Original article

# Surface effects on in-shoe plantar pressure and tibial impact during running

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## Abstract

*Purpose*: This study aims to explore the effects of running on different surfaces on the characteristics of in-shoe plantar pressure and tibial acceleration.

*Methods*: Thirteen male recreational runners were required to run at 12 km/h velocity on concrete, synthetic track, natural grass, a normal treadmill, and a treadmill equipped with an ethylene vinyl acetate (EVA) cushioning underlay (treadmill_EVA), respectively. An in-shoe plantar pressure system and an accelerometer attached to the tibial tuberosity were used to record and analyze the characteristics of plantar pressure and tibial impact during running.

*Results*: The results showed that there were no significant differences in the 1st and 2nd peak plantar pressures (time of occurrence), pressure–time integral, and peak pressure distribution for the concrete, synthetic, grass, and normal treadmill surfaces. No significant differences in peak positive acceleration were observed among the five tested surface conditions. Compared to the concrete surface, however, running on treadmill_EVA showed a significant decrease in the 1st peak plantar pressure and the pressure–time integral for the impact phase ($p < 0.05$). These can be further ascribed to a reduced peak pressure observed at heel region ($p < 0.05$).

*Conclusion*: There may not be an inevitable relationship between the surface and the lower-limb impact in runners. It is, however, still noteworthy that the effects of different treadmill surfaces should be considered in the interpretation of plantar pressure performance and translation of such results to overground running.

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*Keywords:* Peak plantar pressure; Pressure distribution; Running; Surface; Tibia acceleration

## 1. Introduction

Running is a popular activity with high accessibility and low cost. Unfortunately, the high participation in running has been accompanied by a high incidence of running injuries.[1] In a review of various epidemiological studies, it has been reported that up to approximately 60% of runners sustain overuse injuries every year.[2] In long distance running, the repetitive impact forces experienced during ground contact can reach a magnitude ranging from 2 to 3 times body weight, and are considered to be major causes of overuse damages such as stress fracture and patellofemoral pain syndrome.[3] Hence the concept of "cushioning" has been proposed in sports surface and shoe manufacturing to reduce impacts and prevent injuries over the past 30 years.

However, no conclusive consensus has been reached regarding the effects of shoe cushioning in reducing impact forces and external loading. The reasons for the inconclusive results include different musculoskeletal adaptations and subject-specific reactions in athletic activities.[4,5] Meanwhile, the mechanism for these adaptations is still not well understood[6] and systematic studies of the effect of surface cushioning are lacking.

Since in-shoe pressure characteristics are more sensitive than force platform data in detecting effects due to changes of surface,[7] plantar pressure measurement has been widely employed in examining the actual loading applied to the feet to understand injury mechanisms.[8] Several studies have reported the characteristics of the plantar pressure when running on different overground surfaces.[9–13] A number of them suggested that running on grass can induce lower plantar loads and thus may reduce the risk of musculoskeletal injuries among runners.[9,10,12] Tessutti and colleagues[9] found higher peak pressures at the central and lateral rearfoot on asphalt compared to

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natural grass. It was also observed that running on grass produced significantly lower peak pressure at the rearfoot and forefoot than asphalt, concrete, and rubber.[10] It is, however, noteworthy that a considerable number of studies have found that surface does not have an effect on plantar loads and running-related injury.[11,14,15] Tillman et al.[11] reported that maximum plantar force, contact time, and total impulse were not significantly different when running on asphalt, concrete, synthetic, or grass surfaces. A proposed explanation was that runners may utilize internal compensatory mechanisms to deal with the changing surfaces. Moreover, from an epidemiological viewpoint, occurrence of running injuries was independently associated with higher weekly mileage ($p < 0.001$), rather than running and training surfaces ($p > 0.05$).[15,16] Thus, no clear scientific consensus has been reached yet regarding the compliance influence of running surfaces on reducing plantar pressure and/or overuse injury during running.

The impact shock, which is associated with overuse injuries in runners, has been widely quantified by the tibia acceleration.[17–20] A recent study found that running at 5.0 m/s on concrete was associated with significantly greater tibial shock compared to running on a hockey-specific synthetic surface.[21] In addition, Greenhalgh et al.[22] reported that a concrete surface caused a significantly larger tibial shock than the other surfaces (wood, wood with aluminum overlay, and wood with metallic overlay) when performing a fencing lunge. It should be noted that a fencing lunge is not a repetitive movement compared to running, and no traditional running surface was involved in either study. Thus, few well designed studies have been conducted to clearly address the effects of different surfaces on tibial impact in running, which further hinders our understanding of the potential mechanisms of running-related injuries.

Treadmills are widely used in research, training, and recreational exercise.[23] However, whether there are differences in kinematic patterns and foot loading when running on a treadmill compared to overground running remains unclear.[13,24,25] To our knowledge, only one study has compared plantar loads in running on a treadmill, concrete, and natural grass.[13] It showed that running on a treadmill induced lower peak plantar pressure and longer contact time for the total foot and two toe regions. This indicated that the plantar load distribution in treadmill running was indeed different from running on overground surfaces. In this earlier study, however, only one type of treadmill was used to compare with other surfaces. There are, obviously, a variety of treadmills on the market that have different mechanical properties and cushioning functions. Therefore, more data regarding the comparison of different treadmill running conditions and the relationship to overground running are still needed.

Therefore, the purpose of the study was to explore the effects of running on different surfaces on the characteristics of in-shoe plantar pressure and tibial acceleration. Five surfaces were evaluated: concrete, synthetic track, grass, normal treadmill, and treadmill equipped with an ethylene vinyl acetate (EVA) cushioning underlay (treadmill_EVA). We hypothesized that running on both grass and cushioned treadmill would lead to a decrease in plantar pressure as well as tibial impact during stance phase.

## 2. Methods

### 2.1. Subjects

Thirteen male recreational runners (age: $23.7 \pm 1.2$ years; height: $173.7 \pm 5.7$ cm; mass: $65.7 \pm 5.2$ kg) were recruited to participate in this study. The subjects had $3.5 \pm 1.4$ years of running experience on treadmill and overground surfaces with a mean distance of $20.4 \pm 5.2$ km/week. They all ran with a regular rearfoot strike pattern, and had no musculoskeletal injuries of the lower extremity within the past 6 months prior to the testing. A *post-hoc* power analysis was conducted using a statistical power analysis software (version 3.1.9; G*Power, Heinrich-Heine-University, Düsseldorf, Germany) as described before.[26] A two-tailed *t* test was used to determine whether a sample size of 13 was sufficient to avoid type II error for our variables of interest ($p = 80\%$ at $\alpha = 0.05$). Each of them signed an informed consent approved by the Ethics Committee of Shanghai University of Sport.

### 2.2. Running surfaces

Five different surface conditions were tested in this study: concrete, synthetic track, grass, treadmill (SH-A5188; Shuhua Co. Ltd., Jinjiang, China), and treadmill_EVA (SH-5199; Shuhua Co. Ltd.). The two types of customized treadmill had identical structure and materials. The only difference was that a 5-cm EVA cushioning underlay was added between the runner's feet and the treadmill_EVA platform. The velocity could be changed from 1.0 to 14.0 km/h for both treadmills.

The index of ball rebound from American Society for Testing Materials (ASTM) standard was chosen as a reference to indicate the cushioning property of the five surfaces. According to the ASTM F2117-01 standard test method for vertical rebound characteristics of sports surface/ball systems, a standard basketball (size 7# with an air pressure of 0.06 MPa) was vertically dropped from a height of 2 m on each surface. Five trials were recorded and the average rebound height was calculated to indicate the surface hardness (Table 1). A higher rebound height indicates a harder surface. Specifically, the grass and treadmill_EVA were more compliant than the standard treadmill and the track, and the concrete was the least compliant.

In addition, minimally cushioned shoes (Shanghong Shoes Co. Ltd., Shanghai, China) were provided in order to eliminate the cushioning property from the shoes. They were equipped with a rubber outsole and a thin foam insole but no midsole.

Table 1
Comparison of rebound height in ball rebound testing among five different surfaces.

| Surface condition | Rebound height (cm) |
| --- | --- |
| Concrete | $152.0 \pm 1.7$ |
| Synthetic track | $148.7 \pm 1.1$ |
| Grass | $80.5 \pm 6.2$ |
| Treadmill | $125.6 \pm 2.3$ |
| Treadmill_EVA | $104.6 \pm 4.8$ |

Abbreviation: EVA = ethylene vinyl acetate.

## 2.3. Instrumentation

An in-shoe measuring system (version 4.4; T&T Medilogic Medizintechnik GmbH, Schönefeld, Germany) was utilized to collect plantar pressure data during running. The thickness of the insole was 1.2 mm. Each insole contained a maximum of 240 force sensors (depending on insole size and shape) with dimensions of $0.6 \times 0.4$ cm and a working dynamic range of 6–640 kPa. The system uses resistive sensors and has been validated.[27] Each insole was calibrated using the manufacturer's calibration device (T&T Medilogic Medizintechnik GmbH) prior to the study. A small portable datalogger was attached to the subject's waist to enable the data to be transferred to a computer via a wireless connection. The plantar pressure data were collected at a sampling frequency of 300 Hz.

A biaxial accelerometer (Biovision Corp., Wehrheim, Germany) was glued to the tibial tuberosity of the dominant leg.[28] It was stabilized with a stretched elastic strap, which encircled the superior portion of the leg below the knee, to improve congruence of motion with the skin surface.[29] Meanwhile, accelerometer location was marked to ensure accuracy and consistency of placement. After the testing a square indentation was apparent on the skin at the site of attachment. The measurement range of the accelerometer was $\pm 50\,g$ ($g = 9.81$ m/s$^2$) with a bandwidth of DC-1000 Hz, a mass of 4 g, and dimensions of $1.4 \times 0.9 \times 0.5$ cm. Specifically, the accelerometer was aligned with the $x$ axis tangential to the skin surface and parallel to the longitudinal axis of the tibia, and its $y$ axis normal to the skin surface. The acceleration data were collected at a sampling rate of 1200 Hz using a data acquisition system and DASYLab software (version 8.0; DATALOG GmbH, Mönchengladbach, Germany).[30]

## 2.4. Experimental procedure

Outdoor running was conducted on a 30-m straight concrete runway, synthetic track, and straight grass runway. The average temperature and relative humidity during the outdoor testing varied from 18°C to 22°C and 42% to 47%, respectively. Prior to data collection for each condition, subjects practiced on the runway to adapt to the surfaces. They were then required to run at the target velocity (12 km/h) for three times on each of the three surfaces. A marker was placed at the great trochanter of the subject. A high-speed camera (MotionPro X-4; Integrated Design Tools Inc., Pasadena, CA, USA) was used to record the marker trajectory to monitor the velocity of the runner. Specifically, two vertical signs were placed at the start and end points of the measurement zone (7.5–22.5 m). The target running velocity was $12.0 \pm 0.6$ km/h throughout the 15 m.[13] As the sampling rate was 100 Hz, the number of captured frames should be between 428 and 472. If the frame number fell out of this range, the trial was discarded. Plantar pressure data of both feet and tibial acceleration of the dominant leg were collected. Data collection started from 7.5 m to 22.5 m (15 m measurement zone) during the 30 m of running. Ten strides from the 15 m measurement zone were selected to be analyzed.

Treadmill running tests were conducted on both customized treadmill and treadmill_EVA (with an EVA cushioning underlay) in an indoor biomechanics laboratory. The indoor running testing was carried out at a constant room temperature of 21.3°C $\pm$ 0.4°C and relative humidity of 45.6% $\pm$ 1.8%. After the 5 min warm-up to familiarize with treadmill running, the subjects were required to run on the treadmill at a velocity of 12 km/h for 3 min. Plantar pressure data of both feet and tibial acceleration of the leg were collected for 10 strides during the last minute.

The order of the surface conditions was randomized. A rest period of 5 min was provided between surface conditions.

## 2.5. Data reduction

Plantar pressure data were analyzed using Medilogic software (version 4.4). In the current system, the plantar pressure was calculated using force divided by insole area. Specifically, with the Medilogic system plantar pressure was calculated by summing forces over all the sensors in the selected area and dividing by the summed area of those sensors. A regional analysis of each foot was performed by dividing the plantar surface into five selected areas, i.e., forefoot (40% of foot length), midfoot (30% of foot length), heel (30% of foot length), medial (50% of foot width), and lateral (50% of foot width). The use of the above mentioned masks to determine plantar pressure in running has been described in a previous study.[31] Plantar pressure variables of interest included: (1) contact time (CT); (2) 1st and 2nd peak pressure (kPa) of the entire foot (FPP and SPP); (3) the time to FPP and SPP; (4) the pressure–time integral (PTI), which was defined as the impulse of pressure (Fig. 1), was calculated for both the impact phase (from touchdown to the occurrence of FPP) and stance phase (from touchdown to toe-off); (5) the peak pressure distribution of the five selected plantar areas during the heel-contact phase (from touchdown to heel-lift).

The acceleration data were analyzed using DASYLab software (version 8.0). It was filtered through a Butterworth second-order, zero-lag, low-pass filter at a cut-off frequency of
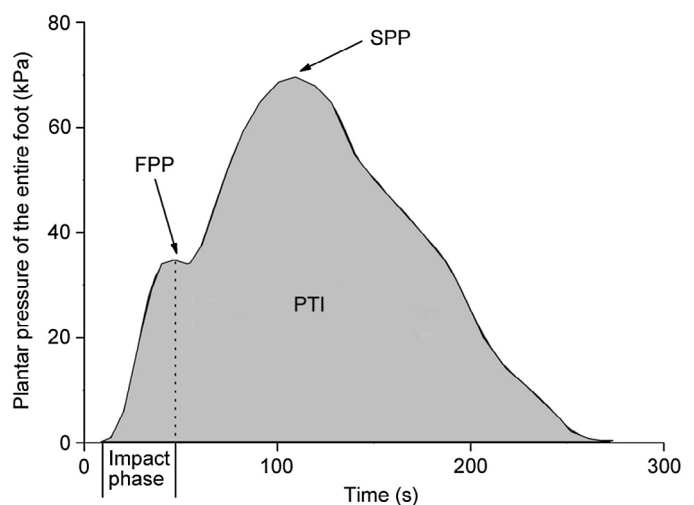


Fig. 1. The in-shoe pressure–time curve during the stance phase of running. FPP = first peak pressure; SPP = second peak pressure; PTI = pressure–time integral.
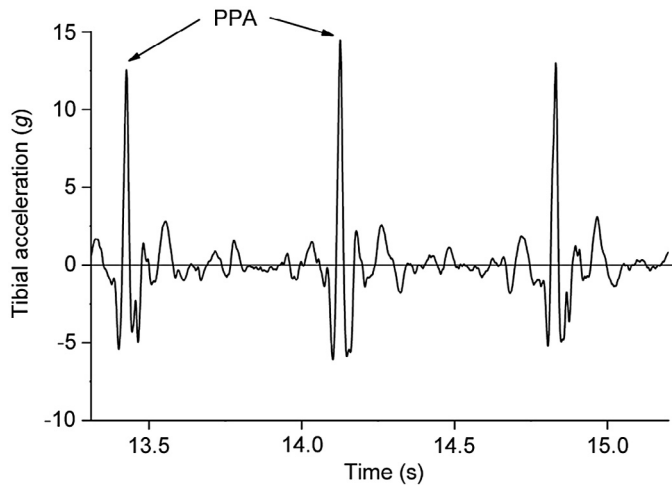
Fig. 2. A representative acceleration curve recorded on the tibial tuberosity during running on grass. PPA = peak positive acceleration.
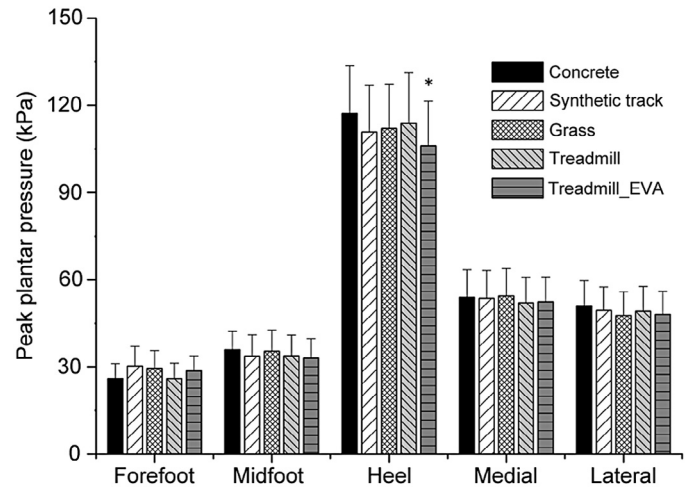


Fig. 3. Comparison of different surfaces in peak pressure distribution during the heel-contact phase. EVA = ethylene vinyl acetate. * $p = 0.039$, compared with concrete.

100 Hz based on a power spectrum analysis.[20] Peak positive acceleration (PPA), which represents peak tibial impact, was determined as the highest positive value on the acceleration waveform. Fig. 2 shows a representative curve of the acceleration waveform and the determination of PPA during running on grass.

### 2.6. Statistical analysis

All data are presented as mean ± SD. Dependent variables were examined using the Shapiro–Wilk test to make sure that their distribution did not differ significantly from normality. Separate one-way ANOVA with repeated measures were executed to determine the effects of surface on plantar pressure characteristics and tibial shocks (SPSS version 13.0; SPSS Inc., Chicago, IL, USA). The significance level was set at $\alpha = 0.05$.

### 3. Results

#### 3.1. Characteristics of plantar pressure

Among the five surfaces, no significant differences were observed in the total CT, the FPP, the SPP, the time to the FPP and SPP, and the PTI during the stance phase (Table 2). However, compared to the concrete surface, running on treadmill_EVA showed a 12.1% decrease in FPP ($F = 3.812$, $p = 0.045$) and a 20.8% decrease in PTI ($F = 4.522$, $p = 0.038$) during the impact phase. Meanwhile, there were no significant

differences in the temporal and plantar pressure variables among the three overground surface conditions, i.e., concrete, synthetic track, and grass.

Results of the peak pressure distribution during the heel-contact phase of running on different surfaces are illustrated in Fig. 3. No surface effect was observed for the peak plantar pressure at the forefoot, midfoot, medial, and lateral areas. Among all the surfaces, a substantially larger peak pressure was revealed at the heel, which ranged from 106.1 to 117.1 kPa. For running on treadmill_EVA, a 9.1% decrease was observed in the peak plantar pressure at the heel compared to running on concrete ($F = 4.182$, $p = 0.039$). However, no significant differences were observed in the peak pressure at the heel among the concrete, grass, synthetic track, and treadmill surfaces.

#### 3.2. Peak tibial acceleration

The PPA ranged from 10.3 to 12.4 $g$ across different surfaces. However, no significant differences in PPA were observed among the concrete ($12.4 \pm 3.1\ g$), grass ($11.1 \pm 3.4\ g$), synthetic track ($10.9 \pm 3.5\ g$), treadmill ($11.6 \pm 3.0\ g$), and treadmill_EVA ($10.3 \pm 3.1\ g$) surface conditions.

### 4. Discussion

The purpose of this study was to examine the effects of surfaces on characteristics of plantar pressure and tibial impact

Table 2
Comparison of temporal and plantar pressure (normalized to body weight) variables for running on five different surfaces.

| Surface condition | CT (ms) | FPP (kPa) | Time to FPP (ms) | SPP (kPa) | Time to SPP (ms) | PTI_IM (kPa × ms) | PTI_ET (kPa × ms) |
|---|---|---|---|---|---|---|---|
| Concrete | 272.6 ± 18.5 | 42.8 ± 3.9 | 36.7 ± 6.2 | 67.6 ± 9.9 | 100.2 ± 16.4 | 1006.5 ± 334.9 | 9186.2 ± 2558.3 |
| Synthetic track | 266.7 ± 28.9 | 37.1 ± 4.6 | 43.3 ± 5.3 | 70.8 ± 8.5 | 102.4 ± 14.2 | 922.3 ± 283.6 | 9049.3 ± 2807.9 |
| Grass | 256.5 ± 8.7 | 40.8 ± 4.3 | 42.4 ± 4.8 | 69.1 ± 7.5 | 101.2 ± 7.2 | 911.8 ± 365.1 | 8787.5 ± 2049.9 |
| Treadmill | 264.2 ± 5.8 | 42.0 ± 4.3 | 39.3 ± 3.5 | 63.3 ± 6.2 | 100.7 ± 3.9 | 961.0 ± 121.9 | 9116.3 ± 2755.6 |
| Treadmill_EVA | 262.6 ± 6.1 | 37.5 ± 4.5[a] | 45.7 ± 4.4 | 64.7 ± 7.5 | 101.9 ± 4.2 | 796.3 ± 133.4[a] | 8976.4 ± 3537.6 |

[a] Significantly different from the concrete ($p < 0.05$).
Abbreviations: CT = contact time; FPP = first peak pressure; SPP = second peak pressure; PTI_IM = pressure–time integral (impulse of pressure) for the impact phase; PTI_ET = pressure–time integral (impulse of pressure) for the entire contact phase; EVA = ethylene vinyl acetate.

in running. Our hypothesis was partially supported by the results which showed that the peak pressure for the total foot and heel region and the PTI were significantly lower on treadmill with an EVA cushioning underlay than on concrete. However, neither the temporal and plantar pressure variables nor tibial acceleration differed significantly among overground surfaces, i.e., concrete, synthetic track, and grass.

## 4.1. Surface effects on characteristics of plantar pressure

Peak pressure and the PTI of entire plantar areas during the impact phase of running were significantly lower in treadmill_EVA than concrete condition. Meanwhile, no significant differences were found in the plantar pressure variables between grass and concrete. In Hong et al.'s study,[13] similar plantar forces during running on concrete and grass surfaces were also observed. Furthermore, in comparison treadmill running is associated with a lower peak plantar pressure at the total foot throughout stance.[13] However, Hong et al.[13] did not mention whether or not there was a significant difference in peak plantar pressure at the entire foot during the heel contact phase between treadmill and overground running. Such a difference between our study and Hong et al.'s can be attributed to the different methods that were being used to calculate the value of peak pressure (force divided by total insole area *vs.* force divided by insole area that is subjected to force), the different structures of the treadmill (SH-5199; Shuhua Co. Ltd. *vs.* 6300HR; Sportsart Fitness), the different testing shoes (minimally cushioned shoes *vs.* running shoes with GEL® cushioning system), and the different running velocities (3.3 m/s *vs.* 3.8 m/s). In addition, we evaluated two types of treadmill, and running on the treadmill without cushioning underlay did not show a significant difference in peak pressure and pressure distribution compared to overground running. We conclude that the treadmill_EVA can alleviate the peak pressure, especially in the heel area, compared to concrete. This indicates that the surface of the treadmill should be taken into consideration as a factor in future studies when examining plantar pressure performance and comparing treadmill and overground running.

It has been proven by a number of studies that running on natural grass may reduce stress on the musculoskeletal system compared to running on a more rigid surface.[9,10,12] Tessutti et al.[9] found that peak pressure and PTI were lower in the central rearfoot, lateral rearfoot, and lateral forefoot regions on the grass compared to asphalt. Similarly, Wang et al.[12] reported that peak pressure increased 12% when running on concrete compared to grass. In the present study, although both the peak pressure and PTI values tended to be smaller on grass compared to on concrete, no statistically significant differences were found between grass and other conditions. The inconsistency might be caused by differences in the characteristics of the surfaces used in our study and others, as the cushioning properties of grass and concrete have not been reported in other studies.

The cushioning property of surfaces has rarely been quantified in studies of the compliance effect of surfaces and plantar pressure during running. In the current study, the order of surfaces from least hardness to greatest hardness was: grass,

treadmill_EVA, treadmill, synthetic track, and concrete. However, neither the FPP nor the SPP increased as the surface hardness increased (Tables 1 and 2). Similar findings have been reported in shod running studies, where insole hardness does not seem to affect peak vertical force[32] and pressure characteristics.[33,34] One possible reason for this phenomenon is that subjects might utilize adaptation or compensation in the lower extremity musculoskeletal system to deal with stiffer surfaces. Tillman et al.[11] found shoe reaction forces, contact time, and impulse were not significantly different among asphalt, concrete, grass, and synthetic track surfaces. It was concluded that runners may be able to compensate for different surfaces in order to moderate the loads to protect themselves from getting injured. Another study collected both kinetics and kinematics data, and reported that the magnitude of impact force was not significantly different among three conventional overground surfaces.[14] Interestingly, they found a more flexed knee position in heel–toe runners when performing shod running on the stiff surface. Previous studies[9,14,35] promoted the idea that runners used compensatory mechanisms by actively changing their limb configuration in response to the changing surfaces; however, it is also possible that such kinematic changes might be a passive mechanical regulation in response to different surfaces. As indicated in a forward dynamic simulation study,[36] kinematic patterns with changing shoe conditions can be regulated by passive mechanisms without any changes to the control parameters of the model. Therefore, without more kinematic and/or electromyography data, we cannot draw firm conclusions about the mechanisms behind kinematic changes associated with different running surfaces.

## 4.2. Surface effects on tibial acceleration

Tibia acceleration was not significantly different among the five overground and treadmill surfaces. Similar to the results of plantar pressure characteristics, the acceleration did not show an association with the surface stiffness. Potthast et al.[19] recently tested the tibial acceleration under external impact on different surfaces. They concluded that the hardness of surface explained less than 10% of the variance of the acceleration, while knee angle and muscle pre-activation explained 25%–29% and 35%–48%, respectively. In other words, muscle force and knee joint angle have greater effects in comparison to interface hardness on the severity of shocks on the lower leg.

During stance phase, humans have the ability to alter leg stiffness to run on different surfaces but maintain similar contact time and characteristics of impact forces.[37,38] Ferris et al.[39] examined the peak ground reaction force, ground contact time, and leg stiffness during running on surfaces with different stiffness. Runners were found to be adjusting the stiffness of their lower extremity in order to achieve a consistent effective vertical stiffness (including the surface stiffness and leg stiffness). Nigg[40] further ascribed the insensitivity of impact forces to sports surfaces to the changes in runner's movement patterns and adaptation effects produced by the surface–athlete combination. These findings partially support the present results.

Runners may need to increase their leg stiffness (actively or passively) on soft surfaces while reducing stiffness on relatively hard surfaces. On the other hand, several studies have shown that running barefoot or with a minimalist shoe causes runners to alter their foot striking pattern, generally inducing them to shift toward a more anterior footstrike.[41] In the current study, however, we ensured that the subjects, who were all heel-strikers, did not change their foot strike pattern across different surfaces. We did this by carefully re-checking our video data and the center of pressure trajectory during stance. It is more likely that the runners would make some adaptation of their lower extremity kinematics instead of totally altering their foot strike strategy.

Furthermore, another factor that needs to be considered when assessing surface effects on tibial acceleration is the running velocity. A recent study[21] measured tibial acceleration on concrete and synthetic sports surfaces (SSS) when subjects were running at 3.3 m/s and 5.0 m/s. They found that the tibial shock was significantly greater on concrete than SSS when running at 5.0 m/s. However, no differences were observed between surfaces when running at 3.3 m/s. In our study, subjects were also running at approximately 3.3 m/s and no difference in tibial acceleration was found. Therefore, it may be that the running speed of 3.3 m/s may not be fast enough to cause the difference in tibial impact when running on different surfaces.

In this study we required subjects to practice running on both treadmills prior to the testing, but one cannot be certain that their running pattern was not affected by factors such as the minimally cushioned shoes, the adaptation of the lower extremity to the running belt transfer speed, and the instability of treadmill itself when being impacted.[13] Furthermore, we used the height of ball rebound as an alternative reference to indicate the cushioning ability of the surface. The interpretations of the findings, therefore, should take these points into consideration. Under the premise of correctly quantifying the mechanical properties of different surfaces, assessment of lower limb kinematics, accompanied with joint kinetics and muscle forces, was warranted to provide further evidence of neuro-musculoskeletal reactions and potential loading information associated with the surface and running-related injuries.

## 5. Conclusion

During overground running, surface conditions did not influence the characteristics of in-shoe plantar pressure and tibial acceleration, yielding no changes in 1st and 2nd peak plantar pressure (and time of occurrence), PTI, peak pressure distribution, and peak tibia acceleration. These findings indicated that different running surfaces do not necessarily affect the peak plantar impact and, by implication, impact-related injuries in runners. It is, however, still noteworthy that running on cushioned treadmill is associated with a reduced peak pressure at the heel compared to a concrete surface. Therefore, surface effects in different treadmills should be considered in the interpretation of plantar pressure performance and translation of results to overground running.

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