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Effect of surface inclination on vertical loading rate and footstrike pattern in trail and road runners

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ABSTRACT

Trail runners have been reported to be more injury prone than road runners. Limited past studies have examined the difference in the running biomechanics between the two groups of runners. More importantly, the effect of surface inclination has not been fully investigated. Hence, this study examined the effect of surface inclination on running biomechanics in trail and road runners. Twenty trails and 20 road runners were recruited in this study. Trail runners appeared to be more experienced and had longer training distance per week ($p < 0.001$) compared to road runners. All participants ran at a self-selected pace on an instrumented treadmill in three inclination conditions (i.e., level, +10% uphill and −10% downhill) in a random order. Vertical average loading rate (VALR), vertical instantaneous loading rate (VILR) and footstrike angle (FSA) were measured using established methods. Trail runners experienced greater VILR ($p = 0.039$, Cohen's $d = 2.9$) with a greater FSA ($p = 0.002$, Cohen's $d = 1.1$) during downhill running than road runners. No significant differences in VALR, VILR and FSA were found between the two groups during level and uphill running. Our findings provide potential biomechanical rationale to explain a higher injury incidence among trail runners.

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Introduction

Distance running is a popular sport worldwide, and there are more than 9 million road runners around the globe (International Institute of Race Medicine, 2019). Apart from road running, trail running is an emerging and fast growing division. The International Trail Running Association (ITRA) reported that there are approximately 1.8 million trail runners worldwide and more than 25,000 trail races conducted across 195 countries (International Trail Running Association [ITRA], 2020). ITRA defines trail running as running on different natural terrains (e.g., forests, mountains, deserts) and a maximum of 20% of the route on paved

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road (International Trail Running Association [ITRA], 2013). Trail running includes longer distances and greater surface inclination changes, for example, the 2023 Flash Trail Challenge in Japan was 77 km and 3,790 m of elevation gain (ITRA, 2023). In contrast, road running includes running on asphalted roads, relative shorter course and smaller surface inclination changes (Sabater Pastor et al., 2023).

Trail runners appear to be more injury prone than road runners (Hamill et al., 2022; Viljoen et al., 2021). Prospective cohort studies found that trail runners sustained 10.7–19.6 running-related injuries in 1,000 hours of training (Hespanhol Junior et al., 2017; Viljoen et al., 2021), while road runners only had 2.5–5.8 injuries per 1,000 hours of running (van Mechelen, 1992). Such higher injury risk may be related to the longer running distance encountered by trail runners (Schuh-Renner et al., 2017). Few previous researchers have also examined the characteristics between these two groups of runners. For example, Sabater Pastor et al. (2023) compared running biomechanics between trail and road runners, and they found no significant differences in cadence, contact time, flight time and vertical stiffness between the two groups during level and inclined surface running. In this particular experiment, participants were not tested during running on a slope, which is a common condition encountered by trail runners. Dar et al. (2020) evaluated the structural integrity of the Achilles tendon using ultrasound imaging between the two groups of runners with similar weekly mileage. They reported greater disorganisation of the fibrillar structure in the Achilles tendon in road runners compared to trail runners. This structural change could possibly be due to exposure to higher loads (Matos et al., 2020). However, it remains unknown whether this greater load on the Achilles tendon is related to a faster training pace, or a forefoot strike landing pattern, which is a biomechanical parameter considered to influence impact loading (Almeida et al., 2015; Giandolini et al., 2016; Kulmala et al., 2013).

Footstrike pattern can be evaluated kinematically by measurement of footstrike angle (FSA) (Altman & Davis, 2012), which is the angle between the foot and the running surface in the sagittal plane at initial contact. Impact loading is usually quantified by vertical average loading rate (VALR) and vertical instantaneous loading rate (VILR), which are the average and maximum slopes of the line through the 20% to the 80% point of the vertical impact peak, respectively (Davis et al., 2016). Previous studies have suggested an interaction effect of running surface (i.e., level, uphill and downhill running) on both footstrike pattern and vertical loading rates (de Almeida et al., 2015; Johnson & Davis, 2022). Specifically, past studies have reported runners experience greater VALR and VILR during downhill running than uphill running (Lemire et al., 2022) and high loading rate may be a key biomechanical risk factor of running-related injuries (Chan et al., 2018; Willwacher et al., 2022).

It is known that runners may experience similar impact loading while running on various running surfaces and textures e.g., concrete, grass and rubber track (Miltko et al., 2022). Thus, it is reasonable to speculate that trail and road runners will respond differently to surface inclination in terms of footstrike pattern and impact loading. Hence, this study sought to compare footstrike pattern and impact loading between trail and road runners during uphill, level and downhill running. We hypothesised that trail runners would experience higher VALR and VILR compared to road runners during sloped running, particularly downhill running (Lemire et al., 2022). We also hypothesised that road runners would exhibit more rearfoot strike (RFS) compared to trail runners while running on slopes, as observed by Kasmer et al. (2016).

Materials and methods

Participants

Forty adult runners (20 road runners and 20 trail runners) were recruited from local running clubs to participate in this study (Table 1). Both groups were similar in gender distribution, age, body height, body weight and average training pace ($p > 0.05$). However, trail runners were more experienced ($p < 0.001$; Cohen's d = 1.3) and ran for a longer distance per week ($p < 0.001$; Cohen's d = 1.7). All participants ran >15 km/week for at least 6 months prior to participating in our study. Participants were classified as trail runners if they had more than 70% of self-reported training time on trails; and road runners if they had more than 70% of self-reported training time on concrete pavement. The exclusion criteria included: individuals who had lower limb surgery or sustained injury in the past 12 months. The experimental procedures were reviewed and approved by the ethics committee of concerning institution (Reference number: HSEARS20181130002). All participants provided written consent prior to the tests.

The sample size was calculated based on the effect size (i.e., d = 0.5) in vertical stiffness reported from a previous study comparing running biomechanics between trail and road runners (Sabater Pastor et al., 2023). Assuming alpha at 0.05 and beta and 0.2, 34 participants were required. Our sample size (i.e., $n = 40$) was deemed sufficient to power the study.

Experimental procedures

All participants had reflective markers affixed onto their 2nd metatarsal head and calcaneus according to a previously established kinematic method to detect footstrike pattern (Altman & Davis, 2012). The trajectory of these markers was recorded with a motion capturing system with 10 high-speed infrared cameras (VICON, Oxford, UK) operating at 200 Hz. Given the highly comparable nature of running biomechanics between running on a treadmill and overground running (van Hooren et al., 2020),

Table 1. Demographic data of participants.

Characteristics	Road runners ($n = 20$)	Trail runners ($n = 20$)	p
Gender	10	12	0.530
Male	10	8	
Female			
Age (year)	33.5 ± 6. 8	34.7 ± 5.8	0.537
Body height (m)	1.74 ± 0.07	1.72 ± 0.08	0.295
Body weight (kg)	63.7 ± 7.2	63.1 ± 7.1	0.792
Running experience (year)	6.5 ± 2.3	10.0 ± 2.9	<0.001*
Weekly mileage (km)	21.0 ± 2.8	25.8 ± 3.0	<0.001*
Average training pace (km/h)	12.9 ± 2.7	13.7 ± 2.8	0.327
Minimalist index (%)	32.0 ± 10.8	29.3 ± 7.4	0.390
Test speed (km/h)	12.1 ± 1.9	12.6 ± 1.9	0.424

Data are presented as mean ± standard deviation (SD).
*denotes a statistical significance.

participants were assessed on an instrumental treadmill (AMTI, MA, USA) sampling at 1,000 Hz (Futrell et al., 2020; Scheltinga et al., 2023) in three inclination conditions (i.e., level, +10% uphill and −10% downhill). Runners were tested with their usual running shoes, and they ran at a self-selected pace; this pace was kept constant across all three conditions (Futrell et al., 2020; Reynolds et al., 2023; Venable et al., 2022). An online randomiser ('www.random.org') was used to randomise the test sequence of different conditions. Kinetic and kinematic data was collected for 1 min after 9 min of adaptation (Cheung & Ng, 2007) and participants had 10 min of rest between trials (Shamsoddini & Hollisaz, 2022).

Data acquisition and analysis

We calculated VALR and VILR from vertical ground reaction force curves obtained from the instrumented treadmill in each condition, using a customised MATLAB code (R2023a, MathWorks, Natick, MA, USA). Force data was filtered with a fourth order, low pass Butterworth filter at 50 Hz (An et al., 2015). VALR was the slope of the line through the 20% to 80% vertical impact peak and VILR was the maximum slope of the same region (Blackmore et al., 2016). Footstrike pattern was classified based on the FSA (Altman & Davis, 2012), with a value larger than or equal to 8° indicating RFS, −1.6° to 8° indicating midfoot strike (MFS), and −1.6° or less indicating forefoot strike (FFS).

Minimalist index

We used the minimalist index, a validated rating scale to quantify the degree of minimalism of the participant's test shoes (Esculier et al., 2015). This instrument quantifies the level of minimalism based on assessments of the shoe weight, stack height, heel-toe drop, flexibility, and stability. The full score of the minimalist index is 100%, where 100% indicates 'extremely minimalist', and 0% indicates 'not minimalist at all' (Esculier et al., 2015).

Statistical analysis

The data was analysed using SPSS (Version 29.0, IBM Corp, Armonk, NY, USA). Data normality and homogeneity were tested by Shapiro–Wilks test and Levene's test. Repeated measures ANCOVA were used to compare the biomechanical variables (i.e., VALR, VILR and FSA) across different surface inclinations (i.e., level, uphill and downhill) between trail and road runners, considering potential covariates, such as running experience, training pace, test speed and minimalist index of the test footwear. If indicated, pairwise comparisons were conducted with Bonferroni adjustment. Global alpha was set at 0.05.

Results

All 40 participants completed the running biomechanics assessment and the two groups were tested at similar speed (Table 1, $p = 0.424$). Repeated measures ANCOVA indicated that training pace, test speed and minimalist index of the test footwear did not present

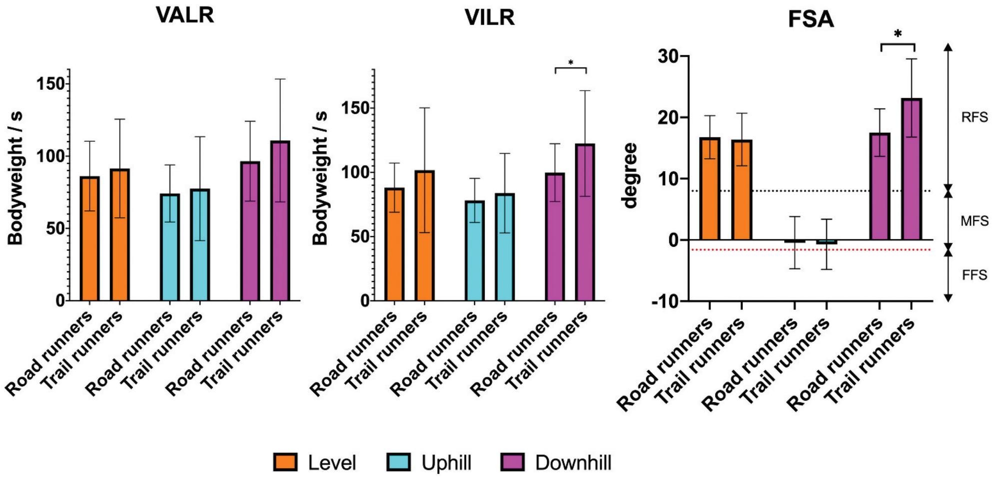

Figure 1. Comparison of vertical loading rates and footstrike angle between trail and road runners.

a significant influence on the dependent variables ($p > 0.05$). However, participants' running experience was recognised as a significant covariate on VILR (Figure S1, $p = 0.041$).

After controlling the covariate effect, we found a significant interaction effect between the two groups of runners and running slope on VALR (F = 8.75; $p < 0.001$), VILR (F = 10.71; $p < 0.001$), and FSA (F = 8.10; $p = 0.005$). However, main group effects of running group were insignificant for VALR (F = 0.60; $p = 0.444$), VILR (F = 1.98; $p = 0.167$), and FSA (F = 2.65; $p = 0.112$). Pairwise comparisons indicated that trail runners experienced a greater VILR ($p = 0.039$, Cohen's d = 2.9) with a greater FSA ($p = 0.002$, Cohen's d = 1.1) during downhill running, than road runners. We did not find any significant difference in VALR, VILR and FSA between trail and road runners during level and uphill running (Figure 1 and Table S1).

In terms of footstrike pattern, all trail and road runners used RFS during both level and downhill running. During uphill running, 15 and 5 road runners switched to a MFS and a FFS, respectively. A similar pattern was also observed among trail runners, with 16 and 4 of them landing with MFS and FFS on inclined surface.

Discussion and implication

The overall objective of this study was to examine the relationship between FSA, VALR, and VILR between trail and road runners during running on different slopes. We found trail runners experienced greater VILR with a more significant RFS than road runners during downhill running, supporting our primary hypothesis. However, no significant differences were observed in VALR, VILR and FSA between trail and road runners during level and uphill running.

Trail runners appeared to sustain a greater impact loading during downhill running than road runners. This can be explained by the difference in FSA between the two groups. Although both trail and road runners exhibited RFS while running on a declined surface, the FSA indicated that trail runners landed with a more dorsiflexed ankle than road runners. As a previous meta-analysis suggested a positive relationship between ankle dorsiflexion with loading rate (Almeida et al., 2015), trail runners may experience a greater vertical loading rate due to a higher body stiffness upon initial contact (Hunter, 2003). We speculate that trail runners used a greater rearfoot strike pattern during downhill running, in order to improve their running economy at a faster running speed (Gruber et al., 2013). Such increase in the vertical loading rate during downhill running has been associated with a higher joint loading in the lower limbs, which in turn may lead to a higher injury risk (Wells et al., 2020).

In the present study, we detected a difference in VILR, but not VALR, between trail and road runners during downhill running. It can be partly explained by the higher sensitivity of VILR over VALR in quantifying impact loading (Ueda et al., 2016). We did not detect any significant differences in biomechanical variables (i.e., VALR, VILR and FSA) during level and uphill running. These findings are similar to a previous investigation on running biomechanics between trail and road runners (Sabater Pastor et al., 2023). Potentially there is a floor effect in level and uphill running conditions, as the loading rate in these conditions is usually lower than downhill running, due to a smaller vertical displacement of centre of mass (An et al., 2015). Dar et al. (2020) suggested there is a possibility of a greater disorganisation of the fibrillar structure in the Achilles tendon among road runners compared to trail runners. Given the fact that we found similar footstrike patterns during level and inclined surfaces between the two groups of runners, the difference in the integrity of Achilles tendon reported by Dar et al. could likely have resulted from a faster running pace in those road runners.

It is important to note that the trail runners in our sample were more experienced and had longer weekly mileage than those road runners in the present study. Anecdotally, most distance runners start with road running, as it is more convenient and there is no driving to trailheads required. With more experience, runners may prefer the adventurous alternative to the monotony of the pavement and start trail running. Possibly due to a longer distance covered by trail than road races, trail runners usually have longer running mileage, and it is also reflected in our sample. This argument is supported by our additional ANCOVA analysis, which found that running experience and running group may influence VILR during running (Figure S1).

Trail runners have been known to sustain more running-related injuries than road runners (Viljoen et al., 2021). Although the nature of a cross-sectional design in the present study cannot confirm causal relationship between running biomechanics and injury, our findings provide potential biomechanical rationale for the greater injury risk among trail runners. As previously stated, our trail runner group ran longer distance per week compared to road runners. A longer exposure to running training has been suggested to increase the cumulative load experienced by musculoskeletal structures and this cumulative load may exceed the mechanical capacity of specific body structures and cause injuries (Bertelsen et al., 2017; Damsted et al., 2019). Additionally, our findings indicate that trail runners may experience greater impact loading. It has been reported that the viscoelastic structures of the musculoskeletal system do not respond well to these impulsive loads (Davis et al., 2016). A previous large scale randomised control trial has reported a causal relationship between high impact loading and running-related injuries (Chan et al., 2018). We therefore speculate that the higher injury risk among trail runners is a result of the combined effects of a longer exposure of excessive impact load on the musculoskeletal system during running, particularly on a downward slope. However, it is also important to note that some previous studies failed to identify impact loading as a predictor of running-related injury (Kliethermes et al., 2021; Schmida et al., 2022). Given the fact that running-related injury is multifactorial in nature (Hollander et al., 2021), future work should investigate the prospective injury risk between trail and road runners in relation to VALR, VILR and FSA.

There are a few limitations in this study that should be considered when interpreting our results. First, this study is a cross-sectional study by design, thus, a causal relationship cannot be confirmed. Second, the degree of inclination in our experiment is small, which may not fully represent the surface inclination encountered in the real-world particularly by the trail runners. Third, we did not examine of the effect of fatigue in the present study. A previous study found that fatigue may alter loading placed on the lower extremities during running (Gao et al., 2022). Finally, acceleration/deceleration and turning while running were not considered. In addition, all researchers and participants were not blinded and were aware of the different test conditions. Future prospective studies are warranted to examine the influence of identified parameters on injury risk. More biomechanics studies are needed to investigate those unconsidered factors, such as fatigue, acceleration and turning during trail and road running.

Conclusion

Trail runners may experience greater impact loading with a greater degree of ankle dorsiflexion upon landing than road runners during downhill running, but not on a flat or inclined running surface. These biomechanical differences may partly explain the higher injury risk among trail runners, when compared to road runners. Further research is necessary to explore the impact of footstrike pattern adjustments among trail runners on vertical loading rates and the risk of running-related injuries.

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