Received: 11 August 2021 | Revised: 21 October 2021 | Accepted: 8 November 2021

DOI: 10.1111/sms.14092

ORIGINAL ARTICLE

WILEY

Effect of concurrent strength and endurance training on run performance and biomechanics: A randomized controlled trial

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Funding information
This research did not receive any external funding support

This parallel-group randomized controlled trial investigated the effect of concurrent strength and endurance (CSE) training on running performance, biomechanics, and muscle activity during overground running. Thirty moderately trained distance runners were randomly assigned to 10-week CSE training (n = 15; 33.1 ± 7.5 years) or a control group (n = 15; 34.2 ± 8.2 years). Participants ran ≥30 km per week and had no experience with strength training. The primary outcome measure was 2-km run time. Secondary outcome measures included lower limb sagittal plane biomechanics and muscle activity during running (3.89 m s^{-1} and maximal sprinting); maximal aerobic capacity ($\dot{V}O_2$max); running economy; and body composition. CSE training improved 2-km run time (mean difference (MD): −11.3 s [95% CI −3.7, −19.0]; p = 0.006) and time to exhaustion during the $\dot{V}O_2$max running test (MD 59.1 s [95% CI 8.58, 109.62]; p = 0.024). The CSE training group also reduced total body fat (MD: −1.05 kg [95% CI −0.21, −1.88]; p = 0.016) while total body mass and lean body mass were unchanged. Hip joint angular velocity during the early swing phase of running at 3.89 m s^{-1} was the only biomechanical or muscle activity variable that significantly changed following CSE training. CSE training is beneficial for running performance, but changes in running biomechanics and muscle activity may not be contributing factors to the performance improvement. Future research should consider other possible mechanisms and the effect of CSE training on biomechanics and muscle activity during prolonged running under fatigued conditions.

KEYWORDS
electromyography, plyometrics, resistance training, running economy, statistical parametric mapping, training adaptations

1 | INTRODUCTION

"Distance running" is the collective term for both middle- (800–3000 m) and long-distance (≥3000 m) running. Distance running performance is largely determined by an athlete's physiological capacity.[1] Maximal oxygen uptake ($\dot{V}O_2$max), the ability to sustain a high percentage of $\dot{V}O_2$max (fractional utilization of $\dot{V}O_2$max), and running economy account for a large amount of variation in distance running performance.[2] Economical runners use less oxygen than runners with poor running economy at the same steady-state speed.[1] This helps runners sustain faster running speeds for longer and reserve vital energy stores, thus facilitating enhanced running performance.[1] While the determinants of distance running performance have traditionally been developed through aerobic running training, there is increasing evidence that concurrent strength and endurance (CSE) training enhances running performance more than endurance training alone.[3,4] A comprehensive systematic review found CSE training has a moderate beneficial effect on middle- and long-distance time trials up to 10 km.[4] The performance enhancement derived from CSE training is thought to primarily be due to improved running economy.[4] Across distance runners of all levels, the improvement in running economy following CSE training ranges from 2 to 8% with effect sizes of 0.14–3.22.[4]

Improvements in running performance and economy following a period of CSE training are often attributed to adaptations in biomechanics and muscle activity during running;[5-9] however, there is little scientific evidence to support these conjectures.[10] Johnston and colleagues[5] suggested that improved muscle strength following CSE training could facilitate changes in running style and metabolic energy cost. The authors did not provide evidence to support their theory. Kelly et al.[8] proposed that CSE training improved three-kilometer run times among recreational runners via an increase in stride length. These authors suggested that increased lower limb strength levels following CSE training may have increased ground reaction force (GRF) production leading to longer stride lengths. Other researchers have also suggested that plyometric training could reduce ground contact times[7] or enhance coordination and timing of ground force application.[9] Most of these CSE training studies[5-8] have not measured changes in biomechanics during running to support these theories. Those studies that have included biomechanical measures have only analyzed stride parameters and findings have been inconsistent.[10] Some researchers have found CSE training has no effect on stride parameters during running,[9,11] while others have found CSE training influences ground contact time[12] or minimizes the loss of stride length that typically occurs during fatiguing running bouts.[13] These inconsistent findings highlight the need for further research on whether CSE training influences running stride parameters.

A recent meta-analysis[10] of 25 CSE training studies found strong evidence that CSE training increases ankle plantarflexor, knee flexor, knee extensor, and squat strength more than running-only training. Moderate evidence also showed CSE training increases knee extension strength, drop jump reactive strength index, and triceps surae tendon stiffness during isometric ankle plantarflexion. During running, the ankle plantarflexors contribute to the forward propulsion of the center of mass during stance, while the muscles of the hip and knee accelerate and decelerate the leg during swing.[14] Accordingly, CSE training may improve distance running performance by increasing the force-generating capacity in the muscles responsible for center of mass propulsion and acceleration of the leg during swing. To date, most measures of biomechanics and muscle activity following CSE training in distance runners have occurred during non-running tasks (eg, leg press, squat, and countermovement jump exercises).[10] Given the limited and inconclusive research on this topic, there is a need to investigate the biomechanical and muscle activity adaptations to a CSE training intervention during running. This novel information may help the prescription of CSE training programs to optimize training adaptations, thus improving the effectiveness and time-efficiency of athlete preparations.

The primary aim of this randomized controlled trial was to determine whether 10 weeks of CSE training improves running performance. It was hypothesized that the CSE training group would improve running performance more than the control group. The secondary aim of this trial was to determine whether CSE training facilitates changes in running economy and sagittal plane joint kinematics, joint kinetics, and muscle activity during running. This study investigated the non-directed null hypotheses that the running biomechanical and muscle activity waveforms were not significantly different between groups following the intervention.

2 | MATERIALS AND METHODS

2.1 | Experimental approach to the problem

This study was a repeated-measures, single-blind, parallel-group randomized controlled trial. This trial was approved by the Deakin University and Australian Institute of Sport (AIS) Human Research Ethics Committees, and registered with the Australian New Zealand Clinical Trials Registry (ANZCTR) #ACTRN12618000880246.

The intervention was 10-weeks duration, and participants attended 3 days of testing in the week prior to and after the intervention period. Day one of testing included a treadmill running test for the collection of physiological outcome measures. Body composition and overground running performance were measured on day two. Day three utilized three-dimensional motion analysis and surface electromyography (EMG) to measure overground running biomechanics and muscle activity.

2.2 | Participants

Participants were recruited from the local distance running community. To be included in this trial, participants were required to (i) be a distance runner, running more than 30 km per week for at least 1 year prior to the study; (ii) have no experience with strength training for at least 1 year prior to the study; and (iv) be injury free and have no previous history of a serious lower limb injury or surgery. An a priori power analysis indicated that (using a randomized controlled trial design, alpha cutoff of 5%, power of 0.80, and an effect size of 0.20) a total of 18 participants were required to detect a change in run performance as the primary outcome measure,[15] while a total of 22 participants were required to detect a change in ground contact time as a secondary outcome measure.[11] Allowing for participant drop out, 30 participants were recruited for this trial. Written informed consent was obtained from participants prior to the commencement of all data collection procedures.

Participant demographics (biological sex, age, body mass, and height), event specialization, weekly endurance training loads, and results of the $\dot{V}O_2$max test at baseline were used to pair match participants to create two similar groups at baseline. Participants were then randomly assigned to either the CSE training (9 male, 6 female; age = 33.1 ± 7.5 years; body mass = 72.7 ± 4.4 kg; height = 1.73 ± 0.09 m) or control group (9 male, 6 female; age = 34.2 ± 8.2 years; body mass = 69.9 ± 10.0 kg; height = 1.75 ± 0.09 m) by a researcher external to this project. Participants were moderately trained distance runners that identified as long-distance track (CSE training: $n = 1$; control: $n = 1$) and long-distance road (CSE training: $n = 14$; control: $n = 14$) runners. The average distance, duration, and frequency of running training for the CSE training and control groups at baseline were 47.9 ± 17.8 vs 49.2 ± 18.4 km per week, 287.6 ± 156.1 vs. 288.9 ± 189.2 min per week, and 4.5 ± 1.6 vs. 4.5 ± 1.2 days per week, respectively.

Several control measures were implemented to minimize the effect of extraneous factors and diurnal variation on outcome measures. Participants were asked to maintain their habitual lifestyles and daily food intake, and not commence any nutritional supplements, during the intervention period. Participants were familiarized with all testing procedures and equipment prior to data collection. The baseline testing schedule was replicated at follow-up testing. Participants were instructed to refrain from any exhaustive or unaccustomed exercise (for 24 h), avoid alcohol (for 48 h), and limit caffeinated drinks (for 4 h) before each testing session. All participants recorded a dietary log during the week of their baseline testing and participants consumed the same diet during the week of their follow-up testing. Participants attended the testing sessions in appropriate running wear and shoes, which were recorded and worn again during follow-up testing. Personal recording and timing devices were not permitted during any testing procedures. Warm-up routines were recorded and repeated during follow-up testing. Baseline and follow-up test results were not shared with any participants until the conclusion of all data collection procedures. Members of the research team and anyone responsible for measuring or analyzing outcome measures were blinded to group allocation.

2.3 | Procedures

2.3.1 | Intervention

In addition to their normal running training, the CSE training group undertook strength training 2 days per week (Tuesday and Thursday evenings) for 10 weeks. This scheduling is in line with recommendations by Alcaraz-Ibañez et al.,[3] who synthesized evidence from 18 CSE training studies and found that improvements in distance running performance can be accomplished using two weekly sessions separated by at least 48 h, over a 6–12 week period. Three Australian Strength and Conditioning Association (ASCA) Level Two Coaches who were external to the research team supervised all strength training sessions, one-repetition maximum (1RM) testing, and individualized exercise progressions. The warm-up comprised of 10 min of stationary cycling or treadmill running followed by guided stretching of the major muscle groups of the lower body. The second part of the training session involved a range of exercises performed in succession (Table 1). The back squat and single-leg deadlift targeted muscular strength of the hip and knee extensors through relatively high-load (70% 1RM), low-velocity movements. These loads were prescribed in accordance with the American College of Sports Medicine (ACSM) guidelines for resistance training in beginners.[16] Participants' 1RM was determined during the first strength training session following the warm-up protocol. Coaches estimated participants load at 70% 1RM; then, participants had five trials to achieve the 1RM load with a 3-min interval between trials. Participants were required to correctly execute the back squat and single-leg deadlift with control for a 1RM attempt to be accepted. This required the thighs to reach parallel to the floor in the squat and for the chest and raised leg to reach parallel to the floor in the single-leg deadlift. The split squat and countermovement jumps were initially performed unweighted and targeted rate of force development of the hip and knee extensors through high intensity,

TABLE 1 Repetition numbers and loads for the CSE training program.

Exercise	Repetitions per set	Load per set
Ankle bouncing	20	Unloaded
Back squat	10	Barbell with 70% 1RM
Hurdle jumps (40 cm)	3 × 5 hurdles	Unloaded
Frontal plank	60 s	Unloaded
High-knee drill or A-skip drill[a]	20 m	Unloaded
Single-leg deadlift	10 (each side)	Kettlebell with 70% 1RM
Split squat jump	10 (each side)	Unloaded or with dumbbells up to 30% BW
Side-stepping	20 m (both directions)	Theraband
Countermovement jump or drop jump (45 cm)[a]	6	Unloaded or with dumbbells up to 30% BW
Glute bridge	10	Unloaded

[a]A-skip and drop jump were exercise progressions of the high-knee drill and countermovement jump, respectively. *1RM* one-repetition maximum; *BW* body weight. There was a rest period of 3 min between sets.

high-velocity movements. Participants competent in performing unweighted split squat jumps were progressed to split squat jumps with dumbbells up to 30% body weight (BW). Participants competent in performing the unweighted countermovement jumps were progressed to 45 cm unweighted drop jumps, then to 45 cm weighted drop jumps with dumbbells up to 30% BW. The ankle bouncing, hurdle jumps, and A-skip targeted reactive strength development and stretch-shortening cycle function of the plantarflexors using unloaded, high-velocity movements. Participants unable to initially execute the A-skip drill were progressed toward this skill using the high-knee drill. Assistive work throughout the 10 weeks consisted of the frontal plank, the glute bridge, and side-stepping with a Theraband to target trunk stability, glute activation, and femoral control for knee stability. Assistive exercises were performed without any additional load. The number of sets per session varied between two and five to avoid injury and overtraining, and because variable strength training programs have been shown to be more effective than unvarying programs.[4,16] The following non-linear programming schedule was implemented for all CSE training group participants from Weeks 1 to 10, respectively: 2, 3, 4, 3, 4, 5, 3, 4, 5, and 3 sets. Exercise progressions (ie, unweighted split squat jump to weighted split squat jump; countermovement jump to drop jumps; and high-knee drill to A-skip) occurred in weeks four and seven when the number of sets per session was reduced to three. During weeks four and seven, 1RM testing of the squat and single-leg deadlift was repeated and participants' training loads were adapted to maintain loads at 70% 1RM or just above. Participants had a 3-min recovery between each set.[16]

Total training time was matched for both groups in accordance with previous CSE training studies.[6,9,12] In addition to their normal running training, the control group performing two low-intensity conditioning sessions per week, each separated by 2–4 days. The low-intensity conditioning sessions consisted of stretching and body weight exercises (eg, sit-ups, lunges) that were performed in succession. All participants were advised not to start any new exercise activities for the duration of the study and to maintain their running training loads. Compliance with the training programs and weekly running training loads were monitored through an online training log (Google Documents; Google). Participants reported the distance, duration, and intensity (rate of perceived exertion) of all running training sessions. Participants also noted the details of interval training sessions (ie, sets, repetitions, recovery, and pace). The training logs were reviewed each week by a colleague external to the research team to ensure that the total weekly frequency, distance, duration, or intensity of weekly running training did not change by more than 20% from baseline.

2.3.2 | Running performance

A 2-km time trial was chosen as an indicator of running performance when neuromuscular fatigue may be occurring.[12] The 2-km time trial was conducted on an outdoor 400 m synthetic running track. Participants performed the time trial individually and were encouraged to pace themselves evenly and to cover the distance as fast as possible. Run times were recorded to the nearest second using a handheld stopwatch and a single assessor performed all recordings. The smallest worthwhile change was 2.0%.[17] Outdoor ambient temperature and humidity were collected from the Australian Bureau of Meteorology mobile weather application (Australian Department of the Environment).

2.3.3 | Physiological measures

All procedures were performed indoors under controlled laboratory conditions (temperature: 21.6 ± 1.1°C; humidity: 32.5 ± 4.6%; and barometric pressure: 714.8 ± 14.0 mmHg). A custom-designed motorized treadmill and open-circuit indirect calorimetric system with associated in-house software were used to monitor gas exchange patterns during running.[18]

Participants performed a self-selected warm-up on the treadmill that was recorded and repeated at follow-up testing. The treadmill was set at a 0% gradient with an initial starting speed of 2.78–3.33 m s^{-1}. Each participant's starting speed was determined following a discussion of their weekly running training load and race times. Speed was increased by 0.56 m s^{-1} every 4 min until participants had completed 16 min of incremental running. The average oxygen consumption ($\dot{V}O_2$) over the last minute of each stage was used as the measure of $\dot{V}O_2$ for a given speed. From post-hoc inspections of $\dot{V}O_2$ data, the maximum speed at which a respiratory exchange ratio (RER) below 1.0 was achieved across all participants was 3.33 m s^{-1}. Therefore, submaximal $\dot{V}O_2$ (mL kg^{-1} min^{-1}) at 3.33 m s^{-1} was used as a measure of running economy for all participants. The energy cost of running (kj kg^{-1} min^{-1}) at 3.33 m s^{-1} was also calculated using the average RER over the same period and the caloric equivalent of $\dot{V}O_2$.[19] In our laboratory, the typical error for the measurement of submaximal $\dot{V}O_2$ is 2.4% so this value was chosen as the smallest worthwhile change for running economy and the energy cost of running.[18]

Following a 5-min rest period, $\dot{V}$O2max was determined during an incremental treadmill running test to volitional exhaustion. Participants resumed running at the speed that they commenced their running economy test at (eg, 2.78 m s^{-1} and 0% gradient). Speed then increased by 0.14 m s^{-1} every 30 s until the treadmill speed reached the maximum speed of their running economy test (ie, starting speed plus 1.67 m s^{-1}). After 30 s at this speed and 0% gradient, the treadmill gradient was increased by 0.50% every 30 s until volitional exhaustion was reached, with participants instructed to attempt to finish the test on a 30 s increment if possible. Maximal effort was deemed to have occurred if there was an increase in oxygen uptake of less than 2.1 mL kg^{-1} min^{-1} between two consecutive stages, and either the RER was greater than 1.15 or the heart rate was ≥90% of their age-predicted maximum.[20] Time to exhaustion during the $\dot{V}O_2$max was also recorded. In our laboratory the typical error for the measurement of $\dot{V}O_2$max is 2.2% so this value was chosen as the smallest worthwhile change in $\dot{V}O_2$max and time to exhaustion.[18]

2.3.4 | Body composition

A Lunar iDXA scanner with associated enCORE (version 14.10.022) software (GE Healthcare Systems) was used to measure total body mass, total fat mass, and total lean body mass. To reduce the effects of daily biological variations, each scan was conducted in the morning after overnight fasting and participants were instructed to refrain from exercising on the previous day (excluding the treadmill running test).

2.3.5 | Running biomechanics and muscle activity

Biomechanical and muscle activity data were collected during overground running on an indoor 110 m synthetic running track. Biomechanical and muscle activity data were collected at two running speeds: 3.89 m s^{-1} and participant's maximal sprinting speed. The speed of 3.89 m s^{-1} was used as it was similar to the pace run during the 2-km time trial at baseline. Running speed was monitored in real-time by two sets of timing gates (SpeedLight V2 timing gates; Swift Performance Equipment) positioned at each end of the 20 m capture space. Trials were accepted if they were within ±5% of the target speed. A period of self-selected recovery was allowed between trials to minimize the effect of fatigue.

Kinematic data were collected using a 22-camera Vicon motion analysis system (Oxford Metrics Ltd) sampling at 250 Hz. A total of 36 retro-reflective markers (14 mm diameter) were taped to participants according to the lower body marker set published by Lai et al.[21] GRF data were simultaneously captured using eight consecutive in-ground 900 x 600 mm Kistler force plates (Kistler) sampling at 2000 Hz. Muscle activity data were collected using a Delsys Trigno™ Wireless System with wireless Trigno™ Avanti sensors (Delsys Inc.) sampling at 2000 Hz. The EMG recordings were measured from participants' dominant limb[22] for eight lower limb muscles: (i) gluteus maximus; (ii) vastus medialis oblique; (iii) rectus femoris; (iv) biceps femoris long head; (v) semitendinosus; (vi) soleus; (vii) gastrocnemius lateralis; and (viii) tibialis anterior. EMG electrode placement and skin preparation were in accordance with the guidelines of the Non-Invasive Assessment of Muscles (SENIAM) project.[23] EMG data were normalized to maximal voluntary contractions (MVCs). MVCs were performed on a treatment table against manual resistance applied by a researcher. Participants were asked to reach their maximal effort contraction after three seconds and to hold their maximal effort for a further three seconds.

MVCs were repeated twice per exercise with sufficient rest between contractions.[23]

Five running trials at 3.89 m s^{-1} and four maximal sprinting trials from baseline and follow-up testing were captured and processed for each participant. Raw marker data were reconstructed and manually labeled in VICON Nexus software before processing using custom MATLAB (version R2017a; The Mathworks Inc.) scripts and OpenSim 4.0 software (OpenSim). Musculoskeletal models of each participant were developed by scaling a generic musculoskeletal model[21] using the scale tool in OpenSim. Following a residual analysis of raw data, marker trajectories and force plate data were low-pass filtered using a zero-lag fourth-order Butterworth filter with a cutoff frequency of 12 Hz. Joint kinematics and kinetics were computed from three-dimensional coordinate data using the inverse kinematics and inverse dynamics tools in OpenSim. Contact and toe-off events were identified using a 10 N threshold in the vertical GRF. Raw EMG signals were filtered using a fourth-order, zero-lag Butterworth digital band pass filter (10–500 Hz) to minimize movement artifact. EMG data were then full-wave rectified and converted to a linear envelope via a fourth-order, zero-lag Butterworth digital low-pass filter (6 Hz). EMG data were amplitude normalized to the peak MVC.[23] Biomechanical and muscle activity data were time normalized to 0–100% of the running stride cycle, and one mean waveform was produced per participant at each running speed.[24]

Outcome measures included (i) hip, knee, and ankle joint angles, angular velocities, torques, powers, and total work in the sagittal plane; (ii) muscle activity for eight lower limb muscles; (iii) stride parameters; and (iv) GRF impulses. Joint angular velocities (deg s^{-1}) were calculated as angular displacement of a joint divided by time. Three-dimensional joint torques were calculated as internal moments normalized to total body weight in kilograms (N kg^{-1}). Joint power generation and absorption (W kg^{-1}) were calculated as a product of the net joint moment and corresponding joint angular velocity. Positive and negative joint work (J kg^{-1}) were computed by integrating the relevant portion of the positive and negative areas, respectively, of the power versus time curve.[24]

2.4 | Statistical analyses

Statistical analyses of discrete data were performed using IBM SPSS Statistics 27 (IBM Corporation). A one-way (between-groups) ANCOVA was used to identify the effects of CSE training on discrete outcome measures with group allocation as a fixed factor and baseline values used as covariates. A two-way mixed ANOVA was used to identify group-by-time effects of weather (ie, temperature and humidity) during the time trial. Between-group standardized mean differences (SMD) with 95% confidence intervals (95% CI) were also calculated using custom MATLAB scripts. The SMD used was the effect size known as Hedges' (adjusted) *g*, which was calculated as the ratio of the difference between the mean change value for each group and the standard deviation of the change value for each group, and included an adjustment for small sample size.[25] 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.[26]

Biomechanical and muscle activity waveform data were analyzed in MATLAB using SPM1D's[27] non-parametric equivalent to the two-way ANOVA with repeated measures on one factor (ie, group-by-time effect). This test is conceptually the same as a univariate two-way ANOVA but the traditional F-statistic, subsequently referred to as SnPM{F}, is calculated over the entire normalized waveform. Random field theory was used to calculate the critical test statistic threshold above which only 5% (ie, value of alpha) of the data would be expected to exceed whether the SnPM{F} statistic resulted from an equally smooth random process. If any regions of the SnPM{F} curve exceeded the critical test statistic threshold, a statistically significant group-by-time effect was noted. Statistical significance was set at $p < 0.05$.

3 | RESULTS

Figure 1 shows a flow diagram of participants progressing through this parallel-group randomized controlled trial. Fourteen participants in the CSE training group and fourteen in the control group completed the trial. One male in the CSE training group sustained a hamstring injury following baseline testing prior to the start of the strength training intervention. One female in the control group sustained a bony stress reaction in her foot during week seven. Both failed to complete follow-up testing due to their injuries. Baseline values for all outcome measures did not differ between the CSE training and control groups. All participants in the CSE training group completing over 95.4% of the prescribed strength training sessions. All participants in the control group self-reported completing over 83.9% of their low-intensity conditioning program.

3.1 | Running performance

CSE training improved 2-km running performance more than the control group ($F(1,25) = 9.22$, $p = 0.006$; SMD −1.19 [−1.99, −0.39]; Figure 2). The mean difference in

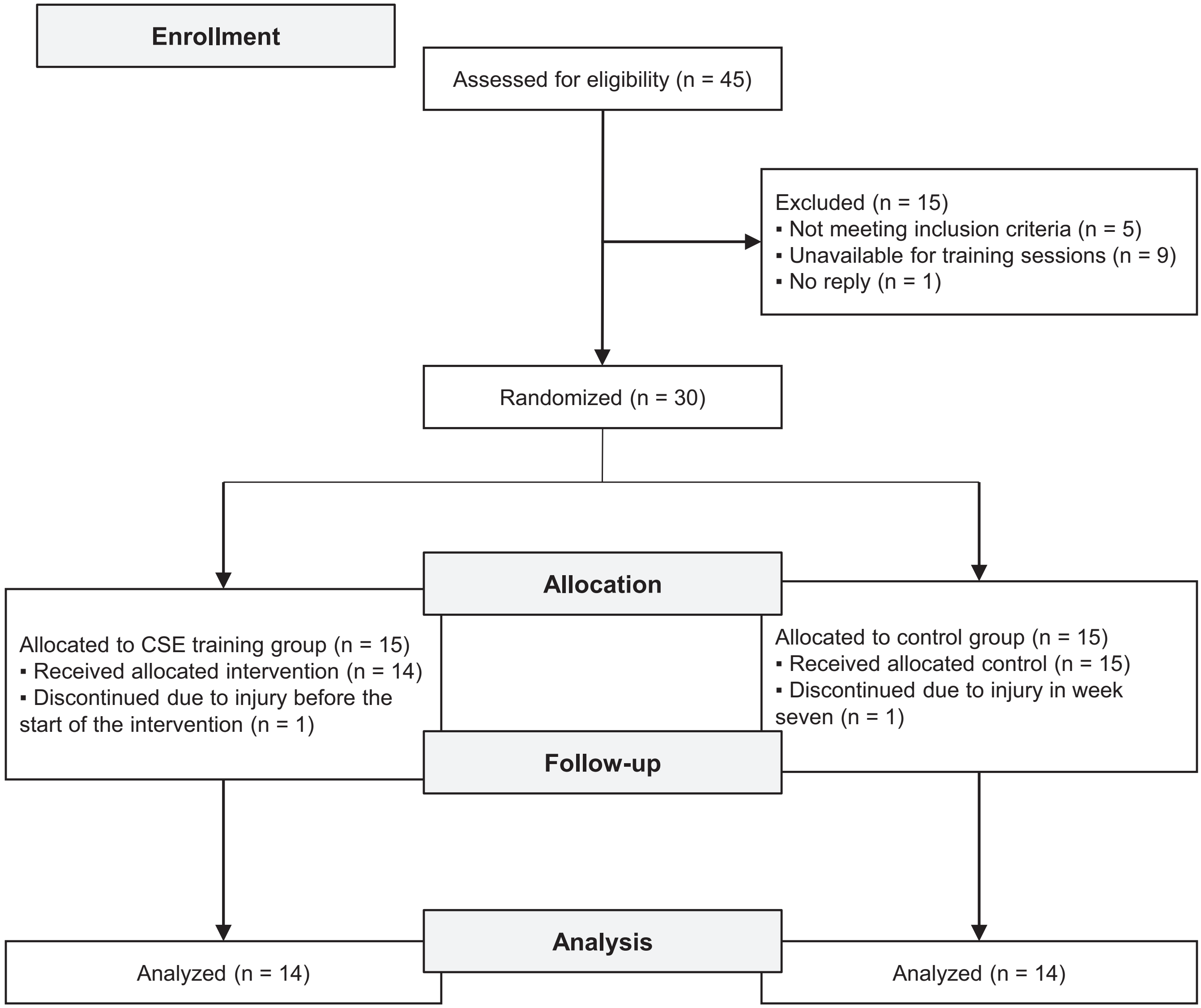

FIGURE 1 Flow diagram of participants progressing through this parallel-group randomized controlled trial

change values between groups was 11.3 s (95% CI [3.7, 19.0]). Following the intervention, 79% of the CSE training group and 29% of the control group improved their 2-km times by ≥2%.

The mean ± standard deviation values for outside temperature were 6.1 ± 4.0°C and 10.0 ± 5.5°C for the CSE training group, and 4.2 ± 5.0°C and 11.5 ± 7.2°C for the control group at baseline and follow-up testing, respectively. The values for humidity were 74.9 ± 24.5% and 62.1 ± 21.5% for the CSE group, and 82.7 ± 20.7% and 63.4 ± 26.0% for the control group at baseline and follow-up testing, respectively. There were no significant group-by-time effects for temperature ($F(1,26) = 1.83$, $p = 0.188$); however, there was a significant main effect for time ($F(1,26) = 20.67$, $p < 0.000$). Similarly, there were no significant group-by-time effects for humidity ($F(1,26) = 0.49$, $p = 0.492$); however, there was significant main effect for time ($F(1,26) = 11.46$, $p = 0.002$).

3.2 | Physiological measures

CSE training did not have a statistically significant effect on $\dot{V}O_2$max ($F(1,25) = 2.81$, $p = 0.106$), though there was a moderate effect size (SMD 0.74 [−0.02, 1.51]; Figure 2). Following the intervention, 64% of the CSE training group and 36% of the control group improved their $\dot{V}O_2$max by ≥2.2%. CSE training had a large effect on time to exhaustion during the $\dot{V}O_2$max test ($F(1,25) = 5.81$, $p = 0.024$; SMD 1.62 [0.77, 2.47], Figure 2). CSE training improved time to exhaustion, with a mean difference between groups of 59.1 s (95% CI [8.58, 109.62]). During the $\dot{V}O_2$max test, 64% of the CSE training group and 50% of the control group improved their time to exhaustion by ≥2.2%. CSE training did not change running economy ($F(1,25) = 2.71$, $p = 0.112$; SMD 0.37 [−0.37, 1.12]) or the energy cost of running ($F(1,25) = 2.004$, $p = 0.169$; SMD 0.22 [−0.97, 0.52]) at

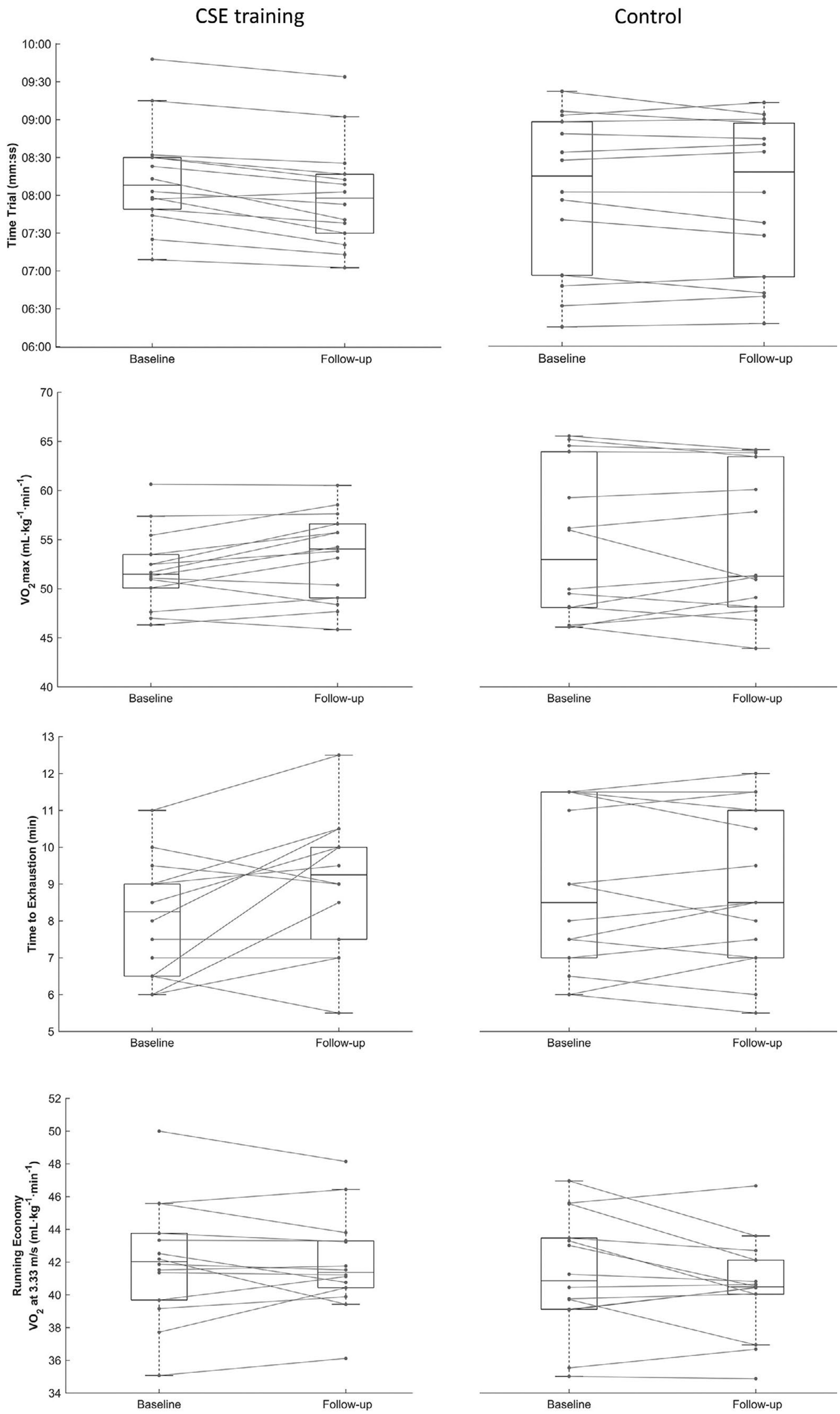

FIGURE 2 Individual values for the CSE training and control groups at baseline and follow-up for the 2-km time trial, $\dot{V}O_2$max, time to exhaustion, and running economy. Box plots represent the median (± interquartile range). Box plot whiskers have endpoints corresponding with the lowest and highest values

3.33 m s^{-1} (Figures 2 and 3). Following the intervention period, 29% of the CSE training group and 36% of the control group improved their running economy and the energy cost of running by ≥2.4%.

3.3 | Body composition

CSE training did not change total body mass ($F(1,25) = 0.997$, $p = 0.328$; SMD −0.35 [−1.10, 0.39]) or total lean body mass ($F(1,25) = 2.319$, $p = 0.140$; SMD 0.57 [−0.19, 1.32]; Figure 3). There was a statistically significant reduction in total body fat in the CSE training group compared to the control group ($F(1,25) = 6.694$, $p = 0.016$; SMD 1.00 [−1.78, −0.21]; Figure 3). The mean difference between groups was 1.05 kg (95% CI [0.21, 1.88]).

3.4 | Running biomechanics and muscle activity

SnPM{F} analysis revealed that CSE training had no statistically significant effects on sagittal plane hip, knee, and ankle joint angles, torques, and powers during running at 3.89 m s^{-1} (Figure 4). There was a statistically significant difference ($p = 0.002$) between groups in sagittal plane hip joint angular velocity during running at 3.89 m s^{-1}, with no differences in knee or ankle joint angular velocities. The statistically significant effect occurred at approximately 49–57% (ie, early swing phase) of the stride cycle, and was the result of an increased hip flexion velocity in the CSE group and a decrease in hip flexion velocity among the control group. At the mid-point of this supra-threshold cluster (ie, 53% of the stride cycle), hip flexion velocity for the CSE training group was 154.28 ± 49.73 deg s^{-1} at baseline and 174.87 ± 37.64 deg s^{-1} at follow-up testing, while the control group was 156.21 ± 55.25 deg s^{-1} at baseline and 137.53 ± 52.90 deg s^{-1} at follow-up testing.

SnPM{F} analysis revealed that CSE training had no statistically significant effects on sagittal plane hip, knee, and ankle joint angles, angular velocities, torques, and powers during maximal sprinting (see Figure, Supplemental Digital Content 1, which presents the SnPM{F} results for joint kinematics and kinetics during maximal sprinting).

SnPM{F} analysis revealed that CSE training had no statistically significant effects on EMG muscle activity during running at 3.89 m s^{-1} (Figure 5) or maximal sprinting (see Figure, Supplemental Digital Content 2, which presents the SnPM{F} results for muscle activity during maximal sprinting).

CSE training had no statistically significant effects on discrete stride parameters, total work, and GRF impulses during running at 3.89 m s^{-1} (Table 2) or maximal sprinting (see Table, Supplemental Digital Content 3, for the discrete biomechanical measures during maximal sprinting).

4 | DISCUSSION

The main finding of this study is that CSE training improved 2-km run time more than the control group. Following the 10-week intervention period, the within-group change in 2-km run time for the CSE training group was −2.9% (−14.0 s) and the between-group difference over time was 2.3% (11.3 s). A 2.3% improvement in 2-km running time would equate to approximately 46 m among this group of participants. This finding is similar to past research showing that CSE training improves middle-distance time trial performance in distance runners by 3–5%.[4] CSE training also had a large effect on time to exhaustion during the $\dot{V}O_2$max test, with the CSE training group increasing their time to exhaustion by 12.5%. These findings provide further evidence that CSE training is beneficial for running performance.

The present findings are consistent with previous research stating that CSE training does not affect $\dot{V}O_2$max among distance runners.[4,28] It is worth noting, however, that there was a moderate-sized trend for greater $\dot{V}O_2$max following CSE training in the present study. This trend is unexpected as an acute bout of resistance training typically demands less than 50% of $\dot{V}O_2$max to perform,[28] which is an insufficient training stimulus for improving $\dot{V}O_2$max in distance runners.[28] CSE training was also associated with a reduction in total body fat. This finding may be perceived as desirable for distance runners, among which a low body fat percentage can benefit performance by improving relative physiological parameters.[1] The rationale for the reduction in body fat is not entirely clear, especially since the control and CSE groups were matched for training volume. While participants were asked to maintain their habitual lifestyles and daily food intake, the CSE training group may have been more motivated to improve, or they may have made subconscious changes to their behavior, due to their awareness of participating in the intervention group.

A previous meta-analysis[29] concluded that strength training (consisting of 2–4 resistance exercises at 40–70% 1RM and plyometric exercises) performed 2–3 times per week for 8–12 weeks was a reliable way to improve running economy among highly trained distance runners. We found no effect on running economy or the energy cost of running when implementing these training guidelines among moderately trained runners, despite lesser trained runners having greater capacity to improve. Running economy and the energy cost of running are influenced

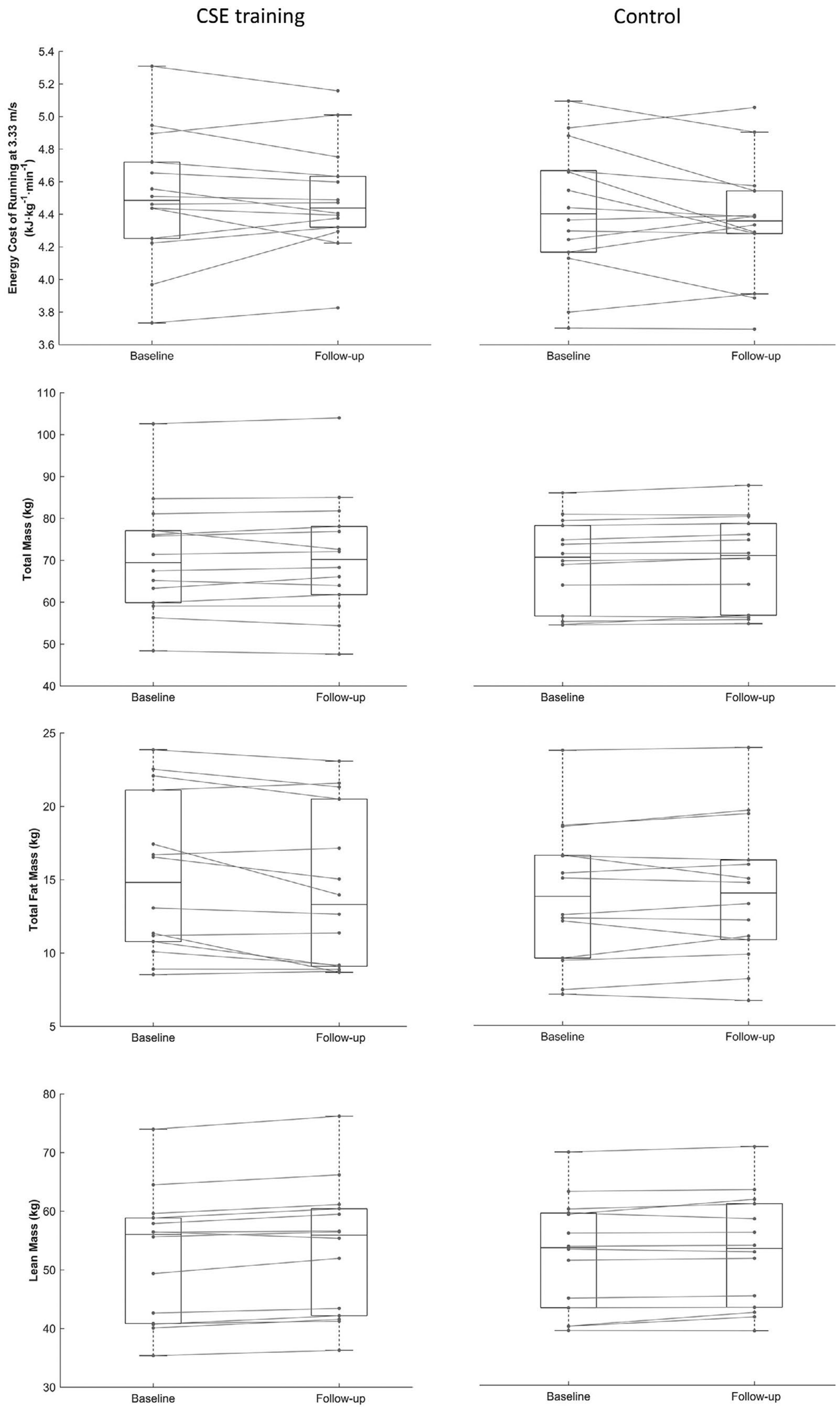

FIGURE 3 Individual values for the CSE training and control groups at baseline and follow-up for the energy cost of running, total mass, total fat mass, and total lean mass. Box plots represent the median (± interquartile range). Box plot whiskers have endpoints corresponding with the lowest and highest values

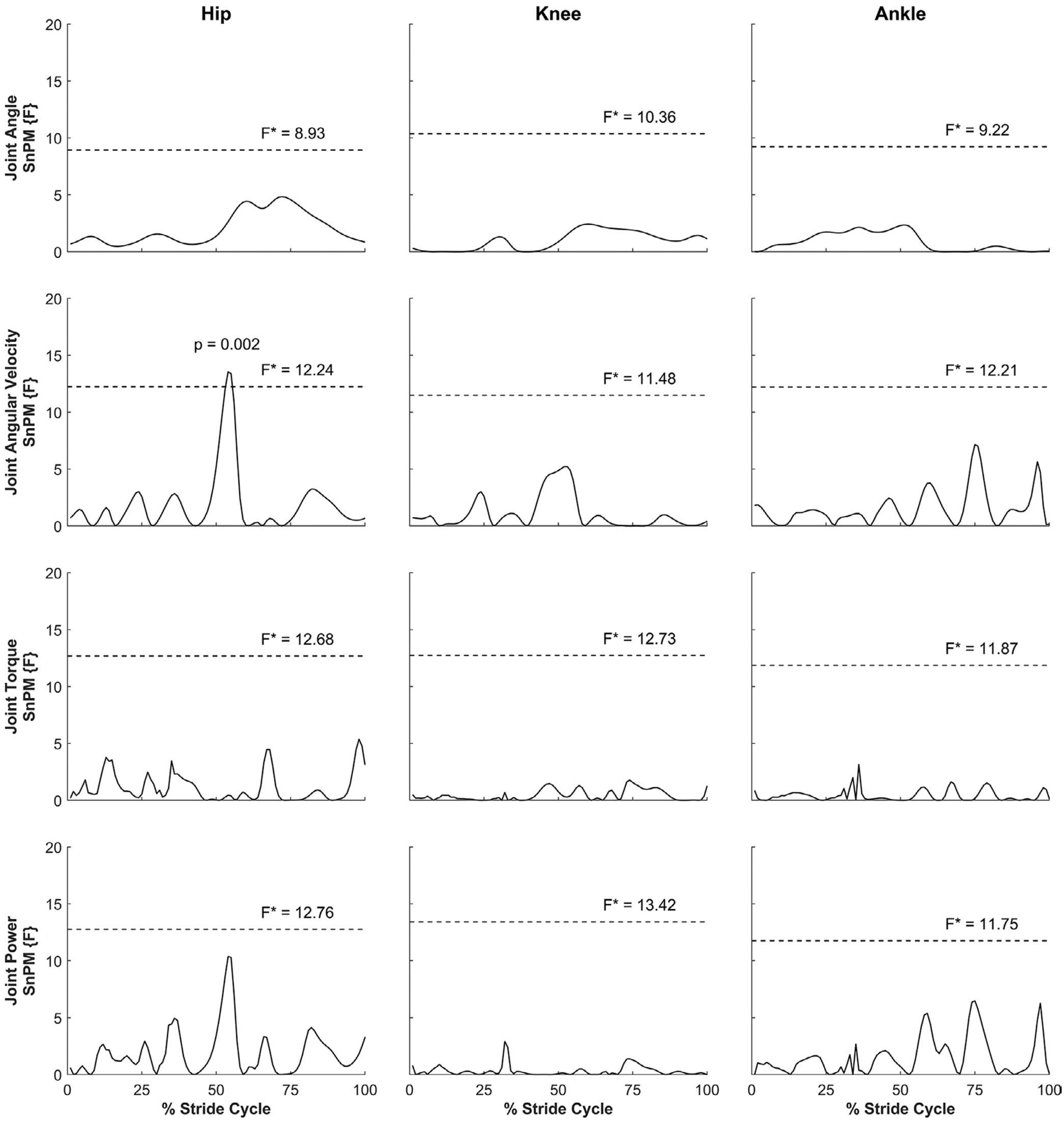

FIGURE 4 SnPM{F} curves of the group-by-time effects for hip, knee, and ankle joint angles, angular velocities, torque, and power during running at 3.89 m s^{-1}

by a variety of factors including the behavior of individual muscle-tendon complexes, muscle fascicles, and the preferential recruitment of motor units.[30] For example, increased triceps surae tendon stiffness could alter plantarflexor muscle fascicle force-velocity profiles during the stance phase of running leading to a decreased energy cost of running.[30] It is possible that the CSE training program was an insufficient mechanical load or too short in duration to induce adaptations in the triceps surae tendon to influence running economy or the energy cost of running. Other researchers[4] have reported no change in running economy following CSE training, while changes in running economy have also been found at specific test speeds without changes at other running speeds.[4] There is increasing evidence that the most valid measure of running economy may be at speeds that reflect a runners specialized training or race pace rather than at common, yet arbitrary, submaximal running speeds.[4]

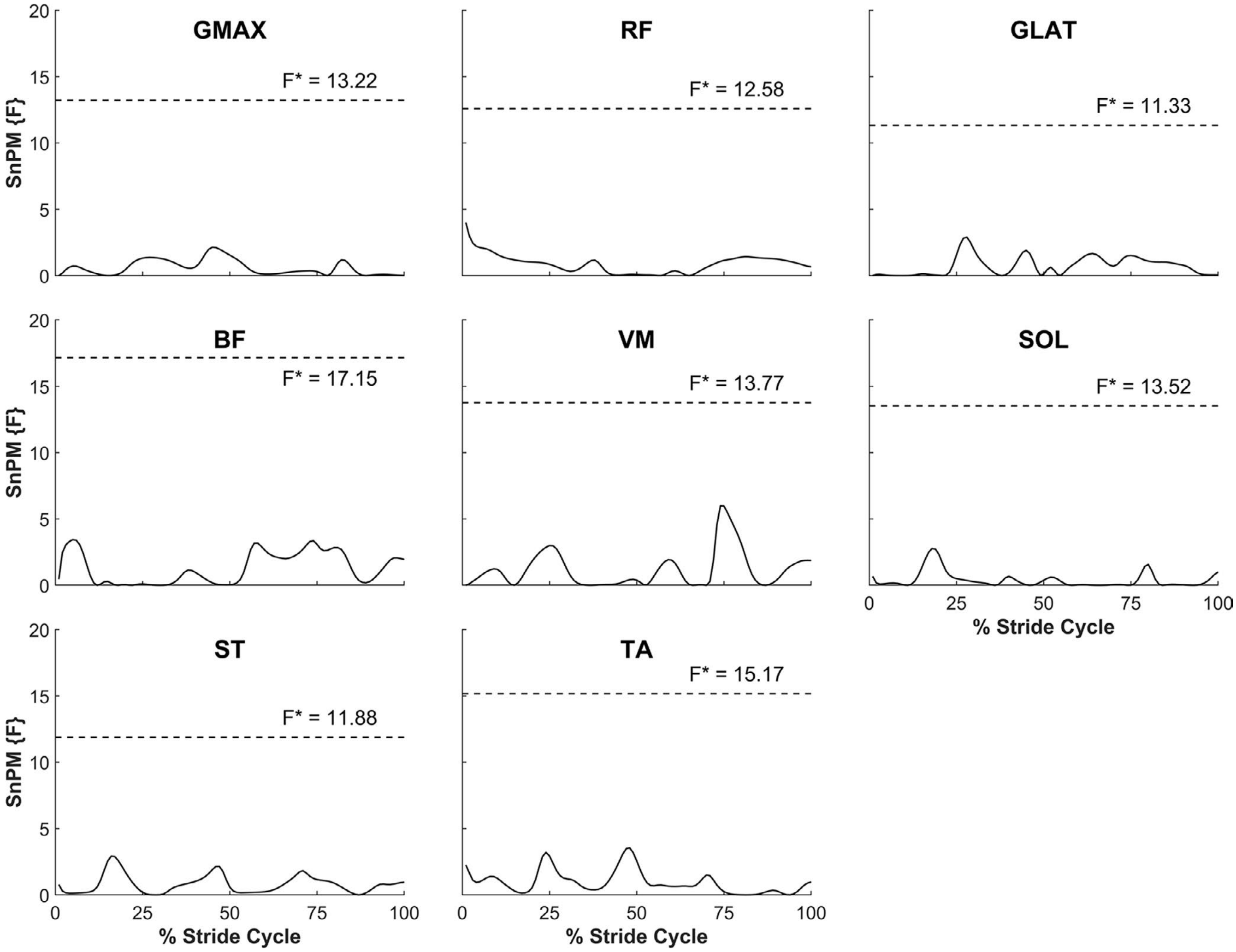

FIGURE 5 SnPM{F} curves of the group-by-time effects for muscle activity during running at 3.89 m s^{-1}

The SnPM{F} analyses of biomechanical data revealed a statistically significant group-by-time effect for sagittal plane hip joint angular velocity during the early swing phase of running at 3.89 m s^{-1}. This finding arose due to a ≈ 13.4% increase in hip flexion velocity in the CSE training group and simultaneous ≈ 12.0% decrease in hip flexion velocity among the control group following the intervention period. There was also a trend in the SnPM{F} curve for increased hip joint power in the CSE training group compared to the control group at the same region of the waveform that hip joint angular velocity changed. This finding is intuitive, given that joint power is the product of joint torque and angular velocity, and hip joint angular velocity increased following CSE training. Similar trends were also present in the SnPM{F} curves during maximal sprinting, with the CSE group exhibiting a faster hip flexion velocity and greater hip joint power generation. A faster hip flexion velocity and greater hip power generation during early swing could theoretically facilitate a faster recovery leg during the swing phase of running and smaller center of mass separation at ground contact. Such adaptations may have the potential to improve running performance by increasing stride frequencies and decreasing braking impulses.[14] However, we did not observe changes in stride frequency or GRF impulses. It is important to acknowledge that sagittal plane biomechanics and muscle activity were only measured on the dominant limb under non-fatigued conditions. CSE training could have influenced biomechanical symmetry or kinematics and kinetics in the frontal or transverse planes, though evidence for this is lacking.[10,31,32] Similarly, collective small changes in each plane of motion may be more important than any one change in the sagittal plane, though the greatest proportion of segmental motion during running occurs in the sagittal plane.[33] The upward and forward propulsion of the center of mass during running is also primarily driven by lower limb joint kinetics in the sagittal plane.[34]

It is possible that the lack of changes in running biomechanics were due to a lack of transfer between the strength training exercises and running. A previous

TABLE 2 Discrete kinematic and kinetic measures during running at 3.89 m s^{-1} at baseline and follow-up testing for the CSE training and control groups

	CSE training		Control		CSE training vs control	
	Baseline	Follow-up	Baseline	Follow-up	SMD(g)	Interpretation
Stride length (m)	2.68 ± 0.17	2.64 ± 0.18	2.67 ± 0.15	2.68 ± 0.11	−0.37 [−1.12, 0.38]	Small
Stride frequency (steps min^{-1})	89.44 ± 4.54	89.99 ± 6.09	88.55 ± 4.17	88.65 ± 4.33	0.17 [−0.57, 0.91]	Trivial
Contact time (s)	0.21 ± 0.02	0.21 ± 0.02	0.21 ± 0.02	0.21 ± 0.02	0.32 [−0.42, 1.07]	Small
Flight time (s)	0.46 ± 0.03	0.46 ± 0.03	0.47 ± 0.03	0.46 ± 0.03	−0.26 [−1.01, 0.48]	Small
Foot to center of mass distance (m)	0.28 ± 0.05	0.28 ± 0.04	0.28 ± 0.03	0.28 ± 0.03	−0.40 [−1.14, 0.35]	Small
Hip negative work-stance (J kg^{-1})	−0.24 ± 0.10	−0.24 ± 0.10	−0.21 ± 0.09	−0.25 ± 0.13	0.70 [−0.06, 1.46]	Moderate
Knee positive work-stance (J kg^{-1})	0.26 ± 0.08	0.27 ± 0.11	0.28 ± 0.08	0.31 ± 0.07	−0.13 [−0.87, 0.61]	Trivial
Knee negative work-stance (J kg^{-1})	−0.60 ± 0.18	−0.57 ± 0.19	−0.59 ± 0.15	−0.58 ± 0.15	0.21 [−0.53, 0.95]	Small
Ankle positive work-stance (J kg^{-1})	0.90 ± 0.17	0.84 ± 0.16	0.93 ± 0.13	0.92 ± 0.12	−0.41 [−1.16, 0.34]	Small
Ankle negative work-stance (J kg^{-1})	−0.59 ± 0.25	−0.54 ± 0.18	−0.61 ± 0.19	−0.59 ± 0.19	0.25 [−0.49, 0.99]	Small
Hip positive work-swing (J kg^{-1})	0.81 ± 0.22	0.84 ± 0.16	0.86 ± 0.19	0.82 ± 0.12	0.55 [−0.21, 1.30]	Small
Knee negative work-swing (J kg^{-1})	−1.12 ± 0.19	−1.09 ± 0.14	−1.14 ± 0.12	−1.12 ± 0.10	0.09 [−0.65, 0.83]	Trivial
Braking impulse (BW)	−0.02 ± 0.00	−0.02 ± 0.00	−0.02 ± 0.00	−0.02 ± 0.00	0.46 [−0.29, 1.21]	Small
Propulsive impulse (BW)	0.02 ± 0.00	0.02 ± 0.00	0.02 ± 0.00	0.02 ± 0.00	−0.16 [−0.91, 0.58]	Trivial
Effective vertical impulse (BW)	0.13 ± 0.02	0.12 ± 0.02	0.13 ± 0.02	0.13 ± 0.02	−0.57 [−1.33, 0.18]	Small

Note: Data are mean ± standard deviation. Effect sizes are standardized mean difference (SMD) [95% confidence interval] and interpreted according to Hopkin's scale.[26] *CSE* concurrent strength and endurance; *g* Hedges' (adjusted) g; *BW* body weight.

clinical study[31] investigated the effect of a hip strengthening and movement training program on runners with abnormal hip mechanics. Despite a large increase in strength during the primary training exercise (ie, single-leg squat), this study reported no changes in running biomechanics. Gait retraining programs utilizing real-time visual, haptic, and/or auditory feedback have achieved acute and short-term (≤3 months) changes in specific biomechanical variables during running.[32] It appears that targeting specific running mechanics and provision of feedback are important components of an effective intervention to elicit changes in running biomechanics. Long-term follow-up studies (ie, ≥1 year) are necessary to determine the retention and persistence of these biomechanical changes.[32]

Biomechanical responses to CSE training may be unique and dependent on individual physiology and anthropometry, and individual changes would not be detected using between-group statistical methods. CSE training may also affect running biomechanics when athletes are experiencing neuromuscular fatigue, such as towards the end of a time trial or race.[8,12] It has previously been shown that CSE training improves 10 km time trial performance, with participants exhibiting faster running speeds during the final 2.8 km of the time trial.[35] Research has found the hip and knee flexors and extensors are important for maintaining stride length when under fatigue.[36] Esteve-Lanao et al.[13] found that 6 weeks of CSE training reduces the loss of stride length among distance runners during fatiguing running bouts. The authors suggested that CSE training minimized the detrimental effects of fatigue on muscle power generation, but they did not examine any other biomechanical or muscle activity variables to support this. This suggests that CSE training improves fatigue resistance, but it remains unclear whether this adaptation is underpinned by changes in running kinematics and kinetics under fatigued conditions.

A limitation of this trial is that the power analysis for this randomized controlled trial was based off previously published changes in time trial performance and ground contact times following CSE training.[11,15] As SPM1D is a novel analysis tool in the field of biomechanics, few studies[37-40] have used SPM1Ds two-way ANOVA to investigate biomechanics during running. None of these studies[37-40] have investigated the effects of a training intervention on running mechanics, and all studies have used within-subjects (not random allocation of participants), repeated-measures design with total sample sizes ranging from 9 to 15 participants. There has been only one high-quality CSE training study[7] that has included a larger sample size than the present study, although that study investigated the effects of jump interval training on aerobic indices and jump parameters, not running biomechanics. This highlights an inherent limitation of exploratory research when there are scarce data available on which to base a sample size calculation. A recent meta-analysis[10] analyzed the quality of 25 previous CSE training studies using the Physiotherapy Evidence Database (PEDro) scale. This meta-analysis found no studies satisfied assessor-blinding and over one-third of the studies did not randomly allocate participants to experimental groups. Not only did the present trial satisfy both of these criteria, but it also included one of the largest sample sizes among all CSE training studies to date.[10] The scientific quality of this study combined with meaningful changes in run performance engender confidence that CSE training benefits distance runners' performance without changes in biomechanics or muscle activity during steady-state running. Finally, we did not investigate the influence of participant motivation, expectation, and learning on performance outcomes following CSE training. It is possible that psychological factors contribute to performance gains and future studies may wish to measure participant expectations and perceptions of the intervention.

5 | PERSPECTIVE

This randomized controlled trial demonstrated a moderately-sized and practically important improvement in 2-km run time following CSE training when compared with the control group. There were no deleterious effects of CSE training on physiological determinants of running performance or body composition. CSE training should be encouraged for performance enhancement in distance running. CSE training had limited effects on sagittal plane joint kinematics and kinetics, muscle activity, and stride parameters during overground running at 3.89 m s^{-1} and maximal speeds. Running athletes should not undertake a short period of CSE training under the premise that it will change their running technique. Future research should consider whether CSE training alters biomechanics and muscle activity during prolonged running, especially in the presence of fatigue or during the final stages of a race.

ACKNOWLEDGMENTS

The authors thank all the participants who were involved in this trial and the staff and researchers at the Australian Institute of Sport for their support throughout this project. This work was supported by a Deakin University Postgraduate Research Scholarship and Australian Institute of Sport PhD Program Stipend.

CONFLICT OF INTEREST

None to declare.

AUTHOR CONTRIBUTIONS

D.T., J.B., and B.V. contributed to the design of the study. D.T. and J.B. performed the data collection. D.T., J.B., and A.F. performed the data analysis. D.T. drafted the manuscript. All authors edited and revised the manuscript, and approved the final version of the manuscript.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

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How to cite this article: Trowell D, Fox A, Saunders N, Vicenzino B, Bonacci J. Effect of concurrent strength and endurance training on run performance and biomechanics: A randomized controlled trial. *Scand J Med Sci Sports*. 2022;32:543–558. doi:10.1111/sms.14092