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Section I – Kinesiology

How Do Spatiotemporal Parameters and Lower-Body Stiffness Change with Increased Running Velocity? A Comparison Between Novice and Elite Level Runners

by
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This study aimed to examine the effect of running velocity on spatiotemporal parameters and lower-body stiffness of endurance runners, and the influence of the performance level on those adaptations. Twenty-two male runners (novice [NR], n = 12, and elite runners [ER], n = 10) performed an incremental running test with a total of 5 different running velocities (10, 12, 14, 16, 18 km/h). Each condition lasted 1 min (30 s acclimatization period, and 30 s recording period). Spatiotemporal parameters were measured using the OptoGait system. Vertical (Kvert) and leg (Kleg) stiffness were calculated according to the sine-wave method. A repeated measures ANOVA (2 x 5, group x velocities) revealed significant adaptations ($p < 0.05$) to increased velocity in all spatiotemporal parameters and Kvert in both NR and ER. ER showed a greater flight time (FT) and step angle (at 18 km/h) ($p < 0.05$), longer step length (SL) and lower step frequency (SF) ($p < 0.05$), whereas no between-group differences were found in contact time (CT) nor in the sub-phases during CT at any speed ($p \geq 0.05$). ER also showed lower Kvert values at every running velocity ($p < 0.05$), and no differences in Kleg ($p \geq 0.05$). In conclusion, lower SF and Kvert and, thereby, longer FT and SL, seem to be the main spatiotemporal characteristics of high-level runners compared to their low-level counterparts.

***Key words**: endurance runners, running kinematics, performance.*

Introduction

The proliferation of recreational running events has increased considerably, especially in recent years (van Dyck et al., 2017). Along with the popularity of running, the number of people suffering from running-related injuries has steadily increased (Abt et al., 2011; Fields et al., 2010). In an effort to combat this high level of injuries, there has been increased demand for running gait research and a growing body of evidence has examined the influence of stride characteristics on the risk of injury (e.g., spatiotemporal parameters such as step frequency [SF], step length [SL], and ground contact time [CT]) (Luedke et al., 2016; Schubert et al., 2014). However, the relationship between the spatiotemporal parameters of running and both performance and injury risk still remains unclear.

Some previous works have analyzed the

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influence of running velocity on spatiotemporal gait characteristics (Brughelli et al., 2010; Mann et al., 2015; Mercer et al., 2002; Ogueta-Alday et al., 2014). It seems logical that, in order to run faster, some changes in spatiotemporal parameters are required: decreases in CT and increases in flight time (FT), SL and SF (Brughelli et al., 2010; Ogueta-Alday et al., 2014; Padulo et al., 2012; Roche-Seruendo et al., 2018). Those adaptations have been associated to changes in running kinematics. For example, the shorter CT with increasing running velocity has been linked with lower ankle flexion during the initial ground contact as well as lower knee and ankle flexion in the mid-stance phase (Brughelli et al., 2010; Daoud et al., 2012).

Despite more and more research is available about running biomechanics and its association with both athletic performance and risk of injury, the evidence about some potential confounding variables (i.e., lower-body stiffness or athletic level) is limited. While some authors have reported a lack of correlation between lower-body stiffness and running economy of runners (Heise and Martin, 1998; Slawinski et al., 2008), others have found significant associations between those variables (Dumke et al., 2010; Dutto and Smith, 2002; Heise and Martin, 2001). Lower-body stiffness has been related to hopping and jumping performance (Granata et al., 2002), running performance (Taylor and Beneke, 2012), running economy (Dutto and Smith, 2002; Heise and Martin, 2001), and injury incidence (Butler et al., 2003; Granata et al., 2002), which suggests that some level of stiffness is required for optimal performance although its value remains a topic of debate among researchers.

This leaves certain questions unanswered, including whether the spatiotemporal parameters of high-level runners adapt to incremental running speed in the same way as for their low-level counterparts, and whether lower-body stiffness changes during running at different velocities similarly for both high- and low-level endurance runners. Therefore, this study aimed to examine the effect of running velocity on spatiotemporal parameters and lower-body stiffness of endurance runners, and the influence of the performance level on those kinematic adaptations. These results are expected to provide evidence regarding the effects of running at incremental velocities on spatiotemporal gait parameters and lower-body stiffness and, more importantly, whether these adaptations differ between high- and low-level endurance runners. The authors hypothesized that high-level runners would adapt better to the need for efficient work output (associated to higher velocity) than low-level runners, so that spatiotemporal adaptations would be different in both groups.

Methods

A unilateral crossover design was used, with all participants performing the same protocol (incremental running test) under the same conditions. The dynamics of spatiotemporal gait characteristics at different velocities were analyzed, and the relationship with vertical and leg stiffness and the influence of the performance level were determined.

Participants

Male endurance runners (n = 22; age: 32 ± 7 years; body height: 176 ± 6 cm; body mass: 71 ± 5 kg) participated in this study. All participants were ≥18 years old and they had not suffered from any injury in the 6 months preceding the data collection. The 22 athletes were selected by convenience according to their performance level (elite [ER] vs. novice runners [NR]). For NR (n = 12; age: 34 ± 7 years; body height: 174 ± 7 cm; body mass: 73 ± 5 kg), the additional inclusion criterion was that the runners must be able to run 10 km in 45-50 min (48.1 ± 1.3 min), whereas ER (n = 10; age: 30 ± 6 years; body height: 179 ± 4 cm; body mass: 69 ± 4 kg) had to have a 10 km personal best of 30-35 min (33.3 ± 1.4 min). After receiving detailed information on the objectives and procedures of the study, each participant signed an informed consent form, which complied with the ethical standards of the World Medical Association's Declaration of Helsinki (2013); it was made clear to the participants that they were free to leave the study at any time. The study was approved by the ethics committee at the San Jorge University (Zaragoza, Spain).

Design and Procedures

Participants were individually tested (between 16:00 and 21:00 h). They refrained from severe physical activity ≥48 h prior to testing, and all tests were performed ≥3 h after the ingestion of a meal. Tests were performed using the participant´s usual training shoes.

Participants performed a warm-up before the running protocol, which consisted of 10 min of continuous running followed by 5 min of general exercises (i.e., high skipping, leg flexion, jumping exercises and short bursts of acceleration). The running protocol was performed on a motorized treadmill (Salter M-835, Salter Int., Barcelona, Spain). Athletes were experienced at running on a treadmill; however, according to a previous study (Schieb, 1986) on human locomotion that showed that accommodation to a new condition occurs within ~6-8 min, the protocol was preceded by a standardized 10-min accommodation program. All participants verbally reported feeling comfortable when running on the treadmill at the set speed.

Participants completed an incremental test with a total of 5 different running velocities (10, 12, 14, 16 and 18 km/h). Each condition lasted 1 min to accommodate an acclimatization period (30 s) and a recording period (30 s). The protocol design was based on previous studies (Roche-Seruendo et al., 2017, 2018), with short duration of the velocity conditions aimed to minimize the effect of fatigue on running kinematics (i.e., the whole running protocol lasted 5 min).

Measures

i) Anthropometry. For descriptive purposes, body height (cm), leg length (cm) and body mass (kg) were determined using a precision stadiometer and a weighing scale (SECA 222 and 634, respectively, SECA Corp., Hamburg, Germany). All measurements were taken while the participants were wearing running shorts and underwear.

ii) Spatiotemporal parameters were measured using the OptoGait system (Optogait; Microgate, Bolzano, Italy), which had been previously validated for the assessment of spatiotemporal parameters of gait in young adults (Lee et al., 2014). This previous study also reported high reliability for different spatiotemporal parameters as assessed by intra-class correlation coefficients (0.785–0.952) and coefficients of variation (1.66–4.06%), standard error of measurement (2.17–5.96%) and the minimum detectable change (6.01–16.52%) (Lee et al., 2014). This system consisted of two parallel bars that were placed on the side edges of the treadmill at the same level as the contact surface. The OptoGait system was connected to a computer controlled by one researcher, and data were recorded and averaged during the 30 s recording period for the subsequent analysis. In accordance with the findings of Brown et al. (2014), limb dominance was not taken into account. Step angle, CT, FT, SL and SF were measured for every step during the treadmill test.

- Contact time (CT) (s) was defined as the time from when the foot contacted the ground to when the toes lifted off the ground.
- Flight time (FT) (s) was defined as the time from the toes lifting off to the initial ground contact of the consecutive footfall.
- Step length (SL) (m) was defined as the distance between two ground contacts, from forefoot to forefoot (e.g. left to right or vice-versa) plus the distance the treadmill belt moved during the flight time (i.e. distance during FT, which is: FT x Horizontal speed).
- Step frequency (SF) (steps/min) was defined as the number of ground contact events per minute.
- Step angle (SA) (º) was defined as the angle of the parable tangent, which was derived from the SL and the height obtained with FT. These parameters allowed to tie SL and FT. The determination of SL is provided above, and the maximal height of the foot during a stride was calculated by the OptoGait system as indicated by a previous study (Santos-Concejero et al., 2014).
- The percentage of ground CT (%CT) at which the different subphases of stance occurred (based on activated LEDs) was automatically measured by the OptoGait system for every step:
    - Initial contact (Phase1) was defined as the time taken from initial ground contact (one LED activated was needed to be considered) to the foot becoming flat (the number of LEDs activated stayed steady ±2).
    - Midstance (Phase2) was defined as the time taken from a foot flat to the initial take-off. During this phase, the number of LEDs stayed steady ± one LED. This

phase finished when the heel came off the ground and the number of LEDs was reduced to ≥2.

- Propulsion (Phase3) was defined as the time taken from the initial take-off (the number of LEDs was reduced ≥2) to the toe lifting off (i.e. when the forefoot came off the ground and the number of LEDs was 0).

iii) Lower-body stiffness. Vertical (Kvert) and leg stiffness (Kleg) were calculated according to the Morin´s method (Morin et al., 2005). The Kvert (kN/m) was defined as the ratio of the maximal force to the vertical displacement of the centre of mass as it reached its lowest point (i.e., the middle of the stance phase) (Farley and González, 1996). The Kleg (kN/m) was defined as the ratio of the maximal force in the spring to the maximum leg compression at the middle of the stance phase (Farley and González, 1996). Kvert represents the overall body stiffness and defines the relationship between the ground reaction force and the vertical displacement of the centre of mass, while Kleg represents the stiffness of the lower extremity complex (e.g., foot, ankle, knee, and hip joints) and describes the ratio between the ground reaction force and the deformation in leg length (Morin et al., 2005).

This method allows the estimation of Kvert and Kleg during running using only a few mechanical parameters (i.e., body mass, forward velocity, leg length, FT, and CT). As indicated by Morin et al. (2005), stiffness values calculated with the sine-wave method are only 0.67-6.93% lower than the ones obtained with the force platform method, which was acceptable. Another paper (Pappas et al., 2014) concluded that the measurements of Kvert and Kleg obtained during treadmill running using the sine-wave method were highly reliable for both intra-day and inter-day designs, exhibiting ICCs between 0.86-0.99.

Statistical analysis

Descriptive statistics are represented as mean (standard deviation). Tests of normal distribution and homogeneity (Shapiro-Wilk and Levene's test, respectively) were conducted on all data before analysis. A one-way analysis of variance (ANOVA) was performed in order to compare the age and anthropometric data between groups (ER vs. NR). A repeated measures ANOVA (2 x 5, group x velocities), with a Bonferroni post-hoc test, was performed to determine the effect of different running velocities on spatiotemporal parameters and stiffness for endurance runners with different performance levels (LLG vs. HLG). A partial correlation analysis, adjusted by the performance level and body mass index, was conducted between lower-body stiffness and spatiotemporal adaptations with increased velocity (Δ) (i.e., CT at 12 km/h CT at 10 km/h). The magnitude of the differences between values was also interpreted using the Cohen's d effect size (*ES*) (within- and between-group differences) (Cohen, 1988). Effect sizes are reported as: trivial (<0.2), small (0.2-0.49), medium (0.5-0.79), and large (≥0.8) (Cohen, 1988). The data were analyzed with SPSS, version 21.0, for Windows (SPSS Inc., Chicago, IL, USA), and the significance level was set at $p < 0.05$.

Results

No between-group differences ($p \geq 0.05$) were found in age, body height or body mass, yet differences were found in the body mass index (BMI, $p = 0.006$).

Figure 1 shows the dynamics of spatiotemporal variables (CT, FT, SF, SA and SL) with increased running velocity (10-18 km/h) and compares NR with ER. The increase of running velocity caused significant changes in all analyzed variables for both groups (within-group differences, $p< 0.001$: ES presented in Table 2). Significant between-group differences were found in FT ($p = 0.005$, ES = 0.121) and SA at 18 km/h ($p = 0.01$, ES = 0.462), in SF and SL at 14 ($p = 0.029$ and 0.045, ES = 1.055 and -0.962, respectively), 16 ($p = 0.006$ and 0.008, ES = 2.192 and -1.333, respectively) and 18 km/h ($p < 0.001$, ES = 1.715); whereas no differences were found in CT at any speed ($p \geq 0.05$, ES < 0.4).

Figure 2 shows the CT-FT percentages during a step cycle (A), and the percentages of the different sub-phases during the ground contact phase (B). An increased running velocity caused significant reductions in both ER ($p < 0.001$, ES > 0.7 for both %CT and %FT) in %CT-%FT -reduction in %CT and an increase in %FT-, and NR ($p < 0.001$, ES > 0.4 for both %CT and %FT) (Figure 2-A); whereas the effect on the sub-phases during the contact period was: unchanged Phase1

(ER: $p = 0.938$, ES < 0.2; and NR: $p = 0.976$, ES < 0.1), longer Phase2 (ER: $p = 0.034$, 0.02 < ES > 0.690, with no post-hoc differences; NR: $p = 0.061$, 0.01 < ES > 0.715) and shorter Phase3 (both groups $p < 0.001$, ES > 0.7, with post-hoc tests revealing differences between 10 and 12 km/h) (Figure 2-B). As for the between-group comparison, no significant differences were found in %CT during the step cycle at any running velocity ($p \geq 0.05$, ES < 0.4), while %FT was significantly greater in ER at 18 km/h ($p = 0.026$, ES = -1.084) (Figure 2-A). No significant between-group differences were found in the sub-phases during the ground contact period at any velocity analyzed ($p \geq 0.05$, ES < 0.4).

Figure 3 shows the ER vs. NR comparison over the entire protocol for Kvert and Kleg. The increased velocity caused significant changes in Kvert for both high- and low-level athletes ($p < 0.001$ in both groups), with post-hoc analysis revealing differences between each velocity in both groups ($p < 0.01$, ES > 0.7). Significant between-group differences were found with higher values for NR at every running velocity (10 km/h: $p = 0.037$, ES = 1.002; 12 km/h: $p = 0.017$, ES = 1.241; 14 km/h: $p = 0.001$, ES = 1.277; 16 km/h: $p = 0.004$, ES = 1.479; 18 km/h: $p = 0.008$, ES = 1.332). As for Kleg, the increased running velocity caused significant changes in ER ($p = 0.001$), with post-hoc tests showing differences between 10-12 km/h ($p = 0.018$, ES > 0.7); whereas within-group differences were found in NR ($p = 0.014$), but the post-hoc analysis reported no significant differences. No significant differences were found between-group at any running velocity ($p \geq 0.05$, ES < 0.4).

The partial correlation analysis, adjusted by the performance level and BMI, revealed some significant correlations between the adaptations that occurred in lower-body stiffness and spatiotemporal parameters when running velocity increased - for the whole group. The vertical stiffness adaptations (ΔKvert) showed significant correlations ($p < 0.01$) with ΔCT (r > - 0.579) at each velocity (10-18 km/h), and with ΔSF (r > 0.616) and ΔSL (r > - 0.451) at 12, 14, 16 and 18 km/h; whereas ΔKleg correlated significantly ($p < 0.001$) with ΔCT (r > - 0.884), ΔFT (r > 0.908) and ΔSA (r > 0.855) over the entire range of velocities.

Table 1

Characteristic of participants according to the performance level (elite [ER] vs. novice runners [LLG]).

	Whole-group (n = 22)	NR (n = 12)	ER (n = 10)	*p*
Age (years)	32.34 (6.95)	34.40 (6.93)	29.87 (6.44)	0.130
Body mass (kg)	71.05 (5.15)	72.67 (5.30)	69.10 (4.48)	0.108
Height (cm)	176.36 (6.11)	174.08 (6.59)	179.10 (4.33)	0.053
BMI (kg/m^2)	22.91 (2.22)	24.03 (2.00)	21.58 (1.72)	0.006

BMI: body mass index

Table 2

Cohen´s d effect size (ES) for spatiotemporal and lower-body stiffness adaptations with increasing running velocity (within-group magnitude of change).

	Elite Runners				Novice Runners			
	10-12 km/h	12-14 km/h	14-16 km/h	16-18 km/h	10-12 km/h	12-14 km/h	14-16 km/h	16-18 km/h
CT	2.1	1.4	1.1	1.5	1.9	1.1	1.2	1.3
FT	2.1	0.8	0.6	0.7	1.2	0.4	0.4	0.1
SF	1.2	0.9	0.1	2.2	1.1	0.9	1.2	1.3
SA	1.7	0.5	0.2	0.4	0.8	0.1	0.2	0.2
SL	3.5	3.4	3.0	2.6	3.0	3.3	2.4	1.1
%CT	2.2	1.1	0.7	1.1	1.4	0.6	0.6	0.4
%FT	2.2	1.1	0.7	1.1	1.4	0.6	0.6	0.4
Phase1	0.1	0.1	0.1	0.2	0.1	0.01	0.01	0.01
Phase2	0.7	0.1	0.1	0.4	0.7	0.01	0.01	0.01
Phase3	1.7	0.2	0.6	0.4	0.9	0.01	0.01	0.01
Kvert	1.1	1.1	1.1	1.4	1.1	1.1	1.7	1.6
Kleg	0.9	0.1	0.1	0.4	0.6	0.1	0.1	0.1

CT: contact time; FT: flight time; SF: step frequency; SA: step angle; SL: step length; %CT: percentage of CT during gait cycle; %FT: percentage of FT during gait cycle; Phase1: initial contact; Phase2: midstance; Phase3: propulsion; Kvert: vertical stiffness; Kleg: leg stiffness

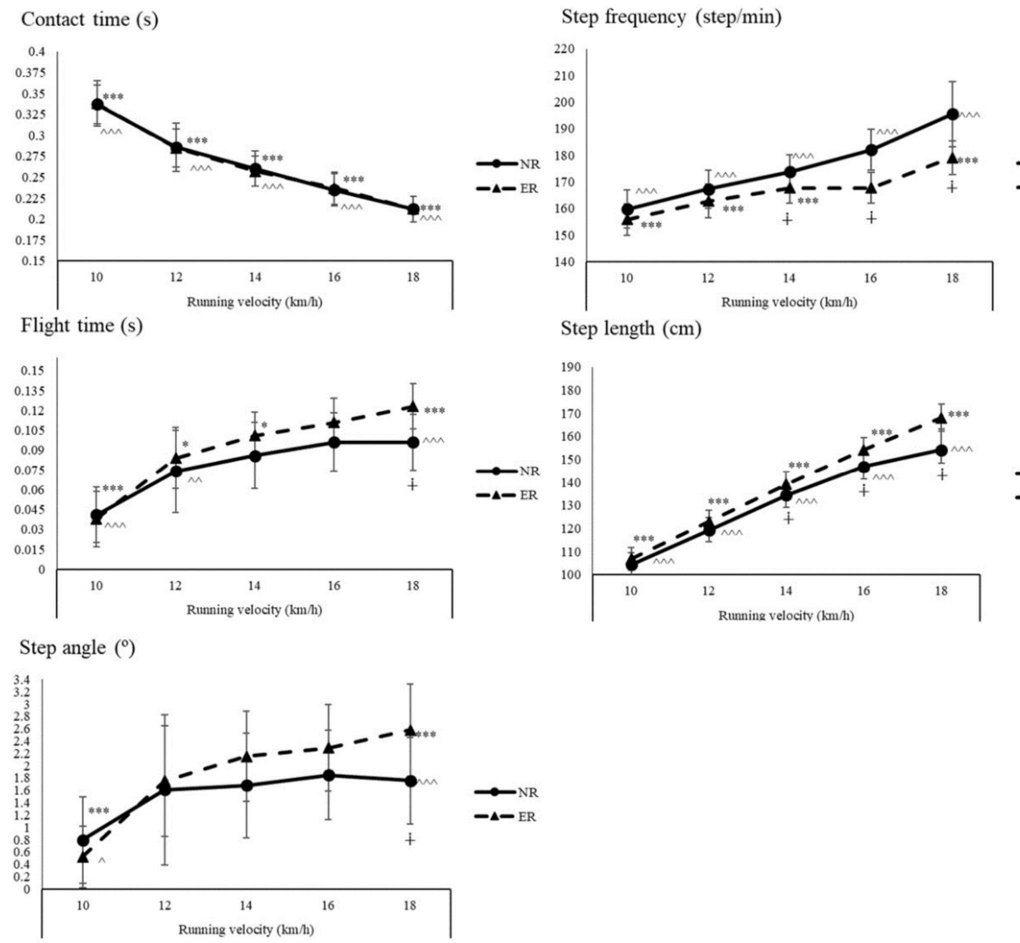
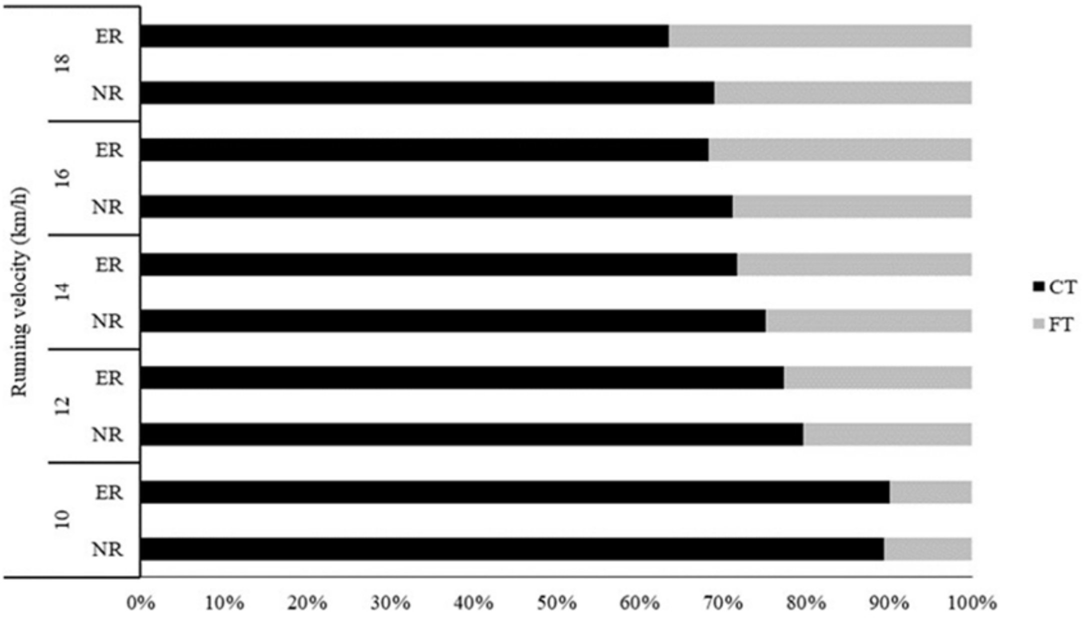


Figure 1

*Dynamics of spatiotemporal variables (contact time, flight time, step frequency, step angle and step length) with increased running velocity (10-18 km/h) according to the performance level (elite [ER] vs. novice runners [NR]). * indicates within-group differences for high-level athletes between running velocity increments (*p < 0.05; **p < 0.01; ***p < 0.001); ^indicates within-group differences for low-level athletes between running velocity increments (^p < 0.05; ^^p < 0.01; ^^^p < 0.001); † indicates between-group differences (p < 0.05)*

(A) CT and FT (%) during a step cycle



(B) Percentages of the different sub-phases during the ground contact period

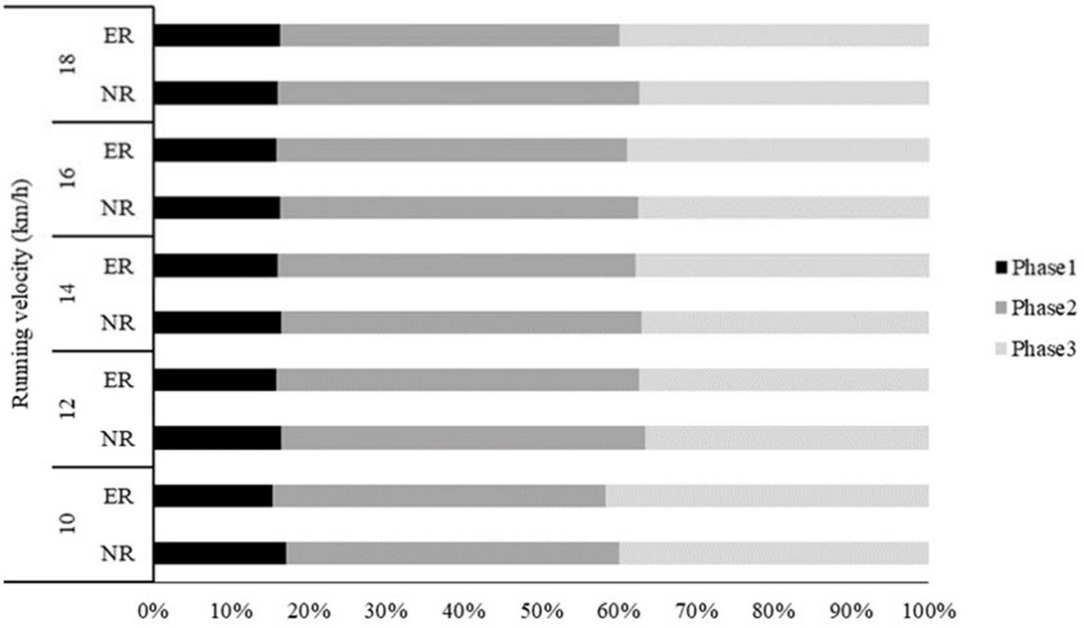


Figure 2

Relative value of spatiotemporal parameters with increased running velocity (10-18 km/h) according to the performance level (elite [ER] vs. novice runners [NR]): (A) Contact and flight times (%) during a step cycle; (B) Percentages of the different sub-phases during the ground contact period. Phase 1: initial contact; Phase 2: midstance; Phase 3: propulsion

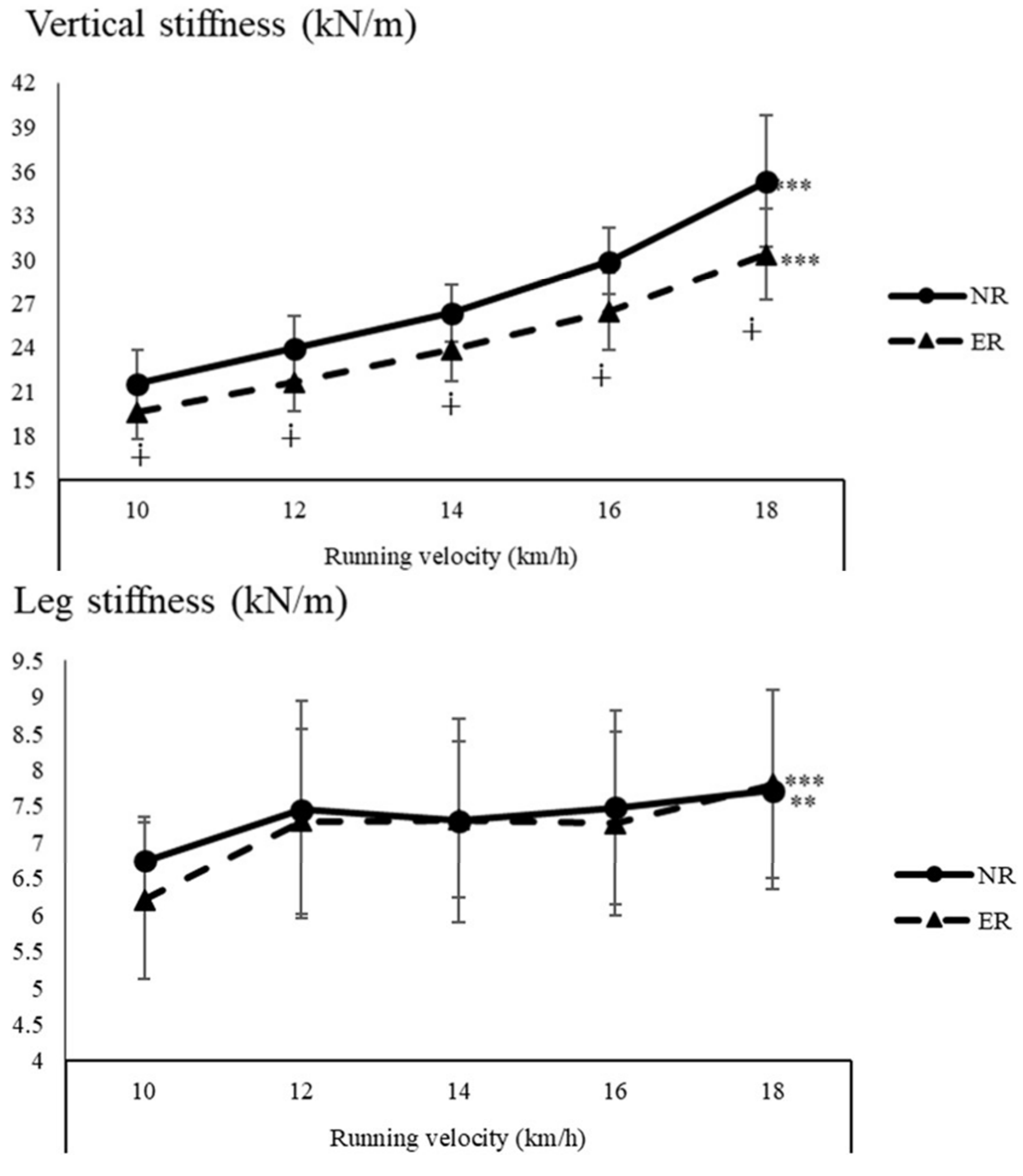


Figure 3

*Vertical (Kvert) and leg stiffness (Kleg) over the running protocol, according to the performance level (elite [ER] vs. novice runners [NR]). * indicates within-group differences, $p < 0.05$; ** indicates within-group differences between each velocity, $p < 0.01$, ***indicates within-group differences between each velocity, $p < 0.001$; † indicates between-group differences ($p < 0.05$)*

Discussion

This study aimed to examine the effect of running velocity on spatiotemporal parameters and lower-body stiffness and the influence of the performance level on those kinematic adaptations. Together with the spatiotemporal adaptations induced by increased running velocity (already reported by previous papers), the main findings of this study included: (i) determining the dynamics of lower-body stiffness when running velocity increased (Kvert increased, while Kleg remained unchanged); (ii) comparing running kinematics in high- and low-level endurance runners at different velocities, with ER showing longer FT, longer SL and lower SF at 14-16-18 km/h, lower Kvert at every velocity tested, and similar CT and Kleg over the entire protocol.

Spatiotemporal adaptations with increased running velocity

The results obtained in the current study reinforce previous studies´ findings. It was observed in a previous study that an increase of 2 km/h in running speed could mean an increase of ~7.4 step/min in SF, ~0.284 m in SL and a decrease of ~0.020 ms in CT, independently of the type of the foot strike pattern (Ogueta-Alday et al., 2014). It seems clear that to run faster, FT needs to be increased and CT needs to be decreased to aid in repositioning the legs during running (Brughelli et al., 2010; Roche-Seruendo et al., 2018). Based on that relationship, SF also needs to be increased to run faster (Morin et al., 2007). More controversial is the dynamics of SL when velocity increases. It has been suggested that SL increases linearly with running velocity up to 25 km/h (Brughelli et al., 2010), which is in consonance with our findings (SL increased over the protocol up to 18 km/h). Changes in these parameters during running have been suggested as influencing factors on impact shock (Heiderscheit et al., 2011; Mercer et al., 2002, 2003) and, thereby, on risk of injury (Lenhart et al., 2014a, 2014b; Mercer et al., 2003). Changes in spatiotemporal parameters at a fixed speed can alter electromyography and kinetics (Heiderscheit et al., 2011; Lenhart et al., 2014a, 2014b; Schubert et al., 2014) and, thereby, the magnitude and rate of impact force loading during the stance phase of running (Mercer et al., 2003). Running injuries may be associated with that magnitude and rate of impact force loading during the stance phase of running (Mercer et al., 2003).

As for the SA, the available information is quite limited which makes comparisons much more difficult. A previous study (Santos-Concejero et al., 2014) points to SA as an easily obtainable measure that reveals more valuable information for running performance and economy. The current study shows that SA increases with an increased running velocity and this finding is in accordance with the results reported by that study (Santos-Concejero et al., 2014). The authors suggest this adaptation may be a marker of the athlete's ability to efficiently maximize FT and minimize CT with effective energy transfer during ground contact. Greater SA would lead athletes to experience shorter CT, allowing better running economy (Novacheck, 1998; Santos-Concejero et al., 2014). This phenomenon could be due to an early contraction of the muscles involved in the movement of a stride during the stance phase, leading the centre of mass to be projected forward more efficiently (Santos-Concejero et al., 2014). All these changes in spatiotemporal parameters have also been associated to athletic performance (Roche-Seruendo et al., 2018; Tartaruga et al., 2012).

Changes in lower-body stiffness with increased running velocity

During locomotion, Kvert is always greater than Kleg because leg length changes exceed those of the centre of mass (Morin et al., 2005; Pappas et al., 2014). Although Kvert and Kleg are derived from similar mechanical concepts, they are not synonymous and adapt differently to changes in running conditions (Farley and González, 1996; Morin et al., 2005; Pappas et al., 2014), therefore examining both Kvert and Kleg is justified.

The lower-body stiffness values reported in the current study are slightly lower than those reported by Morin et al. (2005). Whereas Morin and colleagues reported ~29-46 kN/m (Kvert) and ~7.5-12 kN/m (Kleg), the participants in the current work reached ~20-35 kN/m (Kvert) and ~6.5-8 kN/m (Kleg). The sine-wave method was used in both studies and, thereby, differences in running velocity (12 km/h to 25 km/h in the Morin´s study vs. 10 km/h to 18 km/h in the current study) might explain differences in stiffness.

As for the changes experienced in lower-body stiffness during the incremental protocol, the increase in Kvert and the constancy of Kleg with increasing velocity have been previously noted in the literature (Morin et al., 2005). The current study reinforces that finding with a clear increase in Kvert with increasing running velocity (10-18 km/h), whereas Kleg remained unchanged (except for high-level runners at low velocities of 10-12 km/h).

Some previous studies have suggested a relationship between spatiotemporal parameters and lower-body stiffness (Dumke et al., 2010; Dutto and Smith, 2002; Heise and Martin, 2001). For example, it is known (and the current data support it) that increasing running velocity causes an increase in SF, which results in decreased CT, vertical displacement of the centre of mass, and leg length variation (compression) (Morin et al., 2007; Tartaruga et al., 2012). All these parameters appear to be a strong and direct determinant of lower-body stiffness (Morin et al., 2007). The correlation analysis performed in the current work provides some insight into the relationship between the lower-body stiffness level and spatiotemporal gait characteristics during running. The analysis indicated that changes in lower-body stiffness (ΔKvert and ΔKleg) with increased velocity correlated with spatiotemporal adaptations (changes in CT, FT, SF, SL and SA).

A comparison between ER and NR

Some studies have considered the effect of the performance level on the biomechanical response to different speeds; however, lack of methodological consensus makes the comparison difficult (Gómez-Molina et al., 2016; Ogueta-Alday et al., 2018). The running technique of trained athletes may be expected to adapt better to the need for efficient work output compared to amateur runner, who would react differently to the altered circumstances. That hypothesis seems to be quite controversial. A recent study showed differences in both SF and SL, but not in CT when trained and untrained runners were compared (Gómez-Molina et al., 2016). Trained runners showed higher SF and shorter SL at the same running speeds than untrained ones. Another previous study (Ogueta-Alday et al., 2018) reported no differences between groups created according to the performance level in a half-marathon. The authors found that, at standardized submaximal speeds (11, 13 and 15 km/h), no differences between groups were observed in SF and SL, while CT was shorter in higher level runners (Ogueta-Alday et al., 2018). In the current study, high-level runners showed greater FT, SA (at high velocity, 18 km/h) and SL (at 14-16-18 km/h) with no differences in CT; whereas low-level runners showed higher SF (at 14-16-18 km/h). As mentioned before, lack of methodological consensus makes the comparison difficult.

This study also examines the dynamics of lower-body stiffness during the incremental protocol in both groups (ER vs. NR). NR showed greater Kvert (at every velocity tested: 10-18 km/h), while no differences were observed in Kleg. The relationship between stiffness and running performance is complex and often misunderstood, and the information available to discuss this finding is limited. Some previous studies have found associations between lower-body stiffness and running economy, and thereby, running performance (Dumke et al., 2010; Dutto and Smith, 2002; Heise and Martin, 2001). As indicated by Arampatzis et al. (1999), more compliant quadriceps, tendons and aponeuroses augment force production at submaximal running intensities and thus reduce energy costs. Additionally, a previous study (Morin et al., 2005) concluded that elite middle-distance runners showed higher Kvert and Kleg than novice athletes. Although data should be interpreted with caution due to methodological differences, the authors suggest that the lack of consensus might be due to the influence of other running biomechanical parameters (i.e., foot strike pattern and SF). First, a previous work showed that increases in plantar-flexion angles during ground contact caused significant changes in the spring-mass characteristics describing human motion, with higher stiffness values (Horvais and Samozino, 2013). Unfortunately, this parameter was not controlled in the current study, but a previous work (Latorre-Román et al., 2015) concluded that rearfoot striking was more frequent in lower level endurance runners. Anyway, more evidence is needed to highlight the role of the foot strike pattern in lower-body stiffness during running. Second, a higher SF seems to be related to greater Kvert (Farley and González, 1996). Low-level runners showed a higher SF during the entire protocol which may explain the differences.

Eventually, some potential limitations need to be considered. First, the use of laboratory settings should be taken into account to interpret these findings; however, athletes were well familiarized with treadmill training and testing. Second, although the Morin´s method (Morin et al., 2005) has shown good validity and reliability, it is not a direct measure of lower-body stiffness. Third, foot strike patterns were not considered in this study and, as mentioned earlier, it might influence spatiotemporal characteristics and lower-body stiffness during running. Notwithstanding these limitations, it seems important for coaches and athletes to investigate if spatiotemporal adaptations with increased velocity vary with athletic levels, how stiffness changes, and what role stiffness plays in spatiotemporal gait characteristics while running.

In summary, the current study highlights the effect of increasing running velocity (10-18 km/h) on spatiotemporal parameters and lower-body stiffness – increases in Kvert with Kleg remaining unchanged, as well as running kinematic differences between low- and high-level endurance runners at submaximal velocities. Lower SF and Kvert and, thereby, longer FT and SL, seem to be the main gait characteristics of high-level runners compared to their low-level counterparts.

Since the relationship between lower-body stiffness and running performance is controversial, this study highlights the dynamics of Kvert and Kleg when increasing running velocity by providing some evidence to the spring-mass model for running. Additionally, the high-level vs. low-level runners´ comparison lets us detect some differences in spatiotemporal parameters. This comparison might provide useful information for sport scientists and clinicians working on gait retraining, with a special focus on SF and Kvert.

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References

Abt J, Sell T, Chu Y, Lovalekar M, Burdett R, Lephart S. Running kinematics and shock absorption do not change after brief exhaustive running. *J Strength Cond Res,* 2011; 25(6): 1479–1485

Arampatzis A, Brüggemann GP, Metzler V. The effect of speed on leg stiffness and joint kinetics in human running. *J Biomech*, 1999; 32(12): 1349–53

Brown AM, Zifchock RA, Hillstrom HJ. The effects of limb dominance and fatigue on running biomechanics. *Gait Posture*, 2014; 39(3): 915–9

Brughelli M, Cronin J, Chaouachi A. Effects of running velocity on running kinetics and kinematics. *J Strength Cond Res,* 2010; 24(0): 1–7

Butler RJ, Crowell HP, Davis IM. Lower extremity stiffness: implications for performance and injury. *Clin Biomech*, 2003; 18(6): 511–7

Cohen J. *Statistical power analysis for the behavioral sciences. Statistical Power Analysis for the Behavioral Sciences* (Vol. 2nd); 1988

Daoud AI, Geissler GJ, Wang F, Saretsky J, Daoud YA, Lieberman DE. Foot strike and injury rates in endurance runners: A retrospective study. *Med Sci Sports Exerc*, 2012; 44: 1325–1334

Dumke CL, Pfaffenroth CM, McBride JM, McCauley GO. Relationship between muscle strength, power and stiffness and running economy in trained male runners. *Int J Sport Physiol Perform*, 2010; 5(2): 249–61

Dutto DJ, Smith GA. Changes in spring-mass characteristics during treadmill running to exhaustion. *Med Sci Sports Exerc*, 2002; 34(8): 1324–1331

Farley CT, González O. Leg stiffness and stride frequency in human running. *J Biomech*, 1996; 29(2): 181–186

Fields KB, Sykes JC, Walker KM, Jackson JC. Prevention of running injuries. *Current Sport Med Rep,* 2010. https://doi.org/10.1249/JSR.0b013e3181de7ec5

Gómez-Molina J, Ogueta-Alday A, Stickley C, Tobalina JC, Cabrejas-Ugartondo J, García-López J. Differences in spatio-temporal parameters between trained runners and untrained participants. *J Strength Cond Res*, 2016; 31(8): 2169–2175

Granata KP, Padua DA, Wilson SE. Gender differences in active musculoskeletal stiffness. Part II. Quantification of leg stiffness during functional hopping tasks. *J Electromyogr Kines*, 2002; 12(2): 127–35

Heiderscheit BC, Chumanov ES, Michalski MP, Wille CM, Ryan MB. Effects of step rate manipulation on joint mechanics during running. *Med Sci Sports Exerc*, 2011; 43(2): 296–302

Heise GD, Martin PE. "Leg spring" characteristics and the aerobic demand of running. *Med Sci Sports Exerc*, 1988; 30(5): 750–754

Heise GD, Martin PE. Are variations in running economy in humans associated with ground reaction force characteristics? *Eur J Appl Physiol*, 2001; 84(5): 438–442

Horvais N, Samozino P. Effect of midsole geometry on foot-strike pattern and running kinematics. *Footwear Sci*, 2013; 5(2): 81–89

Latorre-Román PÁ, Muñoz-Jiménez M, Soto-Hermoso VM, Sánchez JS, Molina AM, Robles-Fuentes A, García-Pinillos F. Acute effect of a long-distance road competition on foot strike patterns, inversion and kinematics parameters in endurance runners. *Int J Perf Anal Spor*, 2015; 15: 588–97

Lee MM, Song CH, Lee KJ, Jung SW, Shin DC, Shin SH. Concurrent Validity and Test-retest Reliability of the OPTOGait Photoelectric Cell System for the Assessment of Spatio-temporal Parameters of the Gait of Young Adults. *J Physic Therapy Sci*, 2014; 26(1): 81–5

Lenhart RL, Thelen DG, Wille CM, Chumanov ES, Heiderscheit BC. Increasing running step rate reduces patellofemoral joint forces. *Med Sci Sports Exerc*, 2014; 46(3): 557–564

Lenhart RL, Thelen D, Heiderscheit B. Hip muscle loads during running at various step rates. *The J Orthop Sport Phys Ther*, 2014; 44(10): 766–74

Luedke LE, Heiderscheit BC, Williams DSB, Rauh MJ. Influence of Step Rate on Shin Injury and Anterior Knee Pain in High School Runners. *Med Sci Sport Exerc*, 2016; 48(7): 1244–50

Mann R, Malisoux L, Nührenbörger C, Urhausen A, Meijer K, Theisen D. Association of previous injury and speed with running style and stride-to-stride fluctuations. *Scand J Med Sci Sport*, 2015; 25(6): 638–645

Mercer JA, Devita P, Derrick TR, Bates BT. Individual effects of stride length and frequency on shock attenuation during running. *Med Sci Sports Exerc*, 2003; 35(2): 307–313

Mercer JA, Vance J, Hreljac A, Hamill J. Relationship between shock attenuation and stride length during running at different velocities. *Eur J Appl Physiol*, 2002; 87(4–5): 403–8

Morin JB, Dalleau G, Kyröläinen H, Jeannin T, Belli A. A simple method for measuring stiffness during running. *J Appl Biomech*, 2005; 21(2): 167–180

Morin JB, Samozino P, Zameziati K, Belli A. Effects of altered stride frequency and contact time on leg-spring behavior in human running. *J Biomech*, 2007; 40(15): 3341–8

Novacheck TF. The biomechanics of running. *Gait Posture*, 1998; 7(1): 77–95

Ogueta-Alday A, Morante JC, Gómez-Molina J, García-López J. Similarities and differences among half-marathon runners according to their performance level. *PLoS ONE*, 2018; 13(1): 1-8

Ogueta-Alday A, Rodríguez-Marroyo JA, García-López J. Rearfoot striking runners are more economical than midfoot strikers. *Med Sci Sport Exerc*, 2014; 46(3): 580–585

Padulo J, Annino G, Migliaccio GM, D'Ottavio S, Tihanyi J. Kinematics of Running at Different Slopes and Speeds. *J Strength Condit Res*, 2012. https://doi.org/10.1519/JSC.0b013e318231aafa

Pappas P, Paradisis G, Tsolakis C, Smirniotou A, Morin JB. Reliabilities of leg and vertical stiffness during treadmill running. *Sports Biomech*, 2014; 13(4): 391–399

Roche-Seruendo LE, García-Pinillos F, Haicaguerre J, Bataller-Cervero AV, Soto-Hermoso VM, Latorre-Román PÁ. Lack of influence of muscular performance parameters on spatio-temporal adaptations with increased running velocity. *J Strength Cond Res*, 2018; 32(2): 409–415

Roche-Seruendo LE, García Pinillos F, Auria-Martin I, Bataller-Cervero AV, Latorre Román PA, Soto - Hermoso VM. Effects of different percentages of body weight support on spatiotemporal step characteristics during running. *J Sports Sci*, 2017; 1: 1–6 https://doi.org/10.1080/02640414.2017.1394584

Santos-Concejero J, Tam N, Granados C, Irazusta J, Bidaurrazaga-Letona I, Zabala-Lili J, Gil SM. Stride angle as a novel indicator of running economy in well-trained runners. *J Strength Cond Res*, 2014; 28(7): 1-7

Schieb DA. Kinematic Accommodation of Novice Treadmill Runners. *Res Quart Exerc Sport*, 1986; 57(1): 1–7

Schubert AG, Kempf J, Heiderscheit BC. Influence of stride frequency and length on running mechanics: a systematic review. *Sports Health*, 2014; 6(3): 210–7

Slawinski J, Heubert R, Quievre J, Billat V, Hannon C. Changes in Spring-Mass Model Parameters and Energy Cost During Track Running to Exhaustion. *J Strength Cond Res*, 2008; 22(3): 930–936

Tartaruga MP, Brisswalter J, Peyré-Tartaruga LA, Ávila AOV, Alberton CL, Coertjens M, Kruel LFM. The Relationship Between Running Economy and Biomechanical Variables in Distance Runners. *Res Quart Exerc Sport*, 2012; 83(3): 367–375

Taylor MJD, Beneke R. Spring mass characteristics of the fastest men on Earth. *Int J Sports Med*, 2012; 33(8): 667–70

van Dyck D, Cardon G, de Bourdeaudhuij I, de Ridder L, Willem A. Who Participates in Running Events? Socio-Demographic Characteristics, Psychosocial Factors and Barriers as Correlates of Non-Participation—A Pilot Study in Belgium. *Int J Envir Res Public Health*, 2017; 14(11): 13-15

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