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Original paper

In-shoe plantar pressure distribution during running on natural grass and asphalt in recreational runners

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Abstract

The type of surface used for running can influence the load that the locomotor apparatus will absorb and the load distribution could be related to the incidence of chronic injuries. As there is no consensus on how the locomotor apparatus adapts to loads originating from running surfaces with different compliance, the objective of this study was to investigate how loads are distributed over the plantar surface while running on natural grass and on a rigid surface—asphalt. Forty-four adult runners with 4 ± 3 years of running experience were evaluated while running at 12 km/h for 40 m wearing standardised running shoes and Pedar insoles (Novel). Peak pressure, contact time and contact area were measured in six regions: lateral, central and medial rearfoot, midfoot, lateral and medial forefoot. The surfaces and regions were compared by three ANOVAS (2 × 6). Asphalt and natural grass were statistically different in all variables. Higher peak pressures were observed on asphalt at the central ($p < 0.001$) [grass: 303.8(66.7) kPa; asphalt: 342.3(76.3) kPa] and lateral rearfoot ($p < 0.001$) [grass: 312.7(75.8) kPa; asphalt: 350.9(98.3) kPa] and lateral forefoot ($p < 0.001$) [grass: 221.5(42.9) kPa; asphalt: 245.3(55.5) kPa]. For natural grass, contact time and contact area were significantly greater at the central rearfoot ($p < 0.001$). These results suggest that natural grass may be a surface that provokes lighter loads on the rearfoot and forefoot in recreational runners.

Keywords: Biomechanics; Running; Floors and floor coverings; Athletic injuries; Plantar pressure

1. Introduction

The activity of running has increased consistently since the end of the 1960s and the early 1970s (Tillman et al.[1] and Novacheck[2]). As a consequence of this increase in running worldwide, increasing frequency and distance of training and races among runners may be associated to risk factors in the injuries incidence, according to a review of the literature by van Gent et al.[3]

Some authors have considered that excessive impact forces are associated to the occurrence of overuse injuries.[4,5] Milner et al.[6] found higher vertical loading rates and higher tibial shock in runners with a previous tibial stress fracture. The running distance results in chronic load accumulation that is absorbed by the musculoskeletal system and, even when acute loading is light, its repetitive character would imply that this load accumulation will lead to injuries.[7] Thus, the accumulation of load can produce chronic injuries that worsen in subjects who run more than 64 km per week.[3]

Subjects who developed exercise-related lower-leg injury were observed to run with an increased pronation, prolonged eversion, higher plantar pressure underneath the medial side of the foot, as well as an increased reinversion velocity with an increased lateral roll-off.[8] Therefore, we can assume that alterations in the biomechanical patterns of running, such as in plantar pressure distribution,[8] may lead to injury and identification of these alterations could thus help in the promotion of injury prevention.

The type of running surface is known to have an influence on load absorption/absorption mechanisms. Feehery[9] compared asphalt, concrete and natural grass and observed that a shorter time was needed to reach the first vertical force peak during running on concrete in comparison to grass and

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asphalt, but also found a higher first vertical force peak on grass. The author also stated that a potential cause of injury in subjects running on rigid surfaces might be the rapid transmission of the shock wave through the body from harder surfaces, like concrete and asphalt, and account for the apparent limitation of the runner's ability to dampen the high-frequency shock waves as his speed increases.

Ferris et al.[10,11] obtained a substantial difference in the first vertical force peak during running on hard rubber and soft rubber, culminating in a difference in the loading response of the musculoskeletal system. With these differences, the authors concluded that independent of the surface compliancy, human beings are capable of adapting to a new surface, at first footstrike with the new surface after the change of surface. They based this conclusion only on the trajectory of the center of mass at the transition between surfaces, which remained unaltered because leg stiffness itself was modified. On the other hand, Tillman et al.[1] observed similarities in plantar pressure during running whether or not the surface was more or less hard and concluded that the runner was not exposed to additional risk from the overload of a harder surface, possibly due to the biomechanical compensatory mechanisms as noted by Ferris et al.[10,11]

Thus, many running coaches orient their athletes to use a natural grass surface due to the lower risk of developing musculoskeletal injuries.[12] Therefore, how the musculoskeletal system adapts to these repetitive cyclical loads in running and how these adaptations are influenced by the surfaces utilised has not been established.[13] Thus, investigations reported in the literature continue to attempt to relate the type of surface, its influence on load of the locomotor apparatus and on injuries, with no definitive conclusions.

The objective of the study was to investigate how pressure is distributed over the plantar surface during running on a compliant surface such as natural grass and on a more rigid surface such as asphalt. The premise of this study is that substantial differences in loads occur between compliant (grass) and rigid (asphalt) surfaces. The identification of this difference may be one more of the diverse ways to prevent the development of injuries and regulate the intensity of training by permitting greater control of these variables.

2. Methods

Forty-four adult recreational runners (35.7 ± 6.8 years), 32 men (177 ± 6 cm, 75.5 ± 10.6 kg) and 12 women (163 ± 5 cm, 58.1 ± 4.0 kg), were studied. They had 4 ± 3 years of running experience with a mean volume of 35.7 ± 13.4 km/weekly and the most frequent running velocity was from 13.3 to 15 km/h for 10 km runs. The runners must have had experience running on natural grass and asphalt, run at least 20 km weekly, be asymptomatic at the time of evaluation, had no musculoskeletal injury in the last 6 months, and have a maximum leg length discrepancy of 1 cm. All subjects signed an informed consent term approved by the Ethics Committee of the School of Medicine of the University of São Paulo (Protocol No. 0022/07).

Subjects ran a distance of 40m at 12 km/h[1,14–16] and the speed was timed by a stopwatch for 10 of the 30 m after subtracting the first and the last 10 m. The speed was fixed because its control was essential for the reproducibility of the results using the Pedar system.[17] Running velocity was consistent across trials and across all subjects. In order to minimise errors, two observers simultaneously timed the run by stopwatch and the interobserver assessment was concordant with an ICC of 97%.

The in-shoe plantar pressure was measured by the Pedar X system (Novel, Munich, Germany) at 100 Hz. The insoles were placed between the socks and the standardised neutral strike running shoe (RAINHA SYSTEM, RAINHA, Alpargatas, São Paulo, Brazil, Size USA 7–12). The insoles were connected to equipment inside a backpack juxtaposed on the individual's back.

The runners underwent a pre-trial adaptation phase for the footwear and the running speed was established when the same speed had been achieved in at least three consecutive 40 m runs.[14,16,18] After the pre-trial adaptation phase, the individuals ran 40 m on a natural grass surface and an asphalt surface. The order of the surfaces evaluation was established randomly.

Peak pressure (kPa), contact area (cm^2) and contact time (ms) were measured over six regions. The plantar surface was first divided into three larger areas: R, rearfoot (30% of foot length); M, midfoot (30% of foot length); F, forefoot and toes (40% of foot length).[19] The rearfoot and forefoot were subdivided, respectively, into: MR, medial rearfoot (30% of the rearfoot width); CR, central rearfoot (40% of the rearfoot width); LR, lateral rearfoot (30% of the rearfoot width); MF, medial forefoot (55% of the forefoot width); LF, lateral forefoot (45% of the forefoot width).

The data was tested for normal distribution by the Kolmogorov–Smirnov test and homocedasticity was verified by the Levene test. The differences between feet (right and left) were tested by paired-*t*-test. Only one foot was randomly selected for statistical analysis because asymmetry had been detected between feet. Comparisons of surfaces were made using 3 ANOVAs two-way for repeated measures (2 × 6), with the type of surface as one factor (2) and plantar regions (6) as the other factor, followed by Tukey post-hoc test. The level of significance adopted was 1%.

3. Results

The peak pressure over the different surfaces were statistically significant ($F = 9.39$; $p < 0.001$) in the central ($p < 0.001$) and lateral ($p < 0.001$) rearfoot and the lateral forefoot ($p < 0.001$) (Table 1). The peak pressure was 12.7% greater at the central rearfoot during running on asphalt and 12.2% higher in the lateral rearfoot.

Table 1
Mean and standard deviation of contact area (cm^2), contact time (ms) and peak pressure (kPa) for each foot region in grass and asphalt running.

		Contact area (cm^2)	Contact time (ms)	Peak pressure (kPa)
Medial rearfoot	Grass	12.1 (2.1)	154.0 (30.5)	304.8 (63.5)
	Asphalt	12.0 (2.4)	146.2 (27.8)	315.5 (83.6)
Central rearfoot	Grass	22.4 (6.5)[a]	179.0 (44.9)[a]	303.8 (66.7)[a]
	Asphalt	19.6 (2.3)[a]	157.3 (35.2)[a]	342.2 (76.3)[a]
Lateral rearfoot	Grass	11.2 (2.7)	170.5 (53.0)	312.7 (75.8)[a]
	Asphalt	11.1 (2.9)	171.5 (57.7)	350.9 (98.3)[a]
Midfoot	Grass	42.4 (5.0)	214.0 (35.6)	124.2 (29.8)
	Asphalt	41.6 (6.2)	209.8 (43.0)	124.7 (33.7)
Medial forefoot	Grass	36.5 (2.6)	228.5 (21.1)	353.9 (90.5)
	Asphalt	36.0 (3.9)	220.4 (29.0)	362.0 (98.6)
Lateral forefoot	Grass	37.2 (3.0)	236.8 (21.5)	221.4 (42.9)[a]
	Asphalt	36.6 (4.3)	232.4 (31.2)	245.3 (55.5)[a]

[a] Statistically significant difference between the surfaces in the respective regions ($p < 0.001$).

The contact area was different between surfaces ($F = 5.45$; $p < 0.001$) in the central rearfoot ($p < 0.001$) and the contact time was significantly different for both surfaces ($F = 4.33$; $p < 0.001$) in the central rearfoot ($p < 0.001$) (Table 1). The contact area in the central rearfoot was 12.7% greater on natural grass and the contact time on asphalt was 12.1% shorter. The midfoot region showed no difference between surfaces for any of the variables analysed.

4. Discussion

The objective of the present study was to investigate the plantar pressure distribution during running on natural grass and asphalt: two commonly used surfaces for running. In general, the results showed that asphalt and natural grass were significantly different in all variables analysed, with greater loads on rearfoot and forefoot during running on asphalt. A greater contact time and contact area was observed in the rearfoot and forefoot areas when individuals run on grass. In comparison to natural grass, asphalt provokes a greater load on the lateral rearfoot rather than medial region.

Peak pressure was 12.7% greater at central rearfoot and 12.2% at lateral rearfoot during running on asphalt. This demonstrates how much load asphalt adds in comparison to a more compliant surface.

As expected, the contact area was smaller and the contact time was shorter on the asphalt, especially in the central rearfoot. Given that pressure is the relation between force and contact area, the data was shown to be coherent. Contact area in the central rearfoot was 12.7% greater on natural grass. The shorter contact time on the asphalt (12.1% in relation to grass) may imply a lesser possibility of load absorption during heel-strike confirmed by the observed greater peak pressure in this region. This lesser possibility of load absorption may be influenced by kinematic adaptation by the lower limb when running on surfaces with different stiffness.[4,5,11,20]

Hardin et al.[13] found a higher peak ankle velocity when the increase in the surface stiffness shortened the time for the lower extremity to adjust to this new environment. The reduction of potential adjustments of lower limb joints on more rigid surfaces was confirmed by Dixon et al.[4] who observed smaller ankle and knee flexion at heel-strike when running on asphalt in comparison to a rubber-modified surface, and by Ferris et al.[11] findings of smaller knee and hip flexion on a more rigid rubber surface. The greater the knee flexion the lesser the severity of the impact and, consequently, the decrease of risk for potential injury.[5]

On natural grass, the longer contact time may favour greater variability and flexibility in the distribution of loads and result in a better musculoskeletal ability to absorb plantar pressures duet to distal adaptation mechanisms generating greater mobility, especially in the foot/ankle complex.

The smaller loads observed on the rearfoot when running in the compliant surface (grass) is in agreement with the findings of Eils et al.,[14] who compared natural grass and fine red cinder (compliant and hard, respectively), although the greatest pressure on the rearfoot areas differed. In the present study, the greatest load was observed in the lateral rearfoot, and in the study by Eils et al.,[14] the greatest load occurred in the medial region. This difference may be attributed to the fact that in the present study, the runners wore neutral support running shoes in accordance with the manufacturer's recommendations and the runners in the Eils et al.[14] study wore soccer shoes. In addition, the subdivision of the rearfoot was divided in to only two regions: lateral and medial in the cited study, in contrast to three regions in the present study.

On asphalt, the rearfoot made contact with the surface on the lateral part and remained as in this lateral support during push off phase, as shown by greater pressure on the lateral part of the foot. This fact may indicate a reduction in the degrees of freedom available for the adjustments of the foot/ankle complex on a more rigid surface, and consequently a reduction in the ability to absorb impact forces.

Dixon[4] states that alterations in the characteristics of running surfaces can affect the kinetic pattern of movement, which potentially interferes in the technical performance of motor skills. Ford et al.[16] verified differences in the plantar pressure between surfaces evaluated and demonstrated the significant influence of this factor on the overloads imposed on the locomotor apparatus. Kerdok et al.[21] concluded that the surface compliancy positively affects the economy of running, taking into consideration the relation between biomechanical and physiological factors, without affecting running mechanical support or, in other words, its kinetic and kinematic characteristics.

Thus, Eils et al.[14] and Ford et al.[16] state that depending on the surface compliancy chosen for running, there may be differences in the loads experienced by the feet, that are smaller on more compliant surfaces. The present results support a different conclusion in contrast to Ferris et al.[10,11] and Tillman et al.[1] The divergence of the present study from the study by Tillman et al.,[1] which also evaluated plantar pressure while running on surfaces similar is probably due to the different instruments used by the cited authors and with this, a significant difference in spatial resolution affected the mapping of the plantar surface which would lead to different conclusions. Capacitive insoles with approximately 100 sensors were utilised in the studies by Eils et al.,[14] Ford et al.[16] and the present study. The study by Tillman et al.[1] used 16 resistant sensors.

Another result which warrants discussion is the difference observed in the peak pressure between the medial and the lateral regions which demonstrated that asphalt provokes an overload of 4.5 (rearfoot) to 2.8 (forefoot) times greater in the lateral region in relation to the medial region when compared to natural grass. Considering the hypothesis of the smaller capability for adjustment and movement of the foot complex during contact with the surface due to its greater hardness, pressures are not distributed homogeneously, overloading one region of the rearfoot particularly, the lateral. The compliancy of natural grass may have facilitated the flexibility and the degree of freedom of the lower limb, especially the foot, resulting in a change of loading in the rearfoot. With this, a greater possibility may exist of plantar pressure distribution on the lateral and central rearfoot as well as the lateral forefoot when running on grass.

The additional 11% in peak pressure during a 10 km run on asphalt, could lead to overload of the locomotor apparatus at approximately 280 MPa in relation to the same distance on natural grass. Considering that a recreational runner makes approximately 700 footstrikes each kilometer[22] and that the additional peak pressure was 40 kPa in asphalt, this overload could lead to an increase in the risk of musculoskeletal injuries over time when associated to other risk factors.

Even considering that the runner is able to adapt to additional load situations due to the different amount of compliance each surface presents,[10,11] it is still fundamental for the coach to consider this variable when planning training for runners. A demonstration of this adaptation is found in a study by Dixon,[4] who, using mechanical tests, found peak impact force to be six times greater on asphalt in comparison to rubber. However, this difference was not observed when the same variable was evaluated in runners on these surfaces, demonstrating that the locomotor apparatus absorbed the overload imposed by a more rigid surface such as asphalt, in contrast to what was observed in the mechanical testing.

Notable among the other risk factors associated to the running surface that can increase the runner's risk of developing injuries is the risk of misalignment of the lower limbs as reported by some researchers.[23] While the surface is an important factor when considering loading, the effects of other mechanical factors in postural alignment, training variables and the footwear utilised must also be investigated.

For an in-depth discussion of the consequences of the type of surface on the loads produced, a lower limb kinematic evaluation, associated to the plantar pressure distribution could introduce important information on how the foot/ankle complex adjusts to different surface compliances, and consequently, contribute to the knowledge on prevention of injury in recreational runners.

5. Conclusion

The type of surface utilised in running can contribute significantly to the greater loads on the rearfoot and forefoot due to its compliancy. The longer contact time, area and attenuation of peak pressure on rearfoot and forefoot during running on natural grass may be mainly due to a more flexible adjustment of the distal extremity, particularly the foot/ankle complex, to a more compliant surface which is not observed on an asphalt surface where the load is distributed with greater heterogeneity over the plantar surface and especially overloads the lateral region of the rearfoot.

Thus, considering the volume of training and the fact that training occurs primarily on asphalt surfaces, a more compliant surface such as natural grass can be used to attenuate overloads on the musculoskeletal system and diminish the risk of chronic injuries that a more rigid surface occasions.

Practical implications

- When considering forces across the foot, foot pressures experienced when running on asphalt over medium and long distance runs, could predispose a runner to injuries, especially overuse injuries.
- Running on natural grass is likely to be safer than running on asphalt.
- Non-uniform natural grass surfaces can lead to a risk of acute trauma, particularly when used regularly.

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