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Effects of Isometric Strength and Plyometric Training on Running Performance: A Randomized Controlled Study

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ABSTRACT

Purpose: The aim of the study was to compare the effects of isometric strength (IST) and plyometric training (PT) on endurance running performance. **Methods:** Twenty-six endurance runners (18 males and 8 females; age 36 ± 6 years, stature 1.69 ± 0.05 m body mass 61.6 ± 8.0 kg, VO_{2max} 50.4 ± 5.8 ml·kg^{-1}·min^{-1}) completed the countermovement jump (CMJ), isometric mid-thigh pull (IMTP), 2.4 km run time trial (2.4kmTT), running economy test (RE) and a graded exercise test measures at baseline. They were then randomly assigned to three groups, the control (CON), PT or IST group, and completed the circuit, plyometric or isometric training, respectively, twice a week for 6 weeks, while still continuing to perform their planned running training. They then completed the same set of measures performed at baseline post-intervention. **Results:** Significant time x group interactions and time main effect were observed for 2.4kmTT ($P = .002$, $\eta^2_p = .45$ and $P < .001$, $\eta^2 = 0.72$), maximal aerobic speed (MAS) ($P = .006$, $\eta^2_p = .39$), CMJ height ($P < .001$, $\eta^2_p = .55$) and IMTP relative peak force ($P = .001$, $\eta^2_p = .50$) in favor of PT and IST. Significant main effect for time was observed for 2.4kmTT ($P < .001$, $\eta^2_p = .72$), RE ($P = .048$, $\eta^2_p = .17$), VO_{2max} ($P = .047$, $\eta^2_p = .18$), MAS ($P < .001$, $\eta^2_p = .63$), CMJ height ($P < .001$, $\eta^2_p = .51$) and IMTP relative peak force ($P < .001$, $\eta^2_p = .58$). **Conclusion:** In conclusion, both PT and IST were similarly effective at enhancing running endurance performance. However, IST resulted in greater improvement to RE.

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Countermovement jump; isometric mid-thigh pull; maximal aerobic speed; running economy

Maximum oxygen consumption (VO_{2max}), lactate threshold and running economy (RE) have been reported to be important determinants of endurance performance (Bassett & Howley, 2000; Tanji et al., 2017). It was suggested that neuromuscular characteristics such as maximum strength and rate of force development are also important determinants for endurance performance (Lum et al., 2020; Noakes, 1988). This suggestion was supported by concurrent strength and endurance training studies that used either heavy resistance training (Beattie et al., 2017; Guglelmo et al., 2009; Støren et al., 2008) or explosive strength and plyometric training (PT) interventions (Lum et al., 2019; Paavolainen et al., 1999; Piancentini et al., 2013; Ramírez-Campillo et al., 2014; Spurrs et al., 2003). These researchers have reported that concurrent training resulted in not only increased muscular strength and power but also improved running performances without any change in VO_{2max}. Ramírez-Campillo et al. (2014) reported that runners who participated in 12 sessions of PT improved their performance in the 2.4 km run test, while no improvement was seen in the control group. Furthermore, Lum et al. (2019) reported that 6 weeks of PT also benefitted running performance for longer distance (~10 km) despite significant reduction in weekly training mileage. The improvement in running performances after performing strength training or PT interventions was either due to increased resistance to muscular fatigue, which enabled runners to maintain their running speed (Lum et al., 2019), or improved RE (Paavolainen et al., 1999; Ramírez-Campillo et al., 2014; Spurrs et al., 2003).

Others have claimed that the improved RE post PT was most likely due to an increase in musculotendinous stiffness (Paavolainen et al., 1999; Spurrs et al., 2003). Specifically, by using the oscillation technique, Spurrs et al. (2003) showed increase stiffness in the musculotendinous system of the *triceps surae* in runners who performed PT. This supported the results of Dumke et al. (2010) who reported that increased vertical stiffness (k_{vert}) was associated with lower oxygen consumption during running. Similarly, Barnes et al. (2015) also showed improved RE as a result of increased leg stiffness from exercises performed during the warm-up. The increase in musculotendinous stiffness allowed for greater return in elastic energy and more efficient transmission of force produced, hence reducing the metabolic cost (Burgess et al., 2007; Kovács et al., 2020). Therefore, training methods such as PT, which can result in increased musculotendinous stiffness, are beneficial to RE. However, impact-related ground reaction forces are strongly related to some running injuries (Johnson et al., 2020). As PT also involves high impact, it may increase runners' risk of injury if they are already performing high running mileage. Therefore, having an alternative strength training method to that of PT would be of benefit to endurance runners.

In contrast to PT, isometric strength training (IST) does not result in high impact force to the lower limbs and is often used in injury rehabilitation (Rhyu et al., 2015; Rio et al., 2015). In addition, peak force obtained from isometric squat isometric mid-thigh pull (IMTP) was reported to be highly correlated to sprint (Lum & Joseph, 2019) and endurance (Lum et al., 2020)

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running performance, respectively. Furthermore, IST has been reported to improve muscular force production (Bimson et al., 2017; Kubo et al., 2017; Lum & Barbosa, 2019; Lum et al., 2021; Lum & Joseph, 2019), musculotendinous stiffness (Burgess et al., 2007; Lum & Barbosa, 2019), and even sports related performance outcomes (Albracht & Arampatzis, 2013; Bimson et al., 2017; Lum et al., 2021). Interestingly, Burgess et al. (2007) reported that IST led to a greater increase in musculotendinous stiffness as compared to PT. This finding was supported by Kubo et al. (2017) who also reported greater tendon stiffness after performing a period of IST as compared to PT. This suggests that IST might be as, if not more, beneficial to running performance compared to PT.

Currently, to the authors' knowledge, only the studies by Albracht and Arampatzis (Albracht & Arampatzis, 2013) and Fletcher et al. (2008) have investigated the effects of IST on running endurance performance. Fletcher et al. (2008) reported a 7% improvement in RE at 95% lactate threshold velocity in highly trained male distance runners who performed 2 × 20 s isometric plantar flexion at 80% maximum force, 3 times a week for 8 weeks. These findings were supported by Albracht and Arampatzis (Albracht & Arampatzis, 2013) who recruited 13 long-distance runners to perform 5 sets × 4 reps × 3 s of isometric plantar flexion at maximal voluntary contraction (MVC) for 14 weeks. This IST intervention resulted in improved RE as reflected by decrements of 5% and 3.4% in oxygen consumption, and 4.7% and 3.5% reduction in energy cost, at running velocities of 3.0 $m{\cdot}s^{-1}$ and 3.5 $m{\cdot}s^{-1}$, respectively. Results from these studies indicate that single joint IST was beneficial to running performance in highly trained runners. Despite these findings, no study has investigated the effects of multi-joint IST on endurance running performance. As running is a multi-joint activity, it is possible that strength training with multi-joint exercises might be more effective in improving running performance.

Although both PT and IST have been reported to benefit endurance running performance, to date, no study has compared such effects between the two modes of training. The aim of the current study was to compare the effects of multi-joint exercise IST and PT on RE and endurance running time trial performance. It was hypothesized that IST would result in greater improvements when compared to a control group and similar improvements when compared to PT for all endurance running performance indicators.

Material and methods

Experimental design

A randomized control trial research design was selected. Participants were required to attend a familiarization session for all testing protocols. Subsequently, they had to complete two preliminary test sessions. The first session included a countermovement jump test (CMJ), isometric mid-thigh pull (IMTP) and a 2.4-km run time trial (2.4kmTT). The second session included a RE test and graded exercise test (GXT). Respiratory gas analysis, blood lactate (Bla) concentrations and heart rate (HR) were measured during RE test and GXT. Leg and vertical stiffness and RE were measured during RE test at two running speeds (RE1: female—10.0 $km{\cdot}hr^{-1}$, male—12.0 $km{\cdot}hr^{-1}$; RE2: female 12.0 $km{\cdot}hr^{-1}$, male —14.0 $km{\cdot}hr^{-1}$). Subsequently, participants were randomly assigned to either control (CON), PT or IST group. Participants completed 6 weeks of intervention training twice per week. Posttest sessions were conducted between 72 and 96 hr after the final intervention training session.

Participants

Thirty endurance runners were recruited for participation in this study. However, the total number of participants who completed the posttest was n = 26 [CON: six males and two females, age 32.0 ± 7.3 years, height 1.68 ± 0.05 m, body mass 61.8 ± 7.4 kg; VO_{2max} 49.9 ± 5.3 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$, PT = six males and three females, age 37.7 ± 6.6 years, height 1.70 ± 0.07 m, body mass 64.7 ± 9.2 kg; VO_{2max} 50.6 ± 5.2 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$, IST = six males and three females, age 36.7 ± 6.0 years, height 1.70 ± 0.06 m, body mass 62.8 ± 8.0 kg; VO_{2max} 51.6 ± 7.3 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$]. Two participants from the IST and one participant from CON were not able to complete the posttest measures due to the 2020 pandemic compulsory government ordered lock down, while one participant from PT dropped out due to injury unrelated to the study. To be included in this study, participants must have been between 18 and 45 years of age; were running more than 30 km per week in the last 6 months; had a 2.4 km running time of equal or less than 12 min; and had not sustained any lower limb injury for the last 6 months. Prior to participation in the study, eight participants were participating in two to three sessions of resistance training per week for at least 2 years. The number of participants with resistance training experience in each group was as follows: CON = 2, PT = 3, IST = 3.

Prior to participation, all participants were briefed on the requirements and risks involved with the study. Participants signed a written informed consent prior to the initial testing session. Parental consent was sought for participants below the age of 21 years old. The study commenced after obtaining ethical clearance from the institutional review boards of the local university and sport institute.

Testing sessions

All testing sessions were conducted at the same time of the day to avoid diurnal effect on performance. Participants were requested to refrain from consuming alcohol and caffeine, and from participating in intensive training sessions for 24 hr prior to all testing sessions. Participants were also asked to avoid the consumption of any food and fluids other than water for 2 hr before each testing session. Participants were instructed to record their dietary intake 24 hr leading into the pretest sessions and to consume the same meal prior to posttest sessions. All testing sessions began with a 5 min moderate intensity jogging on a motorized treadmill, followed by dynamic stretching of lower body exercises including body weight squat, stiff leg deadlift, alternating lunge, calf raise, ankle hop and submaximal effort of CMJ. One minute of recovery period was given prior to commencing the test for that session.

Countermovement jump test

The CMJ height was previously reported to be significantly correlated to endurance run performance (Sinnett et al., 2001). The test was conducted during the same sessions as and prior to the IMTP. The CMJ was been performed on dual-force plates (Vald Performance, FD4000, Queensland, Australia) sampling at f = 1 kHz. During the CMJ, participants were asked to keep their arms akimbo to eliminate arm swing and maintain their back upright to reduce angular displacement of the hip. Participants performed three jumps, separated by 30 s passive rest. The commercially available ForceDecks software (Vald Performance, Queensland, Australia) was used to analyze and generate the CMJ height.

Isometric mid-thigh pull

Isometric force-time characteristics obtained from IMTP were previously reported to have significant correlation to endurance running performance indicators (Lum et al., 2020). The test was also performed on the same dual-force plates and follows the procedure described by Comfort et al. (2019) Participants were asked to adopt a posture that reflected the start of the second pull of the clean resulting in a knee flexion angle of 125°–145° and hip flexion angle of 140°–150° stance. A handheld goniometer was used to ensure that participants adopted the required knee and hip angles. Participants were required to hold on to the bar with elbows fully extended. Upon the tester's command, participants were instructed to pull the bar, by driving their feet into the floor, "as hard and fast as possible." Participants had to maintain the tension for a period of 5 s. Participants performed the IMTP twice, if the PF was within 250 N between the two trials; another trial was performed if that was not the case. Each attempt was separated by a 2 min recovery period. The highest relative peak force as calculated by dividing the highest absolute peak force by participant's body weight was then reported.

2.4-km run time trial

This running performance field test was selected because it has been shown to be a valid and reliable test, with high correlation to gas-measured VO_{2max} value during exercise to exhaustion on a treadmill (Burger et al., 1990). Participants performed a 2.4kmTT about 10 min after the completion of the IMTP. The 2.4kmTT was conducted on an outdoor running track under fair weather (temperature: 29–31°C, relative humidity: 70.8–77.3%) condition.

Running economy and graded exercise test

The RE tests and GXT were conducted on a motorized treadmill (Venus; HP-Cosmos, Nussdorf-Traunstein, Germany) under room temperature of 22.2°C and 65% relative humidity. The treadmill was set to 1% grade to simulate external environmental factors (Jones & Doust, 1996). During the RE tests, participants ran for 4 min at 10.0 km·hr^{-1} and 12.0 km·hr^{-1} for female, and 12.0 km·hr^{-1} and 14.0 km·hr^{-1} for male. A 4 min duration was selected as previous studies used running duration between 3 and 5 min when measuring RE (Lum et al., 2019; Piancentini et al., 2013; Spurrs et al., 2003; Tanji et al., 2017). Collection of finger capillary blood samples to assess Bla occurred immediately when the treadmill was stopped during the 1 min rest period between the 4 min of running. The Bla was measured using a lactate analyzer (Lactate Pro; Arkay, Kyoto, Japan). The GXT commenced after a 6-min passive recovery from the second RE test. An initial speed of 8.0 or 9.0 km·hr^{-1} was used. The treadmill speed increased by 1.0 km·hr^{-1} every minute until volitional exhaustion (Pasqua et al., 2018). The following criteria were used to determine the attainment of VO_{2max}: respiratory exchange ratio >1.00; heart rate within 5% of their age-predicted maximum; and/or Bla of 8–10 mmol.L^{-1}. The speed that corresponded to VO_{2max} was considered the individual's maximal aerobic speed (MAS). Capillary blood samples to assess Bla were collected 1 min upon completion of GXT.

Concentrations of O_2 and CO_2 in expired air were analyzed continuously during the RE and GXT using an open-circuit spirometry system (TrueOne 2400MMS; Parvomedics, East Sandy, Utah, USA) which was calibrated before each trial in accordance with the manufacturer's specifications. The sum of the two highest consecutive 30 s values during the two RE run tests and GXT was used to determine each participant's RE_1, RE_2 and VO_{2max}, respectively. Heart rate was measured using an HR monitor (RS400; Polar Electro Oy, Kempele, Finland). For RE test, GXT and 2.4-km run test, HR was recorded at the last 10 s of each stage, and immediately upon completion, respectively.

The RE for each speed was calculated by combining aerobic energy metabolism, calculated from VO_2 and the respiratory exchange ratio (RER), with anaerobic energy metabolism, calculated from the change in Bla as previously described by Tanji et al. (2016). It was reported that RE calculated using this method was highly correlated to RE during 1500-m runs performed at various speeds (r = −0.56 to −0.71, P < .01) (Tanji et al., 2017). Leg stiffness (k_{leg}) during the RE tests was determined using the sine-wave calculation method as previously described by Morin et al. (2005)

Training intervention

Participants were instructed to maintain their running training program as similar as possible to what they had been doing prior to participating in the study. They were also required to fill in a training log to indicate their weekly running mileage. All intervention training sessions were supervised by a certified strength and conditioning specialist. On all intervention training sessions, participants from CON were required to perform three sets of circuit training with a 30 s work and 30 s rest format, followed by 20 min of moderate intensity treadmill run (at individual's marathon pace). The CON's circuit training exercises include body weight squat, lunge with knee lift and arabesque. Participants were instructed to perform as many repetitions as possible within the 30 s for each exercise. Prior to the 20 min treadmill run, PT and IST groups were required to perform either plyometric exercises or maximal isometric exercises as displayed in Table 1. Exercises for PT were previously used in various studies (Lum et al., 2019; Ramírez-Campillo et al., 2014; Spurrs et al., 2003), and training volume was also based on previous study (Lum et al., 2019). The IST included IMTP as this force-time characteristics obtained from this exercise was previously reported to be significantly correlated

Table 1. Plyometric and isometric strength training program.

	PT	IST
Week	Exercise x Sets* x Repetitions	Exercise x Sets# x Repetitions#
1	40 cm depth jump x 3 × 5 Single leg bounding x 3 x 5/side Split Jump x 3 x 5/side	IMTP x 3 × 3 Isometric ankle plantar flexion x 3 × 3
2	40 cm depth jump x 4 × 5 Single leg bounding x 4 x 5/side Split Jump x 4 x 5/side	IMTP x 3 × 3 Isometric ankle plantar flexion x 3 × 3
3	50 cm depth jump x 4 × 5 † Single leg bounding x 4 x 5/side †Split Jump x 4 x 5/side	IMTP x 3 × 4 Isometric ankle plantar flexion x 3 × 4
4	50 cm depth jump x 4 × 5 † Single leg bounding x 4 x 5/side †Split Jump x 4 x 5/side	IMTP x 3 × 4 Isometric ankle plantar flexion x 3 × 4
5	60 cm depth jump x 4 × 5 †† Single leg bounding x 4 x 5/side ††Split Jump x 4 x 5/side	IMTP x 3 × 5 Isometric ankle plantar flexion x 3 × 5
6	60 cm depth jump x 2 × 5 †† Single leg bounding x 2 x 5/side ††Split Jump x 2 x 5/side	IMTP x 2 × 5 Isometric ankle plantar flexion x 2 × 5

*Rest (passive) intervals between sets for PT were 3 min.
#Rest (passive) intervals between sets and repetitions for IST were 3 min and 2 s, respectively.
†Participants will hold a weight plate on each hand that adds up to 5% of their body weight.
††Participants will hold a weight plate on each hand that adds up to 10% of their body weight.

to running performance indicators (Lum et al., 2020). The isometric ankle plantar flexion was included as this exercise was reported to benefit running performance (Albracht & Arampatzis, 2013).

Each training session began with a 15 min of warm up including, jogging, lunges, squats and submaximal vertical jumps. Principle of progressive overload was incorporated into the training program by varying the number of sets and/or repetitions for both training groups (see Table 1). For PT, participants were instructed to jump to maximum height for drop jump and split jump, and maximum distance for single leg bounding, during each repetition. Participants were also instructed to minimize ground contact time for drop jump and single leg bounding. For IST, participants were instructed to exert maximum force as fast as possible and hold each repetition for 3 s duration (Lum et al., 2021). The IMTP exercise was performed in the same position as during the test. During the isometric ankle plantar flexion, participants stood upright where the hips and knees were fully extended, and ankle in 0° plantar flexion. A bar was placed on the shoulder and fixed in position. Participants were required to maximally plantar flex the ankles while maintaining the extended hip and knee positions.

Statistical analysis

All statistical analyses were performed using SPSS (Version 26, IBM, New York, NY, USA). Data was examined using the Shapiro–Wilk test of normality, and Levene's test was used to assess the heterogeneity of variance between groups. All tested variables are expressed by Mean (±1 SD) and 95% of confidence interval. Mixed ANOVAs (between- x within-participant analysis; three training groups x two testing times; $P \leq 0.05$) with Bonferroni's post hoc comparison were used to determine whether any differences existed between the both groups on all test measures prior to and after the training period. Concurrently, it was computed the partial eta squared ($\eta^2 p$) as a standardized effect size was concurrently computed and deemed as: without effect if $0< \eta^2_p \leq 0.01$; small if $0.01< \eta^2_p \leq 0.06$; medium if $0.06< \eta^2_p \leq 0.14$; and strong if $\eta^2_p > .14$ (Cohen, 1988). Cohen's d was calculated as standardized effect size for mean comparisons and deemed a: (i) trivial effect size if $0 \leq |d| \leq 0.2$; (ii) small effect size if $0.2<|d|\leq 0.5$; and (iii) moderate effect size if $0.5<|d|\leq 0.8$; (iv) large effect size if $|d| >0.8$ (Cohen, 1988). The associations between change in CMJ height, change in IMTP relative peak force and change in all running performance indicators were determined using Pearson's product-moment correlation ($P < .05$). Correlational indices were set at: (i) small, if $0.1\leq|r|\leq 0.29$; (ii) moderate, if $0.3<|r|\leq 0.49$; (iii) large, if $0.5\leq|r|\leq 0.69$; (iv) very large, if $0.7\leq|r|\leq 0.89$; (v) near perfect, if $0.9\leq|r|\leq 0.99$; and (vi) perfect, if $|r| = 1$.

Results

Running performance indicators

Large time x group interactions were observed for 2.4kmTT ($P = .001$, $\eta^2_p = .47$), MAS ($P = .005$, $\eta^2_p = .37$) (Table 2). Main effect for time was observed for 2.4kmTT ($P < .001$, $\eta^2_p = .73$), MAS ($P < .001$, $\eta^2_p = .63$) and RE_2 ($P = .041$, $\eta^2_p = .17$) (Table 2). Simple effect for time showed that both PT and IST resulted in small to large improvement in MAS ($P = .002$, $d = 0.41$ and $P = .001$, $d = 1.23$, respectively), 2.4kmTT ($P = .001$, $d = -0.25$ and $P < .001$, $d = -0.22$, respectively). However, the improvement in RE_1 ($P = .008$, $d = -0.28$) and RE_2 ($P = .005$, $d = -0.42$) were observed in IST only, while small increase in VO_{2max} ($P = .009$, $d = 0.41$) was observed in PT only. No change in any variable was observed in CON. There was no change in $k_{leg}1$ *and* $k_{leg}2$ for all groups.

While moderate effect was observed for 2.4kmTT ($P = .338$, $\eta^2_p = .09$), RE1 ($P = .185$, $\eta^2_p = .14$), RE2 ($P = .462$, $\eta^2_p = .07$) and $k_{leg}2$ ($P = .522$, $\eta^2_p = .06$), simple group effect showed no difference in all measures for pretest results. When percentage changes in measured variables were compared, large differences between CON and PT, and CON and IST were observed for 2.4kmTT ($P = .004$, $d = 2.00$ and $P < .001$, $d = 1.88$, respectively), MAS ($P = .018$, $d = 1.32$ and $P = .001$, ES = 1.77, respectively) (Figure 1). When comparing between PT and IST, moderate to large differences were observed for RE_2 ($P = .250$, $d = 0.85$) and MAS ($P = .229$, $d = 0.58$).

Strength performance measures

Large time x group interactions and main effect for time were observed for CMJ height ($P < .001$, $\eta^2_p = .56$, $P < .001$, $\eta^2_p = .53$, respectively) and IMTP relative peak force ($P = .001$, $\eta^2_p = .51$, $P < .001$, $\eta^2_p = .60$, respectively) (Table 3). However, no significant group main effect was observed for both variables.

Simple group effect showed no difference in all measures for pretest results. Posttest results showed large difference in IMTP relative peak force between CON and IST ($P = .009$,

Table 2. Analysis of endurance running performance indicators.

		Mileage [km·week^{-1}]	2.4kmTT [s]	RE1 [J·kg^{-1}·km^{-1}]	k_{leg}1 [N·m^{-1}]	RE2 [J·kg^{-1}·km^{-1}]	k_{leg}2 [N·m^{-1}]	VO_{2max} [ml·kg^{-1}·min^{-1}]	MAS [km·hr^{-1}]
CON	**Pre**	47.4 (11.4)	616 (46)	1.13 (0.12)	6.55 (2.41)	1.12 (0.12)	7.07 (2.25)	49.9 (5.3)	15.6 (1.7)
(*n* = 8)	**Post**	48.1 (11.6)	614 (45)	1.11 (0.07)	6.44 (2.79)	1.10 (0.06)	7.06 (2.80)	50.3 (5.7)	15.7 (1.8)
	95%CI	0.2; 1.3	−8.3; 3.3	−0.08; 0.05	−0.86; 0.63	−0.09; 0.05	−1.03; 1.03	−0.8; 1.5	−0.2; 0.4
	P	0.020	0.344	0.579	0.729	0.507	0.991	0.509	0.501
	***d* (95%CI)**	0.06	−0.04	−0.20	−0.04	−0.21	0.00	0.07	0.06
		(−0.92; 1.04)	(−1.02; 0.94)	(−1.17; 0.79)	(−1.02; 0.94)	(−1.18; 0.78)	(−0.98; 0.98)	(−0.91; 1.05)	(0.93; 1.03)
PT	**Pre**	47.0 (10.3)	598 (61)	1.08 (0.06)	6.87 (2.27)	1.09 (0.07)	7.92 (2.94)	50.6 (5.2)	16.1 (1.6)
(*n* = 9)	**Post**	48.1 (10.6)	584 (64)	1.07 (0.06)	6.70 (2.29)	1.08 (0.07)	7.52 (2.1)	52.6 (6.3)	16.8 (1.8)
	95%CI	0.3; 1.9	−17.9; −11.0	−0.05; 0.03	−1.08; 0.73	−0.04; 0.01	−1.46; 0.65	0.12; 3.88	0.3; 1.0
	P	0.013	<0.001	0.605	0.673	0.347	0.402	0.039	0.002
	***d* (95%CI)**	0.11	−0.22	−0.17	−0.07	−0.14	−0.16	0.35	0.41 (−0.54; 1.32)
		(−0.82; 1.02)	(−1.14; 0.71)	(−1.08; 0.77)	(−1.00; 0.85)	(−1.06; 0.79)	(−1.07; 0.78)	(−0.60; 1.26)	
IST	**Pre**	47.6 (11.8)	579 (72)	1.06 (0.06)	5.84 (1.24)	1.08 (0.10)	6.51 (1.58)	51.6 (7.3)	16.1 (0.7)
(*n* = 9)	**Post**	48.4 (12.2)	561 (73)	1.04 (0.08)	6.14 (1.90)	1.04 (0.09)	6.49 (1.95)	52.1 (7.8)	16.9 (0.6)
	95%CI	0.1; 1.7	−26.0; −10.6	−0.04; −0.01	−0.53; 1.13	−0.06; −0.01	−0.81; 0.75	−2.0; 3.0	0.5; 1.2
	P	0.035	0.001	0.008	0.436	0.005	0.937	0.659	0.001
	***d* (95%CI)**	0.07	−0.25	−0.28	0.19	−0.42	−0.01 (−0.93; 0.91)	0.07	1.23
		(−0.86; 0.99)	(−1.16; 0.69)	(−1.20; 0.66)	(−0.75; 1.10)	(−1.33; 0.53)		(−0.86;0.99)	(0.14; 2.17)
Time x Group	**F**	0.284	9.990	0.228	0.510	0.508	0.301	1.176	6.877
Interaction	***P***	0.738	0.001	0.798	0.607	0.608	0.743	0.327	0.005
	η^2_p	0.03	0.47	0.02	0.04	0.04	0.03	0.09	0.37
Time Main	**F**	23.543	63.015	2.671	<0.001	4.684	0.374	3.711	39.876
Effect	***P***	<0.001	<0.001	0.116	0.988	0.041	0.547	0.067	<0.001
	η^2_p	0.51	0.73	0.10	<0.01	0.17	0.02	0.14	0.63
Group Main	**F**	0.003	1.137	1.818	0.325	0.798	0.669	0.202	0.570
Effect	***P***	0.997	0.338	0.185	0.726	0.462	0.522	0.818	0.573
	η^2_p	<0.01	0.09	0.14	0.03	0.07	0.06	0.02	0.05

Notes: 2.4kmTT = 2.4-km run time trial, RE = running economy, k_{leg} = leg stiffness, VO_{2max} = maximal oxygen consumption, MAS = maximal aerobic speed.

d = 1.35). When percentage changes in measured variables were compared, large differences between CON and PT, and CON and IST were observed for CMJ height ($P < .001$, ES = 2.24 and $P = .020$, ES = 1.41, respectively) and IMTP relative peak force ($P = .138$, $d = 1.06$ and $P < .001$, $d = 2.20$, respectively) (Figure 1). When comparing between PT and IST, large differences were observed for CMJ height ($P = .015$, $d = 1.22$) and IMTP relative peak force ($P = .003$, $d = 1.33$).

Association between running and strength performance measures

The relations between percentage change in running performance indicators and percentage change in CMJ height and IMTP relative peak force is illustrated in Figure 2. The results showed moderate inverse correlation between 2.4kmTT with CMJ height [$r = -0.390$ (−0.676; −0.004), $P = .049$] and IMTP relative peak force [$r = -0.431$ (−0.701; −0.052), $P = .028$]. There was also a trend for a moderate correlation between MAS and IMTP relative peak force [$r = -0.361$ (−0.031; 0.657), $P = .070$].

Discussion

The purpose of the current study was to compare the effects of PT and IST on endurance running performance. The findings showed that PT and IST resulted in similar improvement in 2.4kmTT and MAS. But these improvements were not present in CON, although all groups completed a similar volume for their weekly running mileage over the intervention period. In addition, RE at both running speeds was improved in IST only. While both IMTP relative peak force resulted in improvement in both CMJ height and IMTP relative peak force. A moderate inverse association between the change in 2.4kmTT and change in CMJ height and IMTP peak force was also observed. These findings on running performances were not in full agreement with our hypothesis as RE was only improved in IST but not PT.

Significant Time x Group interactions for 2.4kmTT and MAS were observed in favor of PT and IST, as compared to CON, despite no difference in total weekly mileage. The improvements in running performance indicators were concurrent with improvements in CMJ height and IMTP relative peak force in PT and IST. These findings were in agreement with previous studies that reported greater improvement in running performance in runners who performed resistance training as compared to those who did not (Albracht & Arampatzis, 2013; Paavolainen et al., 1999; Ramírez-Campillo et al., 2014; Spurrs et al., 2003). Furthermore, the current results also showed that an improvement in CMJ height (5.2%) and IMTP relative peak force (4.7%) were moderately and inversely correlated to an improvement in 2.4kmTT (1.9%). This suggests that strength performances have certain degrees of influence on the improvement of running performance.

The improvement in running performance, after a period of resistance training, has been attributed to improved running economy and musculotendinous stiffness (Albracht & Arampatzis, 2013; Paavolainen et al., 1999; Spurrs et al., 2003). However, this was only partially supported by the current findings. The results showed that IST had greater effect on RE as compared to PT and no improvement in leg stiffness in either IST or PT. One possible explanation for the

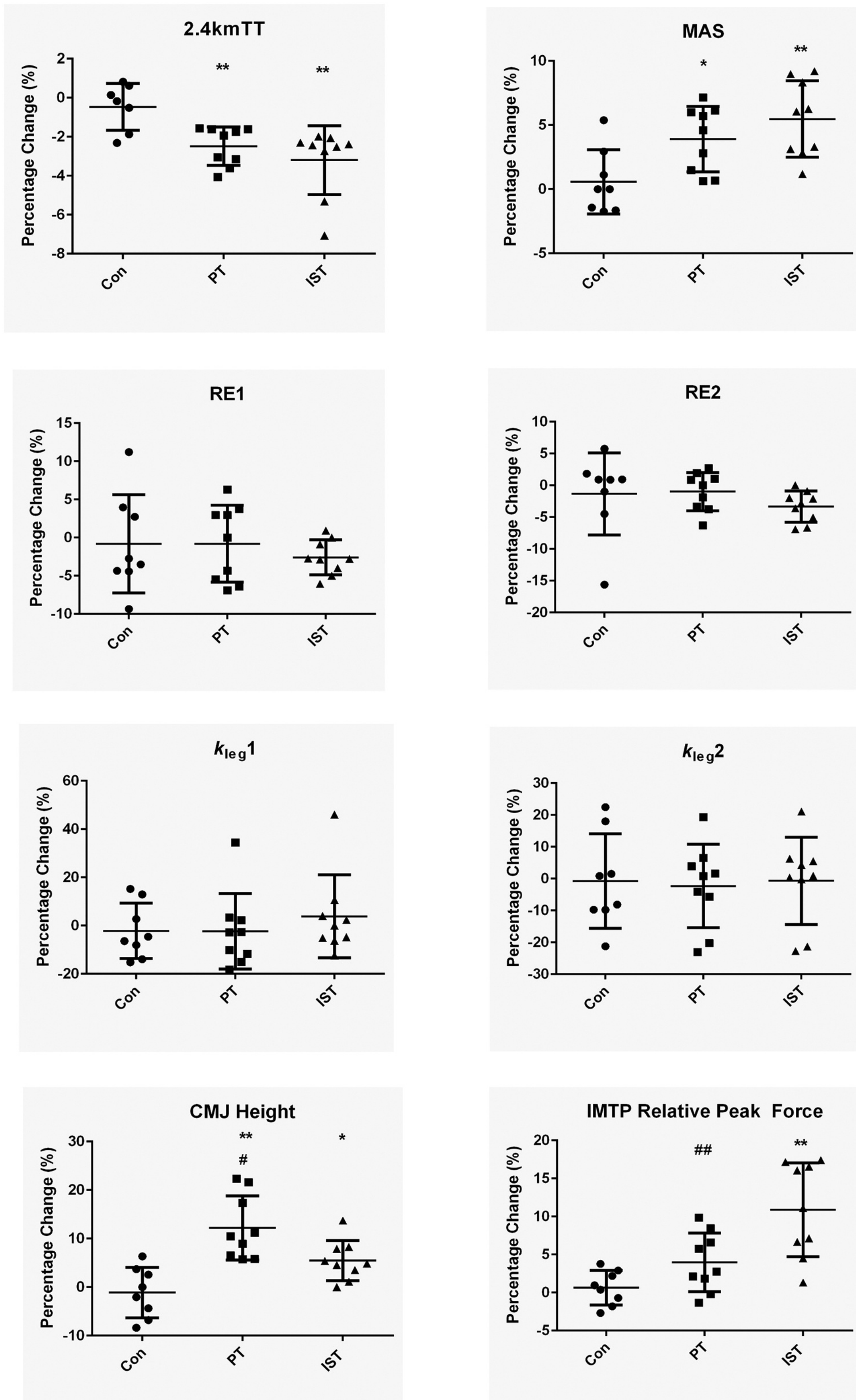

Figure 1. Percentage change in running performance indicators. Denotes different from CON *(P <.05), **(P < .01). Denotes different from IST #(P <.05), ##(P < .01).

improvement in running performance, despite comparable measures of RE or leg stiffness, could be that the force required to maintain a given speed was reduced, relative to the increased muscular strength. This led to reduced rate of fatigue that enabled runners to maintain a higher running speed for a longer period of time (Lum et al., 2019).

Running economy has been reported to be an important determinant of running performance (Bassett & Howley, 2000; Tanji et al., 2016, 2017) and can be improved with increased muscular strength and power (Albracht & Arampatzis, 2013; Paavolainen et al., 1999; Spurrs et al., 2003). The ability to generate force more rapidly reduces the time required to

Table 3. Analysis of countermovement jump and isometric mid-thigh pull.

		CMJ Height [cm]	IMTP Relative Peak Force [N·kg^{-1}]
CON	**Pre**	31.3 (6.6)	29.8 (4.1)
(*n* = 8)	**Post**	30.8 (6.1)	30.1 (4.7)
	95%CI	−1.9; 1.0	−0.3; 0.9
	P	0.490	0.350
	***d* (95%CI)**	−0.08 (−1.05; 0.91)	0.07 (−0.92; 1.04)
PT	**Pre**	28.2 (7.0)	31.8 (4.3)
(*n* = 9)	**Post**	31.4 (6.7)	33.1 (4.8)
	95%CI	2.1; 4.3	0.3; 2.2
	P	<0.001	0.014
	***d* (95%CI)**	0.47 (−0.49; 1.38)	0.29 (−0.66; 1.20)
IST	**Pre**	27.9 (4.9)	33.2 (4.1)
(*n* = 9)	**Post**	29.4 (4.7)	36.9 (5.4)
	95%CI	0.73; 2.14	2.0; 5.3
	P	0.002	0.001
	***d* (95%CI)**	0.31 (−0.63; 1.23)	0.70 (−0.22; 1.69)
Time x Group Interaction	**F**	14.658	11.817
	P	<0.001	<0.001
	η^2_p	0.56	0.51
Time Main Effect	**F**	26.179	34.742
	P	<0.001	<0.001
	η^2_p	0.53	0.60
Group Main Effect	**F**	0.330	2.730
	P	0.722	0.086
	η^2_p	0.03	0.19

Notes: CMJ = countermovement jump, IMTP = isometric mid-thigh pull.

produce a given force, which potentially reduces the metabolic demand of the working muscles and enhances intra-muscular efficiency during running (Bassett & Howley, 2000; Lum et al., 2020). The IST performed in the current study used a rapid maximal and sustained contraction method while adopting lower limb joint positions that was similar to the joint positions during foot contact when running (Li et al., 2021). By doing so, participants in the IST group were able to optimally improve their force production capability at that joint position (Lum & Barbosa, 2019). The enhanced ability to produce greater amount of force at that specific joint position could have contributed to the improvement in RE. The lower magnitude of the improvement of lower limb strength observed in PT group as compared to IST group could be another possible reason for the lack of change in RE.

The absence of improvement in RE for PT is in conflict with previous studies (Beattie et al., 2017; Paavolainen et al., 1999; Spurrs et al., 2003), but similar to Lum et al. (2019), one possible explanation could be that the volume of the PT group in the current study was not sufficient in regard to training load and/or stimuli. The number of jumps in each session in the study by Spurrs et al. (2003) showed enhancement in RE with plyometric training, ranging from 60 to 180 foot contacts per session, whereas the number of jumps per session in the current study was only between 30 and 60 foot contacts. Another possible reason could be that the inclusion of strength training exercises (e.g., back squat and leg press) was required when employing plyometric exercises of lower intensity such as that in the studies by Beattie et al. (2017) and Paavolainen et al. (1999)

Tendon stiffness of the lower limb has been attributed as one of the reasons for improved running performance after a period of resistance training (Albracht & Arampatzis, 2013; Paavolainen et al., 1999; Spurrs et al., 2003). Leg stiffness was reported to have significant large correlation with RE (Li et al., 2021). Nevertheless, the current results showed no significant change in leg stiffness in both PT and IST. Similar to the current findings, Lum et al. (2019) reported no significant change in leg stiffness (using the present study's method to determine leg and vertical stiffness) when running after a period of PT. The discrepancies between the current results and the findings of Albracht and Arampatzis (2013) and Spurrs et al. (2003) in regard to lower limb stiffness could be due to methodological differences and the difference in variables measured. In our study, leg stiffness was determined using an indirect method as proposed by Morin et al. (2005) during running. Conversely, Albracht and Arampatzis (2013) and Spurrs et al. (2003) had specifically assessed the stiffness of the Achilles tendon by measuring the change in the length of muscle-tendon unit during loading. In addition, Kubo et al. (2017) reported that IST resulted in increased stiffness in Achilles tendon but not passive and active stiffness of the *triceps surae* that were measured using the short-range stretch experiment. Moreover, they also reported no change in joint stiffness measured using drop jump test (Kubo et al., 2017). These findings suggest that the measuring of leg stiffness in the current study may not reflect the changes, if any, in the Achilles tendon as leg stiffness can be influenced by factors such as angle of the leg during ground contact, the change in leg spring length, resting leg length and horizontal velocity (Brughelli & Cronin, 2008). Therefore, the current results are not able to specifically determine if change to stiffness of the Achilles tendon is one of the factors contributing to the improvement in RE observed in IST.

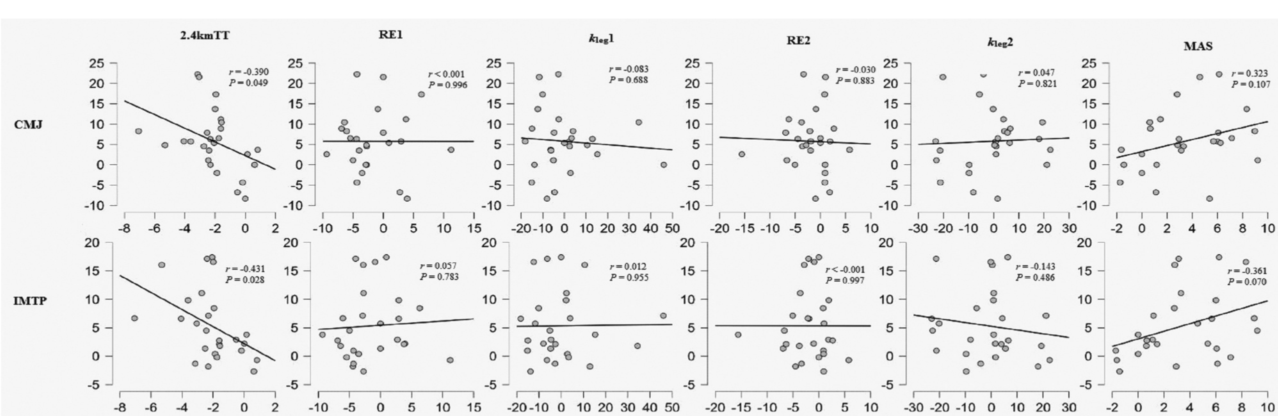

Figure 2. Correlation between running performance indicators with jump height and isometric strength.

Various studies on concurrent strength and endurance training have reported simultaneous improvement in running performance, maximum strength and jump height (Lum et al., 2019; Ramírez-Campillo et al., 2014; Spurrs et al., 2003). These findings were supported by the current results. The current study showed improvement in CMJ height and IMTP relative peak force in both PT and IST. In addition, the results supported the theory of training specificity as evident by the large differences in the percentage change in CMJ height and IMTP relative peak force observed. The differences in neuromuscular adaptations (i.e., CMJ height and IMTP peak force) between the PT and IST were likely the reason for the difference in mechanism that led to the enhanced running performance, i.e., lower 2.4kmTT time and higher MAS.

Several limitations should be taken into consideration for future research and when interpreting the results from this study. Firstly, it has been reported that RE in female runners changes significantly during different phases of the menstrual cycle (Goldsmith & Glaister, 2020). Goldsmith and Glaister (2020) reported ~5% reduced in RE during mid-luteal phase as compared to early and late follicular phase, while the current result showed a range of 6.9% improvement to 6.3% decrease in RE among the female participants. This finding could have been affected by the different phases of menstrual cycle as preliminary and posttests were performed without the considerations to the female participants' menstrual cycle phases. Secondly, the resistance training experience differs among the participants. Some of the participants had never performed resistance training before, while some had to seize their prevailing resistance training program during the intervention period. The magnitude of improvement in strength and dynamic performances might be smaller if all participants had experienced to resistance training prior to participation (Ahtiainen et al., 2003). Despite this, the resistance training experience of participants should have minimal between-group effect as there was similar number of resistant trained participants in each group. Thirdly, although there was no significant difference in weekly running mileage between the PT and IST groups, the intensity of the run might vary among participants (e.g., high-intensity intervals, up or down hill run) and could have affected the outcome of the study. Fourthly, although each group was instructed to perform each repetition of the exercises with maximal effort, the intervention included different modes of resistance training. Therefore, it was not possible to equalize the workload, although attempts were made to equalize perceived intensity. This could have affected the results as training volume could affect strength adaptations. Finally, while the inclusion of multi-joint IST in the current study and single joint IST alone in previous study (Albracht & Arampatzis, 2013) have been shown to benefit endurance running, it is still unknown if the inclusion of multi-joint IST would result in superior outcomes. Future study may attempt to answer this question.

Conclusion

In conclusion, this study showed that both PT and IST resulted in similar improvement to 2.4kmTT and MAS. However, participants who performed IST had greater improvement in RE. In addition, both training methods resulted in different neuromuscular adaptations. The difference in neuromuscular adaptation could be the reason for the different mechanisms that led to the enhanced running performance by both training methods. Hence, runners may include both PT and IST into their training regime to enhance running performance. However, it has been documented that individuals with higher lower limb strength have lower risk of sustaining injury when performing PT (Newton et al., 2001). Therefore, it is recommended that runners who intend to include PT into their training regime to first undergo a period of IST, as this mode of training poses low risk of injury, can improve lower limb strength and is also beneficial to endurance running performance.

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Authors' contribution

DL, TMB and GB conceived and designed research. DL and ARA conducted experiments. DL analyzed data and wrote the manuscript. All authors read, edited and approved the manuscript

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