How does the slope gradient affect spatiotemporal parameters during running? Influence of athletic level and vertical and leg stiffness

Felipe García-Pinillos[a,*], Pedro Á. Latorre-Román[b], Rodrigo Ramírez-Campillo[c], Juan A. Párraga-Montilla[b], Luis E. Roche-Seruendo[d]

[a] Department of Physical Education, Sports and Recreation. Universidad de La Frontera, Temuco, Chile
[b] University of Jaen, Department of Corporal Expression, Campus de Las Lagunillas s/n. D2 Building, Dep. 142, 23071, Jaen, Spain
[c] Universidad de Los Lagos, Department of Physical Activity Sciences, Quality of Life and Wellness Research Group, Laboratory of Human Performance, Osorno, Chile
[d] Universidad San Jorge, Campus Universitario, A23 km 299, 50830. Villanueva de Gállego, Zaragoza, Spain

A B S T R A C T

Background: The current evidence leaves certain questions unanswered, including whether well-trained athletes adapt to different slope gradients in the same way as amateurs, and whether stiffness influences spatiotemporal adaptations during uphill running.
Research question: This study aimed to determine the effect of different slope gradients (0%–11%) on spatiotemporal gait characteristics during running, taking into account the influence of athletic level, vertical and leg stiffness.
Methods: Male endurance runners (12 amateurs, 10 highly-trained) performed a running test on a motorized treadmill. The running velocity was set at 12 km/h, and participants completed six different running conditions (0, 3, 5, 7, 9 and 11% gradients). Spatiotemporal parameters were measured using the OptoGait system. Vertical (Kvert) and leg (Kleg) stiffness were calculated according to the sine-wave method.
Results: A 2 (amateur; highly-trained) × 6 (running conditions) ANOVA found no significant between-group differences in spatiotemporal parameters at any gradient ($P \geq 0.05$); however, significant Kvert and Kleg differences ($P < 0.05$) were found within both groups with increasing gradients. Stepwise linear regression analysis showed that Kleg was strongly associated with contact time ($R^2 = 0.797$, $P < 0.001$), whereas Kvert was associated with spatiotemporal adaptations to different slope gradients ($R^2 = 0.547$, $P = 0.002$).
Significance: An increased slope gradient (0–11%) at a given running velocity ($12\,km.h^{-1}$) caused spatiotemporal adaptations (i.e., increased CT and SF and decreased FT, SL and SA) regardless of the athletic level of the runner, although a non-significant trend differentiated the adaptations between the amateur and highly-trained groups. The results also indicated that leg stiffness plays a key role in the characteristics of spatiotemporal gait during level running, whereas vertical stiffness is strongly associated with spatiotemporal adaptations when running uphill.

1. Introduction

It is well-known that running biomechanics can favour or limit running performance by influencing the economy and efficiency of running [1–4]. Nevertheless, despite trail running has become increasingly popular and it includes a broad range of distances and slope variations, the majority of running biomechanics studies have only considered flat (level) running. Running speed was reported to decrease by 0.1–$0.3\,km.h^{-1}$ per every 1% increase in gradient [5], which led to important biomechanical, neuromuscular and physiological changes.

Thus the study of the physiological and biomechanical changes associated with graded running is important, as the ability to appropriately regulate locomotor behaviour in response to gradient changes is fundamental to the understanding of human locomotion control [6].

Several studies have examined the influence of uphill running on the kinematic variables [6–14], and the results reported are inconclusive. On one hand, uphill running was characterized by a shorter duration of the swing phase and a greater proportion of the stride cycle spent in stance [13]. Higher gradients were also reported to be associated with a higher step frequency (SF) during uphill running [7,9,15].

Conversely, some studies [7,15] did not observe any variation in contact time (CT), flight time (FT), SF and step length (SL) at a given running speed (~ 11 km.h^{-1}) between level running and uphill running.

In addition, limited evidence is available on the influence of potential confounding variables such as stiffness or athletic level. This leaves certain questions unanswered, including whether well-trained athletes adapt to different slope gradients in the same way as amateurs, and whether stiffness influences spatiotemporal adaptations during uphill running. Some studies have considered the effect of athletic level on the biomechanical response to different speeds [16] and different slopes [10]; however, the lack of methodological consensus makes the comparison difficult. In addition, despite stiffness being strongly related to hopping and jumping performance [17], running performance [18], running economy [19,20], and injury incidence [17,21], some level of stiffness appears to be required for optimal performance although its value remains a topic of debate among researchers. Altogether, more evidence is clearly needed to highlight the effect of slope gradient on spatiotemporal gait characteristics during running, and the influence of athletic level and stiffness on this relationship. Therefore, this study aimed to determine the effect of different slope gradients (0%–11%) on spatiotemporal gait characteristics during running, taking into account the influence of athletic level, vertical and leg stiffness. It was hypothesized that an increased slope gradient at a given running velocity would cause spatiotemporal adaptations regardless of the athletic level of the runner, and that stiffness would be associated with spatiotemporal adaptations when running uphill.

2. Methods

2.1. Participants

A group of 22 male endurance runners (age: 32 ± 7 years; height: 176 ± 6 cm; body mass: 71 ± 5 kg) participated in this study (Table 1). All participants were older than 18 years old and were free from injuries in the 6 months preceding their participation in the study. The 22 athletes were selected by convenience according to their athletic level (amateur or highly-trained). For the amateur group (n = 12), the additional inclusion criterion was that the runners must be able to run 10 km in 45–50 min (48.1 $\pm$ 1.3 min), whereas athletes had to have a 10 km personal best of 30–35 min (33.3 $\pm$ 1.4 min) to be included in the highly-trained group (n = 10). 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 [22]. The study was approved by the local ethics committee.

2.2. Procedures

Participants were individually tested (between 16:00 and 21:00 h). Participants refrained from severe physical activity for at least 48 h prior to testing, and all tests were performed at least 3 h of latest meal. Tests were performed using the participant´s usual training shoes and athletic garment to attain their most typical performance.

The participants performed a running protocol on a motorized treadmill (Salter M-835, Salter Int., Barcelona, Spain). The protocol was

Table 1
Characteristics of participants according to their level of athletic performance.

	Whole-group (n = 22)	Amateur (n = 12)	Highly-trained (n = 10)	p-value
Age (years)	32.3 (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

preceded by a standardized 10-min accommodation procedure. Athletes were experienced at running on a treadmill; however, previous studies [23] on human locomotion have showed that accommodation to a new condition occurs within ~ 8 min. The running velocity was set at 12 km/h, as this was considered to be a normal pace for these athletes and was consistent with previous studies [24]. All participants verbally reported feeling comfortable when running on the treadmill at the set speed.

Participants completed a total of 6 different running conditions (0, 3, 5, 7, 9 and 11% of slope gradients). The order of these conditions was incremental (from 0% to 11% [0–6.27º]), and velocity was maintained at 12 km/h. Each condition lasted 1 min (i.e., 30 s of acclimatization, and 30 s of recording). The short duration of the gradient conditions aimed to minimize the effect of fatigue on running kinematics (i.e., the whole running protocol lasted 6 min).

2.3. Materials and testing

Spatiotemporal parameters were measured using the OptoGait system (OptoGait; Microgate, Bolzano, Italy), which was previously validated for the assessment of spatiotemporal parameters of gait in young adults [25]. The device used two parallel bars that were placed on the side edges of the treadmill at the same level as the contact surface. The device was connected to a computer controlled by the researcher, and data were recorded and averaged for the subsequent analysis. In accordance with the findings of Brown et al. [26], limb dominance was not taken into account. Step angle (SA), CT, FT, SL, SF, percentage of ground CT (%CT) and FT (%FT) and sub-phases during ground contact (Phase1: initial contact; Phase2: midstance; Phase3: propulsion) were measured for every step during the treadmill test. Spatiotemporal parameters have been carefully defined by previous studies [27,28]:

- Contact time (CT) (s): time your foot spends in contact with the ground on each step (i.e. from initial contact to the moment when the toes lifted off the ground).
- Flight time (FT) (s): time with no ground contact (i.e. from the toes lifting off, to the initial contact of the consecutive footfall).
- Step length (SL) (m): 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): number of ground contact events per minute.
- Step angle (SA) (º): angle of the parable tangent, which was derived from the SL and the height obtained with FT. These parameters allowed the tying together of 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 [29].
- Percentage of ground CT (%CT) and FT (%FT) during the step cycle. Different sub-phases of stance phase were also determined (based on activated LEDs). This was automatically measured for every step during the treadmill test by the OptoGait system:
  - Initial contact (Phase1): time from initial ground contact (1 LED activated is needed to be considered) to foot flat (the number of LEDs activated stays steady $\pm$ 2 LEDs).
  - Midstance (Phase2): time from foot flat to initial take-off. During this phase, the number of LEDs stays steady $\pm$ 1 LEDs. This phase finishes when the heel comes off the ground and the number of LEDs is reduced ≥ 2.
  - Propulsion (Phase3): time from initial take-off (the number of LEDs is reduced ≥ 2) to toe-off (when forefoot comes off the ground and the number of LEDs is 0).

Vertical (Kvert) and leg stiffness (Kleg) were calculated according to

Morin´s method [30]. 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) [31]. 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 [31]. 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. [30], 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 [32] 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). 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 to compare the groups´ characteristics. A repeated measures ANOVA (2 [amateur; highly-trained] x 6 [running conditions]), with Bonferroni post-hoc test, was performed to determine the effect of different slope gradients on spatiotemporal parameters and stiffness for the whole group and the subgroups. A partial correlation analysis, adjusted by athletic level, was conducted between stiffness and spatiotemporal gait characteristics and between stiffness and spatiotemporal adaptations with increased gradients (Δ) (e.g., CT at 11% - CT at 0%). Finally, a stepwise linear regression analysis was performed between stiffness (Kvert and Kleg), spatiotemporal characteristics and spatiotemporal adaptations with increased gradients. The data were analyzed with SPSS, version 21.0, for Windows (SPSS Inc., Chicago, IL, USA), and the significance level was set at $p < 0.05$.

3. Results

Fig. 1 shows the spatiotemporal variables (CT, FT, SF, SA and SL) with increasing slope gradient (0–11%) and compares the amateur vs. highly-trained group. The 2×6 ANOVA found no significant between-group differences in CT (p = 0.315), FT (p = 0.116), SF (p = 0.189), SA (p = 0.189) and SL (p = 0.266) at any gradient; however, significant within-group differences were observed with increased gradients (relative to level running, 0% slope) in both groups for every variable ($p < 0.05$).

Fig. 2 shows the CT-FT percentages during the step cycle (A), and the percentages of the different sub-phases during the ground contact phase (B). No significant between-group differences were found in CT and FT percentages during the step cycle (%CT: p = 0.131; %FT: 0.191), while significant within-group differences ($p < 0.001$) were found in both groups for CT and FT (relative to level running, 0% slope) (Fig. 2-A). As for the percentages of the different sub-phases of ground contact phase (Fig. 2-B), no between-group differences were found in Phase1 (p = 0.779), Phase2 (p = 0.393) or Phase3 (p = 0.174); however, significant within-group differences ($p < 0.05$) were found in both groups for each variable (relative to level running, 0% slope).

Fig. 3 shows comparison of amateur vs. highly-trained athletes over the entire protocol (0–11% slope gradients) for Kvert and Kleg. Between-group differences were found for Kvert (p = 0.017) which was higher (at 0% slope) in the amateur group, but not for Kleg ($p \geq 0.05$). Relative to level running (0% slope), greater Kvert were found in both the amateur group and the highly-trained group with increased slope gradients ($p < 0.05$). Kvert significantly increased when running on severe slopes (9% and 11%) compared to level running (0%) in both amateurs (p = 0.039 at 9%, p = 0.010 at 11%) and highly-trained athletes (p = 0.004 at 9%, p = 0.006 at 11%). Kleg was significantly

reduced at increased gradients in both amateurs (p = 0.03) and highly-trained athletes (p = 0.043). Amateur athletes reduced Kleg at 3% slope (p = 0.001), 5% slope (p = 0.004) and 7% gradient (p < 0.001) relative to level running, whereas highly-trained athletes reduced Kleg at 5% (p = 0.037) and 7% gradients (p = 0.019).

Partial correlation analysis adjusted by athletic level revealed some significant correlations between stiffness and certain spatiotemporal parameters. During level running (0%), Kvert was significantly correlated with SF and SL (r = 0.674 and -0.665, respectively; $p < 0.001$); while Kleg was significantly correlated with FT, CT and SA (r = 0.852, -0.901 and 0.872, respectively; $p < 0.001$). Spatiotemporal adaptations when running uphill compared to level running (i.e., Δ: 11%-0% comparison) were correlated with Kvert and Kleg. Kvert was shown to be significantly correlated with ΔSF and ΔSL (r = 0.872 and -0.805, respectively; $p < 0.001$), while Kleg was significantly correlated with ΔCT, ΔFT and ΔSA (r = -0.998, 0.875 and 0.893, respectively; $p < 0.001$).

Stepwise linear regression analysis showed significant associations between stiffness and spatiotemporal parameters. During level running (0%), Kvert (dependent variable) showed a significant association with SF ($R^2 = 0.483$, $p < 0.001$), with FT, CT, SL and SA excluded from the model. The Kleg showed a significant association with CT ($R^2 = 0.797$, $p < 0.001$), with the rest of spatiotemporal parameters excluded from the model. Regarding the association between stiffness and spatiotemporal adaptations to different slope gradients, Kvert was associated with ΔCT, ΔFT, ΔSF and ΔSA, with ΔSL excluded from the model ($R^2 = 0.547$, p = 0.002), while Kleg was associated with ΔCT with the rest of the variables excluded from the model ($R^2 = 0.322$, p = 0.003).

4. Discussion

The aim of this study was to determine the effect of different slope gradients (0%–11%) on spatiotemporal gait characteristics during running, taking into account the influence of athletic level, vertical and leg stiffness. The main findings were: (i) at a given speed ($12 \, \text{km.h}^{-1}$), runners increased their CT and SF and decreased their FT, SL and SA at increased gradients (0–11%); (ii) no differences in the spatiotemporal adaptations were found between amateur and highly-trained athletes with increasing gradients, although highly-trained athletes showed a non-significant increased FT, SL, SA, and phase3 during stance period, and reduced CT, SF and phase2; (iii) relative to level running, Kvert increased with severe slopes (9–11%) while Kleg was reduced with moderate slopes (3–7%) regardless of the athletic level and; (iv) Kleg was strongly associated with spatiotemporal parameters during level running, whereas Kvert was associated with spatiotemporal adaptations at increasing gradients (0–11%).

Some previous studies have examined the influence of uphill running on the kinematic variables [6–14], and some differences when compared to level running have been reported. Higher gradients have been reported to be associated with a higher SF during uphill running [7,9,14,15]. Padulo et al. [10] indicated that there was an increase in the phase3 and a decrease of ground reaction force at a constant speed on slopes, which produced a considerable SF increase and SL decrease. Swanson and Caldwell [13] used a speed of $\sim 16 \, \text{km h}^{-1}$ at 0% and 30% gradient and reported a reduction in SL and an increase in SF. Gottschall and Kram [7] also found a decrease in SL and an increase in SF at $\sim 11 \, \text{km.h}^{-1}$ speed and gradients of 3, 6, and 9%. The results from this study support the results of these aforementioned experiments. Conversely, other studies reported no changes or opposing changes when running uphill. For example, Telhan et al. [15] reported no changes in SF and SL when comparing –7% downhill, level (0%), and 7% uphill running at $11 \, \text{km.h}^{-1}$, whereas Gottschall and Kram [7] found no change in CT. One reason for the lack of agreement may be the methodological disparities.

The running technique of the highly-trained athletes may be expected to adapt better to the need for efficient work output than the
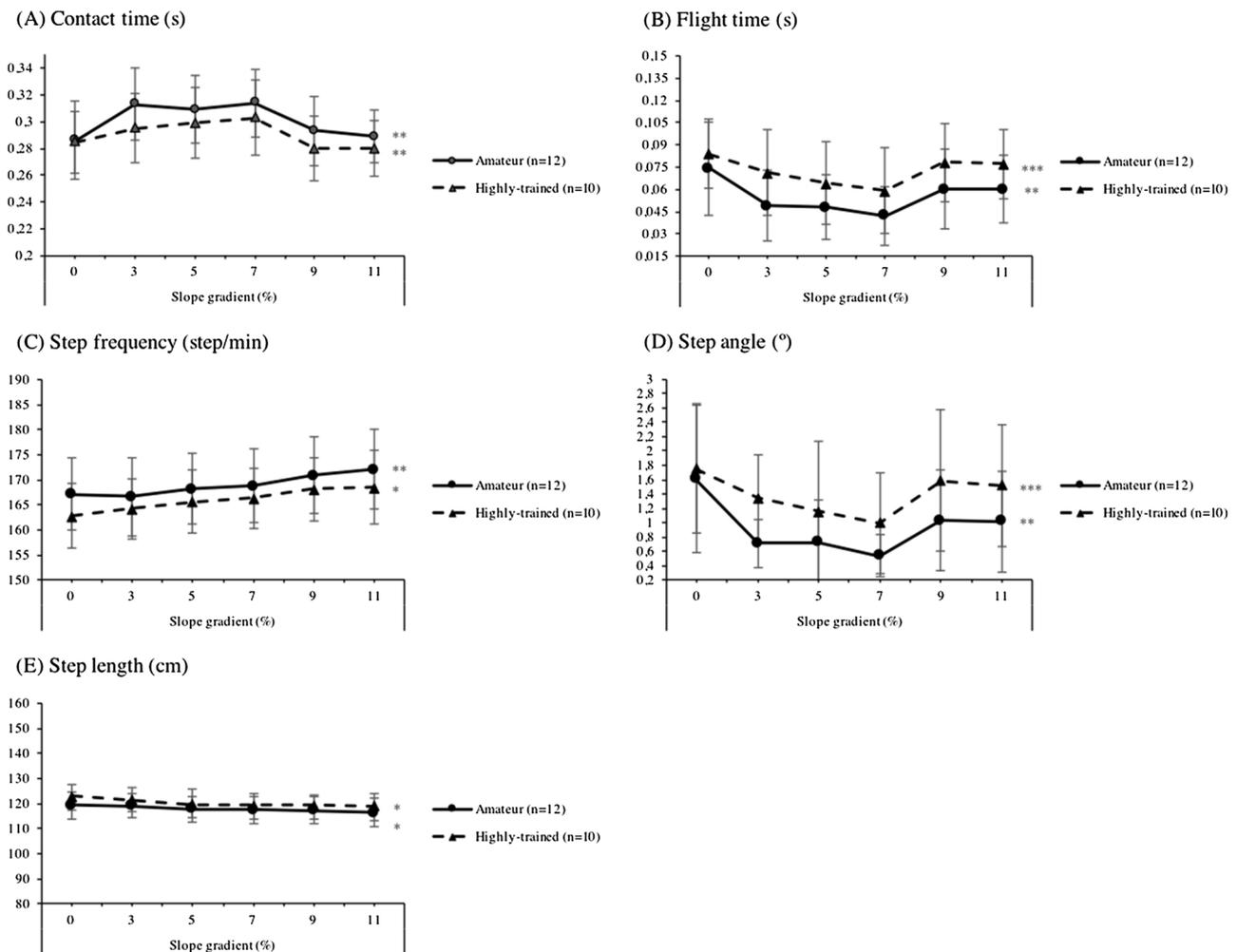
Fig. 1. Dynamics of spatiotemporal variables with increased slope gradients (0–11%) according to the athletic level (amateur vs. highly-trained groups): (A) Contact time; (B) Flight time; (C) Step frequency; (D) Step angle; (E) Step length. * indicates within-group differences, $p < 0.05$; ** indicates within-group differences, $p < 0.01$, ***indicates within-group differences, $p < 0.001$.

amateur runner, who would react differently to the altered circumstances. To the best of the authors' knowledge, only one previous study [10] has examined the dynamics of CT, FT, SL and SF at different running speeds and considering different gradients (0, 2, and 7%), in amateur and elite marathon runners. Padulo et al. [10], reported no differences in the spatiotemporal adaptations to running uphill between amateurs and highly-trained athletes, suggesting that increasing gradients might impair the more efficient ability of highly-trained athletes to use the ground reaction force to increase the SL and FT in a shorter stretch-shortening cycle. These results are in line with the current study results, which found no significant differences between the two athletic groups. However, we must be cautious to interpret data because a no significant trend is observed in the amateur vs. highly-trained comparison (with highly-trained athletes showing increased FT, SL, SA, and phase3 during stance period, and reduced CT, SF and phase2). The authors hypothesize that a greater sample size or a more homogeneous group might reveal differences in spatiotemporal adaptations.

During locomotion, Kvert is always greater than Kleg because leg length changes exceed those of the centre of mass [30,32]. Although Kvert and Kleg are derived from similar mechanical concepts, they are not synonymous and adapt differently to changes in running conditions [30–33], therefore examining both Kvert and Kleg is justified. Limited evidence is available on the effect of running uphill on stiffness. A previous study [14] concluded that Kvert increased when running uphill, whereas Kleg remained constant across the different gradients

under investigation (-8 to +8%). These results partially agree with those reported in this study, which were that Kvert increased with severe gradients (9–11%) while Kleg was reduced with moderate slopes (3–7%) (relative to level running). Methodological differences (i.e., the Lussiana's study was performed at $10\,\mathrm{km.h^{-1}}$ and with slopes -8 to +8%) along with methodological limitations (i.e., the calculation of stiffness during running on slopes, discussed further in the limitations section) make the comparison difficult. Nevertheless, the regression model performed in the current study provides some interesting information about the dynamics of lower-body stiffness during level and uphill running. A strong association between Kleg and spatiotemporal parameters was found during level running, whereas Kvert was associated with spatiotemporal adaptations at increased slope gradients (0–11%). Padulo et al. [10], indicated that increasing the slope may impair the ability to use the ground reaction force to increase the SL and FT in a shorter stretch-shortening cycle. The authors suggest that athletes have to apply greater forces (Fmax in the Morin's equation [30]) to maintain running velocity with increased slope gradients and that, along with the reduction of the centre of mass displacement caused by higher SF [14], increases Kvert during running uphill.

The relationship between stiffness and running performance is complex and often misunderstood [33]. This study reports no differences between the amateur and highly-trained groups, apart from higher Kvert observed during level running in the amateur athletes; whereas, a previous study [30] concluded that elite middle-distance
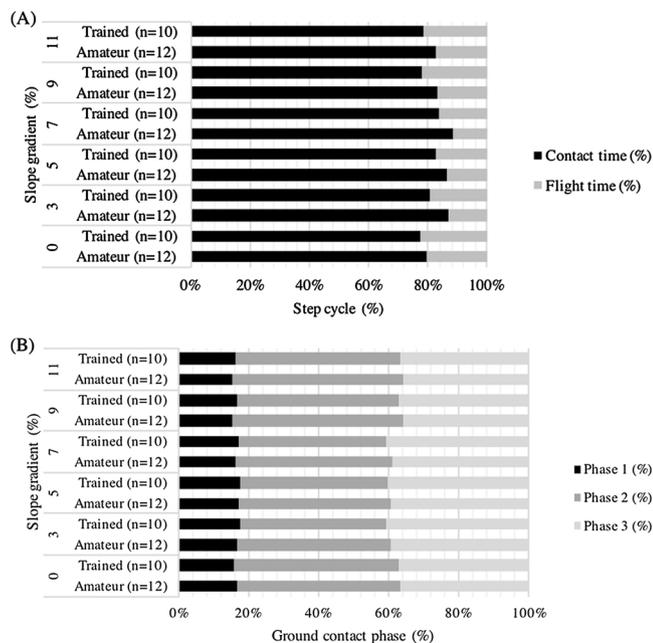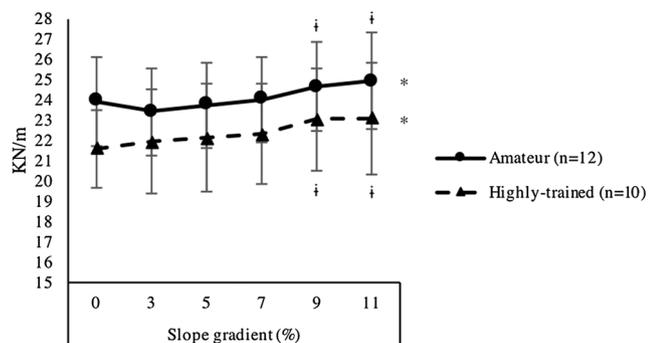
Fig. 2. Spatiotemporal parameters with increased slope gradients: (A) Contact and flight times (in percentages) during the step cycle; (B) Percentages of the different sub-phases during the ground contact period. Phase 1: initial contact; Phase 2: midstance; Phase 3: propulsion.
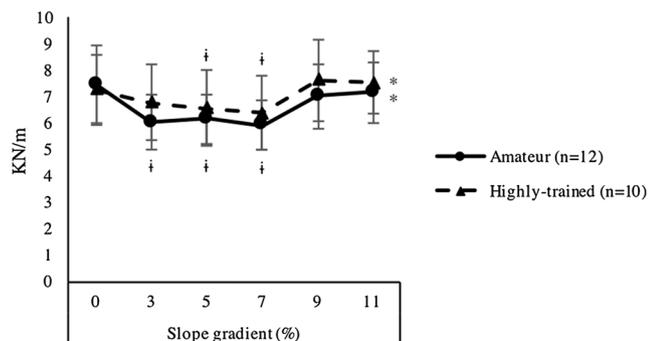

Fig. 3. Vertical (Kvert [A]) and leg stiffness (Kleg [B]) during the running protocol at different slope gradients according to the athletic level (amateur vs. highly-trained comparison). * indicates within-group differences, p < 0.05; † indicates between-group differences (p < 0.05).

runners showed higher Kvert and Kleg than the non-specialists athletes. Again, the data should be interpreted with caution due to methodological differences. The authors suggested that the differences might be

due to the foot strike pattern and/or SF. First, a previous work showed that increases in plantar-foot and plantar-flexion angles during ground contact cause significant changes in the spring-mass characteristics describing human motion, with higher stiffness values [34]. This parameter was not controlled in the current study and therefore more evidence is needed to highlight the role of foot strike pattern. Second, a higher SF seems to be related to a higher Kvert [31]. Amateurs showed a non-significant higher SF during level running which may explain the differences.

Eventually, some limitations of this study need to be considered. First, the use of laboratory settings to simulate uphill running creates significant technical challenges and limits the participant's ability to regulate their running speed [5]. Second, there are limits to the assessment of stiffness during slope running (e.g., the assumption of symmetrical oscillations of the spring-mass model is not entirely respected). Despite this is an important point and readers must be cautious when interpreting and applying these findings, the use of slopes smaller than 15.8% (< 9°) has minor biomechanical implications regarding parameters involved into the sine-wave method [7,8,35] and, thereby, the use of the Morin´s method during uphill running (< 15.8%) seems to be reasonable. Indeed, a previous study already used this method with light slopes (-8 to +8%) [9]. Snyder et al. [8] reported no differences in the elastic energy storage while running uphill across grade up to 15.8%. Similarly, Kowalsky and Li [35] found changes in total lower extremity power absorption and generation with significant slopes (> 15.8%). Regarding ground reaction forces, Gottschall and Kram [7] concluded that the normal active force peaks (i.e., active peak studied by Gottschall and Kram is the Fmax calculated by the sine-wave method by Morin and colleagues [30]) did not significantly change during uphill running using slopes up to +9° (15.8%). Notwithstanding these limitations, it seems important to investigate if spatiotemporal adaptations during uphill running vary with athletic levels, how stiffness changes with gradient, and what role stiffness plays in spatiotemporal gait characteristics while running at different gradients.

In conclusion, an increased slope gradient (0–11%) at a given running velocity (12 km.h^{-1}) caused spatiotemporal adaptations regardless of the athletic level of the runner, although a non-significant trend differentiated the adaptations between the amateur and highly-trained groups. The results also indicated that leg stiffness plays a key role in the characteristics of spatiotemporal gait during level running, whereas vertical stiffness is strongly associated with spatiotemporal adaptations when running uphill.

Conflict of interests

The authors declare that they have no conflict of interests.

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