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Does fatigue alter step characteristics and stiffness during running?

Felipe García-Pinillos [a,*], Antonio Cartón-Llorente [b], Diego Jaén-Carrillo [b], Pedro Delgado-Floody [a], Vanessa Carrasco-Alarcón [a], Cristian Martínez [a], Luis E. Roche-Seruendo [b]

[a] Department of Physical Education, Sports and Recreation, Universidad de La Frontera, Temuco, Chile
[b] Department of Physiotherapy, Universidad San Jorge, Zaragoza, Spain

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ABSTRACT

Background: Describing the response of spatiotemporal gait characteristics, and related variables such as variability and stiffness, to different stressors is important to better understand spring-mass model.

Research question: This study aimed to examine the effect of fatigue induced by a running protocol on spatiotemporal gait parameters, step variability and vertical (Kvert) and leg stiffness (Kleg) during running on a treadmill.

Methods: Twenty-two trained male endurance runners performed a 60-min time trial run. An analysis of spatiotemporal parameters (contact time [CT], flight time [FT], step frequency [SF] and step length [SL]), step variability (in terms of coefficient of variation [CV]) and stiffness was conducted in two different conditions: non-fatigued (before the protocol) and fatigued (after the protocol).

Results: The pairwise comparisons (i.e., non-fatigued vs. fatigued condition) indicated that temporal parameters (i.e., CT and FT) experienced significant changes ($p = 0.001$ and <0.001, respectively). Step variability increased in presence of fatigue, with higher CV in CT ($p = 0.039$), FT ($p = 0.005$), SF ($p = 0.046$) and SL ($p = 0.027$) after the running protocol. The Kleg experienced a reduction in the fatigued condition ($p < 0.001$) whereas the Kvert remained unchanged ($p = 0.602$).

Significance: The results indicate that fatigue induced by a 60-min time trial run causes some adaptations in spatiotemporal gait characteristics and stiffness in trained endurance runners. Specifically, in the presence of fatigue, the athletes showed greater CT and shorter FT, higher step variability and lower leg stiffness.

1. Introduction

The storage and return of elastic energy in the lower-limb during bouncing and running has been described as spring-mass model [1]. From a mechanical standpoint, the stiffness plays a key role in that model [2] and it has been suggested as the main mechanical parameter when using the spring-mass model [3]. To calculate stiffness, ground reaction forces and displacement measurements (i.e., displacement of center of mass, leg length, joints or muscle-tendon unit depending on the stiffness analyzed) are required. Some years ago, measuring those parameters during running required the use of treadmill-mounted force platforms, which is expensive and non-portable. In that context, a method created and tested by Morin and colleagues [3] allows the estimation of vertical and leg stiffness (Kvert and Kleg, respectively) during running using only anthropometric parameters, running speed and spatiotemporal gait characteristics (i.e., body mass, forward velocity, leg length, flight time [FT] and contact time [CT]).

Spatiotemporal gait characteristics during running have been widely studied and have been related either with athletic performance [4] or with risk of injury [5]. Not only its magnitude seems to be important but also its variability. Step variability provides a description of the amount of variability in the time series, and alterations are generally regarded as being evidence for changes in the stability of the coordination pattern [6]. Likewise, some studies have suggested a relationship between step variability and both injuries [7] and endurance performance [8].

Based on all these evidences, describing the response of spatiotemporal gait characteristics, and related variables such as variability and stiffness, to different stressors is important to better understand spring-mass model adaptations to influencing conditions. Some previous studies have examined the influence of running velocity on spatiotemporal gait characteristics [9], step variability [6,10] and stiffness [11]. Likewise, previous works have analysed the effects of slope gradient on those variables [9,12], or the influence of running shod compared to running unshod [13].

Other factor that might affect spatiotemporal gait characteristics and stiffness during running is how fatigued the athlete is. In endurance runners, fatigue has been hypothesized to alter the biome-

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* Corresponding author at: Department of Physical Education, Sports and Recreation, Universidad de La Frontera, Calle Uruguay, 1980, Temuco, Chile.
E-mail addresses: felipe.garcia@ufrontera.cl (F. García-Pinillos); acarton@usj.es (A. Cartón-Llorente); djaen@usj.es (D. Jaén-Carrillo); pedro.delgado@ufrontera.cl (P. Delgado-Floody); vanessa.carrasco@ufrontera.cl (V. Carrasco-Alarcón); cristian.martinez.s@ufrontera.cl (C. Martínez); leroche@usj.es (L.E. Roche-Seruendo)

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chanical (i.e., kinematics [14], step variability [15], kinetics [16]) and neuromuscular factors [17–20]. However, the findings reported are controversial. The authors suggest that might be due to the lack of consistency in the methods conducted (i.e. different protocols and activities to induce fatigue, athletic level and background of participants, monitored parameters).

Therefore, the aim of this study is to examine the effect of fatigue induced by a strenuous running protocol on spatiotemporal gait parameters, step variability and Kvert and Kleg during running on a treadmill for trained endurance runners.

2. Methods

Endurance runners performed a 60-min time trial run. An analysis of spatiotemporal gait characteristics, step variability (in terms of coefficient of variation [CV]) and stiffness was conducted in two different conditions: non-fatigued (before the protocol) and fatigued (after the protocol) in order to determine the effect of fatigue on those variables. An unilateral crossover design was used, with all athletes performing the same protocol and conditions.

2.1. Participants

Twenty-two trained male endurance runners (body mass = 71.1 ± 5.8 kg; body height = 1.76 ± 0.04 m; age = 34.0 ± 7.5 years) participated in this study. Participants met the inclusion criteria: (1) older than 18 years old, (2) able to run 10 km in < 40 min (i.e., 37.2 ± 1.2 min), (3) training on a treadmill at least once per week, (4) free from injury (points 3 and 4 refer to the 6 months preceding the study). After receiving information on the objectives and procedures of the study, participants signed an informed consent form, which complied with the ethical standards of the World Medical Association’s Declaration of Helsinki (2013). The study was approved by the local ethics committee.

2.2. Procedures

Before the running protocol, participants performed a warm-up, with 5 min of continuous running and 5 min of active joint mobilization and dynamic stretching. Then, subjects started running on a treadmill (HP cosmos Pulsar 4 P, HP cosmos Sports & Medical, Gmbh, Germany). Since previous studies on human locomotion have shown that accommodation to a new condition occurs in ∼6–8 min [21,22], the running protocol was preceded by an adaptation period of 10 min at a steady pace of 12 km.h^{-1} – even though participants were familiar with running on treadmill. The last 3 min of this accommodation period were recorded as pre-test (i.e., non-fatigued condition). Then, participants set the treadmill velocity (i.e., self-selected running velocity) and the 60-min time trial run started. The only instructions given to the participants were to maximize running distance by manually adjusting running speed at their own will. Additionally, participants were verbally encouraged during the protocol. The intensity was measured using the 6–20 Borg scale [23] at the end of the protocol (i.e., 19.3 ± 0.9). The mean velocity was 15.1 ± 0.6 km.h^{-1}. Immediately after the protocol, running velocity was set at 12 km.h^{-1} for 3 min and that period was recorded as post-test (i.e., fatigued condition). The slope was maintained at 0 % over the entire protocol.

2.3. Materials and testing

For descriptive purposes, body height (cm) and body mass (kg) were determined using a precision stadiometer and mechanical scale (SECA 222 and 634, respectively, SECA Corp., Hamburg, Germany). All measurements were taken with the participants wearing underwear.

Spatiotemporal parameters were measured using the OptoGait system (Optogait; Microgate, Bolzano, Italy), which was previously validated for the assessment of gait spatiotemporal parameters [24]. The two parallel bars of the device system were placed on the side edges of the treadmill at the same level as the contact surface. This device was connected to a computer controlled by the researcher. Data were recorded and averaged for the subsequent analyses (i.e., 3 min before and 3 min after the protocol). In accordance with the findings from a previous study [25], limb dominance was not taken into account. Spatiotemporal parameters were measured for every step during the treadmill protocol as follows:

- Contact time (CT, in seconds [s]): time from when the foot contacts the ground to when the toes lift off the ground.
- Flight time (FT, in seconds [s]): time from toe-off to initial ground contact of consecutive footfalls (i.e., right-left).
- Step frequency (SF, in steps per minute [spm]): number of ground contact events per minute.
- Step length (SL, in meters [m]): distance between two successive ground contacts, from toe to toe.

Step variability was assessed for each spatiotemporal parameter through the coefficient of variation (CV, in %) as previously suggested [8]. Since step variability has been suggested as a stable measure up to 3 min [10], a duration of 3 min for every recording interval was selected. Likewise, since step variability has been determined as a speed-dependent variable [6,10], running velocity was fixed at 12 km.h^{-1} in both intervals.

Vertical (Kvert) and leg stiffness (Kleg) were calculated according to Morin´s method [3]. 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) [26]. 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 [26]. 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. [3], stiffness values calculated with the sine-wave method ranged from 0.67 to 6.93% less than the force platform method, which was acceptable. Another paper [27] concluded that the measurements of Kvert and Kleg obtained during treadmill running by using the sine-wave method were highly reliable for both intra-day and inter-day designs, exhibiting ICCs between 0.86-0.99.

2.4. Statistical analysis

Descriptive statistics are represented as mean (SD). The normal distribution of data and homogeneity of variances were confirmed through the Kolmogorov-Smirnov and Levene´s tests, respectively ($p > 0.05$). Pairwise comparisons (i.e., t-test) were conducted on the magnitude of each spatiotemporal parameter as well as on variability outcomes (i.e., CV) to examine possible differences between the recording intervals (i.e., non-fatigued vs. fatigued). The magnitude of the differences between values was also interpreted using the Cohen’s d effect size (*ES*) (between-group differences) [28]. Effect sizes are reported as: trivial (<0.2), small (0.2-0.49), medium (0.5-0.79), and large (≥0.8) [28]. The level of significance used was $p < 0.05$. Data analysis was performed using the SPSS (version 21, SPSS Inc., Chicago, Ill).

3. Results

Table 1 shows the magnitude of spatiotemporal parameters, step variability and stiffness during running in both non-fatigued and fatigued conditions. The CT and SF increased while the FT and SL reduced, even though just the temporal parameters (i.e., CT and FT) ex-

Table 1
Magnitude of spatiotemporal parameters and its variability (in terms of CV) and vertical and leg stiffness during running before (non-fatigued condition) and after (fatigued condition) a 60 min time trial.

Variable	Non-fatigued	Fatigued	*P-value*	*ES (d)*
Spatiotemporal gait characteristics (mean, SD)				
Contact time (s)	0.264 (0.018)	0.274 (0.015)	0.001	0.604
Flight time (s)	0.098 (0.020)	0.083 (0.020)	< 0.001	0.750
Step frequency (spm)	166.31 (6.75)	167.91 (6.27)	0.061	0.245
Step length (cm)	120.52 (4.82)	119.25 (4.41)	0.052	0.275
Step variability (CV)				
Contact time (%)	3.88 (3.12)	6.02 (4.78)	0.039	0.530
Flight time (%)	11.22 (4.48)	16.62 (9.02)	0.005	0.758
Step frequency (%)	2.99 (1.19)	3.24 (1.10)	0.046	0.218
Step length (%)	3.44 (2.13)	4.19 (2.36)	0.027	0.341
Stiffness				
Vertical stiffness (kN.m)	23.92 (2.67)	23.80 (2.68)	0.602	0.043
Leg stiffness (kN.m)	8.62 (1.50)	7.86 (1.33)	< 0.001	0.536

CV: coefficient of variation; ES (d): Cohen´s d effect size.

perienced significant changes ($p = 0.001$ and < 0.001, respectively, with medium ES). Step variability increased in presence of fatigue, with higher CV in CT ($p = 0.039$, ES = 0.530), FT ($p = 0.005$, ES = 0.758), SF ($p = 0.046$, ES = 0.218) and SL ($p = 0.027$, ES = 0.341) after the running protocol. The Kleg experienced a reduction in the fatigued condition ($p < 0.001$, ES = 0.536) whereas the Kvert remained unchanged ($p = 0.602$, ES = 0.043).

Figs. 1–3 depict the values before and after the running protocol (i.e., non-fatigued vs. fatigued) and the percentages of change.

4. Discussion

This study aimed to examine the effect of fatigue induced by a 60-min time trial run on spatiotemporal gait parameters, step variability and Kvert and Kleg during running on a treadmill for trained endurance runners. The results demonstrated that fatigue causes changes in spatiotemporal parameters (i.e., 3.8 % increased CT and 15.3 % reduced FT) during running and increases step variability (i.e., from 0.25 % to 5.4 %). Additionally, the data showed that fatigue alters stiffness by causing a significant reduction in Kleg (i.e., 8.8 %) but no significant changes in Kvert.

In order to properly interpret these results, some points need to be taken into consideration. First, in the current project fatigue was induced by a specific protocol for endurance runners (i.e. 60-min time trial), whereas previous studies considered these variables (i.e., step characteristics and stiffness) but causing fatigue thorough non-running exercises (e.g., squat-based protocol [29]). Of note, the athletes reported an almost maximum level of perceived exertion (i.e., 19.3 ± 0.9 in a 6–20 scale) at the end of the protocol performed in the current study. Second, trained endurance runners participated in this study so comparisons with other level groups must be cautious since biomechanical and neuromuscular differences have been reported between amateur and trained endurance runners [12,30]. And third, this study measures Kvert and Kleg during running through the sine-wave method [3]. While some studies have considered the effect of fatigue on stiffness, just one study [19] has analysed stiffness during running with the rest of studies obtained stiffness from hopping protocols [17,18,20,29].

As earlier mentioned, spatiotemporal gait characteristics during running and its variability have been widely studied. Specifically, some studies have analyzed the effects of fatigue on those variables during running [7,15,31] but it seems difficult to get a robust conclusion due to methodological differences between studies. Whereas Meardon et al. [7] focused on changes in step variability after a 5.7-km run on a 300-m indoor track and Paquette et al. [31] analysed foot contact angle variability after a 40-min run at a comfortable running speed (i.e., ~11 $km.h^{-1}$), Hanley and Mohan [16] measuring changes in gait parameters over the course of a 10-km treadmill run, but step variability data were not calculated. Just one study has examined the effects of fatigue on spatiotemporal parameters and its variability [15] and the results reported are not in line with those reported by the current study. Hanley and Tucker [15] reported no significant changes, but high between-subjects variability, in spatiotemporal parameters and step variability during a 10-km time trial treadmill run in trained endurance runners. The authors suggest that differences might be related to the duration of the protocol (i.e., ~35-min vs. 60-min) and, thereby, the intensity (i.e., 17.5 vs. 15.1 $km.h^{-1}$; ~18 vs. ~19 RPE). Therefore, the current study highlights the influence of fatigue on temporal parameters and step variability during running, and it includes the analysis of stiffness during running and its response to fatigue.

Another important finding in the current study is that fatigue induced by 60-min time trial run altered stiffness by reducing Kleg. The authors considered examining both Kvert and Kleg because, despite being derived from similar mechanical concepts, they are not synonymous and adapt differently to changes in running conditions [3,26,27,32]. As expected, Kvert values were greater than Kleg values. During locomotion, Kvert is always greater than Kleg because leg length changes exceed those of the centre of mass [3,27].

Many works have investigated the effect of fatigue on stiffness but just a few studies have focused on determining the effect of fatigue induced by running-based exercises (i.e., a marathon [20], an incremental running test [18], or an ironman triathlon [17]) on stiffness. However, all those studies measured stiffness during hopping protocols while the current study measured stiffness during running through the sine-wave method (Morin et al., 2005). In this sense, just one study used a comparable method. In that work [19], sixteen experienced runners completed a near maximal effort 1-h treadmill run at a constant speed and Kvert and Kleg were determined from vertical force data recorded throughout the run. The authors reported no significant fatigue effects over the run, which is opposing to the finding of the current study with a 8.1 % reduction in Kleg. Some methodological differ-

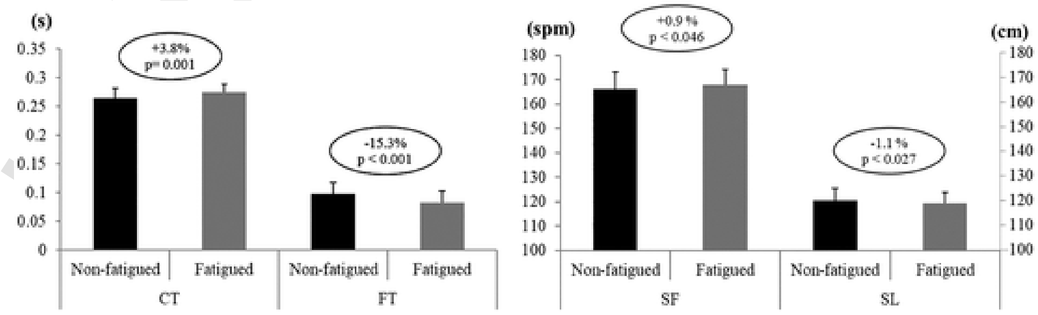

Fig. 1. Spatiotemporal gait characteristics during running in two different conditions (i.e., non-fatigued vs. fatigued). CT: contact time, FT: flight time, SF: step frequency, SL: step length.

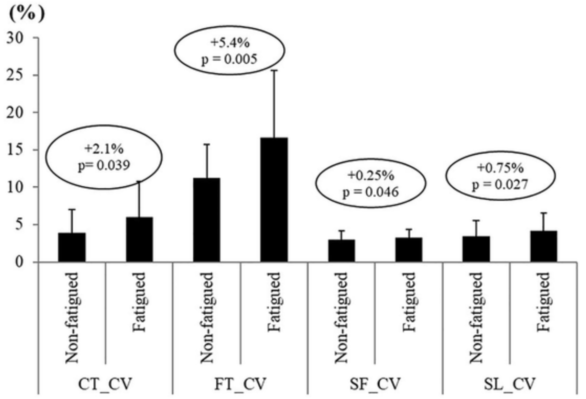

Fig. 2. Step variability, in terms of coefficient of variation (CV), during running in two different conditions (i.e., non-fatigued vs. fatigued). CT: contact time, FT: flight time, SF: step frequency, SL: step length.

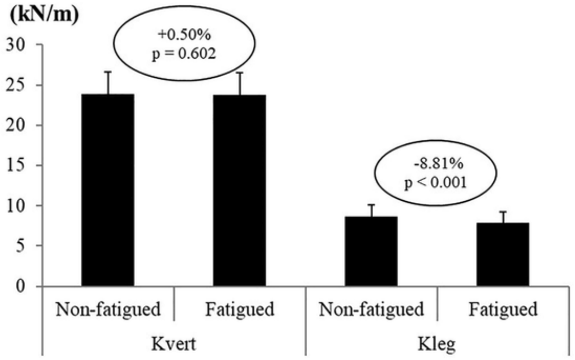

Fig. 3. Vertical and leg stiffness (Kvert and Kleg, respectively) during running in two different conditions (i.e., non-fatigued vs. fatigued).

ences must be considered: (i) how stiffness was measured (i.e., even though the sine-wave method (Morin et al., 2005) has shown good validity and reliability compared to force platforms, it is not a direct measure and it might imply a systematic bias); (ii) the athletic level of participants, since average speeds during 60-min runs ranged from 14.5 to 16.5 km.h^{-1} in our study to 11.0–16.5 km.h^{-1} in that work [19].

Finally, some limitations should be addressed. The 60-min run in this work was performed on a treadmill with a 0 % grade and in a laboratory setting. Such a controlled environment might influence variability so the authors doubt about the repeatability of these results during running outdoor (e.g., obstacles, surfaces). Likewise, the footwear was not standardized, even though all runners wore their own footwear to increase the ecological validity of the study. One more limitation of the present study could be the lack of women. Previous studies have reported sex differences in lower extremity kinematics [33] and stiffness [34] so that between-sex differences might be found in the response to a fatiguing protocol. Notwithstanding these limitations, the current study provides some insights into the effect of fatigue induced by a specific protocol for endurance runners on gait characteristics and stiffness.

4.1. Conclusion

The results indicate that fatigue induced by a 60-min time trial run causes some adaptations in spatiotemporal gait characteristics and stiffness in trained endurance runners. Specifically, in the presence of fatigue the athletes showed greater CT and shorter FT with higher variability in those parameters and lower stiffness in terms of Kleg.

From a practical standpoint, and given the relationship between running biomechanics and both injury risk and athletic performance, this finding might be interesting for clinicians and coaches by warning them about the influence of fatigue on the biomechanical adaptations to a running protocol.

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Declaration of Competing Interest

The authors report no conflict of interest.

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