



Effect of Strength Training on Biomechanical and Neuromuscular Variables in Distance Runners: A Systematic Review and Meta-Analysis

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Abstract

Background Concurrent strength and endurance (CSE) training improves distance running performance more than endurance training alone, but the mechanisms underpinning this phenomenon are unclear. It has been hypothesised that biomechanical or neuromuscular adaptations are responsible for improvements in running performance; however, evidence on this topic has not been synthesised in a review.

Objective To evaluate the effect of CSE training on biomechanical and neuromuscular variables in distance runners.

Methods Seven electronic databases were searched from inception to November 2018 using key terms related to running and strength training. Studies were included if the following criteria were met: (1) population: ‘distance’ or ‘endurance’ runners of any training status; (2) intervention: CSE training; (3) comparator: running-only control group; (4) outcomes: at least one biomechanical or neuromuscular variable; and, (5) study design: randomised and non-randomised comparative training studies. Biomechanical and neuromuscular variables of interest included: (1) kinematic, kinetic or electromyography outcome measures captured during running; (2) lower body muscle force, strength or power outcome measures; and (3) lower body muscle–tendon stiffness outcome measures. Methodological quality and risk of bias for each study were assessed using the PEDro scale. The level of evidence for each variable was categorised according to the quantity and PEDro rating of the included studies. Between-group standardised mean differences (SMD) with 95% confidence intervals (95% CI) were calculated for studies and meta-analyses were performed to identify the pooled effect of CSE training on biomechanical and neuromuscular variables.

Results The search resulted in 1578 potentially relevant articles, of which 25 met the inclusion criteria and were included. There was strong evidence that CSE training significantly increased knee flexion (SMD 0.89 [95% CI 0.48, 1.30], $p < 0.001$), ankle plantarflexion (SMD 0.74 [95% CI 0.21–1.26], $p = 0.006$) and squat (SMD 0.63 [95% CI 0.13, 1.12], $p = 0.010$) strength, but not jump height, more than endurance training alone. Moderate evidence also showed that CSE training significantly increased knee extension strength (SMD 0.69 [95% CI 0.29, 1.09], $p < 0.001$) more than endurance training alone. There was very limited evidence reporting changes in stride parameters and no studies examined changes in biomechanical and neuromuscular variables during running.

Conclusions Concurrent strength and endurance training improves the force-generating capacity of the ankle plantarflexors, quadriceps, hamstrings and gluteal muscles. These muscles support and propel the centre of mass and accelerate the leg during running, but there is no evidence to suggest these adaptations transfer from strength exercises to running. There is a need for research that investigates changes in biomechanical and neuromuscular variables during running to elucidate the effect of CSE training on run performance in distance runners.

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1 Introduction

Concurrent strength and endurance (CSE) training refers to the inclusion of strength training combined with a cardiorespiratory endurance training program [1]. In the context of this review, the term ‘strength training’ refers to resistance training using free weights or weight machines, and plyometric training. In recent times, a number of review articles [2–7] have examined the effects of CSE training on

Key Points

Concurrent strength and endurance training appears to benefit knee flexion, ankle plantarflexion, knee extension and squat strength in distance runners more than endurance training alone.

Concurrent strength and endurance training may improve distance running performance by increasing the force-generating capacity in the muscles responsible for centre of mass propulsion and acceleration of the leg during swing.

No studies have investigated whether changes in biomechanical and neuromuscular variables following concurrent strength and endurance training transfer to running.

indicators of run performance. The collective conclusion is that CSE training improves distance running performance more than endurance training alone, demonstrated by superior 400 m to 10 km time trial results [8–19] and enhanced running economy [8, 9, 12–14, 20–28]. Despite the well-established benefits of CSE training for these athletes, there is limited scientific evidence elucidating the mechanisms underpinning these training adaptations [23, 27]. Consequently, the purpose of this review is not to re-examine the effect of CSE training on distance running performance, but rather to explore the biomechanical and neuromuscular variables that may change as a result of CSE training.

CSE training can enhance run performance via two principal adaptations; it could increase maximal running speed or improve running economy [4]. These adaptations would enable athletes to achieve or sustain faster running speeds, and reserve energy for the deciding stages of races. Improvements in distance running performance following CSE training are often reported in the absence of any significant changes in maximal aerobic capacity (VO_{2max}), body mass, or muscle hypertrophy [8, 9, 20, 23, 29]. This suggests that improvements in running performance are not facilitated by changes in cardiorespiratory fitness. Accordingly, Paavolainen and colleagues [8] proposed a hypothetical model including ‘anaerobic power and capacity’ and ‘neuromuscular capacity’ as potential mechanisms by which CSE training improves running performance and economy. A number of successive researchers have also suggested biomechanical and neuromuscular variables may be responsible for the improved distance running performance, including changes in running style [13, 20], muscle force and power [13, 22, 24, 26, 30], neuromuscular control [8, 10, 14, 20, 25, 28, 30–32] and musculoskeletal stiffness [8, 9, 12, 14, 15, 24, 26, 33]. To substantiate these claims, it is timely

to provide a critical evaluative synthesis of the changes in biomechanical and neuromuscular variables that occur following CSE training.

The purpose of this review is to: (1) systematically evaluate the effect CSE training has on biomechanical and neuromuscular variables in distance runners by reviewing randomised and non-randomised training studies; and, (2) where appropriate, conduct meta-analyses to obtain estimates of pooled effect size to help resolve uncertainty surrounding these variables. A particular emphasis will be placed on current knowledge gaps to support future research in this area. A greater depth of understanding of the effects of CSE training on biomechanical and neuromuscular variables may enable better design of strength training programs to optimise training adaptations, thus improving the effectiveness and time-efficiency of athlete preparation [34].

2 Methods

This systematic review and meta-analysis followed the guidelines established by the PRISMA (Preferred Reporting Items for Systematic Review and Meta-Analyses) statement [35].

2.1 Literature Search Strategy

The databases Academic Search Complete, CINAHL Complete, Global Health, Medline Complete, ProQuest Health and Medical Complete, Scopus and SPORTDiscus were searched from inception. All publications listed up until 20 November 2018 were considered for inclusion. Within each database, journal article titles, abstracts and keywords were searched using the following terms and Boolean operators: (distance run* OR sprint* OR runner OR track and field) AND (train*) AND (strength OR circuit OR plyometric* OR weight*) NOT (obes* OR diabet* OR soccer OR football). Only English articles available in full text were included. No additional filters or search limitations were used. One reviewer (DT) reviewed all the titles and abstracts returned by the database searches. When abstracts suggested that publications may be suitable for inclusion, the full-text versions were obtained and two authors (DT, JB) independently assessed the full-text versions for eligibility based on the inclusion and exclusion criteria. Results were shared and any disagreements were resolved during a consensus meeting. The reference lists of the articles obtained were searched manually to obtain additional studies not identified electronically. If the reference showed any potential relevance, it was screened at the abstract level before obtaining the full-text version if appropriate.

2.2 Inclusion and Exclusion Criteria

In accordance with the PICOS approach [35], studies were eligible for inclusion in this review if they satisfied the following criteria: (1) population: ‘distance’ or ‘endurance’ runners of any training status; (2) intervention: CSE training comprising resistance training using free weights or weight machines, and/or plyometric training; (3) comparator: control group that performed running training but did not receive the strength training intervention; (4) outcomes: at least one biomechanical or neuromuscular variable; and (5) study design: randomised and non-randomised comparative training studies. Studies were excluded from this review if any of the following exclusion criteria were met: (1) the training intervention investigated incline running, resisted-sprint training, vibration training, electromyostimulation, Pilates, stretching or core-strength training only; (2) the intervention period was acute (≤ 7 days); (3) outcomes were not measured within two weeks of the intervention period, or (4) participants were children under the age of 15 years. Children were excluded to minimise the likelihood that training adaptations were confounded by physiological changes related to growth and development [36].

2.3 Key Biomechanical and Neuromuscular Variables

Biomechanical and neuromuscular variables of interest in this review included: (1) kinematic, kinetic or electromyography (EMG) outcome measures captured during running; (2) lower body muscle force, strength or power outcome measures; and (3) lower body muscle–tendon stiffness outcome measures.

2.4 Data Extraction

Characteristics of studies (i.e. authors, year, experimental groups), participants (i.e. sample size, sex, running training status), interventions (i.e. strength and endurance training prescription) and biomechanical and neuromuscular variables were extracted. Participants with a $VO_{2max} \geq 55$ ml/kg/min were classed as ‘trained’ runners, and those with a $VO_{2max} < 55$ ml/kg/min were classed as ‘untrained’ runners [6]. The exercises prescribed in each study were coded according to the five main types of strength training: maximal, explosive power, hypertrophy, reactive, and local muscular endurance [4, 37]. The characteristics and training principles for the different types of strength training are provided in Electronic Supplementary Material Table S1. Group means and standard deviations were extracted for the intervention and control group/s on relevant variables measured after the CSE training intervention. Change scores were not accepted [38]. If follow-up scores were not available,

study results were checked for statistics that could be used to impute the difference between means and standard deviations for the two groups at follow-up using procedures outlined in the Cochrane handbook [38]. If this information was not available, corresponding authors were contacted via email addresses on publications or by searching websites for current contact details. When studies examined multiple strength training intervention groups against a single control group, intervention groups were combined into one group [38]. If studies reported multiple comparisons relevant to a single variable using identical experimental groups, the results of these comparisons were combined into a single mean and standard deviation without combining sample size [38].

2.5 Assessment of Methodological Quality and Risk of Bias

Two authors (DT and JB) independently evaluated all studies included in this analysis using the PEDro scale [39]. Each study was assessed against the PEDro scale’s 11 items, with a score of ‘1’ indicating a study satisfied that item while a score of ‘0’ indicated an item was not satisfied. Final ratings for each reviewer were collated and examined for item discrepancies. Any disagreements were discussed in a consensus meeting and all items were resolved. Studies with scores of 6 or greater were considered to be ‘high-quality’, studies with scores of 4–5 were considered ‘medium-quality’, and studies that scored below 4 were considered to be ‘low-quality’ [39].

2.6 Statistical Analyses

Between-group standardised mean differences (SMD) with 95% confidence intervals (95% CI) were calculated for study comparisons and, where appropriate, meta-analyses were performed by pooling the results on each variable using Review Manager 5.3.4 (The Cochrane Collaboration, Copenhagen, Denmark). The SMD used was the effect size known as Hedges’ (adjusted) g [40]. Hedge’s g is similar to Cohen’s d [41], but includes an adjustment for small sample size. Meta-analyses were conducted where evidence from the studies was statistically homogeneous, determined by the Higgins I^2 statistic [42]. As proposed by Higgins, values of 25%, 50% and 75% were used to indicate small, medium and large levels of heterogeneity among studies. Meta-analyses were not conducted for variables where studies had statistical heterogeneity ($I^2 > 50\%$, $p < 0.05$) [42]. Meta-analyses were performed using a random-effects model (inverse variance method) to calculate the pooled and weighted mean SMD (SMD_p) and 95% CI for each variable [40]. A sensitivity analysis was conducted to test the influence of methodological quality by removing any low-quality studies from the meta-analyses. Effect sizes were interpreted according to

Hopkin's scale [43], where effect size values < 0.20 indicate trivial, 0.20 – 0.59 indicate small, 0.60 – 1.19 indicate moderate, and values ≥ 1.20 indicate large effects. Statistical significance was set at $p < 0.05$.

2.7 Levels of Evidence

The level of evidence for each variable of interest was categorised based on the quantity and PEDro rating of the included studies using a scale developed by Neal et al. [44] and adapted from Van Tulder et al. [45]. Statistical heterogeneity was established using the I^2 statistic [42].

2.7.1 Strong Evidence

Pooled results from three or more studies, including at least two high-quality studies that are statistically homogeneous.

2.7.2 Moderate Evidence

Pooled results from multiple studies that are statistically heterogeneous, including at least one high-quality study, or pooled results from multiple medium-quality or low-quality studies that are statistically homogeneous.

2.7.3 Limited Evidence

Results from one high-quality study, or pooled results from multiple medium- or low-quality studies that are statistically heterogeneous.

2.7.4 Very Limited Evidence

Results from one medium-quality study or one low-quality study.

2.7.5 No Evidence

Insignificant pooled results from multiple studies, regardless of quality, that are statistically heterogeneous.

3 Results

3.1 Search Strategy

The database search identified a total of 1578 potentially relevant journal articles (Fig. 1). Screening of titles and abstracts for inclusion and exclusion criteria resulted in 69 eligible studies, of which 35 were duplicates and were removed from the analysis. The full-text versions for the remaining 34 articles were screened and an additional nine studies were removed. Studies were excluded for: (1) not

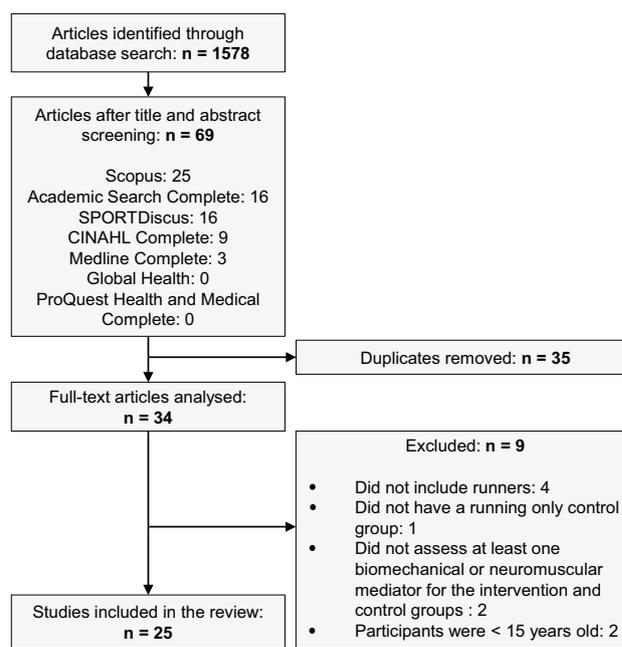


Fig. 1 Study selection flowchart

investigating distance runners [19, 46–48]; (2) failing to include a running-only control group [22]; (3) not assessing at least one biomechanical or neuromuscular variable for the intervention and control groups [49, 50]; or (4) examining participants under the age of 15 years old [51, 52]. The final number of studies included was 25.

3.2 Data Extraction

The 25 studies included in this review were published between the years 1997–2018, and characteristics of studies, participants and training interventions are provided in Table 1. Exercise classifications (as defined in Electronic Supplementary Material Table S1) are denoted by subscripts alongside exercise names in Table 1.

All the included studies were parallel-group design. Twenty-four unique control groups and 29 intervention groups were included in this review. A total of 571 participants completed follow-up testing and the average study size was 21.2 ± 6.5 (range 12–33) participants, with 77.8% of participants being male. The average intervention period was 10.6 ± 7.6 (range 4–40) weeks, and the average number of strength sessions per week was 2.0 ± 0.7 (range 1–3) sessions. Nine studies [8, 13–15, 18, 26, 28, 33, 53] exclusively examined trained distance runners and ten studies examined untrained (i.e. recreational) runners only [10, 20, 21, 23, 31, 32, 54–57]. The remaining studies included a combination of untrained and trained distance runners [9, 12, 16, 25, 58, 59]. All studies examined participants without any strength training experience.

Table 1 Participant, intervention and variable characteristics of included studies

Study	Experimental groups		Participants		Strength training intervention			Endurance training	Biomechanical and neuromuscular variables	
	<i>n</i>	Sex	Running training status	Exercises	Sets x repetitions; rest between sets	Duration (weeks)	Average frequency per week			Additional/replacement
Ache-Dias et al. [32]	1. Jump interval training 2. Control	9 9	MF	Untrained	Continuous vertical jumps ^a	4×6×30 s; 5 min	4	2	Additional	CMJ height CVJ height CMJ peak power CVJ peak power Concentric knee flexion torque Eccentric knee flexion torque Concentric knee extension torque Eccentric knee extension torque Isometric knee flexion torque Isometric knee extension torque
Beattie et al. [53]	1. Strength 2. Control	11 9	M	Trained	Pogo jumps ^a /DJ ₁₅ /CMJ (single)/ CMJ (continuous)/DJ ₁₅ ^a , back squat ^b , Romanian deadlift ^c /SL Romanian deadlift ^c , split squat/ SL squat ^c /reverse lunge ^c /skater squat ^c , jump squat ^a	1-3×2-8 ^b 1-3×5-12 ^c 1-3×3-6 ^a ; NS	40	1.5	Additional	CMJ height RSI IRM squat
Berryman et al. [12]	1. Dynamic weight training 2. Plyometric training 3. Control	12 11 5	M	Mix	1. Concentric semi-squat ^b 2. DJ ₂₀ /DJ ₄₀ /DJ ₆₀ ^a	3-6×8 at 95% peak power output; 3 min	8	1	Additional (matched)	CMJ height
Blagrove et al. [58]	1. Strength training 2. Control	9 9	MF	Mix	Box jump ^a /SL box jump ^a /depth jump ^a , A skip ^a /high knee drill ^a /sprint ^a , hurdle jump ^a , back squat ^b , deadlift ^b /rack pull ^b , SL press ^b / step up ^b , calf raise ^c	3×6-8; 3 min ^b 3×30 m; 90 s ^d 2-3×12; 3 min ^e 3-4×6-8 or 15 m; 90 s ^a	10	2	Additional	20 m sprint SJ height Isometric knee extension force
Damascono et al. [16]	1. Strength training 2. Control	9 9	M	Untrained	Half-squat ^b , leg press ^b , plantarflexion ^b , knee extension ^b	2-3×3-10 RM; 3 min	8	2	Additional	DJ height RSI IRM half-squat
Ferraoti et al. [59]	1. Specific endurance and strength training 2. Specific endurance training (control)	11 9	MF	Mix	1a. Leg press ^d , knee extension ^d , knee flexion ^d , hip extension ^d , ankle extension ^d 1b. Reverse fly ^e , bench press ^e , lateral flexion ^e , trunk extension ^e , trunk flexion ^e , trunk rotation ^e	4×3-5 RM; 3 min ^d 3×20-25 RM; 90 s ^e	8	2	Additional	Contact time Stride length Stride frequency Isometric knee flexion torque Isometric knee extension torque
Fletcher et al. [33]	1. Training 2. Control	6 6	M	Trained	Isometric plantarflexion ^b	4×20 s at 80% MVC; 1 min	8	3	Additional	Isometric plantarflexion torque Triceps surae tendon stiffness

Table 1 (continued)

Study	Experimental groups		Participants		Strength training intervention			Endurance training	Biomechanical and neuromuscular variables																										
	<i>n</i>	Sex	Running training status	Exercises	Sets x repetitions; rest between sets	Duration (weeks)	Average frequency per week			Additional/replacement																									
Taipale et al. [54]	1. Mixed maximal and explosive strength 2. Maximal strength 3. Explosive strength 4. Control	9	M	Untrained	1. Squat ^b , leg press ^b , box jump ^d , vertical jump ^d , sit-up ^c , back extension ^e 2. Squat ^b , leg press ^b , calf exercise ^c , sit-up ^c , back extension ^e 3. Squat ^d , leg press ^d , scissor jump ^a , SJ (single) ^d , SJ (continuous) ^a , sit-up ^c , back extension ^e	2-3×4-6 at 50-85% RM ^b 2×12-15 at 50-60% RM ^c 2-3×5-10, unloaded to 40% RM ^d 2-3×5-10, unloaded to 20 kg ^a 3×20-30 ^c ; 2-3 min	8	1.5	Additional (matched)	Maintained	CMJ height (NR) IRM concentric leg extension (NR) Isometric knee extension force (NR)																								
												Taipale et al. [21]	1. Mixed maximal and explosive strength 2. Control	18	MF	Untrained	Squat ^b , leg press ^b , box jump ^d , vertical jump ^d , sit-up ^c , back extension ^e	2-3×4-6 RM ^b 2-3×8-10 ^d 3×20-30 ^c ; 2-3 min	8	1.5	Additional (matched)	Maintained	CMJ height (NR) IRM concentric leg extension (NR)												
																								Turner et al. [23]	1. Plyometric 2. Control	10	MF	Untrained	Vertical jump ^a , one-legged vertical jump ^a , vertical springing jump ^a , split SJ ^a , incline jump ^a	5-25; NS	6	3	Additional	Maintained	CMJ height SJ height

CMJ countermovement jump; CORR results obtained via correspondence with authors; CVJ continuous vertical jumps; DI_x drop jump from X height (cm); DL double leg; F female only; M male only; MF male and female; Mix trained and untrained participants; MVC maximal voluntary contraction; n number of participants who completed follow-up testing; NR results not reported; NS not specified; reps repetitions per set; RM repetition maximum; RSI reactive strength index; SJ squat jump; SL single leg; Trained participants with maximal oxygen uptake (VO_{2max}) > 55 ml/kg/min; Untrained participants with VO_{2max} ≤ 55 ml/kg/min

^aReactive strength exercise

^bMaximal strength exercise

^cHypertrophy exercise

^dExplosive power exercise

^eLocal muscular endurance exercise

Attempts to contact corresponding authors [14, 18, 21, 28, 31, 54, 56, 57] were made when studies suggested that data had been collected on variables of interest; however, follow-up data had not been published or were not reported adequately for this analysis (e.g. graphed data). Table 1 records these data as ‘not reported’ (NR) following unsuccessful attempts to contact authors, and as ‘correspondence’ (CORR) for unpublished data obtained via contact with authors. Six studies [14, 18, 21, 28, 31, 54] that met the inclusion and exclusion criteria do not contribute data for any variables because of failed attempts to obtain unpublished group means and standard deviations at follow-up.

3.3 Methodological Quality and Risk of Bias

The PEDro scores obtained by each study are available in Electronic Supplementary Material Table S2 and quality ratings (as defined in Sect. 2.5) are displayed in curved brackets following each study in Figs. 2, 3 and 4. The mean methodological quality of the studies was 5.08 ± 0.98 out of 11, with scores ranging from 3 to 7. Nine studies were categorised as high-quality, 14 were medium-quality, and the remaining two had low methodological quality. No studies satisfied allocation concealment (item 3), or subject- (item 5), therapist- (item 6) and assessor-blinding (item 7). It should be taken into account, however, that blinding of participants is a difficult requisite to satisfy in this type of intervention. Most studies failed to list eligibility criteria (item 1, 75%) and intention-to-treat analysis (item 9, 56%). Nine studies did not randomly allocate participants [4, 8, 18, 21, 28, 31, 54, 56, 57].

3.4 Findings

3.4.1 Stride Parameters

There was very limited evidence from one medium-quality study [59] that CSE training had a large effect on ground contact times when running on a treadmill (SMD 1.20 [95% CI 0.23, 2.17], Fig. 2a); however, stride length did not change (SMD 0.55 [95% CI -0.36, 1.45], Fig. 2b).

One high-quality [26] and one medium-quality [59] study provided moderate evidence that CSE training did not change stride frequency during treadmill running at speeds ranging from 2.4 to 5.0 m/s ($I^2=0\%$, SMD_p -0.46 [95% CI -1.13, 0.22], Fig. 2c).

3.4.2 Maximal Running Speed

Pooled findings from low- [8], medium- [15] and high-quality [58] studies provided moderate evidence that CSE training did not significantly change overground 20 m sprint performance ($I^2=0\%$, SMD_p 0.14 [95% CI -0.33, 0.62],

Fig. 2d). Each study [8, 15, 58] reported improvements in 20 m running speed following CSE training that were significantly faster than the control groups; however, SMDs of follow-up scores were small.

3.4.3 Jump for Height

There was strong evidence from four high-quality [9, 13, 15, 16], five medium-quality [12, 23, 32, 55, 56], and one low-quality [53] studies that CSE training did not improve individual countermovement jump (including drop jump) height in distance runners ($I^2=16\%$, SMD_p 0.22 [95% CI -0.09, 0.52], Fig. 2e). In the medium-quality study by Pellegrino et al. [55], there was a significant ($p=0.04$) and moderately-sized difference in countermovement jump height between the intervention and control groups at baseline (SMD -0.95 [95% CI -1.84, -0.06]). Removing this study from the SMD_p did not change the finding (SMD 0.25 [95% CI -0.08, 0.59], $p=0.14$). High-quality evidence from one study [9] found that reactive strength training had a large effect on countermovement jump height in male distance runners (SMD 1.49 [95% CI 0.38, 2.60], $p<0.01$); however, all other studies had non-significant SMDs that were trivial to moderate in magnitude.

There was moderate evidence from two medium-quality studies [23, 58] that CSE training did not improve squat jump height in distance runners ($I^2=0\%$, SMD_p -0.23 [95% CI -0.90, 0.43], Fig. 2f).

Two high-quality [13, 26] and one medium-quality [32] studies provided strong evidence that CSE training did not improve continuous vertical jump height in distance runners ($I^2=0\%$, SMD_p 0.42 [95% CI -0.15, 0.99], Fig. 3a).

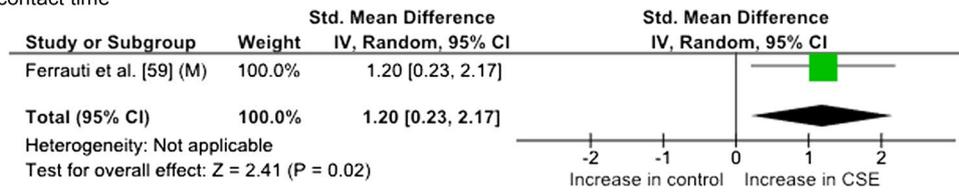
3.4.4 Jump for Distance

Moderate evidence from a high- [9] and low-quality [8] study showed a non-significant but moderate effect favouring CSE training for a larger five-jump for distance (SMD_p 0.71 [95% CI -0.52, 1.94], Fig. 3b). Although not statistically significant ($p=0.08$), there was a medium level of heterogeneity between the studies ($I^2=67\%$). When only the high-quality study [9] was considered, reactive strength training had a significant ($p=0.01$) and large effect on improved five-jump performance in male distance runners (SMD 1.38 [95% CI 0.29, 2.47]).

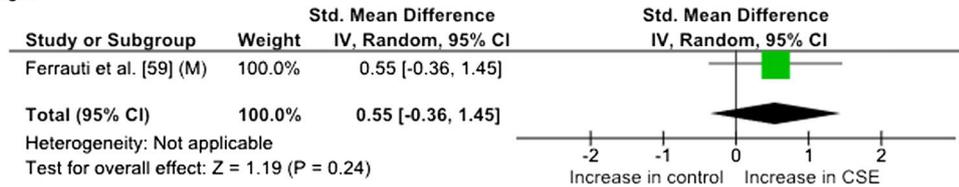
3.4.5 Peak Power of Jump

Very limited evidence from one medium-quality study [32] indicated that additional jump-interval training did not significantly change peak power generated during a countermovement jump in distance runners (SMD -0.24 [95% CI -1.17, 0.69], Fig. 3c).

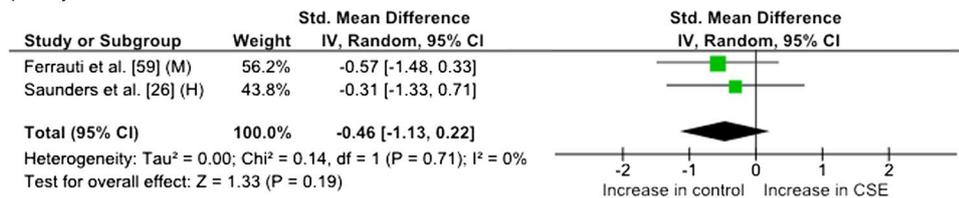
a Ground contact time



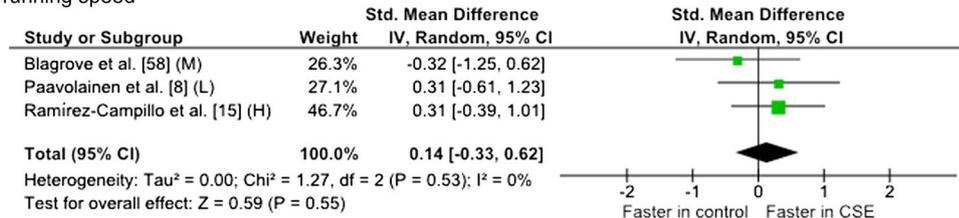
b Stride length



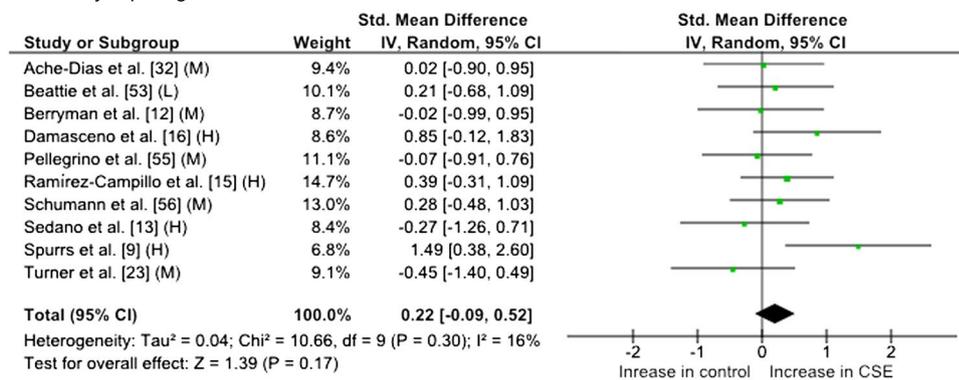
c Stride frequency



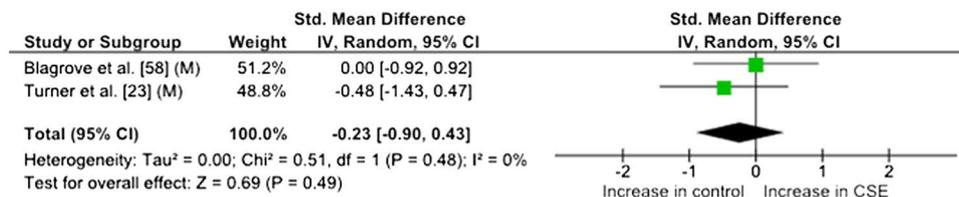
d Maximal running speed



e Countermovement jump height



f Squat jump height



◀**Fig. 2** Forest plots showing individual study and pooled effects (i.e. Hedges' g) of CSE training on biomechanical and neuromuscular variables. Heterogeneity statistics and tests for overall average effect are also presented for each variable. Black squares with horizontal lines indicate the SMD and 95% CI between the intervention and control groups for each study. Black diamonds represent the SMD_p and 95% CI for that variable from all studies in the meta-analyses. A positive SMD favours the CSE training group, and the magnitude of the SMD represents the size of the effect. Curved brackets beside study names refer to methodological quality. *CI* 95% confidence interval, *CSE* concurrent strength and endurance running training, *H* high-quality study, *IV* inverse variance method, *L* low-quality study, *M* medium-quality study, *SD* standard deviation, *Std.* standardised

There was moderate evidence from one high- [26] and medium-quality [32] study indicating that CSE training, focusing on reactive strength development, did not change peak power output during continuous vertical jumping in distance runners (SMD_p 0.25 [95% CI -0.86, 1.37], Fig. 3d). Although no statistically significant ($p=0.15$) heterogeneity was detected, the inconsistency was still moderate ($I^2=51\%$).

3.4.6 Reactive Strength Index

There was moderate evidence from two high-quality [15, 16] and one low-quality [53] studies that CSE training did not change drop jump reactive strength index (RSI) in distance runners ($I^2=0\%$, SMD_p 0.48 [95% CI -0.00, 0.95], Fig. 3e); however, this finding approached statistical significance ($p=0.05$).

3.4.7 Knee Flexion Strength

There was strong evidence from three high-quality [10, 13, 20] and three medium-quality [32, 57, 59] studies that CSE training had a significant and moderate favourable effect on knee flexion strength in distance runners ($I^2=2\%$, SMD_p 0.89 [95% CI 0.48, 1.30], Fig. 3f). In the medium-quality study by Schumann et al. [57], the CSE training group was significantly ($p=0.04$) stronger at baseline (SMD 0.81 [95% CI 0.02, 1.60]). Elimination of this study from the SMD_p did not change the finding (SMD 0.96 [95% CI 0.42, 1.49], $p<0.01$). Two high-quality studies [10, 20] report significant and large SMDs favouring CSE training for increased knee flexion strength in distance runners.

3.4.8 Knee Extension Strength

Moderate evidence from one high-quality [13], five medium-quality [32, 56–59], and one low-quality [8] studies indicates that CSE training had a significant and moderate favourable effect on knee extension strength in distance runners ($I^2=4\%$, SMD_p 0.69 [95% CI 0.29, 1.09], Fig. 4a). In the medium-quality studies by Schumann and colleagues [56,

57], the SMD in one repetition maximum (1RM) leg press and leg extension force may be the result of a decrease in the control group at follow-up.

3.4.9 Plantarflexion Strength

There was strong evidence from four high-quality studies [9, 10, 13, 33] that CSE training had a significant and moderate effect on increasing ankle plantarflexion strength in distance runners ($I^2=0\%$, SMD_p 0.74 [95% CI 0.21, 1.26, Fig. 4b).

3.4.10 Squat Strength

There was strong evidence from five high-quality [10, 13, 16, 20, 25] and one low-quality [53] studies that CSE training had a significant and favourable effect on 1RM squat strength in distance runners ($I^2=28\%$, SMD_p 0.63 [95% CI 0.13, 1.12], Fig. 4c). Two high-quality studies [16, 20] also had significant ($p=0.03$), moderate to large, SMDs demonstrating the benefits of maximal strength training for 1RM squat strength in recreational distance runners.

3.4.11 Triceps Surae Stiffness

Two high-quality studies [9, 33] investigated changes in triceps surae tendon stiffness following CSE training in male distance runners following isometric ankle plantarflexion [33] or reactive strength [9] training. There was moderate evidence to suggest that CSE training did not significantly change triceps surae tendon stiffness during isometric plantarflexion ($I^2=0\%$, SMD_p 0.60 [95% CI -0.16, 1.36], Fig. 4d).

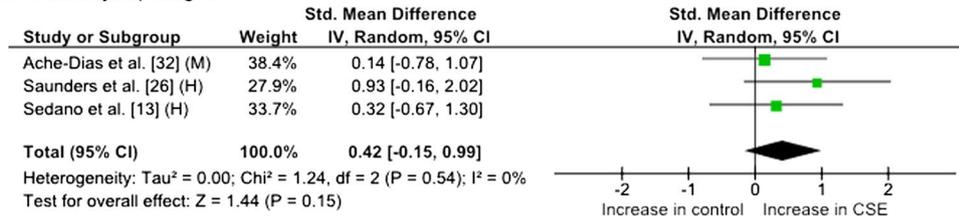
3.4.12 Sensitivity Analysis

The sensitivity analysis showed that methodological quality did not alter the results. When low-quality studies were removed from the meta-analyses, CSE training did not significantly change maximal running speed, countermovement jump height or reactive strength index. There was a significant and moderate effect favouring CSE training for knee extension strength and squat strength.

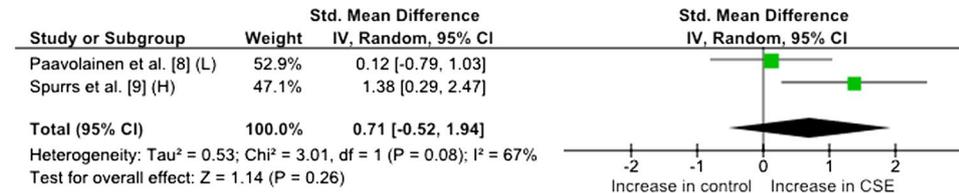
4 Discussion

CSE training has been proposed to enhance distance running performance via adaptations in biomechanical and neuromuscular variables that allow an athlete to rapidly generate high forces during sustained endurance running [4, 8]. This review revealed that there is very limited evidence to substantiate these claims, predominantly due to the paucity of research directly measuring biomechanical

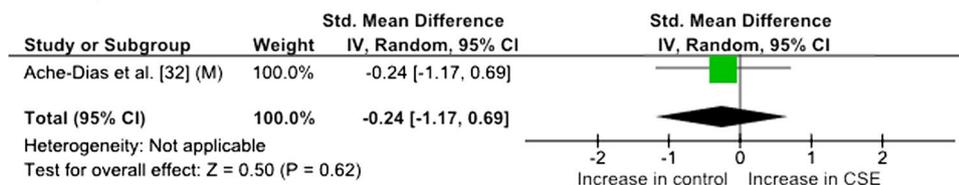
a Continuous vertical jump height



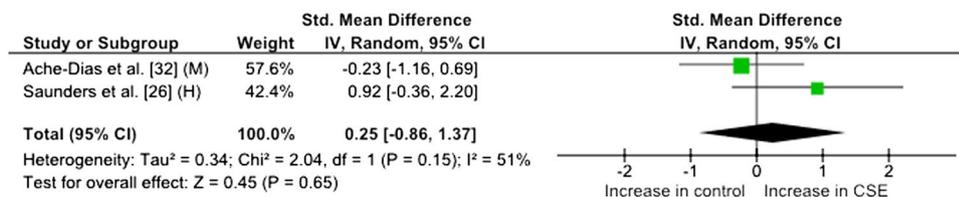
b Jump for distance



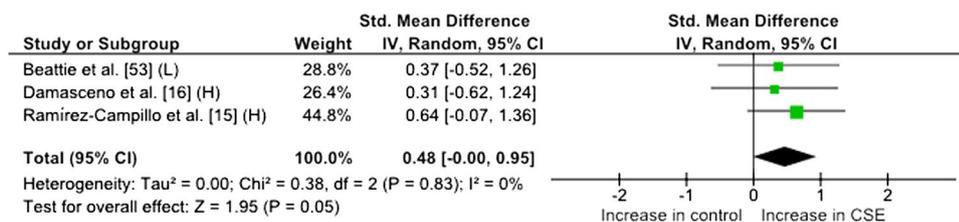
c Countermovement jump power



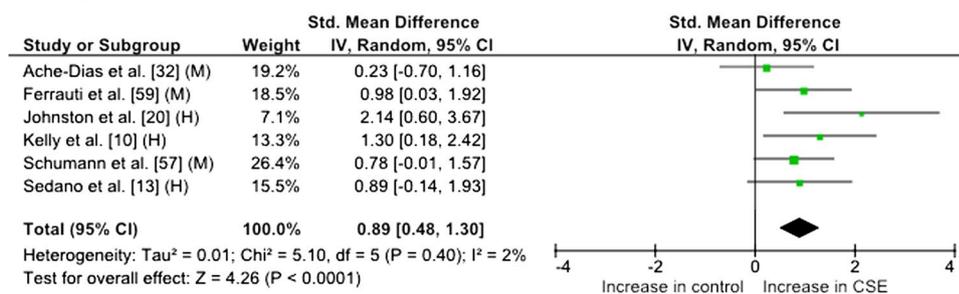
d Continuous vertical jump power



e Reactive strength index



f Knee flexion strength



◀**Fig. 3** Forest plots showing individual study and pooled effects (i.e. Hedges' g) of CSE training on biomechanical and neuromuscular variables. Heterogeneity statistics and tests for overall average effect are also presented for each variable. Black squares with horizontal lines indicate the SMD and 95% CI between the intervention and control groups for each study. Black diamonds represent the SMD_p and 95% CI for that variable from all studies in the meta-analyses. A positive SMD favours the CSE training group, and the magnitude of the SMD represents the size of the effect. Curved brackets beside study names refer to methodological quality. *CI* 95% confidence interval, *CSE* concurrent strength and endurance running training, *H* high-quality study, *IV* inverse variance method, *L* low-quality study, *M* medium-quality study, *SD* standard deviation, *Std.* standardised

and neuromuscular variables during running. We identified strong evidence that CSE training improves knee flexion, ankle plantarflexion and squat strength more than endurance training alone. However, strong evidence suggests that CSE training does not change jump height in distance runners. We found moderate evidence favouring CSE training for increased knee extension strength. There was also very limited evidence for a number of biomechanical and neuromuscular variables and no evidence to support the notion that adaptations in muscle force, neuromuscular control or musculoskeletal stiffness induced by CSE training actually transfer to changes in overground running.

Only two studies [26, 59] reported stride parameters during running following CSE training in distance runners. These studies examined ground contact time [59], stride length [59] and stride frequency [26, 59] at constant running speeds on a treadmill. Ferrauti et al. [59] reported a significant increase in ground contact times at 2.4 and 2.8 m/s following CSE training in recreational marathon runners. This study did not report flight time; however, stride length and stride frequency did not change which implies that flight time must have decreased [60]. Changes in segment positions and inertial parameters were not examined so it is unclear how these changes in ground contact and flight times were achieved [60]. The increase in ground contact time was accompanied by an increase in knee flexion and extension torque during isometric exercises. It is not possible to say whether these improvements in isometric knee torque influenced ground contact times because they were not measured during running, and the relationship between change in knee torque and ground contact times was not analysed. Paavolainen et al. [8] reported a 3.1% improvement in a five kilometre time trial performance and a significant decrease in ground contact times during constant velocity running, while no changes in stride length, stride frequency or ground reaction forces were observed. If ground contact time decreased while stride frequency was unchanged, then it can be assumed that flight time must have increased [60]. Results from this study [8] were not sufficiently reported to include in this meta-analysis; however, the difference between these studies [8, 59] is that Paavolainen et al.

included reactive strength exercises, while Ferrauti et al. used maximal strength exercises. Reactive strength exercises emphasise the development of force over short ground contact times. By rehearsing these skills during training, athletes may have adjusted ground contact times and this adaptation could have transferred to running.

The current findings suggest that CSE training does not change the ratio of stride length to stride frequency when running at constant submaximal speeds; however, no studies have examined whether CSE training enables faster maximal running speeds through changes in stride parameters. We found moderate evidence that CSE training has no effect on overground 20 m sprint performance when we pooled study follow-up scores. However, each individual study [8, 15, 58] reported a significant and beneficial effect of CSE training on sprint performance when change scores were considered, despite no studies having significant differences between groups at baseline. Pooled data may have reported no effect due to large variations in response to the training programs and small effects found. If CSE training does increase running speed in distance runners, future studies should investigate if this is achieved by greater stride lengths, frequencies or a combination of both.

CSE training was found to have a significant and moderate effect favouring an improvement in ankle plantarflexion strength. Strength training that targets the triceps surae could affect plantarflexor power output during running, thus increasing centre of mass propulsion and facilitating larger stride lengths [60]. It is important to note that the ankle plantarflexor tests in each of the included studies required the triceps surae musculotendinous unit to behave differently than during running. The Achilles tendon undergoes repetitive stretch and recoil during running that allows the soleus and gastrocnemius muscle fibers to behave near isometrically while optimising the storage and return of elastic strain energy [61]. During exercises such as the calf raise or isometric ankle plantarflexion, work executed by the triceps surae musculotendinous unit is purely concentric and the storage of elastic strain energy is not possible because the Achilles tendon does not undergo a preceding stretch. The triceps surae will also behave differently between exercises, subject to the ankle joint moment during ground contact and the contraction velocity [62]. As contraction velocity increases at faster running speeds, the triceps surae is unable to develop maximum force [63]. Accordingly, there will be mechanical differences in the behaviour of the triceps surae during running as compared with these exercises. Triceps surae behaviour during the five-jump for distance test is more likely to resemble the fast and forward propulsive action of the plantarflexors during running, and evidence from one high-quality study [9] revealed a significant improvement following plyometric training. Further research is needed to determine if strength training influences plantarflexor output

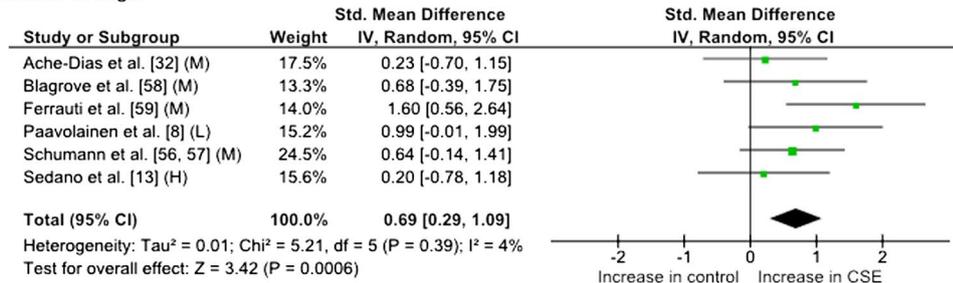
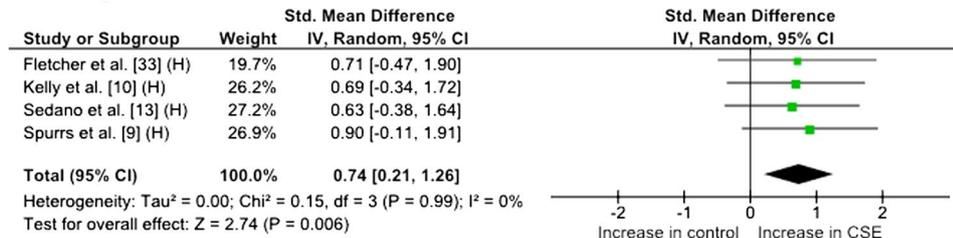
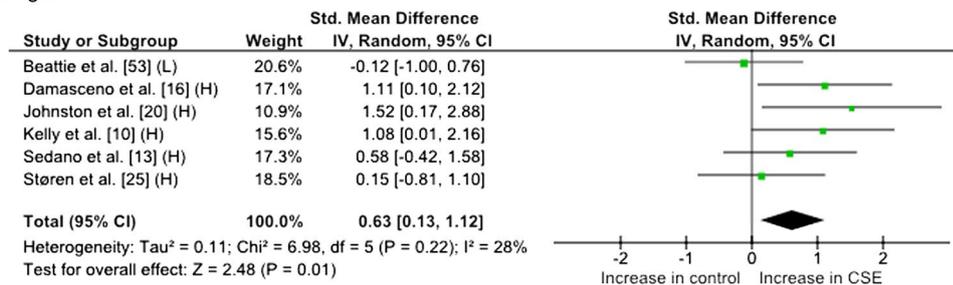
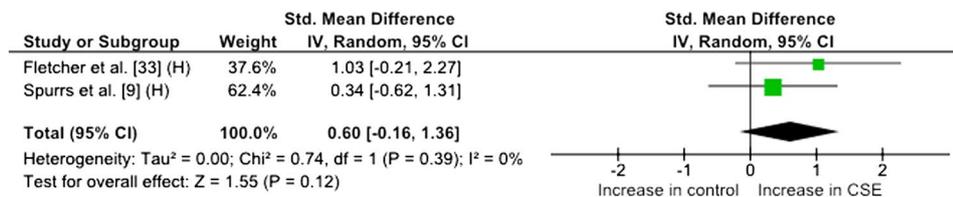
a Knee extension strength**b** Plantarflexion strength**c** Squat strength**d** Triceps surae stiffness

Fig. 4 Forest plots showing individual study and pooled effects (i.e. Hedges' *g*) of CSE training on biomechanical and neuromuscular variables. Heterogeneity statistics and tests for overall average effect are also presented for each variable. Black squares with horizontal lines indicate the SMD and 95% CI between the intervention and control groups for each study. Black diamonds represent the SMD_p and 95% CI for that variable from all studies in the meta-analyses. A positive

SMD favours the CSE training group, and the magnitude of the SMD represents the size of the effect. Curved brackets beside study names refer to methodological quality. *CI* 95% confidence interval, *CSE* concurrent strength and endurance running training, *H* high-quality study, *IV* inverse variance method, *L* low-quality study, *M* medium-quality study, *SD* standard deviation, *Std.* standardised

during overground running, and whether this is associated with changes in stride lengths and faster running speed [60].

CSE training also appears to have a moderate effect on increasing knee flexion, knee extension and squat strength in distance runners, more than endurance training alone.

Increases in hip and knee torque may facilitate improvements in running speed by enabling faster acceleration of the leg during swing. Evidence demonstrates that as running speed increases from 3.50 to 8.95 m/s, peak hip flexion and knee extension torque during initial swing, and peak hip

extension and knee flexion torque during terminal swing, increase by up to six times in magnitude [64]. CSE training appears to increase maximal strength and torque in the bi-articular muscles responsible for rapidly accelerating the hip and knee during fast running, but additional studies are needed to determine whether these changes transfer to over-ground running. It is also worth highlighting that one high-quality study [25] found no significant correlations between changes in 1RM squat strength and running economy following CSE training, which suggests that improvements in hip and knee torque may not be as important at submaximal running speeds compared to maximal running speeds. No additional studies have examined whether changes in hip and knee torque are associated with changes in performance measures.

Damesceno et al. [16] measured 1RM in the half-squat, drop jump height and drop jump RSI to assess neuromuscular adaptations based on the principle that changes in lower body power, when unaccompanied by changes in anthropometry, reflect adaptations in motor unit synchronisation and recruitment [65]. The present findings suggest that CSE training improves 1RM squat strength and may benefit drop jump RSI, but it does not appear to change jump height. Significant changes were also found for knee flexion, knee extension, and ankle plantarflexion strength. Changes in neuromuscular function underpin all of these improvements, yet none of these measures provide insight into the type of neuromuscular change occurring or how these manifest during running. Such changes could be caused by alterations in the timing and/or amplitude of muscle activity, motor unit coordination and synchronisation, muscle co-activation, or any number of other factors [66–68]. For example, strength training could shift the force-length curve of lower limb muscles. This could improve running economy and reserve capacity for high intensity critical sections of a race because type I muscle fibers would be recruited over aerobically inefficient type II fibers [13, 24, 53]. Alternatively, changes in lower limb strength and coordination could alter running biomechanics, consequently improving ground force application or reducing metabolic costs at a given submaximal running speed [20, 69]. Studies utilising EMG recordings combined with kinematics and kinetics might provide greater insight into the potential changes in neuromuscular control during running following CSE training.

This meta-analysis found moderate evidence that CSE training does not significantly increase triceps surae tendon stiffness during isometric ankle plantarflexion in male distance runners; however, the increase in triceps surae tendon stiffness approached statistical significance and further studies will help support or disprove this relationship. Changes in tendon stiffness could affect running performance by influencing a musculotendinous unit's ability to store and return elastic energy or transmit muscle forces to

joint movement [33, 70]. Spurr et al. [9] used an instrumented seated calf raise machine and load cell to assess musculotendinous stiffness, while Fletcher et al. [33] combined dynamometry with ultrasonography. Spurr et al. [9] reported a significant correlation between the change in triceps surae tendon stiffness, five-bound test and running economy across experimental groups, which they believe to represent an increase in horizontal propulsion and reactive power brought about by increased musculotendinous stiffness. Researchers often suggest that changes in jumping [9, 28, 32, 55] and ankle plantarflexion [9, 33] outcome measures (e.g. peak power) represent adaptations in the stretch-shortening cycle of musculotendinous units despite the inability of these tests to detect such changes. This meta-analysis found evidence that CSE training does not change jump height or peak power of jumps; however, two studies report significant correlations between improvements in jump and time trial performance, suggesting that these two parameters may be associated [15, 55]. It is unclear whether the mechanisms by which CSE training improves distance running performance are the same or similar to the mechanisms that affect vertical jumping ability.

4.1 Limitations

Research into the effects of CSE training on distance running is extensive; however, the different types of strength training and prescription variables make it difficult to determine the underlying mechanisms responsible for enhanced performance [6, 71]. Most studies that report favourable effects of CSE training utilise a program with a complex mix of exercises, thus making it difficult to elucidate the effect of the different types of strength training. It is also important to note that, while the present analysis aimed to identify potential variables associated with improved distance running performance following CSE training, mediation analysis were not undertaken. Only four [15, 25, 32, 55] of the included studies performed regression analyses to determine whether changes in variables following CSE training were associated with changes in performance measures. It is evident that there is a clear need for further research, such as mediation studies, to determine whether relationships exist between changes in performance measures and changes in biomechanical or neuromuscular variables.

The present review and meta-analysis also examined distance runners of all training statuses together. This decision was based on the evidence that runners of all abilities demonstrate improvements in time trial performance following CSE training [8–10, 14–16, 18, 55], and strength training does not cause changes in VO_2max in untrained [10, 19, 20, 23, 31, 54, 59] or trained [8, 9, 12–14, 18, 25–27] distance runners. All participants included in this meta-analysis were also inexperienced with strength training; therefore,

it is reasonable to expect that both untrained and trained runners may improve running performance through similar biomechanical and neuromuscular adaptations. While it may be argued that CSE training could have a larger effect on lesser-trained runners biomechanics and neuromuscular control during running, this meta-analysis illustrates the lack of evidence that CSE training changes biomechanical variables during running. Future studies should establish whether CSE training affects these variables during running, before examining whether untrained and trained runners respond differently.

The methodological quality of the published literature should be noted, as only nine of the 25 studies were categorised as high-quality (Electronic Supplementary Material Table S2). Nine studies [4, 8, 18, 21, 28, 31, 54, 56, 57] did not randomly allocate participants, and consequently it is possible that these studies had a systematic bias between the intervention and control groups at the outset of the experiment that may have confounded results. Six medium-quality studies [14, 18, 21, 28, 31, 54] that met the inclusion and exclusion criteria did not contribute data for any variables because of the insufficient reporting of data in publications and failed correspondence with authors. To address these limitations, researchers are advised to consider the CONSORT (Consolidated Standards of Reporting Trials) guidelines [72] to ensure a high methodological quality and the adequate reporting of randomised trials.

5 Conclusions

This is the first systematic review and meta-analysis to synthesise evidence on changes in biomechanical and neuromuscular variables following CSE training in distance runners. CSE training was found to significantly improve knee flexion, ankle plantarflexion, knee extension and squat strength more than endurance training alone, suggesting an increased force-generating capacity in the triceps surae, quadriceps, hamstring and gluteal muscle groups. These muscles play a crucial role in centre of mass propulsion and acceleration of the leg during running, and further research is required to establish whether these adaptations in muscle force transfer to larger stride lengths and faster running speeds. CSE training may also have beneficial effects for drop jump RSI and triceps surae tendon stiffness during an ankle plantarflexion contraction, but caution should be exercised when interpreting the results of the existing literature because adaptations may be task-dependent. These results highlight the need to investigate how adaptations to CSE training transfer to overground running and how distance running kinematics and kinetics change following a period of CSE training. Improved understanding of these mechanisms can have important implications for the prescription

of strength training and taper periods in preparation for competition.

Author Contributions Danielle Trowell performed the database search and identified relevant articles, extracted and analysed data, and is the primary author of the manuscript. Jason Bonacci identified relevant articles, assessed articles for methodological quality and risk of bias, and contributed to the writing of the manuscript. Bill Vicenzino provided guidance on conducting meta-analyses using standardised mean differences and contributed to the writing of the manuscript. Natalie Saunders and Aaron Fox provided guidance and feedback on the manuscript.

Data Availability Statement The datasets analysed during the current review are available in published articles (as referenced) or available from the corresponding author as indicated by 'CORR' in Table 1.

Compliance with Ethical Standards

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Conflict of interests Danielle Trowell, Bill Vicenzino, Natalie Saunders, Aaron Fox and Jason Bonacci declare that they have no conflicts of interest relevant to the content of this review.

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