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Original article

Kinematic alterations after two high-intensity intermittent training protocols in endurance runners

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Purpose: This study aimed to evaluate running kinematic characteristics during the early and late stages of 2 high-intensity intermittent training (HIIT) protocols with similar external load but different average running pace, as well as to compare the fatigue-induced changes during both HIIT protocols at a kinematic level.

Methods: Eighteen endurance runners were tested on a track on 2 occasions: 10 runs of 400 m with 90–120 s recovery between running bouts (10 × 400 m), and 40 runs of 100 m with 25–30 s recovery between runs (40 × 100 m). Heart rate was monitored during both protocols; blood lactate accumulation and rate of perceived exertion were recorded after both exercises. A high-speed camera was used to measure sagittal-plane kinematics at the first and last run during both HIIT protocols. The dependent variables were spatial-temporal parameters (step length and contact and flight time), joint angles during support (relative angles of the hip, knee, and ankle), and foot strike pattern.

Results: High levels of exhaustion were reached by the athletes during both workouts (blood lactate accumulation >12 mmol/L; rate of perceived exertion >15; HR_{peak} > 176 bpm). A within-protocol paired *t* test (first *vs.* last run) revealed no significant changes ($p \geq 0.05$) in kinematic variables during any of the HIIT sessions. A between-protocol comparison with the first run of each protocol revealed the effect of running speed on kinematics: +2.44 km/h during the 40 × 100 m: shorter contact and flight time ($p \leq 0.01$) and longer step length ($p = 0.001$); greater hip flexion ($p = 0.031$) and ankle extension ($p = 0.001$) at initial contact; smaller knee and ankle flexion ($p < 0.001$) at midstance; and greater hip extension at toe-off ($p < 0.001$).

Conclusion: In conclusion, HIIT sessions including runs for 15–90 s and performed at intensity above the velocity associated with maximal oxygen uptake did not consistently perturb the running kinematics of trained endurance runners.

Keywords: Biomechanics; Fatigue-induced; Runners; Running; Training; Two-dimensional

1. Introduction

High-intensity intermittent training (HIIT) is considered one of the most effective forms of exercise for improving the physical performance of athletes,[1–4] and its effectiveness has been widely studied in endurance runners.[5–7] An HIIT-based training program has been shown to be effective in improving maximal oxygen uptake (VO_{2max})[5,6,8] and running economy[9,10] in endurance runners. This has been associated with an increased oxidative capacity of a greater number of muscle fibers and a reduced plasma K^+ concentration, which contributes to the maintenance of muscle function during intense exercise and delays fatigue.[6,8,10]

Compared with lower-intensity running-based workouts, intensive running requires the activation of larger motor units, with increased recruitment of fast oxidative and glycolytic muscle fibers and increased intensity of chemical processes in the muscle, which exert a direct influence on the contractile ability of the muscle.[11,12] Additionally, increases in running speed lead to higher impact forces imposed on the lower limbs[13] and greater levels of neuromuscular engagement (mainly in the hamstring muscles).[14] The concomitant increase in muscle acidity and decrease in phosphagen stores with muscle fatigue alter muscle force generation capabilities[15] and seem to be linked to changes in joint movement patterns—increases in tibial internal rotation and knee internal rotation[16–20] and in

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running mechanics and decreased ankle external rotation moment, knee abduction moment, and hip internal rotation moment,[21] which are often linked to running injury.[21,22] Therefore, despite the lack of prospective studies evaluating injury occurrence, knowledge of the acute changes in running kinematics during HIIT workouts (i.e., whether spatial-temporal parameters or joint angle change in presence of fatigue) might provide key information in terms of development of injuries and training prescription.

The effect of exertion on running kinematics has been extensively studied.[16–21,23–25] Some previous studies reported nonsignificant kinematic alterations after different running exercises (continuous or interval running sessions),[19,23,26] whereas other reports found fatigue-induced changes during running at a kinematic level—i.e., increased hip extension,[27] decreased knee flexion angle at foot strike,[17] increase in step length with a corresponding decrease in cadence,[16] and changes in foot strike pattern.[24,28] However, most of these studies were performed in laboratory conditions and with athletes performing prolonged treadmill runs[16,17,20] or engaged in a running-induced fatigue protocol on treadmills.[15,18,23] Just a few studies have been field based,[24–26] although all were focused on long-distance road racing. The evidence of changes induced by intermittent running protocols is quite limited. From all these studies, only 2 reports[19,29] assessed HIIT-induced changes to the biomechanics of running. Both agreed that HIIT sessions including runs for 1–2 min and performed at intensity close to VO_{2max} did not consistently perturb the running kinematics of trained male runners.

Coaches have questioned whether it would be more effective to perform a higher number of shorter runs or a few long runs during an HIIT workout. It seems clear that changes in the training load during the HIIT protocol (in terms of intensity, volume, and density) will challenge both the metabolic and the neuromuscular systems at different levels. Many variables can be manipulated to prescribe different HIIT sessions; among them, the intensity and duration of work and relief intervals are the key influencing factors.[1,30,31] Likewise, the role of mean training intensity over a season in optimizing athletic performance has been extensively documented.[1–4,30] Thus, taken together, the key point for coaches and athletes is whether at the same absolute training load and volume it is possible to increase the average training pace by modifying other variables, such as intensity or the number of runs, without changing the physiological and neuromuscular impact and without altering dangerously (in terms of risk of injury) running kinematics. In this context, some previous studies[32,33] have tried to answer that question and reported similar acute physiological response to 2 HIIT workouts (10×400 m *vs.* 40×100 m) with identical volume (4 km) and similar work-to-rest ratios (0.65 and 0.67, respectively) but with significant differences in average pace (+3.13 km/h during 40×100 m). Likewise, and despite differences in mean velocity, the aforementioned studies[32,33] reported no impairments in muscular performance parameters after training. What is still unknown is whether the difference in mean velocity will lead to different alterations in running kinematics.

Therefore, the main goal of this study was to evaluate running kinematic characteristics during the early and late stages of 2 HIIT protocols with similar external load but different average running pace (10×400 m *vs.* 40×100 m), as well as to compare the fatigue-induced changes during both HIIT protocols at a kinematic level. The authors hypothesized that running kinematics might change between the first and last runs owing to the high level of exhaustion reached during these HIIT protocols. Additionally, the differences between both protocols might cause different kinematic alterations.

2. Methods

A crossover study design was used to determine the fatigue-induced changes in running kinematics of endurance runners during 2 HIIT protocols, performed on a track by endurance runners.

2.1. Subjects

A group of 18 recreationally trained endurance runners (16 males and 2 females; age = 30.9 ± 11.7 years; body mass = 65.8 ± 9.02 kg; height = 1.72 ± 0.06 m; velocity associated with VO_{2max} (VVO_{2max}) = 17.24 ± 1.4 kmh) voluntarily participated in this study. No general clinical examination was carried out, but all subjects were medically examined annually. The subjects had trained 1–3 h/day, 4–6 days/week year-round for a minimum of 4 years and had no history of an injury in the 3 months before they participated. The study was conducted in November, 2014, during the cross-country season and the competition phase of their yearly program, at a time when most of the athletes were at a high level of competitive fitness. At the time of these observations, the track athletes had completed between 2 and 4 months of training for that season.

After receiving detailed information on the objectives and procedures for the study, each subject signed an informed consent form to participate, which complied with the ethical standards of the World Medical Association's Declaration of Helsinki (2013) and made clear that they were free to leave the study if they saw fit. The study was approved by the Ethics Committee of the University of Jaen (Spain).

2.2. Procedures

The participants were asked not to engage in any high-intensity exercise during the 72 h before the experiment and to have a meal at least 2 h before the beginning of warm-up. All athletes had experience with the exercises to be analyzed. All the training sessions were carried out between 17:00 and 21:00 h on an outdoor 400-m synthetic track. Before the running exercises, the athletes performed a standardized warm-up, then 5 13-mm-diameter retroreflective markers were placed on the right side of the body (fifth metatarsal, lateral malleolus, lateral epicondyle of the femur, greater trochanter, and acromion) (Fig. 1). These landmarks defined the positions of upper body (head, arms, and trunk being taken together), lower legs, and feet. After marker placement, the participants began the running protocol.

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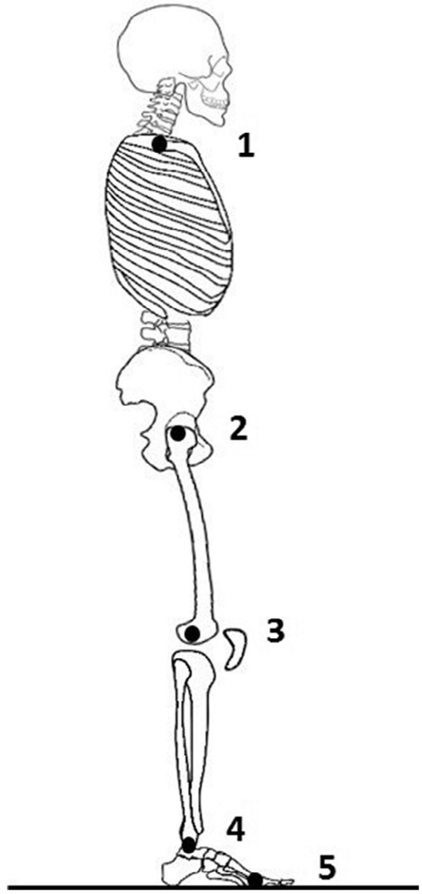

Fig. 1. Landmark placement. 1, acromion; 2, greater trochanter; 3, lateral epicondyle of the femur; 4, lateral malleolus; 5, fifth metatarsal.

Each athlete was tested on 2 occasions separated by 7 days: (1) 10 runs of 400 m with 90–120 s of recovery between running bouts (10 × 400 m) and (2) 40 runs of 100 m with 25–30 s of recovery between runs (40 × 100 m). Both running exercises showed the same volume (4000 m), a similar percentage of total training time in which the athlete was working (39.5% and 40.7%, respectively), and a work-to-rest ratio coefficient between work period and rest period (0.65 and 0.67, respectively), but significant differences in average pace (+3.13 kmh during 40 × 100 m). To avoid an "order effect" the protocol was counterbalanced. Both HIIT protocols were carried out above the VVO_{2max}, which was indirectly measured from the velocity of a 3000-m race.[34,35] Passive recovery between runs was undertaken during both HIIT protocols, as the runners stood upright. Participants were experienced athletes who performed these types of workouts in their training programs, so the only instructions given were to finish the protocols as fast as they could as they maintained a constant speed to the best of their ability. No more guidelines were provided regarding exercise intensity, though subjects were asked to run at self-selected exercise intensities. The physiological response was monitored during both running protocols, and videos were recorded from the sagittal plane in the first and last run of both protocols. The performance of every single run was also recorded through time spent.

2.3. Materials and testing

2.3.1. Anthropometric variables

Height (m) and body mass (kg) were measured at the start of the first testing session, and body mass index was calculated by means of the following equation: body mass (kg)/height^2 (m). A stadiometer (seca 222; seca, Hamburg, Germany) and a calibrated bascule (seca 634) were used for that purpose.

2.3.2. Physiological variables

To monitor the physiological demands of both HIIT protocols, the cardiovascular response was monitored throughout the exercise, using the Garmin Forerunner 405 (Garmin International Inc., Olathe, KS, USA). The peak heart rate achieved and the recovery heart rate at 1 min (HR_{peak} and HR_{rec}, respectively) were used for the analysis. Additionally, blood lactate accumulation (BLa, mmol/l), and the rate of perceived exertion (RPE) were also recorded after the last run of the running exercise, and, for this purpose, a portable lactate analyzer (Lactate Pro; Arkray, Kyoto, Japan) and the 6–20 Borg RPE scale[36] were used.

2.3.3. Athletic performance

The time spent in each run (in seconds) was also recorded during both workouts. The variables used for subsequent analysis were the average running pace of the whole protocol (T400m and T100m, in km/h).

2.3.4. Kinematics

A sagittal plane video (240 Hz) of the first and the last run during both HIIT protocols was recorded using a high-speed camcorder (Casio EXILIM EX-F1; Casio Computer Co Ltd., Tokyo, Japan). Videos were taken from a lateral view, with the camera perpendicularly placed 5 m from the runners so that they could be filmed in the sagittal plane. Filming location was set at the end of the 400-m run, 20 meters before the finish line. For each runner, a complete stride cycle was captured on film, and kinematic variables were measured for the right leg. Video data were analyzed using a two-dimensional video editor (VideoSpeed vs1.38; Ergo Sport, Granada, Spain).

The dependent variables selected for the kinematics analysis are in accordance with previous works[16,24–26,37] and are presented as follows:

1. Relative angle of the hip, knee, and ankle (θhip, θknee, and θankle, respectively) at 3 key points during support: (1) at the initial contact (first visible point during stance when the athlete's foot clearly contacts the ground); (2) at midstance (the maximum knee flexion in the support phase); and (3) at toe-off (the last frame with ground contact). θHip was defined as the sagittal plane angle between the trunk and thigh segments and was considered to be 180° in the anatomic standing position. The θknee was calculated as the sagittal plane angle between the thigh and leg segments and was also considered to be 180° in the anatomic standing position. The θankle was calculated in a counterclockwise direction using the leg and foot segments.[16,26]

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2. Spatial-temporal parameters: step length (SL, in meters)—distance from 1 foot strike to the next foot strike of the opposite foot; and contact time and flight time (CT and FT, respectively, in seconds)—the time duration from initial contact to toe-off, and the time duration from toe-off of 1 foot contact to the initial contact of the opposite foot.
3. Foot strike pattern (FSP) at first contact with the ground, on a 1–5 scale of severity,[24] from rearfoot to forefoot: (1) high rearfoot strike—landing with the second half of the heel (the landing from the back of the heel); (2) rearfoot strike—the ball of the foot landing before the heel; (3) midfoot—the landing of the heel and sole simultaneously; (4) forefoot—landing with the ball of the foot; and (5) high forefoot strike—the ball of the foot made contact with the ground (no contact with the heel, running on tiptoe).

2.4. Statistical analysis

Descriptive statistics are represented as means ±standard deviation and percentages. Tests for normality and homogeneity of variances (Shapiro–Wilk and Levene's, respectively) were conducted on all data before analysis. Paired *t* test was used to compare running kinematic parameters at first run during both HIIT protocols (between-group comparison). Paired *t* test was also used to compare the analyzed variables at the beginning and at the end of both HIIT protocols (within-group comparison: 1st run *vs.* 12th run during the 10 × 400 m, and 1st run *vs.* 40th run during the 40 × 100 m). As for the FSP, the within-group equality of proportions (first *vs.* last run) was checked through McNemar test. A repeated measures analysis of variance, with *post hoc* Bonferroni test, was performed for running pace throughout both HIIT workouts (within protocol, to determine whether changes in pace were found during both protocols). Intra- and interobserver reliability was calculated for FSP (because an observational method was used) using the Cohen's κ coefficient.[38] The level of significance was set at $p < 0.05$. Data analysis was performed using SPSS (version 21; SPSS Inc., Chicago, IL, USA).

3. Results

Intra- and interobserver reliability were calculated using Cohen's κ for FSP (intraobserver – κ = 0.92, proportion of agreement = 95%; interobserver – κ = 0.85, proportion of agreement = 95%).

HR response, BLa, RPE, and average running pace in both exercises are presented in Table 1. No significant differences were found for either HR_{peak} or ΔHR_{rec} between running protocols ($p \geq 0.05$), whereas the HR_{mean} was significantly higher in the 40 × 100 m run ($p < 0.001$). No significant differences ($p = 0.670$) were found in BLa at 1 min postexercise. Significant differences between both HIIT exercises were found for RPE ($p = 0.019$), with lower values in the 40 × 100 m test. Likewise, significant differences between protocols were also found in running pace or VVO_{2max} ($p < 0.001$), with a faster average pace in the 40 × 100 m test (~3 km/h). Finally, the repeated measures analysis showed no significant differences between the time spent in each run throughout both the 10 × 400 m ($p = 0.089$) and the 40 × 100 m ($p = 0.121$) protocols.

Table 1
Heart rate response, lactate accumulation, rate of perceived exertion, and average running pace during 2 high-intensity training protocols (mean ± standard deviation).

Variables	10 × 400 m	40 × 100 m	*p value*
HR_{peak} (bpm)	179.00 ± 9.07	176.25 ± 9.64	0.067
HR_{mean} (bpm)	144.12 ± 14.29	160.60 ± 12.64	<0.001
ΔHR_{rec} (bpm)	31.00 ± 14.09	22.88 ± 14.23	0.091
BLa (mmol/L)	12.87 ± 3.21	12.40 ± 4.14	0.670
RPE (6–20)	16.00 ± 1.24	15.11 ± 1.13	0.019
Running pace (km/h)	18.47 ± 1.51*	21.60 ± 1.72*	<0.001
VVO_{2max} (%)	107.17 ± 2.83	125.40 ± 4.89	<0.001

* No significant differences within running protocols, constant speed; 10 × 400 m: 10 runs of 400 m with 90–120 s of recovery between running bouts; 40 × 100 m: 40 runs of 100-m with 25–30 s of recovery between runs.
Abbreviations: BLa = blood lactate accumulation; HR_{mean}: mean heart rate; HR_{peak} = peak heart rate; ΔHR_{rec} = heart rate recovery in the last run minus that in the first; RPE (6–20) = rate of perceived exertion on a 6–20 Borg scale; VVO_{2max} = velocity associated with maximal oxygen uptake.

Because the 2 protocols were performed at different velocities ($p < 0.001$), Table 2 shows the effect of running velocity on running kinematics by comparing the first run in every protocol (10 × 400 m *vs.* 40 × 100 m). An increased running velocity during the 40 × 100 m protocol yielded a decreased CT (13.02%) and FT (8.85%) and an increased SL (3.87%), as well as some differences in joint angles: at initial contact—a greater hip flexion (2.73%) and ankle extension (7.40%); at midstance—smaller knee and ankle flexion (3.90% and 8.75%, respectively); and at toe-off—a higher hip extension (19.80%).

Running kinematic alterations during both HIIT protocols are shown in Table 3. No significant changes ($p \geq 0.05$) were found during the 10 × 400 m or the 40 × 100 m protocol.

Regarding the FSP (Fig. 2), no significant differences ($p \geq 0.05$) were found between protocols during the first run ($p = 0.135$). No significant alterations were found in the FSP during 10 × 400 m ($p = 0.392$) or 40 × 100 m ($p = 0.317$) protocols.

4. Discussion

The acute physiological and metabolic response[33] and the neuromuscular response[32] to both 10 × 400 m and 40 × 100 m protocols have been previously determined. The results reported by these studies showed that 10 × 400 m and 40 × 100 m are 2 very similar HIIT protocols in terms of metabolic and physiological impact, with similar responses in terms of blood metabolites and cardiovascular response.[33] Some minor differences between both HIIT protocols were found in the neuromuscular response, measured through the acute effect of both HIIT workouts on postural control and power output measurements.[32] Nevertheless, no previous studies have investigated the impact of these HIIT protocols at the kinematic level, and, thus, this study aimed to evaluate running kinematic characteristics during the early and late stages (first *vs.* last run) of the aforementioned HIIT protocols (10 × 400 m *vs.* 40 × 100 m).

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Table 2
Comparative analysis of running kinematics during the first run (unfatigued condition) of both running protocols performed at different running velocities (mean ± standard deviation).

Variables	10 × 400 m	40 × 100 m	%Δ	*p value*	95% CI
Running velocity (km/h)	18.40 (1.48)	20.84 (1.49)	↑13.26	<0.001	−3.20 to −1.68
Spatial-temporal parameters					
Contact time (s)	0.19 ± 0.02	0.17 ± 0.02	↓13.02	<0.001	0.02–0.04
Flight time (s)	0.15 ± 0.02	0.13 ± 0.01	↓8.85	0.010	0.00–0.02
Step length (m)	1.55 ± 0.15	1.61 ± 0.17	↑3.87	0.001	−0.99 to −0.03
Joint angles (°)					
Initial contact					
θHip	150.51 ± 6.00	146.41 ± 4.51	↓2.73	0.031	0.52–9.32
θKnee	160.83 ± 6.04	163.04 ± 5.12	↑2.37	0.487	−4.31–2.16
θAnkle	117.49 ± 6.25	126.18 ± 8.19	↑7.40	0.001	−11.94 to −3.91
Midstance					
θHip	155.75 ± (4.53	155.44 ± 4.98	↓0.99	0.597	−3.06–5.13
θKnee	140.78 ± 5.58	146.27 ± 5.49	↑3.90	<0.001	−8.83 to −4.11
θAnkle	101.77 ± 5.11	110.67 ± 6.74	↑8.75	<0.001	−14.24 to −7.40
Toe-off					
θHip	161.20 ± 6.67	193.13 ± 10.12	↑19.81	<0.001	−41.22 to −25.62
θKnee	163.73 ± 6.22	161.88 ± 5.20	↓1.13	0.810	−3.99–3.18
θAnkle	136.49 ± 6.39	139.18 ± 5.96	↑1.98	0.279	−5.68–1.81

Note: %Δ percentage of change between both values; ↓↑ indicates the direction of change when running velocity increases.
Abbreviations: CI = confidence interval; θ = joint angle.

In this context, the major finding of this study was that despite the high level of exhaustion reached by the athletes during both workouts (BLa > 12 mmol/l; RPE > 15; HR_{peak} > 176 bpm), these HIIT protocols did not consistently perturb the running kinematics of trained endurance runners. No significant changes were observed in joint angles, spatial-temporal parameters, or FSP during either HIIT protocol, which rejects the initial authors' hypothesis. Despite the suggestion that fatigue could alter biomechanical and neuromuscular function in a manner that could possibly lead to an increased risk of sustaining musculoskeletal injury and/or impaired performance,[39] this finding is consistent with some previous studies that did not report alterations in the running kinematics after different running exercises.[19,23,26] However, not all studies on this topic are in agreement, and other works have found fatigue-induced changes during running at a kinematic level.[16–18,20,27] For example, Mizrahi[17] found an increase in knee angle at maximal knee extension and a decrease in knee flexion angle at foot strike after 30 min of continuous running at anaerobic threshold. Focusing on spatial-temporal parameters, some studies[16,17] have reported changes after continuous runs—increased SL with a corresponding decrease in cadence and decreases in CT occurred in conjunction with increases in FT. It is worth noting that the protocols used in these studies are different, so that results are quite difficult to compare and consensus has not yet been reached. As we indicated earlier, just 2 studies have analyzed running kinematics during interval training,[19,29] and, even

Table 3
Comparative analysis of kinematic variables during the first and last run of both high-intensity intermittent training protocols (mean ± standard deviation).

Variables	10 × 400 m protocol		*p value*	95% CI	40 × 100 m protocol		*p value*	95% CI
	1st run	10th run			1st run	40th run		
Spatial-temporal parameters								
Contact time (s)	0.19 ± 0.02	0.18 ± 0.02	0.059	−0.01–0.02	0.17 ± 0.02	0.16 ± 0.02	0.159	−0.01–0.02
Flight time (s)	0.15 ± 0.01	0.14 ± 0.02	0.588	−0.01–0.01	0.13 ± 0.01	0.13 ± 0.02	0.904	−0.01–0.01
Step length (m)	1.55 ± 0.15	1.56 ± 0.14	0.498	−0.07–0.04	1.61 ± 0.17	1.58 ± 0.17	0.325	−0.09–0.03
Joint angles (°)								
Initial contact								
θHip	150.51 ± 6.00	151.54 ± 6.33	0.341	−3.31–1.24	146.41 ± 4.51	145.56 ± 5.83	0.620	−2.72–4.40
θKnee	160.83 ± 6.04	156.86 ± 9.37	0.066	−0.32–8.26	163.04 ± 5.12	160.16 ± 5.71	0.067	−0.22–5.97
θAnkle	117.49 ± 6.25	117.73 ± 5.79	0.847	−3.02–2.53	126.18 ± 8.19	125.46 ± 6.69	0.756	−4.24–5.68
Midstance								
θHip	155.75 ± 4.53	156.72 ± 5.70	0.166	−2.39–0.46	155.44 ± 4.98	153.56 ± 7.27	0.283	−1.71–5.46
θKnee	140.78 ± 5.58	140.38 ± 6.05	0.759	−2.41–3.22	146.27 ± 5.49	145.64 ± 6.02	0.668	−2.45–3.71
θAnkle	101.77 ± 5.11	101.44 ± 6.79	0.813	−2.77–3.44	110.67 ± 6.74	112.03 ± 6.18	0.487	−5.58–2.85
Toe-off								
θHip	161.20 ± 6.67	161.29 ± 6.23	0.868	−1.33–1.13	193.13 ± 10.12	195.82 ± 6.25	0.324	−8.30–2.92
θKnee	163.73 ± 6.22	163.64 ± 5.94	0.941	−2.54–2.73	161.88 ± 5.20	159.58 ± 4.36	0.106	−0.55–5.17
θAnkle	136.49 ± 6.39	137.80 ± 6.75	0.613	−6.87–4.26	139.18 ± 5.96	139.13 ± 5.78	0.977	−3.66–3.77

Abbreviations: CI = confidence interval; θ = joint angle.

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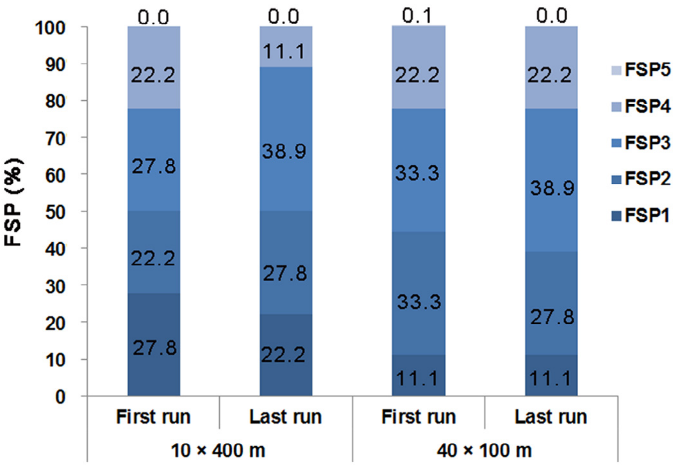

Fig. 2. Foot strike pattern (FSP) and changes induced over 2 different HIIT protocols (10 × 400 m *vs.* 40 × 100 m). FSP1, high-rearfoot strike; FSP2, rearfoot strike; FSP3, midfoot strike; FSP4, forefoot strike; FSP5, high-forefoot strike.

though the running protocol and the controlled variables are not exactly the same, the main findings are in line with our study.

Another interesting finding in the current study was the lack of significant changes in FSP during both protocols (10 × 400 m and 40 × 100 m). The relationship between FSP and running economy, performance, and injury rates in endurance runners has been documented in recent literature.[24,37] From the perspective of injury, it has been suggested, on the one hand, that the risk of injury can be diminished by reducing the magnitude of impact forces, which can be achieved by adopting midfoot or forefoot strikes.[37,40] On the other hand, compared with rearfoot strikes, forefoot strikes cause higher joint moments in the ankle, although lower ones in the knee and hip, which might increase the risk of Achilles tendinopathies, injuries of the foot, and stress fractures of the metatarsals.[37] Although it is not known whether higher joint moments cause injuries, it is clear that the most important difference between rearfoot and forefoot strike, from the perspective of injury, is the nature of the impact peak at the initial contact.[37]

Some previous papers have examined FSP during long-distance road competition[24,25,28] and concluded that in the presence of fatigue, FSP tends to change by diminishing the frequencies of forefoot strikes and increasing midfoot and rearfoot strikes. To the best of the authors' knowledge, no previous studies have examined the fatigue-induced changes in FSP during an HIIT protocol, which makes a comparison difficult. Anyway, because either the influence of fatigue on the FSP[28,37] or the association between rearfoot strikes and the risk of injury in endurance runners has been previously established,[37,40] the lack of changes in FSP after HIIT protocols is an important finding.

Finally, given the between-protocols difference in running velocity and the influence of this variable on running kinetics and kinematics,[15,24,25,37,41] the authors decided to incorporate a between-protocol comparison in unfatigued conditions (at first run of every protocol, with +2.44 km/h during the 40 × 100 m). As for the spatial-temporal parameters, it seems clear that to run faster, CT needs to be decreased to aid in repositioning the legs during running,[41] and the results obtained support that statement, with shorter CT during the 40 × 100 m protocol (~13%). More controversial is the dynamic of SL when velocity increases. It has been suggested that SL increases linearly with running velocity up to 25 km/h,[41] which is in consonance with our findings (SL ~4% longer during the faster protocol).

Regarding the effect of running speed on joint angles, our findings are consistent with previous works.[15,24,25,37,41] Some differences between faster and slower runs were found in the unfatigued condition—increased running velocity led to greater hip flexion and lower ankle flexion at initial contact, lower knee and ankle flexion at midstance, and greater hip extension at toe-off. These differences appear to be totally logical because lower ankle flexion at initial contact has been related to a shorter CT[37,41] and lower knee and ankle flexions at midstance have been associated with shorter CT and higher leg stiffness, all key factors in running performance.[18,42,43] Likewise, increased hip flexion at initial contact has been previously associated with running velocity.[44]

The difference in running velocity has also been demonstrated to influence FSP.[24,37] Despite the lack of differences in FSP between both protocols (10 × 400 m *vs.* 40 × 100 m), the results obtained provide support to this statement, showing a higher prevalence of midfoot and forefoot strikes (~28%–33% midfoot and ~22% forefoot, averaged from both HIIT protocols) than previous studies in which athletes ran at slower velocities (~87%–95% rearfoot).[24,28] Therefore, the lack of differences between protocols reported by the current study might be due to the high velocity reached during both HIIT protocols.

A limitation of the present study is that we focused only on sagittal plane movements. It is likely that fatigue also causes alterations in movements in the frontal and transverse planes. Another limitation is that subjects might run asymmetrically between left and right lower extremities; however, only the right leg was analyzed. For future reference, setting more cameras on both sides of the race and from different planes could minimize some of these limitations and increase validity. Obviously, all these limitations are related to the use of a two-dimensional motion analysis. However, notwithstanding these limitations, the current field-based study offers some insight into the running kinematic alterations during typical HIIT protocols for endurance runners and provides helpful data for coaches and athletes.

5. Conclusions

In summary, the results obtained showed that HIIT sessions that included runs for 15–90 s and were performed at an intensity above the velocity associated with maximal oxygen uptake did not consistently perturb the running kinematics of trained endurance runners. Additionally, a comparison made between runs performed at different velocities and in unfatigued conditions revealed some differences in spatial-temporal parameters and joint angles that must be taken into consideration when the intensity of running exercises is prescribed. Finally, in focusing on the 10 × 400 m *vs.* 40 × 100 m comparison—because previous

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studies had suggested that 40 × 100 m might be a more efficient HIIT for improving the performance of endurance runners because of a faster average running pace with similar physiological and neuromuscular response—this study reinforces that statement, with no kinematic alterations observed during any of those running exercises.

From a practical point of view, this study indicates that coaches and runners need not fear substantial detrimental effects from HIIT protocols on running technique. Such information is essential for the design of more effective training programs for injury prevention and performance enhancement in running. Knowledge about the effect of every training session on the athlete plays a key role in proper training prescription, which means that a further description of the impact of the most typical running exercises on endurance runners is needed, which can lead to better understanding and accuracy in the training prescription process. Additionally, because most injuries in running can be attributed to overuse from repeated bouts of activity, more evidence is needed about the cumulative effects of HIIT-based running sessions.

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Authors' contributions

FGP conceived of the study, carried out the data collection, performed the statistical analysis, and drafted the manuscript; AMM participated in its design and coordination; JAPM helped to draft the manuscript; and PALR participated in its 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.

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