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Plantar Loading during Uphill and Flat Jogging on Ground and Treadmill

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Abstract: This study aimed to compare plantar loading during uphill and flat jogging on both outdoor ground and treadmill surfaces. Twelve healthy male runners, equipped with in-shoe pressure measurement devices (Podoon insoles), completed uphill and level running sessions at 7 km/hr on both ground and treadmill surfaces. One-minute steady-state data were collected and analyzed. Results indicated no significant interaction effect of surface and slope on peak impact force and peak active forces ($p > 0.05$). However, uphill running led to significantly lower peak impact forces and higher peak active forces compared to level running ($p < 0.05$). In conclusion, uphill running, whether on ground or treadmill, can reduce peak impact forces and increase active forces. It is recommended that runners with prior lower limb injuries undergo uphill jogging training on a treadmill with controllable slope to mitigate impact loads.

1. Introduction

Jogging is a popular form of aerobic exercise that can be practiced both outdoors (ground) and indoors (treadmill). Uphill running is often used as a form of resistance training to enhance athletic performance [1]. However, it can be challenging for runners to find a suitable slope and length for outdoor uphill running, leading some to use a treadmill with controllable slope and speed for training [1,2]. Research has indicated that uphill running on a treadmill at a slower pace can produce similar metabolic stimulation to flat running while reducing loading rate and peak active force [3]. Therefore, uphill running on a treadmill is considered a safer method of resistance training compared to running on flat surface, which is in line with the principles of biomechanics.

Although jogging has many health benefits, it also carries a risk of injury due to the impact force on the feet during landing, leading to lower limb sports injuries [4–7]. Jogging results in two peak vertical ground reaction forces (vGRF) during contact. The first peak, known as the peak impact force [8–10], occurs when initial contact with the ground and is generally linked to lower limb injuries [8,11]. The second peak, the peak active force [8,9], occurs during the mid-stance phase of landing. Previous studies on the effect of slope running on plantar impact force have used various methods, such as treadmill experiments with force plates [3,12], ground experiments with force plates [13–15], and experiments on treadmills with varying slopes using wireless in-shoe pressure measuring insoles [16]. Despite extensive research on the effects of running on different surfaces, differences still exist [17–19]. Previous studies have shown that compared to running on a flat ground, treadmill jogging results in lower peak active forces in vertical directions and peak medial forces [17]. As a result, the reaction force patterns during uphill running on a treadmill and on the ground may differ. However, few studies have examined this phenomenon simultaneously, particularly regarding whether the peak impact force and peak active force in plantar during uphill treadmill running are equivalent to those during uphill ground running. Therefore, further investigation is necessary to clarify this issue.

Wireless in-shoe pressure measurement refers to the use of insoles placed inside a runner's shoe to detect the plantar reaction force during each step of running. It can capture the reaction force of multiple steps during natural running on both ground and treadmill environments. Unlike force plate experiments, which are limited to data collection only on the force plate and may result in an unnatural gait, wireless in-shoe pressure measurement can collect data on a larger number of steps during natural gait. Studies have shown that the peak running reaction force measured by the insole and the force plate exhibit excellent consistency (ICC: 0.92-0.94), making wireless in-shoe pressure measurement an effective and reliable tool for measuring ground reaction force [20]. This study aimed to use wireless insole pressure measurement to compare peak impact force and peak active force in plantar during running on flat ground and uphill, both on a ground and on a treadmill. We hypothesized that uphill running result in lower peak impact force and higher peak active force, and that there are differences between ground and treadmill conditions. These findings will provide valuable insights into the effects of different training environments on plantar impact force during jogging.

2. Materials and Methods

2.1. Participants

Twelve healthy male who regularly engaged in jogging participated in this study (age: 24.33 ± 1.25 years old, height: 175.67 ± 4.5 cm, mass: 80.67 ± 7.36 kg, BMI: 26.05 ± 1.05 kg/m^2). All participants had been running for 3.50 ± 0.50 years and had no history of lower extremity nerve, muscle, bone, tendon, ligament, or cardiovascular diseases within one year prior to the experiment. Before the experiment, each participant was fully informed about the research methods, procedures, and precautions, and provided informed consent to participate in the study. The Podoon pressure measuring insole (Paodong Inc., China, Fig. 1) with a sampling frequency of 100 Hz was used in this study to measure the plantar reaction force. It comprised of 3 pressure sensors (Fig. 1b) positioned at the first phalanx where the inner longitudinal arch and transverse arch met, the fifth phalange where the outer longitudinal arch met the transverse arch, and the heel where the inner longitudinal arch met the outer longitudinal arch. The insole body was made of EVA, and it also had a Bluetooth transmission chip and battery.

(a) (b)

Figure 1: Podoon pressure sensitive insole (a) and sensors placements (b).

2.2. Validity experiment

To ensure the accuracy of the Podoon insole's measurements, a validity check was conducted prior to the formal experiment. The participants wore Nike Free running shoes with Podoon insoles while running on a Kistler force plate (Type 9287, Kistler, CH) at a speed of 7km/hr with a 2000Hz sampling frequency. They ran three times and the results were analyzed. The Podoon insole measurements were found to be highly correlation with the vGRF-time profiles measured by the Kistler force plate, and a correlation coefficient of r = 0.98 was obtained through Pearson correlation analysis. After the absolute value was converted by the linear regression equation (y = 1.0744x-146.62, R^2 = 0.97), it is highly consistent with the force plate (Fig 2).

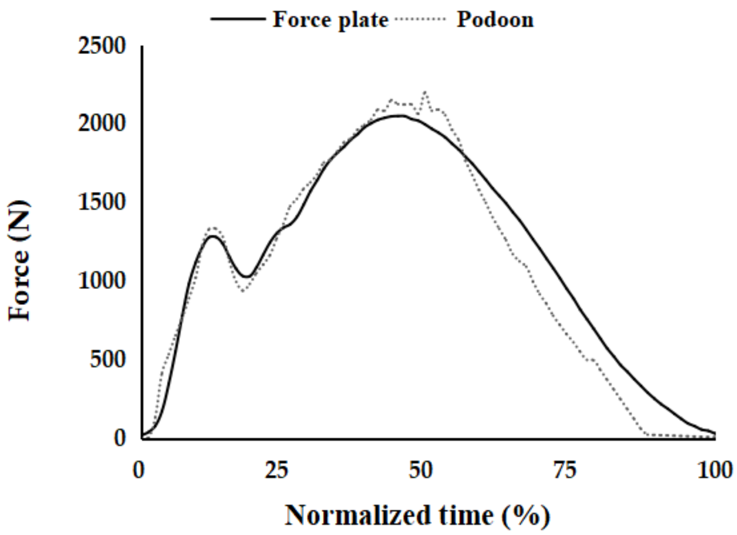

Figure 2: Representative absolute GRF-time profiles derived from the Podoon insole (grey dotted curve) and force plates (black solid curve) during jogging. The exemplary data was considered representative as they were derived from the participant with the median r among participants.

2.3. Running experiment

The participants performed in random order both 500m of 6° uphill running [18] and 0° flat running tests, which were conducted on both a treadmill and a ground at a speed of 7km/hr.

2.4. Data processing

A 20-Hz low-pass filter was used to eliminate high-frequency noises. The peak impact force and peak active force of each step during a 1-minute stable period were analyzed. The peak force data were standardized by body weight when standing statically on flat ground. The peak impact force was determined as the first peak value generated after landing, and the peak active force was determined as the largest peak occurred during mid-stance.

2.5. Statistical Analyses

The statistical analyses conducted by using SPSS 23.0 software. Two-way repeated-measures ANOVA was performed to compare the effects of different surfaces (ground, treadmill) and slopes (uphill, flat) on the peak impact force and peak active force. The statistical results also presented net Eta square (η_p^2) and statistical test power (1-β). The significant level was set at $\alpha = 0.05$.

3. Results

No significant interactions were observed between surfaces (ground, treadmill) and slopes (uphill, flat) for both peak impact force and peak active force ($p > 0.05$, Table 1). However, significant differences were found ($p < 0.05$) among different slopes for both peak impact force and peak active force. Specifically, uphill running had a significantly lower peak impact force but a higher peak active force ($p < 0.05$) compared to flat running.

Table 1: Peak reaction force of running under different surfaces and slopes (N=12).

					Two-way repeated measures ANOVA results				
		Overground	Treadmill	Average		F	p	η_p^2	power
Peak impact force (BW)	Flat	1.86 ±0.38	1.97 ±0.49	1.92 ±0.43[a]	Surface	0.014	0.907	0.001	0.051
	Uphill	1.74 ±0.49	1.59 ±0.51	1.67 ±0.50[a]	Slope	7.432	0.020*	0.403	0.700
	Average	1.80 ±0.43	1.81 ±0.54		Surface*Slope	3.427	0.091	0.238	0.394
Peak active force (BW)	Flat	1.62 ±0.18	1.74 ±0.23	1.68 ±0.21[a]	Surface	3.112	0.105	0.221	0.364
	Uphill	1.76 ±0.08	1.93 ±0.29	1.84 ±0.22[a]	Slope	10.239	0.008*	0.482	0.829
	Average	1.69 ±0.15	1.85 ±0.28		Surface*Slope	0.667	0.431	0.057	0.116

*$p < 0.05$; [a]Significant difference between flat and uphill

4. Discussion

This study analyzed the plantar peak impact force and peak active force during running on different slopes (flat vs uphill) and surfaces (ground vs treadmill), confirming that slope significantly affects both peak impact force and peak active force. Specifically, uphill running resulted in lower peak impact force but higher peak active force, supporting the study's hypothesis. Contrary to expectations, the type of surface did not significantly affect these variables, with no significant difference found between running on the ground and on the treadmill in terms of their effects on peak impact force and peak active force with slope. This study provides valuable insights into the biomechanical changes that occur during running on different slopes and has practical implications for designing training programs to improve performance and reduce the risk of injury.

This study provides support for previous research [19] indicating that there are no significant differences in the peak values of plantar impact force and active force between running on a ground and running on a treadmill. Additionally, the study found that there were no significant differences in the peak values of plantar impact force and active force between running uphill at 7km/hr on a ground and running on a treadmill at a 6° incline. These results suggest that the ground surface does not significantly affect the peak values of plantar impact force and active force during uphill running. Based on the findings of this study, runners can be reassured that running uphill on a treadmill does not significantly increase the vertical impact load on the soles of their feet compared to running uphill on the ground.

It is important to note that this study did not analyze the horizontal reaction force, which may exhibit differences between the ground and treadmill. Previous research has indicated differences in peak propulsive force and reaction force on the medial and lateral sides when running on a treadmill. As a result, further research is warranted to investigate differences in anteroposterior and medial-lateral forces when running uphill on the ground versus on a treadmill.

The findings of this study are consistent with previous research that has shown that running uphill results in lower peak impact force, peak horizontal braking force, and peak heel pressure, as well as higher peak horizontal propulsion force compared to running on flat ground [12,14–16]. These results suggest that running uphill may be advantageous because it reduces the impact force on the heel when running uphill, and high impact forces have been linked to an increased risk of injury [11,21,22]. Moreover, the increase in active force during uphill running is associated with higher muscle contraction intensity and energy expenditure, as well as increased activation of the rectus femoris, vastus lateralis, gastrocnemius, and soleus muscles of the lower limbs. This is due to the greater demand for generating active force when pushing against the increased slope. Studies have shown that uphill running can result in increased energy expenditure and muscle activation in the lower limbs [3,23]. Therefore, for runners who want to improve their running performance, running uphill can be an effective training method as it can increase muscle activation and energy expenditure and reduce impact force. Additionally, it is worth noting that running on a treadmill with a controlled slope and speed can provide a safer and more convenient environment for uphill running compared to outdoor terrain, which may be uneven and unpredictable.

This study exists limitations. Although it found a significant difference in peak impact force among slopes ($p = 0.02$), the statistical power was slightly below 0.8 (power = 0.700), which raises the risk of a Type II error. The small sample size may be the reason for this. Additionally, this study used a plantar pressure measurement insole to compare the plantar reaction force between the ground and treadmill at different slopes, but the device did not measure the horizontal reaction force. Therefore, the study could not determine if there were differences in the horizontal reaction force between the two surface conditions. Lastly, this study only tested a fixed slope and speed, limiting the generalizability of the findings to the specific exercise conditions used in the experiment.

5. Conclusions

Based on the findings of this study, it can be concluded that uphill running, whether performed on a treadmill or on the ground, results in lower peak impact force and higher peak active force than flat running. Furthermore, the changes observed in plantar reaction force during uphill running were similar between the two conditions. Therefore, individuals, especially runners or those with a history of lower limb injury, may consider using a treadmill with controlled slope and speed for uphill running training to reduce the impact load on their lower limbs during foot contact.

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