from, an early review (30), which was recently updated (31), that reported a moderate effect size (g = 0.54 [0.34, 0.74]) from 27 studies. However, in the previous review (31) only five studies had examined lower-limb passive ROM in healthy populations. A similar, recently published review included 18 studies but included both fascicle length and active ROM as outcome measures with only four studies examining passsive lower-limb ROM. The inclusion of both active and passive ROM in clinical and healthy populations is problematic as mechanisms underpinning changes in active and passive ROM, and distinct differences in neuromuscular properties across clinical populations (e.g., spasticity, contracture, pain), will likely influence the potential for ROM change. Importantly, the inclusion of fascicle length as an outcome measure is problematic as changes in fascicle length and ROM are not correlated (32, 33). Furthermore, increases in ROM have been reported without change in fascicle length after muscle stretching (18, 33) and eccentric training (48) programmes. However, the systematic searches completed in the current review located 17 studies reporting 22 lower-limb passive ROM outcome measures that confirm the efficacy of eccentric training to provide large increases in ROM. The substantially greater number of studies included within the present meta-analysis provides a more comprehensive view of the literature and provides greater confidence in the magnitude of effect of eccentric training on lower-limb joint ROM.

When examining changes in ROM, previous reviews have extensively examined the effects of muscle stretching (13–15), which is unsurprising as stretching is the primary exercise modality used in athletic and clinical environments. More recently, however, the effects of resistance training on ROM have been examined (21, 22), with a recent meta-analysis confirming similar small effect sizes after muscle stretching and resistance training (22). However, as the previous review (22) included upper-limb studies and active ROM outcome measures, we performed a meta-analysis on the five studies (49–53) reporting 11 passive lower-limb ROM measures from the previous review (22) to provide a more appropriate comparison with the present review. We confirmed small effect sizes after muscle stretching (g = 0.29 [-0.05, 0.63]) and traditional resistance training (g = 0.49 [0.18, 0.81]) interventions with similar absolute increases in lower-limb passive joint ROM (4.0 – 4.9°). However, the study by Morton et al. (53) reported very large effect sizes (g = 2.61-2.83) and when this trial was excluded during a sensitivity analysis, the effect sizes for the group were reduced to negligible-to-small (g = 0.13-0.35), with small absolute changes in ROM (1.2-2.8°). Importantly, the large effect sizes calculated in the current meta-analysis (g = 0.86) with larger mean increases in ROM (5.7°) are substantially greater than those reported in the previous review (22), which is indicative of eccentric training being a superior training modality for increasing lower-limb passive ROM. Where direct comparisons with other training modalities were made in studies included in the present review, eccentric training provided greater increases in ROM than foam rolling (45) and concentric training (38, 54), and similar changes to static stretching (28) and traditional resistance training (46). Therefore, while the present data are encouraging, more research is needed with studies making direct comparisons against other training modalities under the same experimental conditions to prevent differences in study design from influencing outcomes and to confirm (or otherwise) the greater efficacy of eccentric exercise than other interventions currently used in clinical and athletic practice.

Although the present meta-analysis revealed a large increase in ROM after eccentric training, individual study effect sizes ranged from negligible (46) to very large (27, 28, 40) (g = 0.08-2.09). The I^2 statistic was 47%, indicating a level of heterogeneity that was likely explained by methodological differences across studies. Subgroup analyses were also performed to determine the influence of the intervention duration and frequency, muscle group trained, and methods used to impose the eccentric training (i.e., contraction mode). Regarding training duration and frequency, training programme durations within the 17 studies ranged from 4-14 weeks, which enabled the temporal changes in ROM to be explored. A moderate effect (g = 0.63) was calculated after shorter duration studies (4-5 weeks) (38, 40, 44, 45, 55), which increased to a large effect (g = 0.98) after 6-8 weeks (26–28, 40–42, 48, 54, 56–58). However, as programme duration increased further (9-14 weeks) (38–40, 46), a moderate effect (g = 0.75) was calculated. The lack of further increases as programme duration increased from 6-8 to 9-14 weeks appears indicative of a ceiling effect for the capacity of ROM to increase. However, a closer examination of the average weekly training frequency across the studies revealed a similar average total number of exposures for 6-8 week (18.1 exposures) and 9-14 week (21.5 exposures). The similar number of exposures may explain the similar pooled effect sizes and is indicative of a dose-response rather than ceiling effect, although further studies are required to determine the duration at which further ROM improvements become negligible.

Training frequency ranged from one (38) to seven (41, 45) sessions/week, which substantially influenced the total number of exposures across studies. To further explore potential dose-response relations, studies were grouped by total number of exposures. Where studies included a limited number of training sessions (4-9 exposures) (38, 40, 54), a medium effect was calculated (g = 0.66), which increased to a large effect after 11-20 sessions (g = 0.80) weeks) (26–28, 40, 44, 46, 48, 55–57) and then remained large after 23-42 sessions (g = 1.04) (39–41, 45, 58). Given the substantial differences in training duration and, possibly more importantly, the differences in weekly sessions completed between studies, these data highlight the importance of closely examining both programme duration and weekly frequency to ensure conclusions drawn from meta-analyses are robust. Additionally, subgroup analyses of training volume may help to better describe the temporal and dose-response effects underpinning the adaptive processes and magnitude of change in ROM following eccentric exercise.

To determine whether similar changes in ROM were apparent across lower-limb joints, studies were pooled by the muscle group trained. Similar effect sizes were detected in knee extension (g = 0.83) and hip flexion (g = 0.78), and as they measure the effect of training on the hamstrings group, these studies were pooled. Large effect sizes were calculated in both dorsiflexion (g = 1.12) (27, 39–41, 45), and hip flexion/knee extension (g = 0.82) (26, 28, 42, 44, 46, 56–58), whereas only a small effect was calculated for knee flexion (g = 0.41) (38, 48, 54, 55). Although subgroup analysis revealed a significant difference between dorsiflexion and knee flexion, indicative of disparate effects across muscle groups, the number of exposures in studies that examined knee flexion averaged only 9.4 sessions whereas studies testing dorsiflexion and knee extension imposed 22.2 and 17.8 sessions, respectively. Given the clear dose-response effect described above, the small effect in knee flexion very likely reflects the receipt of relatively fewer training exposures (~50%) rather than a true muscle- or joint-specific effect. Whilst more, longer-duration studies with a greater number of exposures are required to confirm the efficacy of eccentric exercise to promote large increases in knee flexion ROM, these preliminary findings suggest that it may be an effective training strategy. Given that the muscle groups examined in the present review account for the majority of lower-limb muscle strain injuries (59), eccentric exercise may be considered an effective intervention to improve joint ROM and reduce injury risk.

A final subgroup analysis was conducted to examine the effect of eccentric contraction mode (i.e. isotonic or isokinetic) on ROM outcomes. A noticeable but non-significant difference in magnitude of change was observed, with a large effect after isokinetic (g = 1.07) (27, 38, 40, 48, 54) and moderate effect after isotonic (g = 0.77) (26, 28, 39, 41, 42, 44–46, 55–58) eccentric training, indicating that isokinetic training may evoke a superior, albeit non-significantly greater, increase in ROM under some conditions. However, closer analysis of the number of exposures revealed that isotonic studies averaged 23.9 sessions whereas isokinetic studies included only 11.5 sessions. The greater effect size following isokinetic training despite the ~50% fewer exposures provide circumstantial evidence of a superior training modality. However, all studies using isokinetic exercises required the performance of maximal intensity contractions, whereas either bodyweight or resistance machines were used to impose loading in isotonic studies. Therefore, submaximal intensities were used in isotonic training to enable the fixed load to overcome internal muscle force. Importantly, greater increases in ROM have been previously reported following higher intensity traditional resistance training programmes (60), indicating an intensity-dependent adaptive response that may explain the potentially superior effect of isokinetic contractions to increase ROM. Regardless, the ability of velocity-controlled isokinetic machines to force lengthening in (voluntarily) maximally contracted muscles provides the opportunity for greater tissue loading than load-dependent isotonic contractions. Whilst these data are of clinical interest, a practical limitation is that isokinetic machines are expensive, require substantial training for use, and are usually restricted to research centres and some large clinics. Thus, they are not practical for implementation in the wider public.

Clinical implications

The present data can inform recommendations for ‘best practice’ guidelines for clinical exercise prescription. The weekly and dose-response findings indicate that longer duration studies and more sessions/week stimulate greater ROM increases, with recommendations that programme duration should be a minimum of six weeks with twice-weekly exposures to provide a large effect. Eccentric exercise also appears to be more effective in the knee flexors and plantar flexors than knee extensors, although there is currently no literature available reporting the implications on the knee extensors following >12 exposures, with more research needed to confirm the greater efficacy in these muscle groups. Currently no studies have tested the effects of contraction speed, determined the minimum number of sets or repetitions required, or examined whether holding the muscle ‘on stretch’ at the end of an eccentric contraction before relaxation (i.e., a combination of eccentric contraction and passive muscle stretch or isometric contraction ‘on stretch’) would be more effective for providing large increases in ROM. Preliminary evidence indicates that isokinetic exercise is more effective than isotonic exercise and should be used if feasible, however the effect is possibly explained by the greater contraction intensity enabled rather than the contraction mode itself; this requires explicit examination in future studies. Whilst unaccustomed high-intensity eccentric exercise can induce substantial transient functional impairment and pain (delayed onset muscle soreness) for several days after exposure (61, 62), reviews (63, 64) have confirmed that these effects can be removed by well-designed interventions that gradually increase exercise intensity. Furthermore, the lower metabolic cost (~25%) of eccentric exercise (65) reduces perceived exertion (66), making the exercises more tolerable, even in individuals with cardiorespiratory impairments (67). Collectively, these findings confirm that high-intensity eccentric training can be broadly recommended, although a gradual increase in intensity in the early weeks of programme delivery is advised to minimise potential adverse effects. Further research is required to provide a fully comprehensive list of 'best practice' recommendations.

The present review examined the impact of eccentric exercise in healthy populations. However, ROM is also compromised in a range of clinical conditions including, but not limited to, stroke (7), cerebral palsy (8), cystic fibrosis (9), fibromyalgia (10), diabetic peripheral neuropathy (11), and arthritis (12). Importantly, reviews have reported limited efficacy of muscle stretching for increasing ROM in a range of clinical populations (19), highlighting the need to investigate alternative therapies. The large effect sizes reported in the present meta-analysis are greater than those reported following static stretching and thus, eccentric exercise might be trialled more extensively in clinical conditions in which joint ROM is compromised and current therapies are ineffective. This suggestion is supported by clinically relevant improvements in ROM being reported after eccentric exercise in patients with contracture secondary to multiple sclerosis (68), emphasising the potential for eccentric exercise to be an effective alternative therapy to enhance ROM in clinical populations. Furthermore, the present review examined passive rather than active ROM, and given that muscular strength is also frequently compromised in clinical conditions, measuring active ROM may highlight important functional (mobility) adaptations. However, our searches revealed only two studies that measured active ROM after eccentric training (69, 70) and given the likely beneficial impact of eccentric training on both ROM and strength, further investigation into the impact on active ROM is needed.

ROM is commonly thought to be influenced by neural (e.g. stretch tolerance/pain perception), mechanical (e.g. tissue stiffness), or structural (e.g. muscle-tendon architecture [fascicle length/angle]) factors (71–73), and the impact of muscle stretching training comes from increased stretch tolerance (i.e. increased peak passive joint torque at full ROM) (71–73) and/or decreased muscle stiffness (32, 33). However, of the 17 eccentric training studies included in the present analyses, only a limited number examined potential mechanisms, and given the disparate study designs, meta-analysis was not possible. Furthermore, despite increases in fascicle angle (48) or fascicle length (39, 58), decreases in MTU (27, 39, 41, 48) and muscle stiffness (27), and increases in peak passive torque at full ROM (27, 48) (indicative of increased stretch tolerance) being reported after eccentric training, relationships between changes in ROM and changes in these mechanical and physiological variables were rarely explored. It is therefore not yet possible to identify the mechanisms underpinning ROM improvements after eccentric training. Of practical interest, however, is that increases (27, 39, 48) or no change in tendon stiffness (41) were reported even when ROM increased significantly, strongly suggesting that increases in tendon stiffness can be elicited even whilst ROM improvements are gained through eccentric training. Collectively, these findings confirm that the high-intensity loading experienced during eccentric muscle actions is sufficient to promote wide-ranging neurological, structural, mechanical adaptations that have been previously associated with increases in ROM, the precise mechanisms of ROM change in response to eccentric training are yet to be determined.

The present data also have clear implications for muscle strain injury risk as limited joint ROM has been cited within its primary aetiology (4–6), with a prospective study reporting a mean difference of 6-8° in the quadriceps and hamstrings between injured and non-injured athletes (74). Whilst muscle stretching exercises are commonly used to increase ROM in an attempt to reduce injury risk, reviews often report somewhat limited (13) or equivocal (75) efficacy of muscle stretching to reduce injury risk. However, the large increases in ROM, speculatively in combination with the substantial changes in muscle architecture, mechanical properties, and increases in muscle strength (also cited within muscle strain aetiology) (20), likely explain the substantial reductions reported in both new and recurrent muscle strain injuries following eccentric exercise programmes (76–78). Collectively, these findings suggest a superior and wide-ranging adaptive profile of eccentric exercise when compared with static stretching programmes and may partly explain the superior preventative effect of eccentric exercise on muscle strain injury incidence, with important implications for exercise prescription in both clinical (injured) and healthy athletic populations.

CONCLUSION

This systematic review with meta-analysis provides high-quality evidence that eccentric training is highly effective for increasing lower-limb joint ROM, with large effect sizes suggesting it to be a potentially superior method of increasing ROM to traditional resistance training or static stretching programmes. Interestingly, evidence was found to enable 'best practice' recommendations with clear dose-response characteristics enabling the minimum dosage necessary for large effect. The evidence also suggests that greater increases in ROM might be achieved with isokinetic than isotonic exercise, although this might reflect an effect of contraction intensity (higher in isokinetic training); more research is required to fully determine the impact of eccentric contraction modes and contraction intensity on ROM outcomes. The large increase in ROM detected in healthy populations after eccentric training has implications for exercise prescription across a range of clinical populations in which ROM is compromised and current therapies are ineffective. However, further research is required in clinical populations to examine the efficacy and identify potential contraindications to enable clinicians to prescribe eccentric exercise as a primary exercise modality for use in developmental, preventative, and rehabilitative training programmes.

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Author Contributions

All authors were involved in conception and design. BAB performed the literature searches, with BAB and ADK selecting articles for exclusion and inclusion, with any disagreement resolved by discussion with MWH. Full texts were assessed by BAB and ADK, with any disagreement resolved by discussion with AJB. BAB and ADK extracted all data from the included studies and assessed study quality, with any disagreement resolved by discussion with AJB. ADK conducted the meta-analysis. All authors contributed to the writing and revision of the manuscript.

Conflicts of interest and Sources of funding

No conflict of interest exist. No funding was received for this work. The results of the present study do not constitute endorsement by ACSM. The results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

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TABLE & FIGURE CAPTIONS

Table 1. Sample size, muscle group, contraction mode and eccentric training programme volume of the studies included for review.

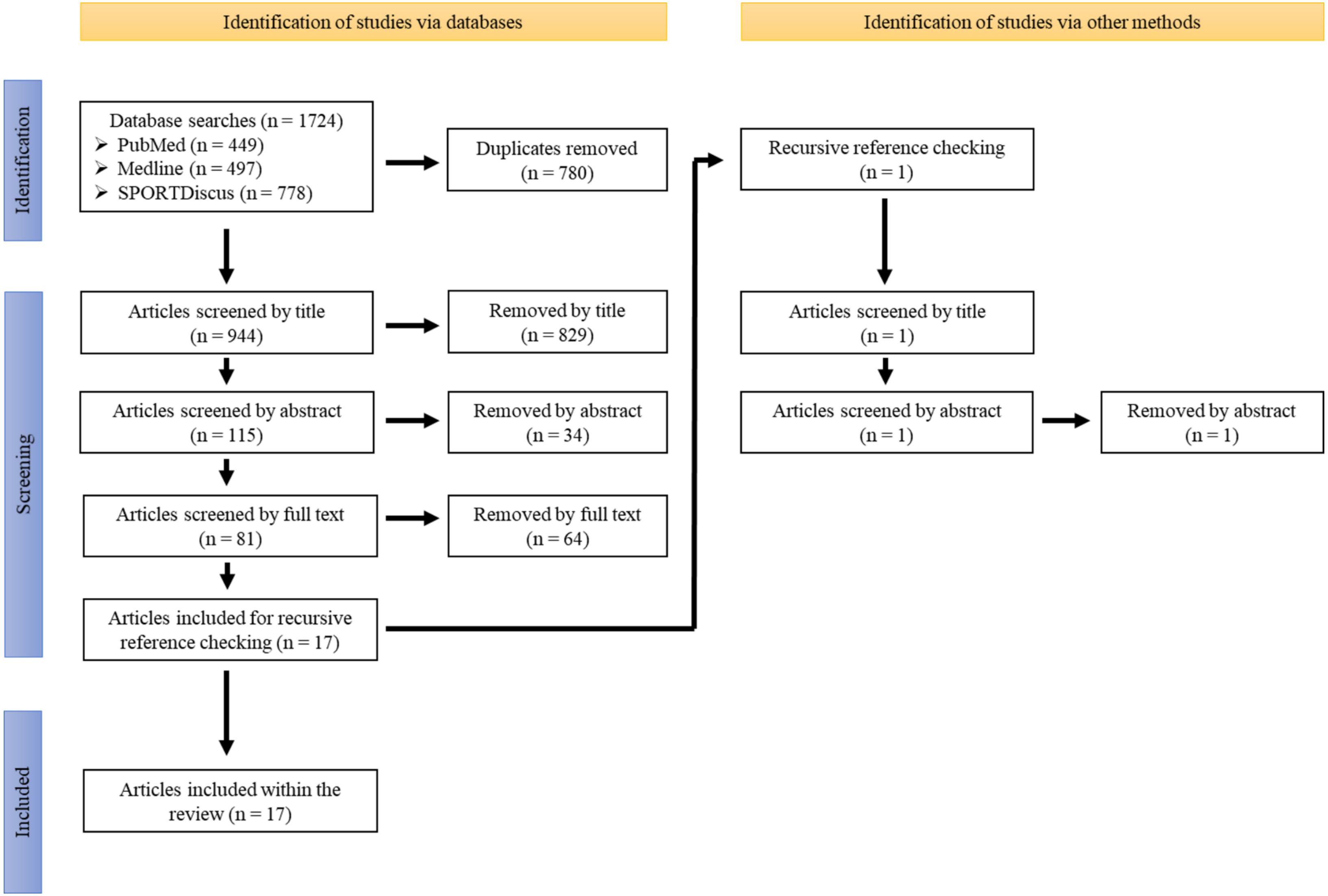
Study	**n**	**Muscle**	**Mode**	**Comparator**	**Duration (w)**	**Frequency**	**Total sessions**	**Intensity**	**Sets × Reps**
Abdel-Aziem et al. [42]	40	KF	Isotonic	Control	6	5	30	40% 1RM	5 × 6
Aune et al. [45]	11	PF	Isotonic	FR	4	7	28	BW	3 × 15
Delvaux et al. [26]	13	KF	Isotonic	Control	6	2-3	15	BW	2-3 × 6-10
Fernandez-Gonzalo et al. [55]	14	KE	Isotonic	Control	4	3	12	45-55% 1RM	3 × 10
Foure et al. [39]	11	PF	Isotonic	Control	14	2-3	34	BW	n/a
Geremia et al. [40]	20	PF	Isokinetic	Control	4/8/12	1-2	7/15/23	100% ecc	3/4/5 × 10
Guex et al. [57]	10	KF	Isotonic	Control	6	1-2	11	80-110% 1RM	2-3 × 6-12
Kay et al. [27]	13	PF	Isokinetic	None	6	2	12	100% ecc	5 × 12
Kay et al. [48]	13	KE	Isokinetic	Control	6	2	12	100% ecc	5 × 12
Leslie et al. [44]	9	KF	Isotonic	Control	4	3	12	80-90% iso	3-6 × 8
Mahieu et al. [41]	35	PF	Isotonic	Control	6	7	42	BW	3 × 15
Margaritelis et al. [38]	12	KE	Isokinetic	Concentric	4/9	1	4/9	100% ecc	5 × 15
Mjølsnes et al. [46]	11	KF	Isotonic	TRT	10	2	20	BW	2-3 × 5-12
Nelson & Bandy [28]	24	KF	Isotonic	Control, SS	6	3	18	n/a	1 × 6
Paschalis et al. [54]	10	KE	Isokinetic	Concentric	8	1	8	100% ecc	5 × 15
Potier et al. [58]	11	KF	Isotonic	Control	8	3	24	100% ecc	3 × 8
Vatovec et al. [56]	20	KF	Isotonic	Control	6	2	12	BW	2-3 × 5-8

Acronyms: n – sample size; w - weeks; 1RM – one repetition maximum; KF - knee flexors; PF - plantar flexors; KE - knee extensors; BW - body weight; con - concentric; ecc – eccentric; iso - isometric; FR - foam rolling; TRT - traditional resistance training; SS - static stretching.

Table 2. PEDro scale assessing external (eligibility criteria) and internal validity to determine study quality.

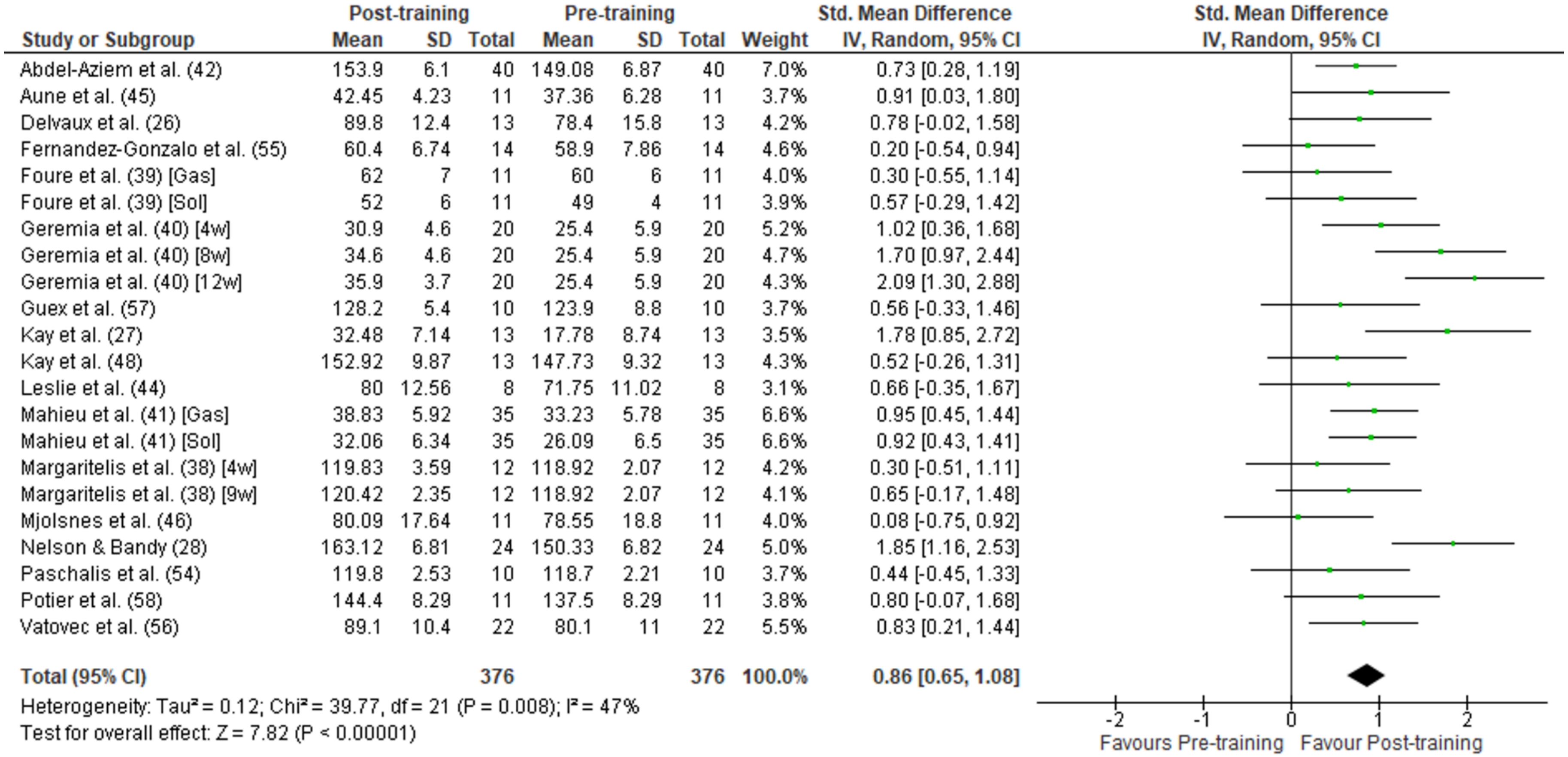
Study	Eligibility	Random allocation	Concealed allocation	Groups similar	Blinded subject	Blinded therapist	Blinded assessor	Follow up >85%	ITTA	BGA	PMV	Score
Abdel-Aziem et al. [42]	1	0	1	1	0	0	1	1	1	1	1	**7**
Aune et al. [45]	1	1	0	1	0	0	1	1	1	1	1	**7**
Delvaux et al. [26]	1	1	1	1	0	0	1	1	1	1	1	**8**
Fernandez-Gonzalo et al. [55]	1	1	1	1	0	0	0	1	1	1	1	**7**
Foure et al. [39]	1	1	1	1	0	0	0	1	1	1	1	**7**
Geremia et al. [40]	1	1	1	1	0	0	0	0	1	1	1	**6**
Guex et al. [57]	1	1	1	1	0	0	0	1	1	1	1	**7**
Kay et al. [27]	1	0	0	1	0	0	0	1	1	0	1	**4**
Kay et al. [48]	1	1	1	1	0	0	0	1	0	1	1	**6**
Leslie et al. [44]	1	1	1	1	0	0	0	1	1	1	1	**7**
Mahieu et al. [41]	1	1	1	1	0	1	1	1	0	1	1	**8**
Margaritelis et al. [38]	1	1	1	1	0	0	0	1	1	1	1	**7**
Mjølsnes et al. [46]	1	1	1	1	0	1	1	1	1	1	1	**9**
Nelson & Bandy [28]	1	1	1	1	0	1	1	1	1	1	1	**9**
Paschalis et al. [54]	1	1	1	1	0	0	0	1	1	1	1	**7**
Potier et al. [58]	1	1	1	0	0	0	0	1	1	1	1	**6**
Vatovec et al. [56]	1	1	1	1	0	0	0	1	0	1	1	**6**

Acronyms: ITTA - intention to-treat analysis; BGA - between-group-analysis; PMV - point measure and variability; 1 - meets criteria; 0 - does not meet criteria; Score - study quality classified as ‘poor’ (<4/10), ‘fair’ (4-5), ‘high’ (6-8), or ‘excellent’ (9-10).



670

671 **Figure 1.** PRISMA flowchart of the article identification, screening, and inclusion process. Acronyms: n = number of articles.

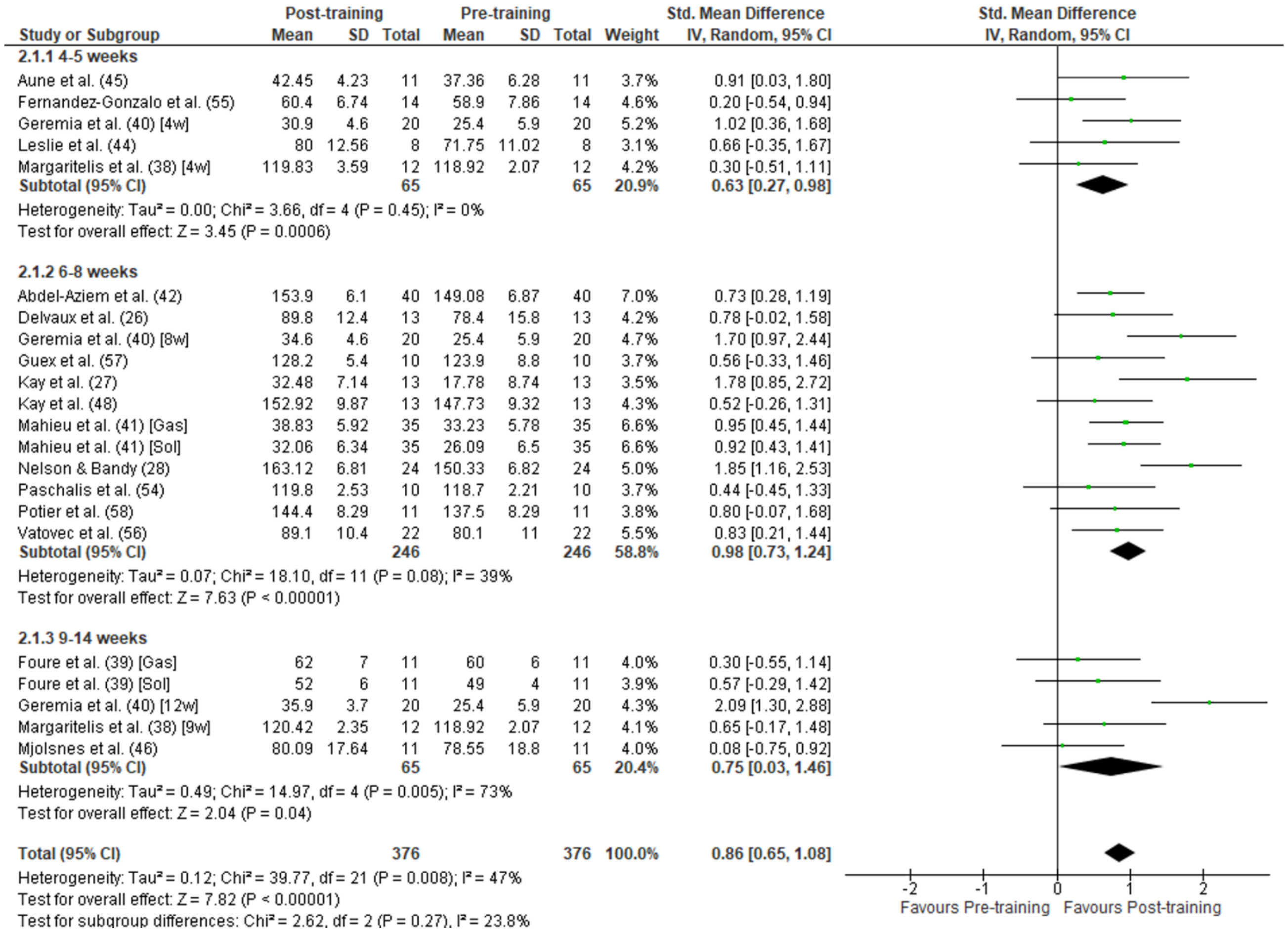


Study or Subgroup	Post-training Mean	Post-training SD	Post-training Total	Pre-training Mean	Pre-training SD	Pre-training Total	Weight	Std. Mean Difference IV, Random, 95% CI
Abdel-Aziem et al. (42)	153.9	6.1	40	149.08	6.87	40	7.0%	0.73 [0.28, 1.19]
Aune et al. (45)	42.45	4.23	11	37.36	6.28	11	3.7%	0.91 [0.03, 1.80]
Delvaux et al. (26)	89.8	12.4	13	78.4	15.8	13	4.2%	0.78 [-0.02, 1.58]
Fernandez-Gonzalo et al. (55)	60.4	6.74	14	58.9	7.86	14	4.6%	0.20 [-0.54, 0.94]
Foure et al. (39) [Gas]	62	7	11	60	6	11	4.0%	0.30 [-0.55, 1.14]
Foure et al. (39) [Sol]	52	6	11	49	4	11	3.9%	0.57 [-0.29, 1.42]
Geremia et al. (40) [4w]	30.9	4.6	20	25.4	5.9	20	5.2%	1.02 [0.36, 1.68]
Geremia et al. (40) [8w]	34.6	4.6	20	25.4	5.9	20	4.7%	1.70 [0.97, 2.44]
Geremia et al. (40) [12w]	35.9	3.7	20	25.4	5.9	20	4.3%	2.09 [1.30, 2.88]
Guex et al. (57)	128.2	5.4	10	123.9	8.8	10	3.7%	0.56 [-0.33, 1.46]
Kay et al. (27)	32.48	7.14	13	17.78	8.74	13	3.5%	1.78 [0.85, 2.72]
Kay et al. (48)	152.92	9.87	13	147.73	9.32	13	4.3%	0.52 [-0.26, 1.31]
Leslie et al. (44)	80	12.56	8	71.75	11.02	8	3.1%	0.66 [-0.35, 1.67]
Mahieu et al. (41) [Gas]	38.83	5.92	35	33.23	5.78	35	6.6%	0.95 [0.45, 1.44]
Mahieu et al. (41) [Sol]	32.06	6.34	35	26.09	6.5	35	6.6%	0.92 [0.43, 1.41]
Margaritelis et al. (38) [4w]	119.83	3.59	12	118.92	2.07	12	4.2%	0.30 [-0.51, 1.11]
Margaritelis et al. (38) [9w]	120.42	2.35	12	118.92	2.07	12	4.1%	0.65 [-0.17, 1.48]
Mjolsnes et al. (46)	80.09	17.64	11	78.55	18.8	11	4.0%	0.08 [-0.75, 0.92]
Nelson & Bandy (28)	163.12	6.81	24	150.33	6.82	24	5.0%	1.85 [1.16, 2.53]
Paschalis et al. (54)	119.8	2.53	10	118.7	2.21	10	3.7%	0.44 [-0.45, 1.33]
Potier et al. (58)	144.4	8.29	11	137.5	8.29	11	3.8%	0.80 [-0.07, 1.68]
Vatovec et al. (56)	89.1	10.4	22	80.1	11	22	5.5%	0.83 [0.21, 1.44]
Total (95% CI)			**376**			**376**	**100.0%**	**0.86 [0.65, 1.08]**

Heterogeneity: Tau² = 0.12; Chi² = 39.77, df = 21 (P = 0.008); I² = 47%

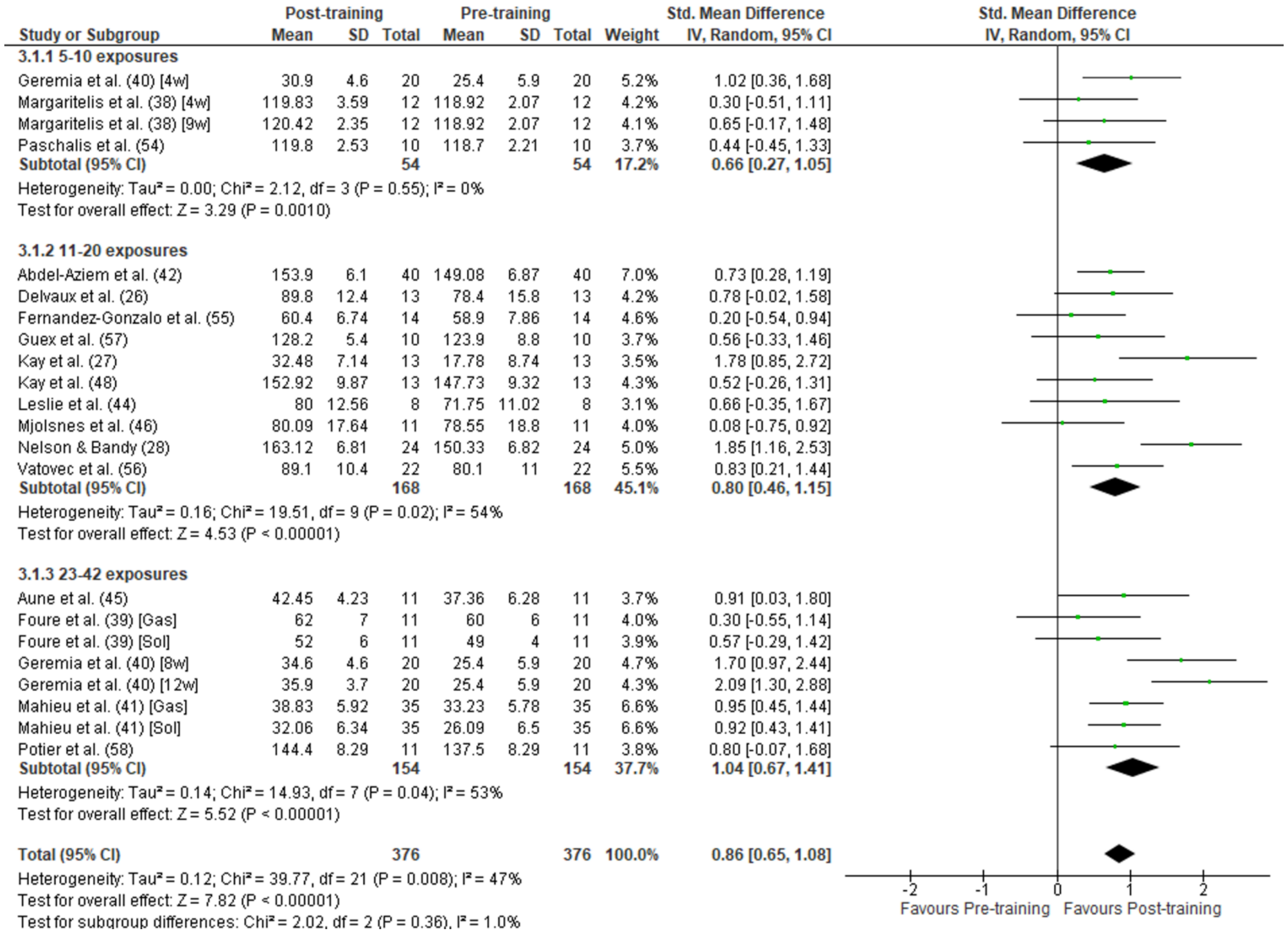
Test for overall effect: Z = 7.82 (P < 0.00001)

Figure 2. Forest plot of joint range of motion changes following eccentric training programmes. Acronyms: Std. = standardised, SD = standard deviation, IV = inverse variance, CI = confidence interval, Gas = gastrocnemii, Sol = soleus, w = week.



	Post-training			Pre-training				Std. Mean Difference
Study or Subgroup	**Mean**	**SD**	**Total**	**Mean**	**SD**	**Total**	**Weight**	**IV, Random, 95% CI**
2.1.1 4-5 weeks								
Aune et al. (45)	42.45	4.23	11	37.36	6.28	11	3.7%	0.91 [0.03, 1.80]
Fernandez-Gonzalo et al. (55)	60.4	6.74	14	58.9	7.86	14	4.6%	0.20 [-0.54, 0.94]
Geremia et al. (40) [4w]	30.9	4.6	20	25.4	5.9	20	5.2%	1.02 [0.36, 1.68]
Leslie et al. (44)	80	12.56	8	71.75	11.02	8	3.1%	0.66 [-0.35, 1.67]
Margaritelis et al. (38) [4w]	119.83	3.59	12	118.92	2.07	12	4.2%	0.30 [-0.51, 1.11]
Subtotal (95% CI)			**65**			**65**	**20.9%**	**0.63 [0.27, 0.98]**
Heterogeneity: Tau² = 0.00; Chi² = 3.66, df = 4 (P = 0.45); I² = 0%								
Test for overall effect: Z = 3.45 (P = 0.0006)								
2.1.2 6-8 weeks								
Abdel-Aziem et al. (42)	153.9	6.1	40	149.08	6.87	40	7.0%	0.73 [0.28, 1.19]
Delvaux et al. (26)	89.8	12.4	13	78.4	15.8	13	4.2%	0.78 [-0.02, 1.58]
Geremia et al. (40) [8w]	34.6	4.6	20	25.4	5.9	20	4.7%	1.70 [0.97, 2.44]
Guex et al. (57)	128.2	5.4	10	123.9	8.8	10	3.7%	0.56 [-0.33, 1.46]
Kay et al. (27)	32.48	7.14	13	17.78	8.74	13	3.5%	1.78 [0.85, 2.72]
Kay et al. (48)	152.92	9.87	13	147.73	9.32	13	4.3%	0.52 [-0.26, 1.31]
Mahieu et al. (41) [Gas]	38.83	5.92	35	33.23	5.78	35	6.6%	0.95 [0.45, 1.44]
Mahieu et al. (41) [Sol]	32.06	6.34	35	26.09	6.5	35	6.6%	0.92 [0.43, 1.41]
Nelson & Bandy (28)	163.12	6.81	24	150.33	6.82	24	5.0%	1.85 [1.16, 2.53]
Paschalis et al. (54)	119.8	2.53	10	118.7	2.21	10	3.7%	0.44 [-0.45, 1.33]
Potier et al. (58)	144.4	8.29	11	137.5	8.29	11	3.8%	0.80 [-0.07, 1.68]
Vatovec et al. (56)	89.1	10.4	22	80.1	11	22	5.5%	0.83 [0.21, 1.44]
Subtotal (95% CI)			**246**			**246**	**58.8%**	**0.98 [0.73, 1.24]**
Heterogeneity: Tau² = 0.07; Chi² = 18.10, df = 11 (P = 0.08); I² = 39%								
Test for overall effect: Z = 7.63 (P < 0.00001)								
2.1.3 9-14 weeks								
Foure et al. (39) [Gas]	62	7	11	60	6	11	4.0%	0.30 [-0.55, 1.14]
Foure et al. (39) [Sol]	52	6	11	49	4	11	3.9%	0.57 [-0.29, 1.42]
Geremia et al. (40) [12w]	35.9	3.7	20	25.4	5.9	20	4.3%	2.09 [1.30, 2.88]
Margaritelis et al. (38) [9w]	120.42	2.35	12	118.92	2.07	12	4.1%	0.65 [-0.17, 1.48]
Mjolsnes et al. (46)	80.09	17.64	11	78.55	18.8	11	4.0%	0.08 [-0.75, 0.92]
Subtotal (95% CI)			**65**			**65**	**20.4%**	**0.75 [0.03, 1.46]**
Heterogeneity: Tau² = 0.49; Chi² = 14.97, df = 4 (P = 0.005); I² = 73%								
Test for overall effect: Z = 2.04 (P = 0.04)								
Total (95% CI)			**376**			**376**	**100.0%**	**0.86 [0.65, 1.08]**
Heterogeneity: Tau² = 0.12; Chi² = 39.77, df = 21 (P = 0.008); I² = 47%								
Test for overall effect: Z = 7.82 (P < 0.00001)								
Test for subgroup differences: Chi² = 2.62, df = 2 (P = 0.27), I² = 23.8%								

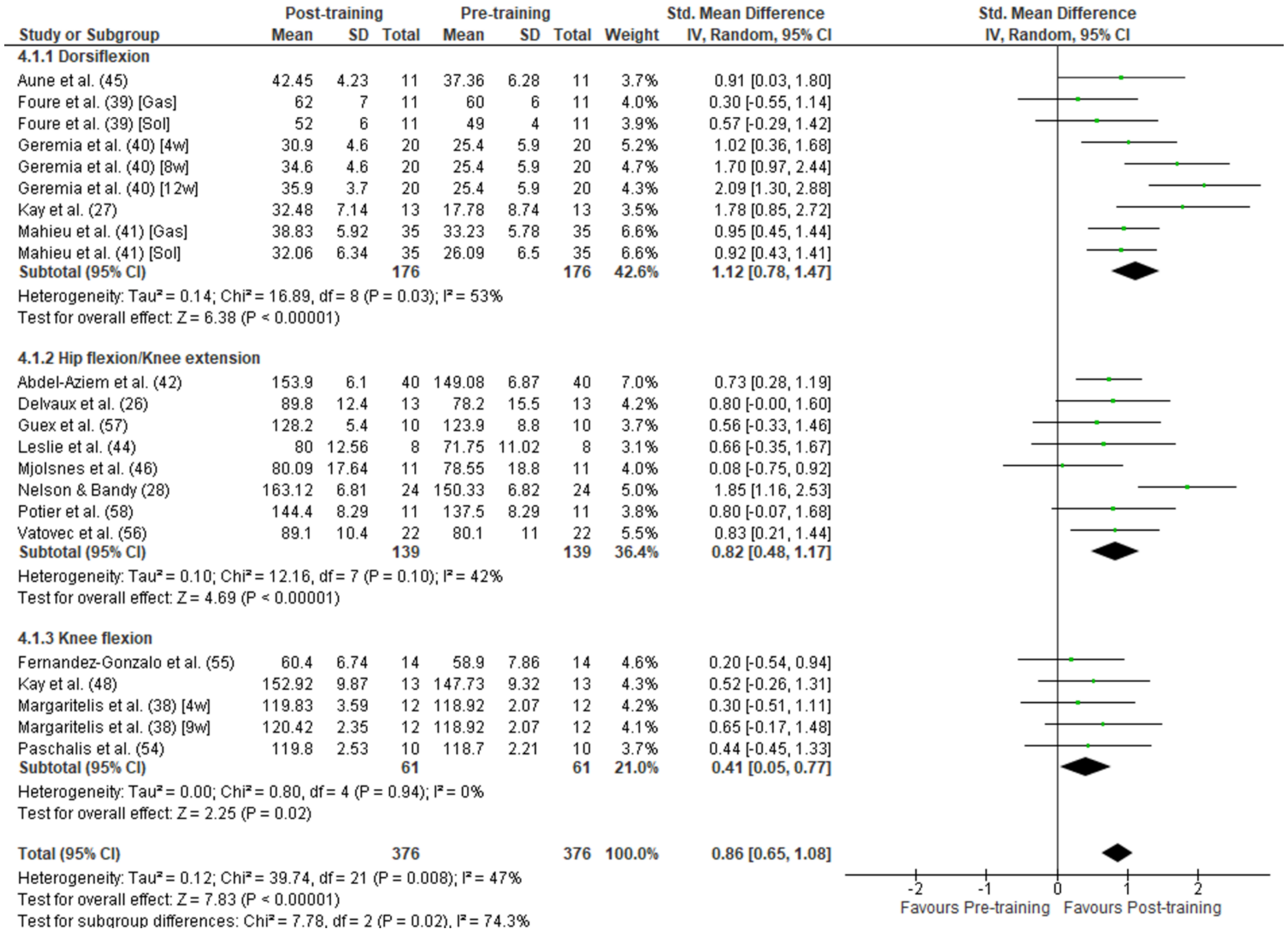
Figure 3. Subgroup forest plot of joint range of motion changes following eccentric training programmes pooled by training durations of 4-5 weeks, 6-8 weeks, or 9-14 weeks. Acronyms: Std. = standardised, SD = standard deviation, IV = inverse variance, CI = confidence interval, Gas = gastrocnemii, Sol = soleus, w = week.



Study or Subgroup	Post-training Mean	Post-training SD	Post-training Total	Pre-training Mean	Pre-training SD	Pre-training Total	Weight	Std. Mean Difference IV, Random, 95% CI
3.1.1 5-10 exposures								
Geremia et al. (40) [4w]	30.9	4.6	20	25.4	5.9	20	5.2%	1.02 [0.36, 1.68]
Margaritelis et al. (38) [4w]	119.83	3.59	12	118.92	2.07	12	4.2%	0.30 [-0.51, 1.11]
Margaritelis et al. (38) [9w]	120.42	2.35	12	118.92	2.07	12	4.1%	0.65 [-0.17, 1.48]
Paschalis et al. (54)	119.8	2.53	10	118.7	2.21	10	3.7%	0.44 [-0.45, 1.33]
Subtotal (95% CI)			**54**			**54**	**17.2%**	**0.66 [0.27, 1.05]**
Heterogeneity: Tau² = 0.00; Chi² = 2.12, df = 3 (P = 0.55); I² = 0%								
Test for overall effect: Z = 3.29 (P = 0.0010)								
3.1.2 11-20 exposures								
Abdel-Aziem et al. (42)	153.9	6.1	40	149.08	6.87	40	7.0%	0.73 [0.28, 1.19]
Delvaux et al. (26)	89.8	12.4	13	78.4	15.8	13	4.2%	0.78 [-0.02, 1.58]
Fernandez-Gonzalo et al. (55)	60.4	6.74	14	58.9	7.86	14	4.6%	0.20 [-0.54, 0.94]
Guex et al. (57)	128.2	5.4	10	123.9	8.8	10	3.7%	0.56 [-0.33, 1.46]
Kay et al. (27)	32.48	7.14	13	17.78	8.74	13	3.5%	1.78 [0.85, 2.72]
Kay et al. (48)	152.92	9.87	13	147.73	9.32	13	4.3%	0.52 [-0.26, 1.31]
Leslie et al. (44)	80	12.56	8	71.75	11.02	8	3.1%	0.66 [-0.35, 1.67]
Mjolsnes et al. (46)	80.09	17.64	11	78.55	18.8	11	4.0%	0.08 [-0.75, 0.92]
Nelson & Bandy (28)	163.12	6.81	24	150.33	6.82	24	5.0%	1.85 [1.16, 2.53]
Vatovec et al. (56)	89.1	10.4	22	80.1	11	22	5.5%	0.83 [0.21, 1.44]
Subtotal (95% CI)			**168**			**168**	**45.1%**	**0.80 [0.46, 1.15]**
Heterogeneity: Tau² = 0.16; Chi² = 19.51, df = 9 (P = 0.02); I² = 54%								
Test for overall effect: Z = 4.53 (P < 0.00001)								
3.1.3 23-42 exposures								
Aune et al. (45)	42.45	4.23	11	37.36	6.28	11	3.7%	0.91 [0.03, 1.80]
Foure et al. (39) [Gas]	62	7	11	60	6	11	4.0%	0.30 [-0.55, 1.14]
Foure et al. (39) [Sol]	52	6	11	49	4	11	3.9%	0.57 [-0.29, 1.42]
Geremia et al. (40) [8w]	34.6	4.6	20	25.4	5.9	20	4.7%	1.70 [0.97, 2.44]
Geremia et al. (40) [12w]	35.9	3.7	20	25.4	5.9	20	4.3%	2.09 [1.30, 2.88]
Mahieu et al. (41) [Gas]	38.83	5.92	35	33.23	5.78	35	6.6%	0.95 [0.45, 1.44]
Mahieu et al. (41) [Sol]	32.06	6.34	35	26.09	6.5	35	6.6%	0.92 [0.43, 1.41]
Potier et al. (58)	144.4	8.29	11	137.5	8.29	11	3.8%	0.80 [-0.07, 1.68]
Subtotal (95% CI)			**154**			**154**	**37.7%**	**1.04 [0.67, 1.41]**
Heterogeneity: Tau² = 0.14; Chi² = 14.93, df = 7 (P = 0.04); I² = 53%								
Test for overall effect: Z = 5.52 (P < 0.00001)								
Total (95% CI)			**376**			**376**	**100.0%**	**0.86 [0.65, 1.08]**
Heterogeneity: Tau² = 0.12; Chi² = 39.77, df = 21 (P = 0.008); I² = 47%								
Test for overall effect: Z = 7.82 (P < 0.00001)								
Test for subgroup differences: Chi² = 2.02, df = 2 (P = 0.36), I² = 1.0%								

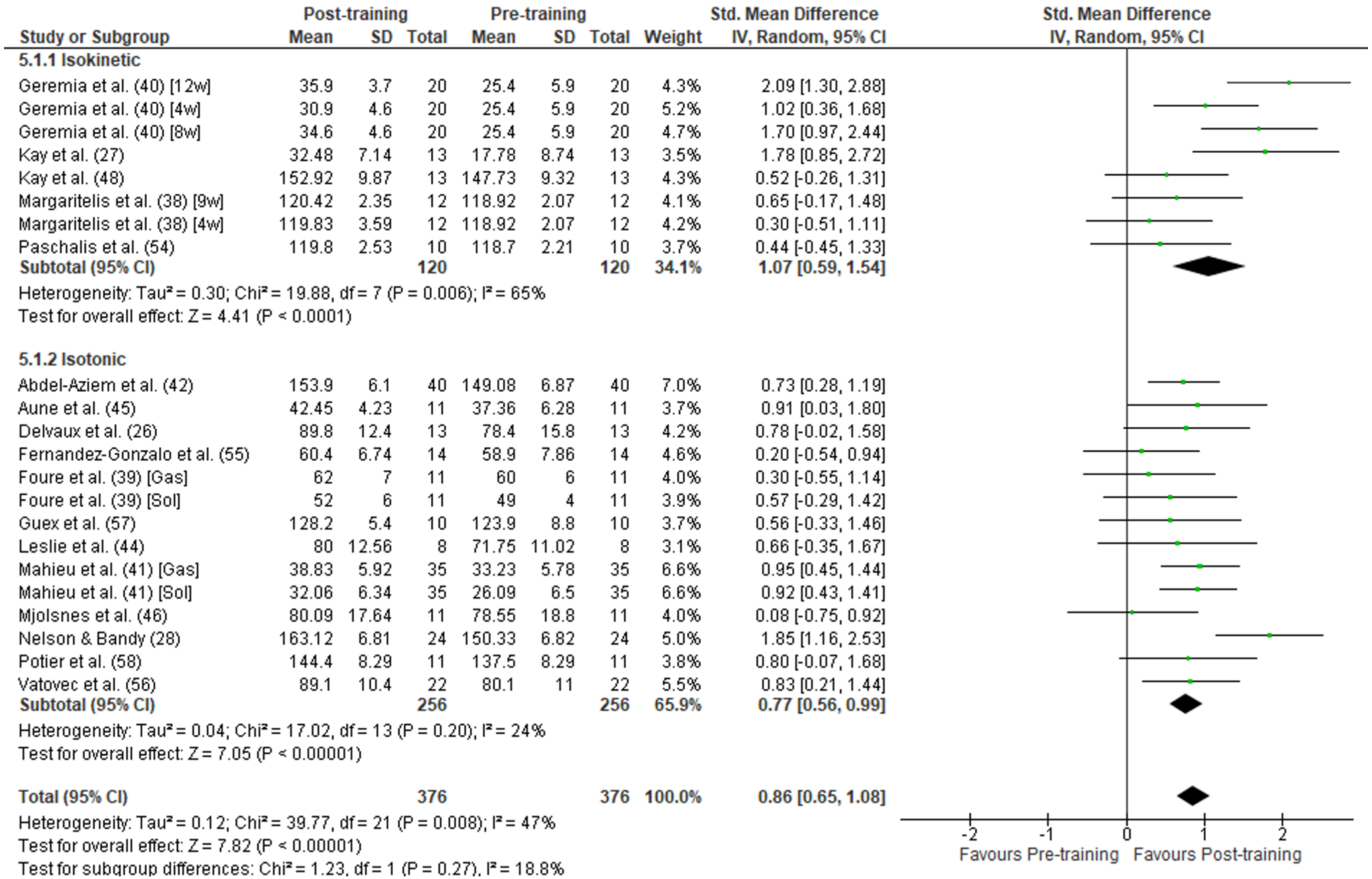
681

Figure 4. Subgroup forest plot of joint range of motion changes following eccentric training programmes pooled by number of exposures of 4-9 sessions, 11-20 sessions, or 23-42 sessions. Acronyms: Std. = standardised, SD = standard deviation, IV = inverse variance, CI = confidence interval, Gas = gastrocnemii, Sol = soleus, w = week.



Study or Subgroup	Post-training Mean	Post-training SD	Post-training Total	Pre-training Mean	Pre-training SD	Pre-training Total	Weight	Std. Mean Difference IV, Random, 95% CI
4.1.1 Dorsiflexion								
Aune et al. (45)	42.45	4.23	11	37.36	6.28	11	3.7%	0.91 [0.03, 1.80]
Foure et al. (39) [Gas]	62	7	11	60	6	11	4.0%	0.30 [-0.55, 1.14]
Foure et al. (39) [Sol]	52	6	11	49	4	11	3.9%	0.57 [-0.29, 1.42]
Geremia et al. (40) [4w]	30.9	4.6	20	25.4	5.9	20	5.2%	1.02 [0.36, 1.68]
Geremia et al. (40) [8w]	34.6	4.6	20	25.4	5.9	20	4.7%	1.70 [0.97, 2.44]
Geremia et al. (40) [12w]	35.9	3.7	20	25.4	5.9	20	4.3%	2.09 [1.30, 2.88]
Kay et al. (27)	32.48	7.14	13	17.78	8.74	13	3.5%	1.78 [0.85, 2.72]
Mahieu et al. (41) [Gas]	38.83	5.92	35	33.23	5.78	35	6.6%	0.95 [0.45, 1.44]
Mahieu et al. (41) [Sol]	32.06	6.34	35	26.09	6.5	35	6.6%	0.92 [0.43, 1.41]
Subtotal (95% CI)			**176**			**176**	**42.6%**	**1.12 [0.78, 1.47]**
Heterogeneity: Tau^2 = 0.14; Chi^2 = 16.89, df = 8 (P = 0.03); I^2 = 53%								
Test for overall effect: Z = 6.38 (P < 0.00001)								
4.1.2 Hip flexion/Knee extension								
Abdel-Aziem et al. (42)	153.9	6.1	40	149.08	6.87	40	7.0%	0.73 [0.28, 1.19]
Delvaux et al. (26)	89.8	12.4	13	78.2	15.5	13	4.2%	0.80 [-0.00, 1.60]
Guex et al. (57)	128.2	5.4	10	123.9	8.8	10	3.7%	0.56 [-0.33, 1.46]
Leslie et al. (44)	80	12.56	8	71.75	11.02	8	3.1%	0.66 [-0.35, 1.67]
Mjolsnes et al. (46)	80.09	17.64	11	78.55	18.8	11	4.0%	0.08 [-0.75, 0.92]
Nelson & Bandy (28)	163.12	6.81	24	150.33	6.82	24	5.0%	1.85 [1.16, 2.53]
Potier et al. (58)	144.4	8.29	11	137.5	8.29	11	3.8%	0.80 [-0.07, 1.68]
Vatovec et al. (56)	89.1	10.4	22	80.1	11	22	5.5%	0.83 [0.21, 1.44]
Subtotal (95% CI)			**139**			**139**	**36.4%**	**0.82 [0.48, 1.17]**
Heterogeneity: Tau^2 = 0.10; Chi^2 = 12.16, df = 7 (P = 0.10); I^2 = 42%								
Test for overall effect: Z = 4.69 (P < 0.00001)								
4.1.3 Knee flexion								
Fernandez-Gonzalo et al. (55)	60.4	6.74	14	58.9	7.86	14	4.6%	0.20 [-0.54, 0.94]
Kay et al. (48)	152.92	9.87	13	147.73	9.32	13	4.3%	0.52 [-0.26, 1.31]
Margaritelis et al. (38) [4w]	119.83	3.59	12	118.92	2.07	12	4.2%	0.30 [-0.51, 1.11]
Margaritelis et al. (38) [9w]	120.42	2.35	12	118.92	2.07	12	4.1%	0.65 [-0.17, 1.48]
Paschalis et al. (54)	119.8	2.53	10	118.7	2.21	10	3.7%	0.44 [-0.45, 1.33]
Subtotal (95% CI)			**61**			**61**	**21.0%**	**0.41 [0.05, 0.77]**
Heterogeneity: Tau^2 = 0.00; Chi^2 = 0.80, df = 4 (P = 0.94); I^2 = 0%								
Test for overall effect: Z = 2.25 (P = 0.02)								
Total (95% CI)			**376**			**376**	**100.0%**	**0.86 [0.65, 1.08]**
Heterogeneity: Tau^2 = 0.12; Chi^2 = 39.74, df = 21 (P = 0.008); I^2 = 47%								
Test for overall effect: Z = 7.83 (P < 0.00001)								
Test for subgroup differences: Chi^2 = 7.78, df = 2 (P = 0.02), I^2 = 74.3%								

Figure 5. Subgroup forest plot of joint range of motion changes following eccentric training programmes pooled by muscle group including plantar flexors (dorsiflexion ROM), knee flexors (knee extension and hip flexion ROM), and knee extensors (knee flexion ROM). Acronyms: Std. = standardised, SD = standard deviation, IV = inverse variance, CI = confidence interval, Gas = gastrocnemii, Sol = soleus, w = week.



	Post-training			Pre-training				Std. Mean Difference
Study or Subgroup	**Mean**	**SD**	**Total**	**Mean**	**SD**	**Total**	**Weight**	**IV, Random, 95% CI**
5.1.1 Isokinetic								
Geremia et al. (40) [12w]	35.9	3.7	20	25.4	5.9	20	4.3%	2.09 [1.30, 2.88]
Geremia et al. (40) [4w]	30.9	4.6	20	25.4	5.9	20	5.2%	1.02 [0.36, 1.68]
Geremia et al. (40) [8w]	34.6	4.6	20	25.4	5.9	20	4.7%	1.70 [0.97, 2.44]
Kay et al. (27)	32.48	7.14	13	17.78	8.74	13	3.5%	1.78 [0.85, 2.72]
Kay et al. (48)	152.92	9.87	13	147.73	9.32	13	4.3%	0.52 [-0.26, 1.31]
Margaritelis et al. (38) [9w]	120.42	2.35	12	118.92	2.07	12	4.1%	0.65 [-0.17, 1.48]
Margaritelis et al. (38) [4w]	119.83	3.59	12	118.92	2.07	12	4.2%	0.30 [-0.51, 1.11]
Paschalis et al. (54)	119.8	2.53	10	118.7	2.21	10	3.7%	0.44 [-0.45, 1.33]
Subtotal (95% CI)			**120**			**120**	**34.1%**	**1.07 [0.59, 1.54]**
Heterogeneity: Tau² = 0.30; Chi² = 19.88, df = 7 (P = 0.006); I² = 65%								
Test for overall effect: Z = 4.41 (P < 0.0001)								
5.1.2 Isotonic								
Abdel-Aziem et al. (42)	153.9	6.1	40	149.08	6.87	40	7.0%	0.73 [0.28, 1.19]
Aune et al. (45)	42.45	4.23	11	37.36	6.28	11	3.7%	0.91 [0.03, 1.80]
Delvaux et al. (26)	89.8	12.4	13	78.4	15.8	13	4.2%	0.78 [-0.02, 1.58]
Fernandez-Gonzalo et al. (55)	60.4	6.74	14	58.9	7.86	14	4.6%	0.20 [-0.54, 0.94]
Foure et al. (39) [Gas]	62	7	11	60	6	11	4.0%	0.30 [-0.55, 1.14]
Foure et al. (39) [Sol]	52	6	11	49	4	11	3.9%	0.57 [-0.29, 1.42]
Guex et al. (57)	128.2	5.4	10	123.9	8.8	10	3.7%	0.56 [-0.33, 1.46]
Leslie et al. (44)	80	12.56	8	71.75	11.02	8	3.1%	0.66 [-0.35, 1.67]
Mahieu et al. (41) [Gas]	38.83	5.92	35	33.23	5.78	35	6.6%	0.95 [0.45, 1.44]
Mahieu et al. (41) [Sol]	32.06	6.34	35	26.09	6.5	35	6.6%	0.92 [0.43, 1.41]
Mjolsnes et al. (46)	80.09	17.64	11	78.55	18.8	11	4.0%	0.08 [-0.75, 0.92]
Nelson & Bandy (28)	163.12	6.81	24	150.33	6.82	24	5.0%	1.85 [1.16, 2.53]
Potier et al. (58)	144.4	8.29	11	137.5	8.29	11	3.8%	0.80 [-0.07, 1.68]
Vatovec et al. (56)	89.1	10.4	22	80.1	11	22	5.5%	0.83 [0.21, 1.44]
Subtotal (95% CI)			**256**			**256**	**65.9%**	**0.77 [0.56, 0.99]**
Heterogeneity: Tau² = 0.04; Chi² = 17.02, df = 13 (P = 0.20); I² = 24%								
Test for overall effect: Z = 7.05 (P < 0.00001)								
Total (95% CI)			**376**			**376**	**100.0%**	**0.86 [0.65, 1.08]**
Heterogeneity: Tau² = 0.12; Chi² = 39.77, df = 21 (P = 0.008); I² = 47%								
Test for overall effect: Z = 7.82 (P < 0.00001)								
Test for subgroup differences: Chi² = 1.23, df = 1 (P = 0.27), I² = 18.8%								

Figure 6. Subgroup forest plot of joint range of motion changes following eccentric training programmes pooled by isotonic eccentric or isokinetic eccentric training modes. Acronyms: Std. = standardised, SD = standard deviation, IV = inverse variance, CI = confidence interval, Gas = gastrocnemii, Sol = soleus, w = week.