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Original Article

Effects of intermittent sprint and plyometric training on endurance running performance

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Abstract

Purpose: The purpose of this study was to compare the effects of intermittent sprint training and plyometric training on endurance running performance.
Methods: Fourteen moderately trained male endurance runners were allocated into either the intermittent sprint training group ($n = 7$) or the plyometric training group ($n = 7$). The preliminary tests required subjects to perform a treadmill graded exercise test, a countermovement jump test for peak power measurement, and a 10 km time trial. Training included 12 sessions of either intermittent sprint or plyometric training carried out twice per week. On completion of the intervention, post-tests were conducted. Both groups showed significant reduction in weekly training mileage from preintervention during the intervention period.
Results: There were significant improvements in the 10 km time trial performance and peak power. There was also significant improvement in relative peak power for both groups. The 10 km time trial performance and relative peak power showed a moderate inverse correlation.
Conclusion: These findings showed that both intermittent sprint and plyometric training resulted in improved 10 km running performance despite reduction in training mileage. The improvement in running performance was accompanied by an improvement in peak power and showed an inverse relationship with relative peak power.

Keywords: Endurance training; Explosive strength training; Leg stiffness; Muscular power; Running economy; Stretch-shortening cycle

1. Introduction

Maximum oxygen uptake (VO_{2max}), fractional utilization of VO_{2max}, and running economy have been traditionally viewed as determinants of endurance performance. However, in one review, Noakes[1] suggested that muscle power factors affected by an interaction of neuromuscular and anaerobic characteristics may be better determinants of the performance of endurance athletes at the elite level. This may be due to the possibility that endurance athletes who have been training for many years may have reached a plateau for VO_{2max} development.[2]

Plyometric training (PT) is a form of explosive strength training that uses explosive movements to develop muscular power, which is the ability to generate a large amount of force quickly. Plyometric exercises involve a rapid eccentric movement, followed by a short amortization phase, which is then followed by an explosive concentric movement, enabling the synergistic muscles to engage in the myotatic-stretch reflex during the stretch-shortening cycle (SSC). This type of training has also been shown to improve performance of endurance runners.[3–11]

The improvement in running performance after undergoing PT has been attributed to increased musculotendinous stiffness, because such training method did not improve VO_{2max}.[7,10] These studies also showed improved running economy (RE), which was characterized by reduced oxygen consumption at a specific running speed. These results supported the earlier findings by Heise and Martin,[12] who showed that increased vertical stiffness (k_{vert}) was associated with lower oxygen consumption during running. Therefore, it would be expected that PT improved running performance by improving RE via increase in the musculotendinous stiffness.

Intermittent sprint training (IST) is defined as short-duration (≤10 s) "all-out" sprints with recovery periods that are long

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enough for near-complete recovery (60–300 s).[13] It is also an explosive type of training because it requires SSC movements similar to PT. It has been shown that IST resulted in similar neuromuscular adaptations to those of PT.[5] Because the mechanics of sprint running is specific to endurance running, it is likely that IST would be more beneficial to endurance running performance than PT. However, studies on the effects of IST compared with PT on endurance running performance are lacking in the sports science literature. Moreover, existing studies on the effect of PT on running performance were mostly measured over middle running distances of 2.4 km,[14] 3 km,[9,10] and 5 km.[7] Currently, studies have shown that PT is effective in improving running performance up to 5 km, but no studies have shown the benefit of PT for running distances longer than 5 km. Additionally, no study has investigated the effect of IST on long-distance running.

Therefore, the purpose of this study was first to compare the effects of IST and PT on RE. The second purpose was to investigate whether the effects of IST and PT would benefit running performance over a 10 km distance. It was hypothesized that sprint training would result in greater improvement in RE than PT, and that the effects of both training methods would improve 10 km running performance.

2. Methods

2.1. Subjects

Fourteen moderately trained distance runners (age: 28.9 ± 3.4 years; height: 171.3 ± 6.5 cm; body mass: 66.3 ± 6.8 kg) were recruited for participation in this study. This sample size was selected because previous studies of explosive strength training showed that it was sufficient to elicit significant results.[8,10] Subjects were restricted to moderately trained male distance runners who did distance running at least 3 times a week for a weekly mileage of >20 km. All subjects participated in the study during the off-season period, when they were not intending to participate in any races within 3 months of the start of the experimental period. Subjects were to refrain from any form of exercise in the 24 h prior to all testing sessions.

Prior to participation, all subjects were briefed on the requirements and risks involved with the study. All subjects signed the written informed consent prior to the initial testing session. The study commenced after obtaining clearance from the Institutional Review Board at Nanyang Technological University and Singapore Sports Institute.

2.2. Procedure

This study used a randomized design in which subjects were required to complete 2 preliminary test sessions separated by 72 h. The first session included a graded exercise test (GXT). The second session included a countermovement jump test (CMJ) and a 10 km running time trial. Gas analysis, blood lactate (BLa) concentrations, and heart rate (HR) were measured during all running tests. Leg stiffness (K_{leg}) and K_{vert} were measured during GXT at 10 km/h and 12 km/h running paces. Subsequently, subjects were randomly assigned to either the PT group or the IST group. Both groups completed 6 weeks of intervention training twice per week. At the end of the intervention, subjects repeated the 4 preliminary tests. All preliminary and post-tests were conducted at the Singapore Sports Institute Human Performance Laboratory. The training sessions were conducted at an outdoor 400 m running track.

2.2.1. GXT

The GXT was conducted on a motorized treadmill (Venus; h/p/cosmos, Nussdorf-Traunstein, Germany). It was conducted in a steplike fashion, utilizing 4 min work and 30 s rest periods. The treadmill was set to 1% grade to simulate external environmental factors.[15] An initial speed of 8 km/h was used as the athletes' warm-up. Subsequently, a 1 km/h increase in running speed occurred over each step until volitional exhaustion.[6] Collection of earlobe capillary blood samples to assess BLa occurred during the 30 s period between each stage. The GXT was used to determine VO_{2max}, lactate threshold 2 (LT_2), and RE at 10 km/h and 12 km/h. The LT_2 was determined using the modified D_{max}, identified as the point on the regression curve that yielded the maximal perpendicular distance to the straight line formed by the two end data points.[16]

Concentrations of O_2 and CO_2 in expired air were analyzed continuously during the GXT using an open-circuit spirometry system (TrueOne 2400; Parvo Medics, East Sandy, UT, USA), which was calibrated before each trial in accordance with the manufacturer's specifications. The sum of the 2 highest consecutive 30 s values during the GXT was used to determine each participant's VO_{2max} and RE at running speeds of 10 km/h and 12 km/h.

Blood was obtained via earlobe prick and during the 30 s interval between stages for GXT. The BLa was measured using a lactate analyzer (Lactate Pro; Arkray, Kyoto, Japan). HR was measured using an HR monitor (RS400; Polar Electro Oy, Kempele, Finland). For both the GXT and the 10 km time trial, HR was recorded at the last 10 s of each stage and immediately upon completion.

2.2.2. CMJ

During the second testing session, subjects perform the CMJ on an FT700 Isotronic Ballistic Measurement System (Fitness Technology, Adelaide, Australia). This incorporated the 400 series force plate (sampling at 600 Hz) to record the peak power, and the Ballistic Measurement System PT5 linear position transducer was fitted on the FT700 overhead tracking cradle to record vertical displacement and velocity of the participant. Subjects attempted each jump test 3 times, separated by 5 s intervals. The highest power obtained was recorded. Relative peak power was calculated by dividing the highest power obtained by the participant's body mass.

2.2.3. 10 km time trial

Subjects completed a 10 km time trial at least 48 h after completion of the GXT. The 10 km time trial was conducted on a 400 m running track. Subjects started at 1 min interval staggered timing to minimize pacing. Subjects were instructed to perform at their best effort and to strive for their best 10 km run time.

2.2.4. K_{leg} and K_{vert}

k_{leg} and k_{vert} during GXT at running speeds of 10 km/h and 12 km/h were determined using the sine-wave calculation method.[17] The equations for the calculations are as follows:

$$k_{leg} = F_{max} / \Delta L \quad (1)$$

$$k_{vert} = F_{max} / \Delta y_c \quad (2)$$

$$\Delta L = L - \left[\sqrt{L^2 - (vt_c/2)^2}\right] + \Delta y_c \quad (3)$$

$$\Delta y_c = -(F_{max}/m)(t_c^2/\pi^2) + g(t_c^2/8) \quad (4)$$

$$F_{max} = mg(\pi/2)(t_f/t_c + 1) \quad (5)$$

where F_{max} = maximal ground reaction force during ground contact, ΔL = peak displacement of leg spring, L = leg length (greater trochanter to ground), Δy_c = peak vertical displacement of center of mass, v = running velocity, t_c = ground contact time, g = gravitational force, m = body mass, t_f = flight time, k_{leg} = leg stiffness, and k_{vert} = vertical stiffness.

Kinematic data for calculation of the stiffness characteristics were obtained by placing an optical system consisting of 2 bars (Optogait; Microgate, Bolzano, Italy) beside the moving belt of the treadmill. Speed for analysis was preset, and measurements were taken for a period of 2 min for each speed after subjects had started running for 1 min.

2.2.5. Training

All subjects were instructed to continue with their usual running regimen and to keep a running log. Subjects were required to perform either PT or IST twice per week, for a total period of 6 weeks. There was no control group in the current study because previous studies had already shown that PT was beneficial to running performance.[7,9,10,14]

Prior to all training sessions, subjects completed 15 min of warm-up, including jogging, side shuffles, high knee exercises, lunges, squats, and submaximal vertical jumps. The principle of progressive overloading was incorporated into the training program by varying the number of sets and/or repetitions for both training groups (Table 1). For PT, subjects were instructed to jump to maximum height for each repetition. For IST, subjects were instructed to sprint as fast as they could. All training sessions were planned with reference to the study by Markovic et al.[5] and conducted by the lead author, who is a certified strength and conditioning specialist accredited by the National Strength and Conditioning Association.

As mentioned by Markovic et al.,[5] it was not possible to match the overall training volumes for both IST and PT because some plyometric exercises required bilateral force production, whereas sprint running included only unilateral force. However, the rest intervals between sets and the total training duration for both training interventions were similar.

2.2.6. Post-test

Subjects returned to complete a second ultrasound scan and GXT at least 72 h after the final intervention training session to determine the effect of training intervention on VO_{2max}, RE, k_{leg}, and k_{vert} at running speeds of 10 km/h and 12 km/h. Subjects then returned at least 48 h after GXT to complete the CMJ and 10 km time trial.

Table 1
Plyometric and sprint training program.

Week	Plyometric training	Intermittent sprint training
	Exercise × sets* × repetitions	Exercise × sets# × repetitions#
1	Alternate leg bounding × 3 × 30 Double-leg 30 cm hurdle hop × 3 × 10 40 cm depth jump × 3 × 10	30 m sprint × 4 × 3
2	Alternate leg bounding × 4 × 30 Double-leg 30 cm hurdle hop × 3 × 10 40 cm depth jump × 3 × 10	30 m sprint × 4 × 4
3	Alternate leg bounding × 4 × 30 Single-leg 30 cm hurdle hop × 3 × 5/side Double-leg 30 cm hurdle hop × 3 × 10 40 cm depth jump × 3 × 10	40 m sprint × 4 × 3
4	Alternate leg bounding × 4 × 30 Single-leg 30 cm hurdle hop × 4 × 5/side Double-leg 30 cm hurdle hop × 4 × 10 50 cm depth jump × 3 × 10	40 m sprint × 4 × 4
5	Alternate leg bounding × 4 × 40 Single-leg 30 cm hurdle hop × 4 × 5/side Double-leg 30 cm hurdle hop × 4 × 10 50 cm depth jump × 4 × 10	50 m sprint ×4 × 3
6	Alternate leg bounding × 4 × 40 Single-leg 30 cm hurdle hop × 4 × 5/side Double-leg 30 cm hurdle hop × 4 × 10 60 cm depth jump × 4 × 10	50 m sprint ×4 × 4

* Rest (passive) intervals between sets for plyometric training were 3 min.
# Rest (passive) intervals between sets and repetitions for intermittent sprint training were 3 and 1 min, respectively.
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2.3. Statistical analysis

All tested variables were expressed by mean ± SD. An independent t test was used to determine whether any differences existed between the groups on all test measures prior to and after the training period. Differences within groups from pre- to post-test were analyzed using pairwise t tests. Cohen's d was calculated as an effect size index for mean comparisons and was considered (1) a trivial effect size if $0 \le |d| \le 0.2$; (2) a small effect size if $0.2 < |d| \le 0.5$; (3) a moderate effect size if $0.5 < |d| \le 0.8$; and (4) a large effect size if $|d| > 0.8$. The α level was set at $p < 0.05$.

Pearson correlation analysis was selected to determine the association between peak power and running performance as well as between relative peak power and running performance. Correlational indices were set at (1) small if $0 \le |r| \le 0.2$; (2) moderate if $0.2 < |r| \le 0.5$; and (3) strong if $|r| > 0.5$.

3. Results

Both training groups showed significant reduction in their weekly training mileage from preintervention to the intervention period. No differences were found between groups in both evaluation moments. No between-group differences were observed for pre- and post-tests results for the 10 km time trial.

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Table 2
Participants' weekly training mileage, 10 km time trial timing, physiological and biomechanical variables during graded exercise text and muscle power (mean ± SD).

Variables	Intermittent sprint training				Plyometric training			
	Pre-	Post-	*p*	*d*	Pre-	Post-	*p*	*d*
Weekly training mileage (km)	**32.7 ± 15.8**	**28.8 ± 16.1**	**0.03**	**0.3**	**26.1 ± 8.6**	**20.4 ± 11.3**	**0.004**	**0.6**
10 km time trial timing (min)	**53′57″ ± 8′36″**	**51′57″ ± 7′56″**	**0.03**	**1.4**	**50′28″ ± 6′45″**	**48′21″ ± 7′06″**	**0.03**	**1.3**
Physiological variable								
VO_{2max} (mL/kg/min)	53.9 ± 7.4	54.6 ± 6.7	0.47	<0.1	54.4 ± 5.0	53.7 ± 6.7	0.56	0.1
HR_{max} (bpm)	185 ± 6	188 ± 11	0.86	0.2	183 ± 11	185 ± 12	0.69	0.1
LT_2 (km/h)	12.2 ± 1.5	12.3 ± 1.5	0.31	<0.1	12.4 ± 1.0	12.4 ± 1.0	0.92	<0.1
RE (mL/kg/min)								
10 km/h	38.5 ± 3.3	37.3 ± 3.1	0.33	0.2	37.9 ± 2.1	36.8 ± 1.7	0.42	0.3
12 km/h	45.1 ± 3.4	44.7 ± 4.1	0.86	0.2	45.3 ± 1.8	44.6 ± 2.3	0.41	0.3
HR (bpm)								
10 km/h	152 ± 15	152 ± 16	0.81	<0.1	152 ± 18	151 ± 18	0.51	<0.1
12 km/h	171 ± 14	169 ± 14	0.46	0.1	161 ± 15	163 ± 13	0.35	0.1
BLa (mmol)								
10 km/h	2.6 ± 1.2	2.5 ± 1.2	0.50	<0.1	2.5 ± 1.4	2.2 ± 1.0	0.09	0.3
12 km/h	5.2 ± 2.8	4.5 ± 2.3	0.32	0.2	4.5 ± 2.4	3.5 ± 1.3	0.10	0.5
Biomechanical variables								
FT (s)								
10 km/h	0.043 ± 0.027	0.043 ± 0.028	0.97	<0.1	0.042 ± 0.014	0.044 ± 0.013	0.18	0.2
12 km/h	0.065 ± 0.030	0.069 ± 0.024	0.18	0.2	0.062 ± 0.001	0.063 ± 0.006	0.62	<0.1
CT (s)								
10 km/h	0.293 ± 0.021	0.294 ± 0.018	0.59	<0.1	0.300 ± 0.011	0.300 ± 0.018	0.52	<0.1
12 km/h	0.268 ± 0.018	0.267 ± 0.029	0.88	<0.1	0.263 ± 0.009	0.260 ± 0.012	0.41	0.1
k_{leg} (Kn/m)								
10 km/h	6.43 ± 1.71	6.15 ± 1.19	0.21	0.2	5.21 ± 0.50	5.18 ± 0.47	0.88	0.1
12 km/h	6.87 ± 1.64	6.79 ± 1.28	0.41	0.2	6.12 ± 0.45	6.12 ± 0.20	0.98	<0.1
k_{vert} (kN/m)								
10 km/h	12.70 ± 3.21	11.93 ± 2.32	0.12	0.2	10.01 ± 1.03	10.09 ± 1.18	0.85	<0.1
12 km/h	16.47 ± 4.10	15.81 ± 2.20	0.41	0.2	14.14 ± 1.20	14.18 ± 1.21	0.96	<0.1
Muscle power								
Peak power (W)	**3274 ± 133**	**3368 ± 136**	**0.002**	**0.7**	**3100 ± 269**	**3287 ± 247**	**0.01**	**0.7**
Relative peak power (W/kg)	**48.1 ± 6.7**	**49.5 ± 6.9**	**0.007**	**0.2**	**48.9 ± 5.8**	**51.7 ± 5.4**	**0.01**	**0.5**
Jump height (m)	0.44 ± 0.05	0.45 ± 0.05	0.61	0.3	0.40 ± 0.03	0.41 ± 0.02	0.44	0.4

Values in bold means significant difference.
Abbreviations: BLa = blood lactate; HR_{max} = maximal heart rate; LT_2 = lactate threshold 2; RE = running economy; VO_{2max} = maximal oxygen uptake; CT = contact time; FT = fight time; k_{leg} = leg stiffness; k_{vert} = vertical stiffness; RE = running economy.

Both groups showed significant reductions with large effect sizes in the 10 km time trial from pre- to post-training.

There were no inter- and intra-group differences in pre- and post-test measurements for VO_{2max}, HR_{max}, and speed at LT_2. Post-test results also showed no inter- and intra-group pre- and post-test differences in RE, HR, and BLa at 10 km/h and 12 km/h. All results showed trivial to moderate differences.

There were trivial and no significant within- and between-group differences in pre- and post-test results for the biomechanical variables measured during the GXT.

There were no differences between groups for pre- and post-test peak power, relative peak power, and jump height. Post-test results for peak power showed significant and moderate improvement after training for both groups. There was also significant improvement in relative peak power for both groups. However, there were no significant changes in jump height for both groups.

As far as potential associations go, Pearson correlation test showed no significant correlation between 10 km run time and peak power ($r = -0.1$, $p = 0.59$). However, there was a moderate inverse correlation between 10 km running time and relative peak power ($r = -0.4$, $p = 0.01$) (Table 2).

4. Discussion

The purposes of the study were to compare the effects of IST and PT on RE and to investigate whether such explosive strength training would be beneficial to a 10 km running performance. The present 6-week intervention resulted in improvement in 10 km run time and peak power for both groups, despite a concomitant reduction in weekly running mileage. These results supported our hypothesis that both interventions will benefit performance for a distance longer than 5 km. However, our other hypothesis was not supported because there were no significant changes in RE in either groups when running at 10 km/h and 12 km/h during the GXT.

The current study was the first to investigate the effects of explosive strength training on 10 km running performance. It was also the first study to look at the effects of IST on endurance running performance. Both programs allowed an improvement in the 10 km time trial. It was shown that PT benefited running performance at distances of 2.4 km,[14] 3 km,[9,10] and 5 km.[7] Sedano et al.[9] stated that improvement in the time trial might be a reliable proxy of improvement in the official race. Although IST was included in the intervention in the study by Paavolainen et al.,[7] it was not known whether the performance improved owing to the effect of PT or the effect of IST. The current findings showed that when employed individually, both IST and PT were effective in improving running performance over a 10 km distance.

Additionally, subjects from both groups in the current study reported reduction in weekly training mileage during the intervention period, citing poor weather conditions and busy work schedules as main reasons. This showed that both IST and PT were good forms of cross-training when aiming to improve running performance in runners who plan to reduce their training mileage. These findings were supported by previous studies that showed improved running performance when explosive strength training was included while reducing running mileage.[6,7] Furthermore, replacing a portion of high-volume running sessions with sprint or PT might help to prevent overuse injuries.

Previous studies with well-trained runners (VO_{2max} > 60 mL/kg/min) investigating the effects of PT on endurance running performance have shown that running performance improved without the concurrent changes in VO_{2max}, HR_{max}, and speed at LT_2.[3,6-8,10] Despite having subjects with lower aerobic fitness (VO_{2max} < 60 mL/kg/min), the current findings were in line with the results of previous studies, because both groups showed no significant changes in those variables. However, previous studies on repeated sprint training showed improvement in VO_{2max},[18,19] which was in conflict with the current findings. This was most likely due to the difference in rest periods between the sprint training protocols. The current study employed a long rest period (≥60 s) between repetitions, whereas the previous studies used a shorter rest period (≤30 s). It was suggested that individuals with VO_{2max} above 40 mL/kg/min would need to exercise at more than 45% of VO_2 reserve to induce changes to VO_{2max}.[11] Owing to the long rest period and passive recovery method, the IST in the current study might not have induced enough aerobic stress in the subjects to allow for any significant adaptations in the cardiovascular system.

Running economy has been defined as the rate of oxygen uptake per unit mass when running constantly at a given speed, and it has been shown that faster runners have higher RE (lower VO_2 at specific speed).[20-22] Improvement in RE after PT was one of the factors being attributed to the improvement in running performance.[7,9] It was shown that RE improved at running speeds of 11.3 km/h, 12 km/h, 14 km/h, 16 km/h, and 18 km/h after PT.[6,8-11] However, the current finding showed no improvement in VO_2 at running speeds of 10 km/h and 12 km/h for both groups. Similar to the current findings, some studies did not find significant improvement in VO_2 at 10 km/h and 12 km/h.[6,23] Saunders et al.[8] suggested that PT may be more beneficial in improving RE at higher running speeds (i.e., 18 km/h) because elastic mechanisms are reported to prevail over contractile machinery at higher speeds. This means that as running speed increases, runners would store more elastic energy during foot contact than is released during push off. In addition, the proportion of voluntary muscular contractions for push off during each stride decreases with increasing speed owing to the increase in elastic energy utilization. The current study was not able to clarify this statement because our subjects did not have the high aerobic capacity to sustain such intense workload. Furthermore, the current findings showed no pre- and post-test differences in stride length, stride frequency, flight time, and contact time for either group when running at 10 km/h and 12 km/h. Another reason for the lack of improvement in RE could be the low running volume of the subjects. The average weekly training mileage of the subjects in the current study (IST: 27.75 km, PT: 21.00 km) was much lower than that reported in previous studies (60–107 km).[7,9,10] These studies also showed improved running performance for distances of 3–5 km. Altogether, this suggests that a high training mileage (>30 km/week) might need to be performed concomitantly with IST or PT to elicit improvement in RE.

SSC is a function of the muscle in which a muscle contraction is preceded by a stretch. Running induces SSC in the musculotendinous system of the lower limbs, causing repeated lengthening and shortening of the muscles and tendons. Cavagna et al.[24] suggested that without contribution from elastic energy storage, there would be a 30%–40% increase in oxygen consumption during running. Based on these findings, the elastic properties of the musculotendinous system in the lower limbs should contribute to the efficiency and performance of long distance runners. In addition, Arampatzis et al.[25] suggested that runners with higher stiffness in the musculotendinous system of the lower limbs have higher RE, because increased stiffness allows elastic energy that is stored during foot contact to be used at push off more efficiently. In support of this, Spurrs et al.[10] mentioned that explosive strength training led to improvement in RE by increasing the stiffness of the musculotendinous system.

Results from the current research were not able to support the findings of previous studies. Both IST and PT groups showed no changes in k_{leg} and k_{vert} when running at 10 km/h and 12 km/h. Although other studies[7,8] have attributed the improvement of RE to enhance k_{vert}, Spurrs et al.[10] were the only ones who measured stiffness of the musculotendinous system post-PT. The authors utilized the oscillation technique, which measured the musculotendinous stiffness during isometric contraction, whereas the current study utilized an analytical method in which an optical system was used to capture the flight and contact times during treadmill running. Kinematic data were then used to estimate k_{leg} and k_{vert} with the sine-wave calculation method. The difference in method of measurement might be a reason for the conflicting findings. Vertical stiffness and RE have been reported to be inversely related.[25] The trivial changes in stiffness in this research are due to nonsignificant variations in the running kinematics between pre- and post-tests. It is therefore logical that the lack of improvement in RE was accompanied by the lack of change in k_{leg} and k_{vert} in the current study. In summary, these findings showed that 6 weeks of IST and PT did not have any effect on running biomechanics of moderately trained subjects.

Saunders et al.[8] suggested that the underlying reason for the improvement in running performance without concurrent improvement in aerobic capacity could be improved muscle power development and utilization of stored elastic energy. In support of this statement, the current study showed that there was improvement in peak power during the CMJ test after the training intervention in both groups. Additionally, the results showed a moderate correlation between relative peak power and 10 km run time.

In support of this association, previous studies have also shown concurrent improvement in running performance and muscular power after explosive strength training.[3,7] The increase in peak power might have made a standard submaximal workload relatively lower in intensity, thus lowering the rate of fatigue and leading to improved running performance. However, despite the increase in muscular power, the current results showed that there was no increase in post-test jump height. This was in conflict with previous studies of sprint training and PT.[10,14,26] Turner et al.,[11] who also found no improvement in jump height after PT, suggested that the absence of improvement could be the lack of intensity of the PT. Another possible reason could be the lack of specificity in training. The PT in our study employed exercises that required fast SSC jumping ability (contraction time <0.25 s), whereas CMJ tests slow SSC jumping ability (contraction time >0.25 s). It was found that fast SSC jumping, slow SSC jumping, and sprinting are separate and independent motor abilities.[27]

It was verified that sprinting ability showed only 23% common variance with slow SSC jumping ability, whereas fast SSC jumping ability showed only 17% common variance with slow SSC jumping ability.[27] Therefore, training with fast SSC exercises might not benefit slow SSC exercise performance. This could be a reason why there were no changes in jump height for either group despite the increase in peak power. Based on this and the current findings, runners would be required to continue their running training when including PT or IST to allow for the increase in muscular power to be transferred to improvement in running performance.

There were several limitations to this study. First, the current study did not control the volume of endurance training of the subjects. The significant reduction in training volume might have offset some of the positive effects of IST and PT on running performance. Future studies could investigate the effects of different running mileages while including explosive strength training in endurance runners' training programs. Second, this was the first study to investigate the effects of IST on endurance running performance. Hence, there were no previous data for comparison. The current findings might be a reference for future studies on this topic. Third, similar to other studies, the current study was able to show only the short-term effect (6–12 weeks) of explosive strength training. The long-term (>12 weeks) effects of such training on running performance are yet to be known. Therefore, future studies investigating the effect of explosive strength training on running performance can take these into consideration. Finally, the results of the study showed a large variation in response to intervention training within each group. Readers should be cautious when interpreting the results because different individuals might respond differently to each training method.

5. Conclusion

The current study showed that IST and PT led to improvement in 10 km time trials in moderately trained endurance runners despite reduction in weekly training mileage. The improvement in running performance was accompanied by an improvement in peak jumping power. However, no other biomechanical or physiological variables selected showed significant post-training changes. This suggested that the improvement in running performance after a 6-week intervention was most likely due to the improvement in muscular power. Based on the findings in this study, practitioners and runners can include IST or PT twice a week in their training program. IST should begin with a sprint distance of 30 m, then increase the distance by 5–10 m every 2 weeks up to 50 m. It is recommended that runners complete 4 sets of 3–4 repetitions of sprints per session.

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Authors' contributions

DL conceived of the study; carried out the training intervention, VO_{2max} test, and 10 km time trial; and participated in the analysis and drafted the manuscript. FT and JP carried out the VO_{2max} test and performed the statistical analysis. TMB participated in test design and coordination and helped to draft the manuscript. All authors have read and approved the final version of the manuscript and agree with the order of presentation of the authors.

Competing interests

None of the authors declare competing financial interests.

References

1. Noakes TD. Implications of exercise testing for prediction of athletic performance: a contemporary perspective. *Med Sci Sports Exerc* 1988;**20**:319–30.
2. Rusko H. Development of aerobic power in relation to age and training in cross-country skiers. *Med Sci Sports Exerc* 1992;**24**:1040–7.
3. Berryman N, Maurel D, Bosquet L. Effect of plyometric *vs*. dynamic weight training on the energy cost of running. *J Strength Cond Res* 2010;**24**:1818–25.
4. Bonnette R, Spanoiol F, Melrose D, Ocker L, Dyer R. The effect of agility, plyometric, and sprint training on the speed endurance and power of high school soccer players. *J Strength Cond Res* 2011;**25**(Suppl. 1):S119.
5. Markovic G, Jukic I, Milanovic D, Metikos D. Effects of sprint and plyometric training on muscle function and athletic performance. *J Strength Cond Res* 2007;**21**:543–9.
6. Mikkola JS, Rusko H, Nummela A, Pollari T, Hakkinen K. Concurrent endurance and explosive type strength training improves neuromuscular

and anaerobic characteristics in young distance runners. *Int J Sports Med* 2007;**28**:602–11.
7. Paavolainen L, Hakkinen K, Hamalainen I, Nummela A, Rusko H. Explosive-strength training improves 5-km running time by improving running economy and muscle power. *J Appl Physiol* 1999;**86**:1527–33.
8. Saunders PU, Pyne DB, Peltola EM, Gore CJ, Cunningham RB, Hawley JA. Short-term plyometric training improves running economy in highly trained middle and long distance runners. *J Strength Cond Res* 2006;**20**:947–54.
9. Sedano S, Marín PJ, Cuadrado G, Redondo JC. Concurrent training in elite male runners: the influence of strength versus muscular endurance training on performance outcomes. *J Strength Cond Res* 2013;**27**:2433–43.
10. Spurrs RW, Murphy AJ, Watsford ML. The effect of plyometric training on distance running performance. *Eur J Appl Physiol* 2003;**89**:1–7.
11. Turner AM, Owings M, Schwane JA. Improvement in running economy after 6 weeks of plyometric training. *J Strength Cond Res* 2008;**17**:60–7.
12. Heise GD, Martin PE. "Leg spring" characteristics and the aerobic demand of running. *Med Sci Sports Exerc* 1998;**30**:750–4.
13. Girard O, Mendez-Villanueva A, Bishop D. Repeated-sprint ability—Part I: factors contributing to fatigue. *Sports Med* 2001;**41**:673–94.
14. Ramírez-Campillo R, Álvarez C, Henríquez-Olguín C, Baez EB, Martínez C, Andrade DC, et al. Effects of plyometric training on endurance and explosive strength performance in competitive middle- and long-distance runners. *J Strength Cond Res* 2014;**28**:97–104.
15. Jones AM, Doust JH. A 1% treadmill grade most accurately reflects the energetic cost of outdoor running. *J Sports Sci* 1996;**14**:321–7.
16. Bishop D, Jenkins D, Mackinnon T. The relationship between plasma lactate parameters, W_{peak} and 1-h cycling performance in women. *Med Sci Sports Exerc* 1998;**30**:1270–5.
17. Morin JB, Dalleau G, Kyröläinen H, Jeannin T, Belli A. A simple method for measuring stiffness during running. *J Appl Biomech* 2005;**21**:167–80.
18. Dawson B, Fizsimon M, Green S, Goodman C, Carey M, Cole K. Changes in performance, muscle metabolites, enzymes and fiber types after short sprint training. *Eur J Appl Physiol* 1998;**78**:163–9.
19. Meckel Y, Gefen Y, Nemet D, Eliakimi A. Influence of short *vs.* long repetition sprint training on selected fitness components in young soccer players. *J Strength Cond Res* 2012;**26**:1845–51.
20. Anderson T. Biomechanics and running economy. *Sports Med* 1996;**22**:76–89.
21. Daniels JT, Yarbrough RA, Foster C. Changes in VO_{2max} and running performance with training. *Eur J Appl Physiol* 1978;**39**:249–54.
22. William KR, Cavanagh PR. Relationship between distance running mechanics, running economy, and performance. *J Appl Physiol* 1987;**63**:1236–45.
23. Taipale RS, Mikkola J, Nummela A, Vesterinen V, Capostagno B, Walker S, et al. Strength training in endurance runners. *Int J Sports Med* 2010;**31**:468–76.
24. Cavagna GA, Saibene FP, Margaria R. Mechanical work in running. *J Appl Physiol* 1964;**19**:249–56.
25. Arampatzis A, De Monte G, Karamanidis K, Morey-Klasping G, Stafilidis S, Brüggermann GP. Influence of the muscle-tendon unit's mechanical and morphological properties on running economy. *J Exp Biol* 2006;**209**:3345–57.
26. Ferrari Bravo D, Impellizzeri FM, Rampinini E, Castagna C, Bishop D, Wisloff U. Sprint *vs.* interval training in football. *Int J Sports Med* 2008;**29**:668–74.
27. Salaj S, Markovic G. Specificity of jumping, sprinting, and quick change-of direction motor abilities. *J Strength Cond Res* 2011;**25**:1249–55.

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