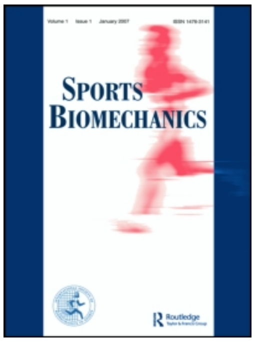

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Concurrent endurance training with either plyometric or dynamic body-weight training both improve running economy with minimal or no changes in running biomechanics

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ABSTRACT
We compared the effects of two 8-week concurrent strength and endurance trainings (CSETs) on running economy (RE) and running biomechanics, and we explored whether the effects on running biomechanics were mediated by responder status [high vs low responder based on −2.6% change in RE]. Thirty-one male recreational runners were randomly assigned to a standard endurance running training combined with either plyometric (CSET-PLY) or dynamic body-weight (CSET-DYN) training. RE and running biomechanics [contact (t_c) and flight (t_f) time, step frequency (SF), duty factor (DF), and leg stiffness (k_{leg})] were measured pre- and post-intervention. RE significantly improved following CSET (RE = −2.1 ± 3.9%; $p = 0.005$) and no changes in t_c, DF, SF, and k_{leg} ($p \geq 0.10$) but a shorter t_f ($p \geq 0.03$) from pre- to post-intervention were seen. The prevalence of high responders was 42% (RE = −5.7 ± 2.4%). Among high responders, there were no changes in running biomechanics except participants following CSET-DYN who increased their SF (+3%). These results indicate that improvements in RE obtained through CSET-PLY and CSET-DYN involve minimal to no changes in running biomechanics and that there was not a training modality, which was better than the other. More detailed biomechanical assessments involving kinematics, kinetics, and electromyography could shed light on the underlying mechanisms of RE improvement.

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Introduction

High maximal oxygen uptake ($\dot{V}O_{2max}$) (Poole & Jones, 2017), lactate threshold (Jones et al., 2019), and running economy (RE) (Moore, 2016) measures have been identified as the key physiological determinants of running performance. In a homogeneous group of runners in terms of $\dot{V}O_{2max}$, $\dot{V}O_{2max}$ is insufficient to distinguish between higher- and lower-achieving runners (Morgan et al., 1989). Instead, RE, defined as the steady-state of oxygen consumption at a given submaximal running speed, can suitably discern which runners outperform others (Barnes & Kilding, 2015a). In runners with a similar $\dot{V}O_{2max}$, RE can differ by as much as 30% between runners and is a better predictor of running performance than $\dot{V}O_{2max}$ itself (Barnes & Kilding, 2015a). Moreover, RE is greater in trained than untrained runners and can improve following a range of interventions (Barnes & Kilding, 2015b), highlighting how training is an important determinant of RE (Saunders et al., 2004).

Endurance (Moore et al., 2012), high-intensity interval (Barnes, Hopkins, McGuigan, & Kilding, 2013), and altitude (Saunders et al., 2009) running training are strategies shown effective in improving RE from 2% to 8%. The long-term physiological adaptations resulting from years of endurance running can improve RE by as much as 15% (Jones, 2006). Beyond running training, improvements in RE up to 8% are possible with short-term (6–12 weeks) strength training, such as plyometric (Saunders et al., 2006; Spurrs et al., 2003; Turner et al., 2003) and resistance (Barnes, Hopkins, McGuigan, Northuis, et al., 2013; Guglielmo et al., 2009; L. Paavolainen et al., 1999; Støren et al., 2008) training, as well as short-term (6–10 weeks) concurrent strength and endurance training (CSET) that combines endurance running with plyometric (CSET-PLY), resistance, or dynamic body-weight training (CSET-DYN) (Barnes & Kilding, 2015b; Berryman et al., 2010; Meszler et al., 2019; Patoz et al., 2021; Pellegrino et al., 2016).

Plyometric training aims to improve the storage and release of elastic energy of the musculotendinous unit by focusing on having a short ground contact time (t_c) and a high leg stiffness (k_{leg}) during the eccentric-concentric contraction cycles (Anderson, 1996). Various jumps, bounds, and hops in both horizontal and vertical planes are typical plyometric training exercises (Spurrs et al., 2003). On the other hand, resistance and dynamic body-weight training aims to develop power production by focusing on concentric contractions (Kawamori & Haff, 2004). Squats jumps and dynamic lunges are typical dynamic body-weight training exercises (Patoz et al., 2021).

Plyometric training implies shorter t_c than resistance and dynamic body-weight training. As running is often described as a succession of plyometric contractions with legs acting as springs (Blickhan, 1989), plyometric training can be considered more representative of the running gait than resistance and dynamic body-weight training. Nonetheless, plyometric, resistance, and dynamic body-weight training are reported to improve RE (Barnes, Hopkins, McGuigan, Northuis, et al., 2013; Barnes & Kilding, 2015b; Meszler et al., 2019; Patoz et al., 2021; Saunders et al., 2006). RE enhancements are likely due to an improved neuromuscular function (Barnes & Kilding, 2015b). However, there is no evidence to suggest the neuromuscular adaptations linked to plyometric, resistance, or dynamic exercises transfer to changes in running biomechanics (Trowell et al., 2020). A recent review reported very limited evidence that CSET affects running biomechanical variables, such as t_c or step frequency (SF) (Trowell et al., 2020). It may be that the type of strength training performed concurrently with the running endurance training impacts biomechanical responses and, when different CSET modalities are considered together, no biomechanical changes are overall observed. For example, t_c has been shown to decrease after CSET with a strength training involving explosivity (L. Paavolainen et al., 1999), but increased when involving trunk (strength endurance program) and leg muscle (high-intensity program) training (Ferrauti et al., 2010).

The limited evidence regarding biomechanical changes with CSET might also stem from individual differences in response to training, where high responders show large responses to an intervention, whereas low responders show small to no responses (Mann et al., 2014). Furthermore, low responders to a specific intervention or training can be high responders to another type of training or intervention (Hautala et al., 2006). Therefore, pooling all runners together might mask an effect that would be observed when only considering high responders and changes in running biomechanics following an intervention might be present only in high responders.

Running biomechanics, especially during ground contact, influences RE (Moore, 2016). For instance, a greater k_{leg} was shown to benefit RE (Dalleau et al., 1998). In addition, an experienced runner adopts a self-optimised SF which is ~3% above the mathematically derived optimal (Cavanagh & Williams, 1982; de Ruiter et al., 2014). For such runner, any deviation between the naturally chosen and mathematically optimal SF would have a negligible impact on RE. However, SF of novice runners is not as effectively self-optimised because of their lack of running experience (~8% difference) (de Ruiter et al., 2014). Nonetheless, following a 6–10 weeks running program could lead to biomechanical adaptations that would improve RE (Moore, 2016). However, the relationship between RE and t_c, as well as between RE and swing time [and therefore flight time (t_f) and duty factor (DF), i.e., the proportion of time in contact with the ground during a running stride] are conflicting in the scientific literature (Barnes et al., 2014; Moore, 2016; Williams & Cavanagh, 1987). For instance, superior RE has been linked with both long (Støren et al., 2008) and short (L. M. Paavolainen et al., 1999) t_c, while Williams and Cavanagh (1987) found no significant relation between RE and t_c.

Hence, we aimed to compare the effects of CSET-PLY and CSET-DYN on RE and running biomechanics. We hypothesised that 1) participants following CSET-PLY and CSET-DYN would improve their RE, and 2) participants following CSET-PLY would decrease t_c and DF, increase t_f and k_{leg}, and keep their SF unchanged while participants following CSET-DYN would increase t_c and DF, decrease t_f and k_{leg}, and keep their SF unchanged. Furthermore, we explored whether the effects of CSET-PLY and CSET-DYN on running biomechanics would be larger for participants considered as high responders in terms of RE improvement compared to low responders.

Materials and methods

Experimental approach to the problem

After providing written informed consent, 37 participants performed an initial submaximal running test to determine their RE and running biomechanics and a maximal incremental running test to determine their peak treadmill speed (PTS). Each participant was then randomly assigned to one of two 8-week CSET modalities, i.e., CSET-PLY ($n = 18$) or CSET-DYN ($n = 19$). The submaximal running test was performed again post-intervention (at the end of the 8-week CSET) to determine if there was any improvement in RE and any change in running biomechanics. Participants were labelled as high responders when RE improved by more than 2.6% and low responders otherwise. This follows from the concept of the smallest worthwhile change (magnitude of change required to elicit a meaningful or significant improvement) to determine the practical significance of intervention, which was reported to be 2.6% at 14 km/h for RE (Barnes & Kilding, 2015a; Saunders et al., 2004). As this smallest worthwhile change was calculated for 14 km/h and faster speeds, but not for the running speed used herein, i.e., 12 km/h, the smallest worthwhile change at the closest speed was used, i.e., 14 km/h.

Participant characteristics

An existing database of 37 recreational and regular runners was explored to extract those for which RE and running biomechanics was available pre and post a CSET (Patoz et al., 2021). RE and running biomechanics for pre- and post-intervention was available for 35 runners (4 females and 31 males). Considering that sex might influence RE and running biomechanics (Barnes et al., 2014; Xie et al., 2022), the present study only included the male runners (age: 30 ± 9 years, height: 177 ± 8 cm, body mass: 73.7 ± 12.5 kg, weekly training sessions: 2.6 ± 1.3), leading to 14 and 17 participants in CSET-PLY and CSET-DYN groups, respectively. For study inclusion, participants were required to be in good self-reported general health with no current or recent (<3 months) musculoskeletal injuries, not following a periodised training plan, and not previously undertaken any structured strength training. Participants signed an institutionally approved informed consent document to participate in the study after being informed of the benefits and risks of the investigation and that they could withdraw at any time from study participation. The Institutional Review Board of the University of Bourgogne Franche-Comté approved the study protocol prior to participant recruitment (CPP: 2014-A00336-41), which was conducted in accordance with international ethical standards (Harriss et al., 2017) and adhered to the latest Declaration of Helsinki of the World Medical Association.

Procedures

Submaximal running test

After a 5-min warm-up run on a treadmill at 9 km/h, participants ran for 5 min on the same treadmill at 12 km/h. Gas exchange was measured breath-by-breath using a gas analyser (Cortex Metamax 3B, Cortex Biophysik, Leipzig, Germany), which was calibrated using ambient air (O_2: 20.93% and CO_2: 0.03%) and a gas mixture of known composition (O_2: 15.00% and CO_2: 5.00%). A 3-L syringe was used to calibrate the spirometer. Breath-by-breath data were subsequently averaged over 10 s intervals throughout the test and respiratory exchange ratio (RER) and oxygen uptake ($\dot{V}O_2$) were averaged over the last minute of the 5-min running trial. To include the data in the analysis, RER had to remain below 1.0 during the trials, otherwise the corresponding data were excluded as deemed not representative a submaximal effort. In this case, the selected submaximal speed was lowered iteratively by 1 km/h (following a 5-min passive recovery in a seated position) until achieving an RER below 1.0. This resulted in submaximal testing speeds of 9 ($n = 1$), 10 ($n = 6$), 11 ($n = 5$), and 12 km/h ($n = 25$). These individualised speeds were maintained during post testing.

RE was expressed as the oxygen cost per mass to the power of 0.75 per kilometre (ml/kg$^{0.75}$/km) to minimise the influence of body mass *per se* on $\dot{V}O_2$ during running (Svedenhag & Sjödin, 1994). A higher RE value indicates a less economical runner. Therefore, a negative change would indicate an improved RE value.

An optical measurement system (Optojump Next, MicroGate Timing and Sport, Bolzano, Italy) sampling at 1,000 Hz was used to measure t_c and t_f, which allowed computation of SF as $SF = \frac{1}{t_c + t_f}$ and duty factor (DF) as $DF = \frac{t_c}{2(t_c + t_f)}$, which represents the proportion of time spent in contact with the ground during a running stride (Folland et al., 2017). The test–retest reliability of the Optojump system was shown to be excellent, with low coefficients of variation (2.7%) and high intraclass correlation coefficients (range 0.982–0.989) (Glatthorn et al., 2011). Of note, no test-retest was performed in this study, which precluded us to measure the reliability of the Optojump system used herein. In addition, the spring-mass characteristics of the lower limb was estimated using a sine-wave model as defined by Morin et al. (2005). More explicitly, k_{leg} was calculated as [Equation (1)]:

$$k_{\text{leg}} = \frac{F_{\text{max}}}{\Delta L}. \quad (1)$$

F_{max} represents the maximal vertical ground reaction force and was estimated using $F_{\text{max}} = mg\frac{\pi}{2}\left(\frac{t_f}{t_c} + 1\right)$. The maximal leg compression of the spring during stance (ΔL) was modelled using the absolute displacement of the centre of mass during stance (Δz) given by [Equation (2)]:

$$\Delta z = \frac{F_{\text{max}} t_c^2}{m\,\pi^2} - g\frac{t_c^2}{8}, \quad (2)$$

leading to [Equation (3)]:

$$\Delta L = L - \sqrt{L^2 - \left(\frac{s t_c}{2}\right)^2} + \Delta z, \quad (3)$$

where m is the body mass, s the running speed, and L the participant's leg length estimated as 0.53 of body height. For all biomechanical measures and for each participant, the values extracted from the last minute of the submaximal running test, considering both legs, were averaged for subsequent statistical analyses.

Maximal incremental running test

After a 5-min passive recovery in a seated position following the submaximal running test, participants performed a maximal incremental running test. The treadmill speed was set to 8 km/h and was increased by 0.5 km/h every minute until volitional exhaustion. The PTS was defined as the running speed of the last fully completed increment (MAS) plus the fraction of time spent in the following uncompleted increment (α) multiplied by the running speed increment ($\Delta s = 0.5$ km/h) (Kuipers et al., 2003):

PTS = MAS + $\alpha\Delta s$. To ensure attainment of maximal values during the test, participants received strong verbal encouragement.

Endurance running training

A basic endurance running training was followed by all participants in line with their habitual running training [see (Patoz et al., 2021) for more details]. The endurance training was divided into three different intensity zones based on the PTS: aerobic, threshold, and high-intensity zones, which corresponded to PTS running speeds of less than 80% of PTS, from 80% to less than 95%, and from 95% to less than 105%, respectively. Endurance sessions consisted of continuous running between 45 and 75 min in the aerobic zone and some unstructured bouts (10–25 min per session) of faster running in the threshold zone. Interval sessions consisted of a 15-min warm-up run in the aerobic zone followed by repeated interval bouts (30 s to 2 min) in the high-intensity zone (6–12 min of fast running per session). For instance, an interval session of two blocks of six repetitions of 30 s at 100% PTS + 30 s at 60% PTS with 2 min recovery between each block was performed in the beginning of the 8-week training plan, while an interval session of 3 blocks of 2 repetitions of 90 s at 105% PTS + 90 s at 60% PTS with 5 min recovery between each block was performed at the end of the 8-week training plan. Table 1 describes the prescribed time in each of the training zones during the 8-week running endurance training.

Plyometric or dynamic body-weight training

Participants had to perform a predetermined circuit training composed of six exercises and designed as plyometric or dynamic body-weight training [Figure 1; see (Patoz et al., 2021) for more details]. Typical plyometric exercises were repeated rebound jumps in horizontal and vertical planes as well as exercises that focus on a fast transition between the eccentric and concentric contraction cycles (e.g., plyometric lunge, plyometric lateral step up, or downhill running). Typical dynamic body-weight training used exercises focusing on concentric contractions (e.g., squat, lunge, or uphill running). Participants performed the same circuit training during the entire protocol, but the number of cycles and exercise—rest ratio was progressively increased over the 8 weeks. The total training load (total duration including resting periods) was equivalent between plyometric and dynamic body-weight training despite different exercises. Participants should complete as many repetitions as possible within the set time, and each repetition should be performed with maximum intent. Body-weight loads were used because participants had no previous experience in strength training. Table 2 gives the details of the 8-week strength training program.

Table 1. Characteristics of the 8-week running endurance training.

Weeks	1	2	3	4	5	6	7	8
Volume (min)	130	135	145	150	160	165	170	175
Aerobic zone (min)	104 (80%)	106 (79%)	113 (78%)	114 (76%)	121 (76%)	121 (73%)	122 (72%)	123 (70%)
Threshold zone (min)	17 (13%)	19 (14%)	21 (14%)	24 (16%)	27 (17%)	30 (18%)	33 (19%)	35 (20%)
High intensity zone (min)	9 (7%)	10 (7%)	11 (8%)	12 (8%)	13 (7%)	14 (9%)	16 (9%)	17 (10%)

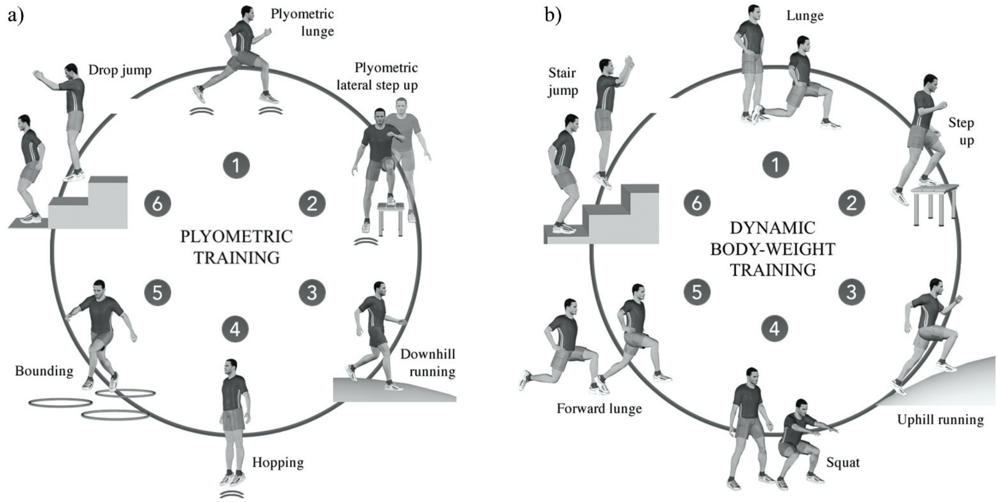

Figure 1. Circuit training protocol for the plyometric training (a) and dynamic body-weight training (b). Adapted from Patoz et al. (2021) with permission.

Table 2. Characteristics of the 8-week strength training.

Weeks	1	2	3	4	5	6	7	8
Volume (min)	40	40	62	62	62	62	80	80
Session * cycle (per week)	1 × 4	1 × 4	1 × 4 + 1 × 2	2 × 4 + 1 × 2	3 × 4 + 1 × 2	4 × 4 + 1 × 2	2 × 4	2 × 4
Warm up (min)	7	7	7	7	7	7	7	7
Time per exercise (sec)	20	25	30	30	35	35	40	40
Rest between exercise (sec)	40	35	30	30	25	25	20	20
Rest between cycle (min)	3	3	3	3	3	3	3	3

Statistical analysis

The difference in RE improvement between a CSET and control group was previously investigated using 7 to 10 participants per group (L. Paavolainen et al., 1999; Saunders et al., 2006), which is smaller than the 14 and 17 participants attributed to CSET-PLY and CSET-DYN herein. Descriptive statistics are presented using mean ± standard deviation as well as corresponding 95% confidence intervals [lower, upper]. The normality of the data was verified using Kolmogorov–Smirnov tests (p range: 0.09–0.95) and homogeneity using Levene tests (p range: 0.06–0.94). Unpaired two-sided Student's t-tests were used to compare participant characteristics, initial PTS as well as pre-intervention RE and running biomechanics (t_c, t_f, SF, DF, and k_{leg}) between CSET-PLY and CSET-DYN groups. Then, two-way [pre-post × intervention (CSET-PLY and CSET-DYN)] repeated measures ANOVAs that considered a potential pre-post × intervention interaction effect were used to analyse RE and the five previously mentioned biomechanical variables. Cohen's d effect size was calculated for the change in RE and the five biomechanical variables between pre- and post-intervention (Cohen, 1988), and classified as small, moderate, and large when d values were larger than 0.2, 0.5, and 0.8, respectively (Cohen, 1988). Finally, participants were split into high and low responders for both CSETs and effect size was calculated for the change in RE and the five biomechanical variables between pre-and post-intervention and separately for high and low responders. Statistical analysis was performed using Jamovi (version 1.6.23, retrieved from https://www.jamovi.org) with a level of significance set at $p \leq 0.05$.

Results

The baseline characteristics of CSET-PLY and CSET-DYN were similar between groups ($p \geq 0.10$; Table 3) except that a longer t_f was reported before the intervention for participants attributed to CSET-PLY than participants attributed to CSET-DYN ($p = 0.05$; Table 3).

The repeated measures ANOVA revealed no significant pre-post × intervention interaction effect ($p = 0.31$) and no significant main intervention effect ($p = 0.79$) on RE. However, RE significantly improved following an 8-week CSET (ΔRE = −2.1 ± 3.9% [−2.3%, −1.8%]; main pre-post effect; $p = 0.005$; $d = 0.3$; small effect size; Figure 2). RE improved by 2.83 ± 4.4% [0.5%, 5.1%] ($d = 0.4$; small effect size) for participants following CSET-PLY and by 1.4 ± 3.4% [0.2%, 3.0%] ($d = 0.2$; small effect size) for participants following CSET-DYN.

The repeated measures ANOVA revealed no significant pre-post × intervention interaction effect ($p \geq 0.15$) and no significant main intervention effect ($p \geq 0.09$) on the five tested biomechanical variables (Table 4). There was no significant main pre-post effect ($p \geq 0.10$) across biomechanical variables except for t_f which was shorter following

Table 3. Participant characteristics, initial peak treadmill speed, as well as pre-intervention running economy and running biomechanics (contact time, flight time, step frequency, duty factor, and leg stiffness) for participants following concurrent running endurance training with either plyometric (CSET-PLY) or dynamic body-weight training (CSET-DYN).

Characteristics	CSET-PLY	CSET-DYN	*p*
Age (y)	30 ± 11 [24, 36]	30 ± 8 [26, 33]	0.94
Height (cm)	175 ± 9 [170, 179]	179 ± 7 [176, 182]	0.10
Body mass (kg)	70 ± 9 [65, 74]	77 ± 14 [70, 84]	0.11
Weekly training sessions	3 ± 1 [2, 3]	3 ± 1 [2, 3]	0.94
Initial peak treadmill speed (km/h)	16.0 ± 1.2 [15.3, 16.6]	15.8 ± 1.5 [15.0, 16.5]	0.69
Running economy (ml/kg$^{0.75}$/km)	630 ± 41 [608, 651]	621 ± 46 [599, 642]	0.57
Contact time (ms)	276 ± 20 [265, 286]	285 ± 22 [274, 295]	0.57
Flight time (ms)	89 ± 21 [78, 100]	74 ± 22 [63, 84]	**0.05**
Step frequency (Hz)	2.78 ± 0.23 [2.66, 2.90]	2.80 ± 0.09 [2.75, 2.84]	0.85
Duty factor (%)	38.3 ± 3.3 [36.6, 40.1]	39.8 ± 3.0 [38.4, 41.2]	0.21
Leg stiffness (kN/m)	10.2 ± 1.7 [9.3, 11.1]	10.8 ± 2.3 [9.7, 11.9]	0.41

Data are mean ± standard deviation as well as 95% confidence intervals [lower, upper]. Significant differences ($p \leq 0.05$) between CSET-PLY and CSET-PLY groups as determined by unpaired Student's *t*-tests are indicated in bold.

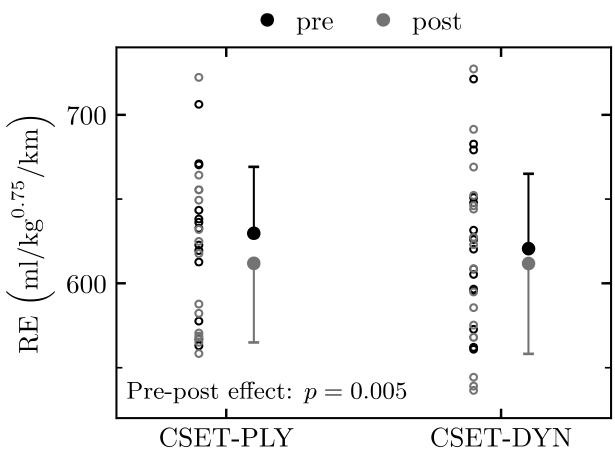

Figure 2. Pre- and post-intervention running economy (RE) for participants following concurrent running endurance training with either plyometric (CSET-PLY) or dynamic body-weight training (CSET-DYN). Two-way repeated measures ANOVA identified a significant pre-post effect ($p \leq 0.05$).

a CSET ($p = 0.03$; Table 4). Effect sizes were small ($d \leq 0.3$) for all tested biomechanical variables.

Thirteen participants (42%) were considered high responders (ΔRE = −5.7 ± 2.4% [−7.1%, −4.4%]; $d = 1.0$; large effect size) and 18 participants (58%) were considered low responders (ΔRE = 0.5 ± 2.1% [−0.4%, 1.5%]; $d = 0.1$; small effect size). Hence, participants were further split according to their CSET and responder status, leading to four different subgroups: high responders who followed CSET-PLY ($n = 6$), high responders who followed CSET-DYN ($n = 7$), low responders who followed CSET-PLY ($n = 8$), and low responders who followed CSET-DYN ($n = 10$).

Moderate to large effect sizes ($d \geq 0.7$) were reported for the improved RE between pre- and post-CSET for high responders. This was accompanied with a larger SF post- compared to pre-intervention ($d = 0.8$; large effect size) for high responders who followed CSET-DYN (Table 5). However, these runners did not modify their other biomechanical variables post- compared to pre-intervention ($d \leq 0.4$; small effect size; Table 5) and there were no changes in running biomechanics post- compared to pre-intervention for high responders who followed CSET-PLY ($d \leq 0.3$; small effect size; Table 5).

Low responders who followed CSET-PLY reported a larger SF and a shorter t_c post- compared to pre-intervention ($d = 0.5$; moderate effect size; Table 5). These runners did not modify their other biomechanical variables post- compared to pre-intervention ($d \leq 0.3$; small effect size; Table 5) and there were no changes in running biomechanics post- compared to pre-intervention for low responders who followed CSET-DYN ($d \leq 0.1$; small effect size; Table 5).

Discussion and implications

According to the first hypothesis, participants following CSET-PLY and CSET-DYN improved their RE. No changes in t_c, DF, and k_{leg} from pre- to post-intervention were seen for both CSETs, refuting our second hypothesis.

Table 4. Pre- and post-intervention running biomechanics (contact time, flight time, step frequency, duty factor, and leg stiffness) as well as 95% confidence intervals [lower, upper], corresponding changes in running biomechanics (expressed in percent units), and Cohen's *d* effect size for participants following concurrent running endurance training with either plyometric (CSET-PLY) or dynamic body-weight training (CSET-DYN).

Variable	Group	Pre	Post	Change (%)	*d*
Contact time (ms)	CEST-PLY	276 ± 20 [265, 286]	271 ± 17 [262, 280]	−1.8 ± 4.2 [−4.0, 0.4]	0.3
	CEST-DYN	285 ± 22 [274, 295]	285 ± 23 [274, 296]	0.2 ± 3.1 [−1.3, 1.7]	0.0
	Main intervention effect: 0.12 Main pre-post effect: 0.24 Interaction pre-post x intervention: 0.15				
Flight time (ms)	CEST-PLY	89 ± 21 [78, 100]	84 ± 26 [70, 98]	−6.0 ± 13.1 [−12.9, 0.9]	0.2
	CEST-DYN	74 ± 22 [63, 84]	69 ± 21 [59, 79]	−6.4 ± 16.8 [−14.4, 1.6]	0.2
	Main intervention effect: 0.06 Main pre-post effect: 0.03 Interaction pre-post x intervention: 0.88				
Step frequency (Hz)	CEST-PLY	2.78 ± 0.23 [2.66, 2.90]	2.81 ± 0.21 [2.71, 2.92]	1.1 ± 5.5 [−1.8, 4.0]	0.1
	CEST-DYN	2.80 ± 0.09 [2.75, 2.84]	2.83 ± 0.12 [2.77, 2.89]	1.3 ± 2.9 [−0.1, 2.7]	0.3
	Main intervention effect: 0.80 Main pre-post effect: 0.13 Interaction pre-post x intervention: 0.91				
Duty factor (%)	CEST-PLY	38.3 ± 3.3 [36.6, 40.1]	38.1 ± 3.2 [36.4, 39.8]	−0.6 ± 5.7 [−3.6, 2.4]	0.1
	CEST-DYN	39.8 ± 3.0 [38.4, 41.2]	40.3 ± 2.9 [38.9, 41.7]	1.4 ± 3.9 [−0.5, 3.2]	0.2
	Main intervention effect: 0.09 Main pre-post effect: 0.63 Interaction pre-post x intervention: 0.26				
Leg stiffness (kN/m)	CEST-PLY	10.2 ± 1.7 [9.3, 11.1]	10.5 ± 1.8 [21.7, 25.1]	2.7 ± 10.4 [−2.7, 8.2]	0.2
	CEST-DYN	10.8 ± 2.3 [9.7, 11.9]	10.8 ± 2.6 [23.3, 27.6]	−0.5 ± 7.1 [−3.9, 2.8]	0.0
	Main intervention effect: 0.10 Main pre-post effect: 0.10 Interaction pre-post x intervention: 0.29				

Data are mean ± standard deviation. Significant differences ($p \leq 0.05$) as determined by the two-way repeated measures ANOVAs are indicated in bold. Effect size is classified as small, moderate, and large when *d* values are larger than 0.2, 0.5, and 0.8, respectively (Cohen, 1988).

However, SF stayed unchanged and t_f decreased post-intervention for both CSETs, partly validating the second hypothesis. Among high responders, participants following CSET-DYN increased their SF but did not modify the other biomechanical variables investigated herein, and there were no changes in running biomechanics for participants following CSET-PLY. Low responders to both CSETs did not modify their running biomechanics. These results indicate that the improvements in RE obtained through the CSET-PLY and CSET-DYN involve minimal to no changes in running biomechanics and that there was not a training modality which was better than the other.

Table 5. Pre- and post-intervention running economy (RE) and running biomechanics (contact time, flight time, step frequency, duty factor, and leg stiffness) as well as 95% confidence intervals [lower, upper], corresponding changes in RE and running biomechanics (expressed in percent units), and Cohen's d effect size for high and low responders of concurrent running endurance training with either plyometric (CSET-PLY) or dynamic body-weight training (CSET-DYN).

		High responders				Low responders			
Intervention	Variables	Pre	Post	Change (%)	*d*	Pre	Post	Change (%)	*d*
CSET-PLY	RE (ml/kg$^{0.75}$/km)	637 ± 23	592 ± 37	−7.0 ± 2.3	1.8	625 ± 52	627 ± 57	0.3 ± 2.2	0.0
		[618, 655]	[570, 614]	[−8.8, −5.2]		[589, 660]	[587, 667]	[−1.2, 1.8]	
	Contact time (ms)	269 ± 18	270 ± 19	0.3 ± 1.7	0.0	281 ± 21	272 ± 16	−3.1 ± 4.4	0.5
		[255, 283]	[254, 285]	[−1.1, 1.7]		[267, 295]	[261, 283]	[−6.2, −0.0]	
	Flight time (ms)	83 ± 22	77 ± 23	−7.8 ± 12.6	0.3	94 ± 21	90 ± 29	−6.7 ± 17.4	0.2
		[66, 101]	[58, 95]	[−17.8, 2.4]		[80, 108]	[70, 110]	[−18.8, 5.4]	
	Step frequency (Hz)	2.93 ± 0.26	2.90 ± 0.25	−0.8 ± 6.6	0.1	2.67 ± 0.13	2.75 ± 0.15	2.9 ± 3.8	0.5
		[2.72, 3.14]	[2.70, 3.10]	[−6.1, 4.4]		[2.58, 2.77]	[2.64, 2.86]	[0.2, 5.6]	
	Duty factor (%)	39.4 ± 4.1	39.0 ± 2.5	−0.5 ± 6.5	0.1	37.5 ± 2.6	37.4 ± 3.6	−0.4 ± 4.5	0.0
		[36.1, 42.7]	[37.0, 41.0]	[−5.7, 4.7]		[35.7, 39.3]	[34.9, 39.9]	[−3.5, 2.7]	
	Leg stiffness (kN/m)	9.7 ± 1.1	9.5 ± 1.1	−1.9 ± 3.8	0.2	10.6 ± 2.0	11.2 ± 1.9	6.8 ± 13.7	0.3
		[8.8, 10.6]	[8.6, 10.4]	[−4.9, 1.1]		[9.2, 12.0]	[9.9, 12.5]	[−2.7, 16.4]	
CSET-DYN	RE (ml/kg$^{0.75}$/km)	599 ± 43	570 ± 38	−4.7 ± 2.2	0.7	636 ± 43	641 ± 47	0.7 ± 2.1	0.1
		[566, 631]	[543, 598]	[−6.3, −3.1]		[609, 662]	[612, 670]	[−0.6, 2.0]	
	Contact time (ms)	275 ± 14	274 ± 14	−0.3 ± 2.9	0.1	291 ± 24	293 ± 25	0.6 ± 3.3	0.1
		[265, 286]	[264, 185]	[−2.5, 1.8]		[276, 306]	[277, 308]	[−1.5, 2.6]	
	Flight time (ms)	81 ± 21	73 ± 19	−10.1 ± 5.9	0.4	68 ± 22	66 ± 22	−0.1 ± 28.4	0.1
		[66, 97]	[59, 87]	[−14.5, −5.7]		[55, 82]	[53, 80]	[−17.7, 17.5]	
	Step frequency (Hz)	2.81 ± 0.10	2.89 ± 0.11	2.9 ± 3.3	0.8	2.79 ± 0.10	2.79 ± 0.11	0.1 ± 2.2	0.0
		[2.74, 2.88]	[2.80, 2.97]	[0.5, 5.3]		[2.73, 2.85]	[2.72, 2.86]	[−1.2, 1.5]	
	Duty factor (%)	38.7 ± 2.7	39.6 ± 2.6	2.5 ± 1.9	0.4	40.5 ± 3.0	40.8 ± 3.1	0.7 ± 4.6	0.1
		[36.7, 40.6]	[37.7, 41.6]	[1.1, 4.0]		[38.6, 42.4]	[38.9, 42.7]	[−2.1, 3.5]	
	Leg stiffness (kN/m)	10.5 ± 1.9	10.7 ± 2.6	1.7 ± 7.3	0.1	11.1 ± 2.6	10.8 ± 2.7	−2.6 ± 5.5	0.1
		[9.0, 11.9]	[8.8, 12.6]	[−3.7, 7.1]		[9.5, 12.7]	[9.1, 12.5]	[−6.0, 0.8]	

Data are mean ± standard deviation. Effect size is classified as small, moderate, and large when *d* values are larger than 0.2, 0.5, and 0.8, respectively (Cohen, 1988).

RE significantly improved by 2.1 ± 3.9% following an 8-week CSET (Figure 2) but there was no main effect of the training modality on RE ($p = 0.79$) suggesting that both CSETs were equivalent and useful to improve RE. Our result is in the lower range of the RE improvement previously reported in the literature (2–8%) (Barnes & Kilding, 2015b), which might be explained by several reasons. As the endurance and strength training sessions were unsupervised, the compliance with instructions might have varied between participants, but this most often represents real-life conditions. In addition, exercise intensities were not controlled using control variables such as training intensity and training volume. Individuals reported that they did not perform any other type of training during the training period. Thus, the observed effects should be due to the proposed intervention, though the training of participants was not externally controlled (e.g., using a smart watch), which could not guarantee their statement. Moreover, as runners were novice to strength training, a body-weight load was used to avoid injuries. However, higher training loads might have led to greater RE improvements (Alexander et al., 2020). Furthermore, the duration of the intervention (8 weeks) might have been too short for marked RE improvements. Indeed, longer training periods of 9–21 weeks were shown to likely result in greater RE improvements than shorter training periods of 6–8 weeks (Denadai et al., 2017). Altogether, this could also partly explain the lower prevalence of high responders in terms of RE (42%) versus low responders (58%) and the large interindividual differences observed.

Improved RE was not associated with changes in running biomechanics except for a shorter t_f following CSET but with a small effect size (Table 4). Overall, these results corroborate the findings of a recent review which reported very limited evidence that CSET affects t_c or SF (Trowell et al., 2020). Besides, increasing the absolute time spent in the swing phase has been associated with better RE by several researchers, while others have failed to find any relationship between these two variables (Barnes et al., 2014; Moore, 2016; Williams & Cavanagh, 1987). Our results (an improved RE accompanied with a shorter t_f) further add on conflicting evidence about the relationship between RE and t_f (and swing time). Notably, changes in t_c and t_f should impact the SF and stride length of a runner, and it might be the relationship between these variables that should be considered. DF (the product of t_c and SF) might be the variable of choice to investigate this relationship. The present study did not report any change in DF with CSET, which corroborates previous findings reporting that DF was not related to RE at endurance running speeds (Patoz et al., 2022). Runners were shown to self-optimise their global running pattern (Williams & Cavanagh, 1987) and this concept was extended upon by Moore (2016). Indeed, runners were shown to naturally adopt a running biomechanics (t_c, SF, and k_{leg}) that is energetically optimal, or at least near optimal (Moore, 2016; Moore et al., 2019). In addition, RE was proposed to result from a weighted influence of several biomechanical variables (Williams & Cavanagh, 1987). Hence, these statements suggest that CSET might lead to RE improvement with little to no change in running biomechanics, as observed herein. Instead, the enhancement in RE might be due to an improved neuromuscular function (Barnes & Kilding, 2015b) and neural adaptations leading to increased muscular strength (Häkkinen et al., 2000). Assuming neuromuscular adaptations, though not investigated herein, the present results corroborate previous findings showing that neuromuscular adaptations do not lead to running biomechanical adaptations; more specifically, of the running stride parameters (Trowell et al., 2020). Nonetheless, determining the global running pattern of a runner might inform which variables are contributing the most to RE. Hence, slight alterations in suboptimal and interconnected variables might confer RE advantages at an individual level, notwithstanding that most biomechanical fine-tuning to improve RE may have already occurred in trained and experienced runners (Moore, 2016).

The prevalence of high responders in terms of RE was 42%. This result corroborates previous observations showing that individuals could either demonstrate a large, small, or even no response to a training intervention (Mann et al., 2014). The high responders to the CSET-PLY showed no changes in running biomechanics from pre- to post-intervention (based on effect size calculation) despite RE improvements of 7.0 ± 2.3% (Table 5). These results contradict previous findings which showed that a 9-week CSET with strength training involving explosivity (plyometric exercises; $n = 10$) significantly decreased t_c by ~15 ms (~7%) for a similar improvement in RE than the one observe here (~7%) (L. Paavolainen et al., 1999). The different level of runners involved in these two studies can potentially partly explain the diverging biomechanical findings given that recreational runners were involved herein versus elite runners in L. Paavolainen et al. (1999). On the other hand, our results align with the lack of change in the stride rate of highly-trained male distance runners ($n = 7$) observed after a 9-week plyometric training despite RE improvements of~4% (Saunders et al., 2006). Overall, these results suggest that the high responders to CSET-PLY or explosive type trainings improve their RE without marked changes in their running biomechanics, at least not in terms of spatio-temporal or modelled stiffness variables. Of interest, the SF of the high responders to the CSET-PLY intervention was higher than the SF of the low responders (Table 5). This result suggests that to positively respond to a plyometric training, a runner might need to have a higher SF. In this context, SF may be a useful tool to identify recreational runners likely to respond favourably to CSET-PLY.

The RE improvement of 4.7 ± 2.2% seen in the high responders to the CSET-DYN was associated with an increase in SF from pre- to post-intervention (+3%; large effect size; Table 5). These results somewhat contradict previous findings which found no change in SF following a CSET focused on leg and trunk training (Ferrauti et al., 2010). However, RE in the latter study was not improved, which was attributed to the small sample size ($n = 11$) and short intervention period (8 weeks). On the other hand, no change in running biomechanics was seen in the low responders to the CSET-DYN in our study (small effect sizes; Table 5). Overall, our results suggest that the high responders to the present CSET-DYN intervention transitioned towards running with a higher SF, which was associated with an improved RE. Although running with a higher SF has been associated with improved RE (Quinn et al., 2019), it is difficult to ascertain whether the increase in SF was involved in causing the improved RE or a biproduct of the improved RE.

This study provides support that both 8-week CSETs were equivalent and useful to improve RE without changing running biomechanics, implying that runners might benefit following a CSET to improve their RE. In addition, this study suggests that the improvement in RE following an 8-week CSET is dependent on the responder status of distance runners. High responders of both CSETs (CSET-PLY and CSET-DYN) improved their RE but with minimal to no changes in running biomechanics, at least when based on spatiotemporal and modelled stiffness variables. Nonetheless, a more detailed biomechanical analysis that includes running kinematics, kinetics, and electromyography rather than purely spatiotemporal or modelled stiffness variables could assist in identifying changes in biomechanics related to RE improvements with CSET.

This study presents a few limitations. This study did not involve a running-only intervention control group, which makes it hard to discern whether improvements in RE were due to participants completing the endurance training sessions and following a structured running plan or to the CSET. Nonetheless, the endurance training sessions were in line with their habitual running training, hence most likely not providing enough stimuli to improve RE (Barnes & Kilding, 2015b). Moreover, this study did not involve a CSET combining both plyometric and dynamic body-weight training. However, this combination might provide better training effects than a CSET with isolated plyometric or dynamic body-weight training. Hence, further work within the filed might involve longitudinal studies comparing the effects of CSET combining both plyometric and dynamic body-weight training, CSET-PLY, and CSET-DYN on RE and running biomechanics. Furthermore, as no strength measures were performed, the suggestion of RE improvement due to neuromuscular adaptations without running biomechanical adaptations could not be justified. Finally, a pre-post endurance running performance measurement, e.g., a 3-km time trial, would have been welcome to objectively measure if improvements in RE would lead to improved performance.

Conclusion

To conclude, two different 8-week concurrent strength and endurance training modalities (CSET-PLY and CSET-DYN) led to RE improvement of 2.1 ± 3.9%. No changes in t_c, DF, SF, and k_{leg} but a decrease in t_f were seen from pre- to post-intervention for both CSETs. These two CSETs were equivalent and useful to improve RE with nearly no change in running biomechanics, implying that runners might benefit following a CSET to improve their RE. There was a 42% prevalence of high responders with improvements in RE of 5.7 ± 2.4%. Among high responders, there were no changes in running biomechanics for participants following CSET-PLY, while participants following CSET-DYN increased their SF from pre- to post-intervention (+3%). Low responders to both CSETs did not modify their running biomechanics. These results indicate that improvements in RE obtained through CSET-PLY and CSET-DYN involve minimal to no changes in running biomechanics and that there was not a training modality which was better than the other. More detailed biomechanical assessments involving kinematics, kinetics, and electromyography could shed light on the underlying mechanisms of RE improvement.

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Data availability statement

The dataset supporting this article is available on request to the corresponding author.

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