



PLANTAR PRESSURE AND FOOT TEMPERATURE RESPONSES TO ACUTE BAREFOOT AND SHOD RUNNING

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ABSTRACT

Purpose. Increased contact pressure and skin friction may lead to higher skin temperature. Here, we hypothesized a relationship between plantar pressure and foot temperature. To elicit different conditions of stress to the foot, participants performed running trials of barefoot and shod running. **Methods.** Eighteen male recreational runners ran shod and barefoot at a self-selected speed for 15 min over different days. Before and immediately after running, plantar pressure during standing (via a pressure mapping system) and skin temperature (using thermography) were recorded. **Results.** No significant changes were found in plantar pressure after barefoot or shod conditions ($p > 0.9$). Shod running elicited higher temperatures in the forefoot (by 0.5–2.2°C or 0.1–1.2% compared with the whole foot, $p < 0.01$) and midfoot (by 0.9–2.4°C, $p < 0.01$). Barefoot running resulted in higher temperature variation in the rearfoot (0.1–10.4%, $p = 0.04$). Correlations between skin temperature and plantar pressure were not significant ($r < 0.5$ and $r > -0.5$, $p > 0.05$). **Conclusions.** The increase in temperature after the shod condition was most likely the result of footwear insulation. However, variation of the temperature in the rearfoot was higher after barefoot running, possible due to a higher contact load. Changes in temperature could not predict changes in plantar pressure and vice-versa.

Key words: sports, thermography, shoes, gait

Introduction

Increased contact pressure and friction in different foot regions can impact both plantar pressure and skin temperature [1–3]. Recently, foot thermal profiles were obtained pre- and post-treadmill walking at slow speed (10 min walking at 3.2 km/h) in order to examine the relationship between triaxial loading and temperature responses [1]. The authors reported only a moderate linear relationship between triaxial plantar stresses and walking-induced temperature increases [1]. Additionally, Shimazaki and Murata [2] suggested a possible relationship between contact load and the increase of foot temperature during walking. However, although tissue stresses experienced during walking may be of interest in the study of sensorial disorders (e.g., diabetes), it is during running that increased load is experienced and higher lower extremity injury rates are observed [4]. Also, previous studies have shown that distance running leads to changes in plantar pressure as evidenced by static measures of plantar pressure [3, 5].

Foot temperature in particular may help to understand the effects of footwear, environmental factors and exercise in humans [6]. For example, acute injuries such as

skin blisters may promote increases in foot temperature after running (as a result of friction forces during foot contact with the ground) [7]. In addition, skin temperature was recently suggested as a diagnostic criterion in detection of Charcot arthropathy and neuropathic ulcers in diabetics [8, 9]. The aforementioned literature suggests skin temperature to be an important variable in the study of the foot stress and its relationship with injury risk. Although the stress conditions imposed on the foot could provide an adequate framework in the investigation of the relations between mechanical loads and skin temperature, there is limited evidence on the relationship between plantar pressure and skin temperature in runners.

Addressing the hypothetical relationship presented above when comparing shod and barefoot running could be of interest due to the different stress conditions imposed on foot skin and could help in the clinical management of foot injury. Barefoot running conditions are a subject of increased attention among sport scientists and coaches [10–12], in which a number of investigations revealed a reduction in the risk of injury during barefoot running [13, 14]. This reduction in injury risk was supported firstly by the forefoot strike pattern induced by barefoot running, resulting in a reduction of peak ground forces, and secondly by an increase in the proprioception and muscle strength of the intrinsic foot muscles [12]. However, controversy on barefoot running literature is still evident, and reveals a lack of consensus

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on its final benefits or disadvantages [11]. While shod running has been associated with a higher risk of patellofemoral pain syndrome and tibial stress fractures [10], barefoot and minimalist shoe running have been associated with foot injuries such as stress fractures in the metatarsus, plantar fasciitis, plantar fascia rupture, Achilles tendinitis, and puncture wounds [10, 15, 16].

Despite the current discussion on injury resulting of shod and barefoot running, the two conditions nonetheless impose different loads on the foot [17, 18]. Higher peak and average shock as measured by accelerometry are observed in barefoot running [17] as well as higher plantar pressure in the forefoot during running barefoot and minimalist running [19, 20]. In this regard, we examined barefoot and shod running in order to elicit different stress conditions on the foot. We hypothesized a relationship between plantar pressure and foot temperature particularly in shod running as a result of increased contact pressure and friction on the foot.

Material and methods

Participants

Eighteen physically active individuals (11 males and 7 females; age 24 ± 4 years, body mass 65 ± 17 kg, height 170 ± 11 cm, and body mass index 22 ± 4 kg/m²) volunteered to participate in this study and provided informed consent. All of the participants presented right footedness [21]. The study procedures were performed in agreement with Declaration of Helsinki and approval was received by the Committee of Ethics in Research with Humans of the local university.

Before the experiment began, a footprint image was taken with a podoscope to assess foot posture. Three researchers confirmed foot type (planus, normal, or cavus) based on a majority decision (two out of three). Only participants with normal feet were included in the study. Visual inspection of running kinematics determined that all were rearfoot strikers.

In order to control for confounding variables, the participants were asked to avoid high-intensity or exhaustive exercise, drinking coffee or other stimulants, wearing any jewelry, sunbathing or being exposed to UV radiation, and using sunscreen at least 24 h before the laboratory trials. They were also informed to refrain from drinking alcohol or smoking at least 12 h and not eat anything 2 h before the test (particularly any heavy meal).

Experimental design

Participants ran shod and barefoot on two different days. Each running trial lasted 15 min and was performed on a commercial motorized treadmill. In the first trial, participants were asked to self-select a comfortable running pace eliciting moderate perceived exertion [17]. The speed

was then maintained in both trials (7.3 ± 1.6 km/h among the participants). Plantar pressure data and thermographic images were recorded before and after each running trial.

Plantar pressure

A Matscan pressure mapping system (Tekscan, USA) with 2288 resistive sensors (1.4 sensors/cm²) operating at 400 Hz was positioned on a flat surface. Plantar pressure was recorded in the static condition, which was recently shown to be more sensitive to changes in pressure distribution after short distance running [5]. This assessment required the participant to stand still for 30 s and look at a point at eye-level on a wall 2.5 m from the participant. Three measurements before and after each running trial were collected and averaged. Mean plantar pressure in forefoot, midfoot, and rearfoot was computed by considering each foot region as 50%, 19%, and 31% of the foot length, respectively [22]. Data from each foot region were then normalized to body mass [23] and also converted to percentage load of total plantar pressure [24].

Thermography

Thermographic measurements were taken using an E60 thermographic camera (FLIR, USA) with an infrared resolution of 320×240 px, thermal sensitivity $< 0.05^\circ\text{C}$, and accuracy of $\pm 2^\circ\text{C}$. The camera was calibrated using a black body target (BX-500 IR Infrared Calibrator, CEM, China). Each participant underwent three measurements [25]: before the running test (after 10 min adaptation to the thermal environment of the laboratory [26]), immediately after the test, and then again after a 10 min interval. Images were taken of the soles of both feet while seated with the legs inclined (avoiding contact between the soles and ground). The camera was positioned perpendicularly at a distance of 1 m from the soles. The images were collected in a light- and temperature-controlled room with an ambient temperature of $20 \pm 3^\circ\text{C}$ at $63 \pm 5\%$ relative humidity (Digital Thermo-Hygrometer, TFA Dostmann, Germany). No other individuals (apart from the infrared operator and the participant) were in the room and any electrical equipment was at least 5 m from the measurement location. An anti-reflective panel was placed behind the soles of the feet to minimize the effects of reflected infrared radiation [27].

Images were stored and offline analyses were performed using commercial software (Thermacam Researcher Pro 2.10, FLIR, USA). All images were processed using an emissivity factor of 0.98 to obtain skin temperature in which air temperature, relative humidity, and reflected temperature were defined at the moment of recording. The mean values of skin temperature were extracted from images of three regions of interest (ROI)

corresponding to the forefoot, midfoot, and rearfoot. The foot regions were determined in the same way as for plantar pressure analysis. Skin temperature of the ROIs were normalized and averaged by the percentage variation of temperature and by the percentage temperature of the whole foot. From the percentage variation of the temperatures the following variables were obtained:

1. Temperature variation 1 (ΔT) – percentage of difference between the temperatures immediately after and before the running test
2. Temperature variation 2 (ΔT_{10}) – percentage of difference between the temperatures 10 min after and before the running test.

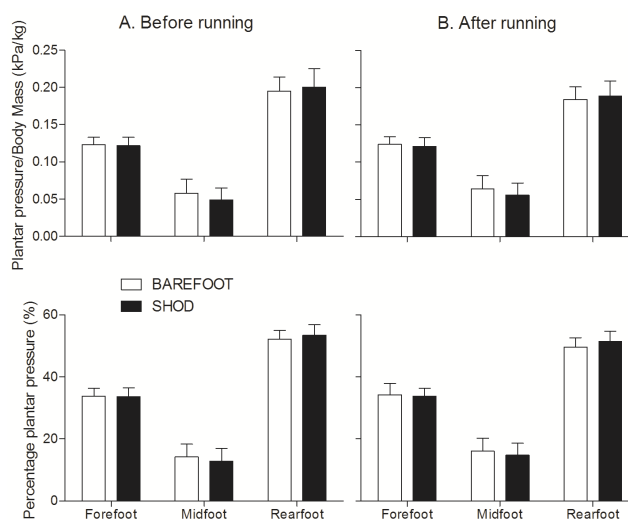
Statistical analysis

Data were exported for analysis with the SPSS Statistics 21.0 package (IBM, USA). After the Shapiro–Wilk test confirmed the normal distribution of the data ($p > 0.05$), an ANOVA with repeated measures was applied to analyze the differences in plantar pressure (normalized by body mass and by percentage pressure) between the measurement time points (before and after running) and the conditions (barefoot and shod running). Similar analysis was conducted for the temperature variables (absolute temperature, temperature normalized by percentage variation, and by the percentage temperature of the whole foot). The Pearson correlation coefficient was used to examine the relationship between skin temperature (percentage temperature and ΔT), and plantar pressure (percentage pressure and plantar pressure/body mass) for each foot region (forefoot, midfoot and rearfoot), before running, after shod running, and after barefoot running. Data are reported as means and standard deviations in the graphs and in the text with 95% confidence intervals (95% CI). Statistical significance was defined at $p < 0.05$. Statistical significance of correlations was defined at $p < 0.05$ and above a moderate relationship ($r > 0.5$ or $r < -0.5$ [28]) for all analyses.

Results

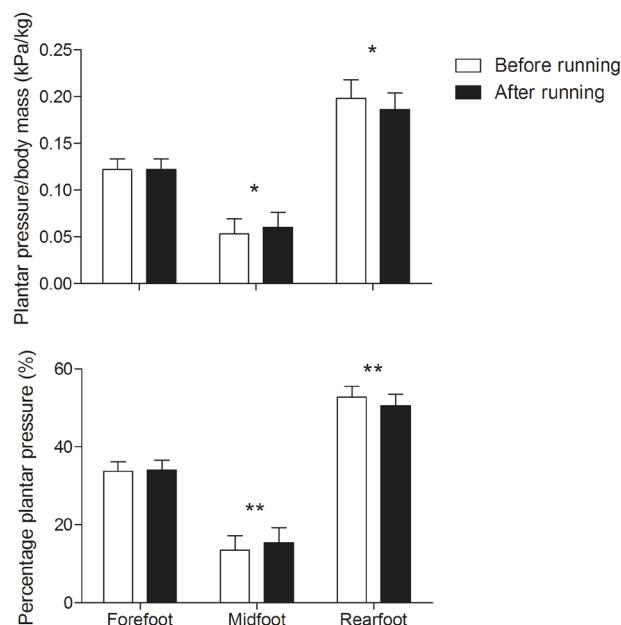
Normalized plantar pressure ($p = 0.960$) and percentage pressure ($p = 0.930$) after running were similar between the barefoot and shod running conditions (Figure 1). As a result, we used repeated measures ANOVA excluding the factor condition (barefoot or shod running) to analyze plantar pressure from the two different time points (before and after running).

Normalized plantar pressure was found to shift towards the midfoot after running, regardless of the condition (barefoot or shod) (Figure 2). Normalized plantar pressure in the midfoot increased ($p = 0.02$, 95% CI [0.01–0.001 kPa/kg]) while in the rearfoot it decreased ($p = 0.01$, 95% CI [0.02–0.002 kPa/kg]) after running. Similar results were found for percentage pressure in



no significant differences were observed in the comparisons

Figure 1. Normalized plantar pressure and percentage of plantar pressure before and after running in the three foot regions (forefoot, midfoot, and rearfoot) between running conditions (barefoot and shod running)

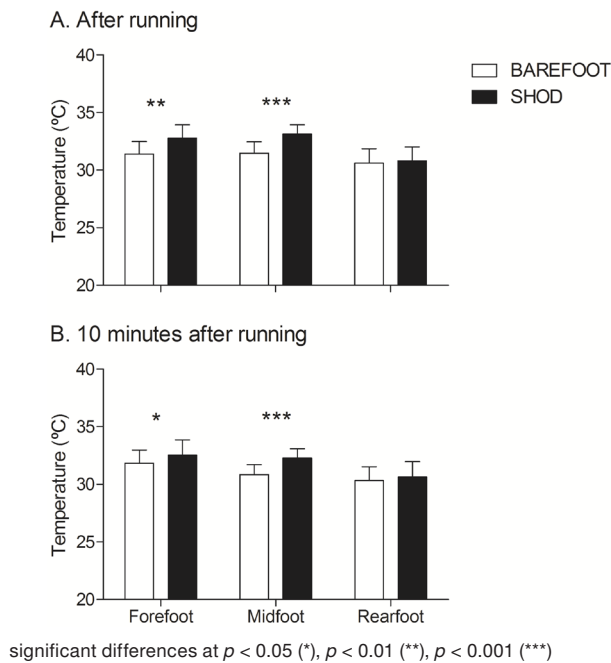


significant differences at $p < 0.05$ (*) and $p < 0.01$ (**)

Figure 2. Differences in normalized plantar pressure and percentage of plantar pressure before and after running in the three foot regions (forefoot, midfoot, and rearfoot)

the midfoot ($p = 0.003$, 95% CI [0.8–3.1%]) and rearfoot ($p = 0.004$, 95% CI [0.8–3.7%]). Normalized and percentage of plantar pressure in the forefoot did not change after running ($p > 0.5$).

Thermography showed differences in the response to running (Figure 3). The shod running condition resulted in higher temperatures in the forefoot ($p = 0.003$, 95% CI [0.5–2.2°C]), and midfoot ($p < 0.001$, 95% CI



significant differences at $p < 0.05$ (*), $p < 0.01$ (**), $p < 0.001$ (***)

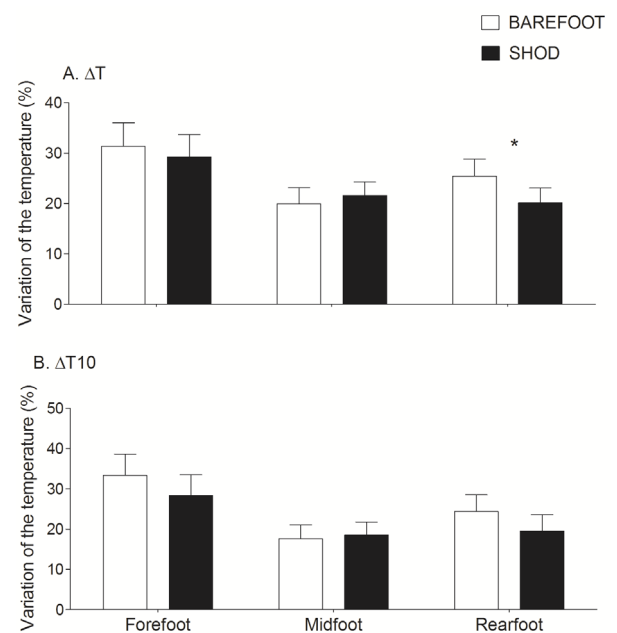
Figure 3. Skin temperature immediately after and 10 min after running compared in the three foot regions (forefoot, midfoot, and rearfoot) between conditions (barefoot and shod running)

[0.9–2.4°C]). Temperatures remained elevated in the forefoot ($p = 0.04$, 95% CI [0.03–1.39°C]) and midfoot ($p < 0.001$, 95% CI [0.8–2.1°C]) 10 min after the running test. Rearfoot skin temperature was similar between shod and barefoot running immediately ($p = 0.09$) and 10 min after test completion ($p = 0.08$).

Percentage temperature distribution after barefoot running was 31.5% in the rearfoot (95% CI [30.6–32.4%]), 32.9% in the midfoot (95% CI [32.3–33.5%]), and 33.6% in the forefoot (95% CI [33.2–34.0%]). Immediately after shod running, temperature distribution was 31.3% in the rearfoot (95% CI [30.4–32.3%]), 33.1% in the midfoot (95% CI [32.0–34.1%]), and 34.2% in the forefoot (95% CI [33.6–34.8%]). Percentage temperature of the forefoot in relation to the whole foot area was higher after shod than barefoot ($p = 0.01$, 95% CI [0.1–1.2%]) running. No statistically significant differences were found between barefoot and shod running in the percentage temperatures of the midfoot and rearfoot.

After barefoot running, temperature variation (ΔT) was higher in the rearfoot than after shod running ($p = 0.04$, 95% CI [0.1–10.4%]) (Figure 4). No statistically significant differences were found in the temperature variation between barefoot and shod running in the forefoot and midfoot.

No significant correlation was observed between skin temperature and plantar pressure ($p > 0.05$ and $r < 0.5$ or $r > -0.5$) (Table 1).



significant differences at $p < 0.05$ (*)

Figure 4. Variation in skin temperature before, immediately after (ΔT), and 10 min after ($\Delta T10$) running compared in the three foot regions (forefoot, midfoot, and rearfoot) between conditions (barefoot and shod running)

Discussion

In this study, we hypothesized a relationship between plantar pressure and foot temperature. To elicit different stress conditions in the foot, we examined the acute effects of barefoot and shod running. Our study expands upon what has previously been investigated in the literature [1], adding a number of novel findings including that: a) static plantar pressure distribution after shod and barefoot running is similar, b) higher temperatures are observed in the forefoot and midfoot after shod than barefoot running, c) there is a larger variation in rearfoot temperature after barefoot than shod running, and d) no significant correlation exists between skin temperature and static plantar pressure.

We observed that after both shod and barefoot running plantar pressure increases in the midfoot and decreases in the rearfoot, which is in agreement with previous reports on the acute effects of running on plantar pressure [3, 5]. The similar plantar pressures after shod and barefoot running may rely on the fact that the participants in this study were physically active subjects, and none had experience with running. These results could be expected if the study considered runners who modified their landing strategy from a rearfoot to a midfoot/forefoot strike technique [18, 29, 30], which was not the case in our study. Indeed, pressure changes are most likely related to technique rather than shoe condition, as previously discussed in both barefoot running and running with minimalist shoes [19, 20, 31].

Table 1. Correlation coefficients between skin temperature and plantar pressure before running, after shod running and after barefoot running in the three foot regions (forefoot, midfoot and rearfoot); no significant relationships were observed

		Before running					
		Percentage temperature (%)			Variation of temperature (ΔT)		
		Forefoot	Midfoot	Rearfoot	Forefoot	Midfoot	Rearfoot
Percentage plantar pressure (%)	<i>r</i>	0.316	0.090	-0.011	-0.149	0.191	-0.149
	<i>p</i>	0.016	0.502	0.319	0.263	0.150	0.265
Plantar pressure/body mass	<i>r</i>	0.205	0.101	-0.209	-0.051	0.137	0.035
	<i>p</i>	0.123	0.452	0.115	0.703	0.304	0.794
		After shod running					
Percentage plantar pressure (%)	<i>r</i>	0.378	0.113	-0.040	-0.070	0.022	0.018
	<i>p</i>	0.043	0.558	0.836	0.718	0.911	0.928
Plantar pressure/body mass	<i>r</i>	0.218	0.141	-0.068	-0.123	-0.022	-0.240
	<i>p</i>	0.257	0.466	0.725	0.524	0.908	0.211
		After barefoot running					
Percentage plantar pressure (%)	<i>r</i>	0.212	0.076	-0.020	-0.377	0.425	-0.116
	<i>p</i>	0.270	0.694	0.920	0.044	0.022	0.548
Plantar pressure/body mass	<i>r</i>	0.179	0.150	-0.280	0.008	0.364	0.355
	<i>p</i>	0.352	0.437	0.141	0.968	0.052	0.059

Repetitive friction between the foot and footwear, environmental temperature, human thermoregulation, and footwear insulation/breathability can be major factors influencing foot temperatures [2, 6]. If barefoot running produces higher friction in forefoot region due to higher pressures as previously suggested [19, 20, 31], the temperature in this foot region should increase after running [2]. However, we observed that shod running resulted in higher temperatures in the forefoot and midfoot regions compared with barefoot running. This could indicate that the effect of footwear insulation on midfoot and forefoot regions can be greater than friction effects of barefoot running.

Considering that all participants were rearfoot strikers, impact peak naturally occurred at the rearfoot [32]. In this sense, a systematic review of the literature concluded that loading rates are higher during barefoot running if the runner is a rearfoot striker [33]. Interestingly, we observed higher variations in the temperature of the rearfoot after barefoot running than after shod running. We hypothesize that this higher variation of temperature may be explained by the higher contact loads experienced by the heel during barefoot running in rearfoot strikers.

Before running, the lack of a relationship between plantar pressure and temperature can be most likely explained by the method of measuring foot temperature, which was performed when the foot was not in contact with the ground. Therefore, any temperature variation would be due to thermoregulation rather than the effects of loading. However, no significant relationships be-

tween both variables were observed even immediately after running. This may be explained by the relatively small changes observed in plantar pressure (of 0.02 kPa/kg in midfoot and rearfoot) while the temperature variations were larger (increases of up to 2°C). Similar findings were recently reported [1], indicating that a non-linear approach may be more applicable to investigate the associations between foot load and pressure with skin temperature.

The present study has two inherent limitations. Despite the participants using regular running shoes, we did not control for shoe design used in the shod running trials in order to avoid influencing running patterns. For this reason, we performed paired comparisons to minimize the influence of shoe design. Furthermore, to avoid the effects of fatigue, we considered a short running protocol (15 min), which most likely explains the lack of differences in plantar pressure after shod and barefoot running regardless of the significant changes in foot temperature.

Conclusions

Plantar pressure was consistent before and after running in both barefoot and shod conditions, while foot temperature presented higher variability. No correlations were observed between foot temperature and plantar pressure in any of the tested conditions.

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