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Footwear outsole temperature may be more related to plantar pressure during a prolonged run than foot temperature

Irene Jimenez-Perez[a,b], Marina Gil-Calvo[a,c], Rosario Salvador Palmer[b], Rosa Mª Cibrián Ortiz de Anda[b], Pedro Pérez-Soriano[a*], Jose Ignacio Priego-Quesada[a,b]

Affiliations

[a] Research Group in Sports Biomechanics (GIBD), Department of Physical Education and Sports, University of Valencia, St: Gascó Oliag, 3, 46010, Valencia, Spain.

[b] Research Group in Medical Physics (GIFIME), Department of Physiology, University of Valencia, Ave: Blasco Ibáñez, 15, 46010, Valencia, Spain.

[c] Department of Physiatry and Nursing, Faculty of Health and Sport Science (FCSD), University of Zaragoza, Ronda Misericordia, 5, 22001 Huesca, Spain.

* Corresponding author
Dr. Pedro Pérez Soriano
Postal address: Research Group in Sports Biomechanics (GIBD), Department of Physical Education and Sports
St: Gascó Oliag, 3. 46010. Valencia, Spain.
Phone office: +34 963864363

e-mail: pedro.perez-soriano@uv.es

Abstract

Objective: The temperature of the sole of the foot has been suggested as an alternative to the measurement of plantar pressure during running despite the scarce evidence about their relationship. The temperature of the footwear outsole could also be representative of plantar pressure distribution due to its less multifactorial dependence. The aim of the study was to determine if plantar pressure during a prolonged run could be related to plantar temperature, either of the sole of the foot or the footwear outsole. *Approach:* Thirty recreational runners (15 males and 15 females) performed a 30-minute running test on a treadmill. Thermographic images of the sole of the foot and the footwear outsole were taken before and immediately after the test, and dynamic plantar pressure was measured at the end of the test. Pearson correlations and stepwise multiple linear regressions were performed. *Main results:* Plantar pressure percentage was related to a moderate correlation with plantar temperature percentage in forefoot and rearfoot (P<0.05), showing a greater relationship with the footwear outsole than with the sole of the foot (r=0.52–0.73 vs r=0.40–0.61, respectively). Moreover, moderate correlations were also observed between footwear outsole and sole of the foot temperature variables, especially in rearfoot. *Significance:* Footwear outsole temperature may be better related to plantar pressure distribution than sole of the foot temperature, in the forefoot and rearfoot. The midfoot is the most sensitive and variable region to analyze, as it does not seem to have any relationship with plantar pressure.

WC: 246

Keywords: infrared thermography; plantar load; feet; shoes; running; sport science.

1. Introduction

The foot is a very important structure during locomotion as it supports the weight of the body (Gil-Calvo *et al.*, 2017). Moreover, it is the first segment of the body that interacts with the ground, so it is exposed to the impact of each strike in the first place, and must be able to deal with the different loads and movements of the human body (Cubukcu *et al.*, 2005; Gil-Calvo *et al.*, 2017). It has been found that high plantar pressures in specific areas can increase the risk of pain, ulceration, and injuries such as stress fractures, metatarsalgia, calcaneus spur or plantar fasciitis (Nagel *et al.*, 2008; Ribeiro *et al.*, 2011; Willems, De Ridder and Roosen, 2012). In addition, high plantar load during running increases the risk of injury and reduces performance (Willems, De Ridder and Roosen, 2012; Chow, Chen and Wang, 2018; Murray, Beaven and Hébert-Losier, 2019). In this sense, the measurement of plantar pressure is an interesting technique to study the distribution of the plantar load in order to be able to detect areas with excessive loads, and propose strategies that can reduce them, so reducing the risk of injury (Chow, Chen and Wang, 2018).

There are plantar pressure measurement systems that facilitate measurement because they are wireless, however, the transmitter or the possibility of the insole slipping may alter runner's technique (Razak *et al.*, 2012). In addition, the high number of measurements taken in the clinical field, added to the stress caused by running, makes the life expectancy of plantar pressure measurement insoles limited, which implies a significant associated economic cost (Saito *et al.*, 2011). For this reason, some studies have investigated the possibility of using alternative techniques such as plantar temperature (Yavuz *et al.*, 2014; Priego Quesada *et al.*, 2015; Reddy *et al.*, 2017; El-Nahas *et al.*, 2018). This idea is based on the principle of energy conservation, where the mechanical energy produced by the repeated loads that the foot suffers in its interaction with the ground is transformed into thermal or calorific energy

(Shimazaki and Murata, 2015). For example, the study of Yavuz et al. (2014) observed a moderate linear relationship between the increase in triaxial plantar loads and increases in plantar temperature as a consequence of gait. Likewise, Shimazaki and Murata (2015) found that the regions with the highest temperatures (hallux and heel) also coincided with the regions with the highest contact loads. However, the studies of Priego Quesada et al. (2015) and Reddy et al. (2017) did not observe any association between vertical loads and temperatures. Although Priego Quesada et al. (2015) studied this relationship in a sport context, the protocol was of short duration, low intensity, and plantar pressure was measured in a static position after running. For this reason, it is necessary to evaluate this relationship in studies that assess plantar pressure dynamically during running, as it is more representative of the real situation (Hawrylak *et al.*, 2019), and over a prolonged run where runners reach higher and more damaging pressures (Willems, De Ridder and Roosen, 2012).

The absence of associations observed between foot skin temperature and plantar pressure has also been related to the great dependence of foot sole temperature on a high number of factors: intrinsic subject characteristics, environmental conditions, measurement protocol conditions, foot thermoregulation or footwear insulation/breathability (Kuklane, 2004; Zaproudina *et al.*, 2008; Shimazaki and Murata, 2015; Gil-Calvo *et al.*, 2017). The temperature of the outsole of the footwear, therefore, could be a better predictor of plantar load than the temperature of the sole of the foot, as it could be a more stable measurement and less influenced by individual factors (Gil-Calvo *et al.*, 2017). To the best of our knowledge, no studies have examined the temperature of the footwear outsole, nor its relationship with plantar pressure.

Therefore, the aim of the study was to determine whether plantar pressure during a prolonged run could be related to plantar temperature, either of the sole of the foot or the footwear outsole. We hypothesized that plantar pressure would be related to the footwear outsole temperature, but not to the sole of the foot temperature due to the multifactorial dependence of the foot temperature.

2. Materials & Methods

2.1. Participants

Thirty recreational runners (15 males and 15 females (Mean (standard deviation): age 32 (7) years; body mass 62.5 (9.8) kg; height 1.69 (0.08) m; BMI 21.8 (2.1) kg/m^2; running training distance 32.3 (12.0) km⁄week; running experience 7 (6) years; VO_2/kg 52 (6) ml/min/kg)) participated voluntarily in this study. All participants were free of injuries and provided written informed consent. The study procedures complied with the Declaration of Helsinki and were approved by the University Ethics Committee (approval number H1457612626675). A pedigraph image of static dominant footprint was taken to assess foot type. It was observed that 1 participant had planus feet, 7 normal feet, 7 normal/cavus feet, 14 cavus feet and 1 extreme cavus feet.

2.2. Protocol

First of all, runners performed a maximum incremental test on a treadmill (Trackmaster, Norav Medical Ltd., Yokneam, Israel), to determine the speed corresponding to their maximum oxygen consumption (VO_{2max}). VO_{2max} was determined through gas exchange analysis (Cortex Metalyzer 3B-R3, Leipzig, Germany). Wasserman's workload protocol (Wasserman *et al.*, 1999) was followed, starting to walk at a speed of 1.11 m/s and increasing

0.28 m/s every minute until athlete's exhaustion. Then, runners carried out a laboratory test that consisted of running 6 minutes progressively as warm-up, and then 30 minutes at 75% of their VO_{2max} on a treadmill (Excite Run 900, TechnoGymSpA, Gambettola, Italy) with 1% of slope, to simulate a customary training of a recreational runner, both in duration and intensity (MacLean, Van Emmerik and Hamill, 2010; Clansey *et al.*, 2012). In addition, socks were standardized, all runners wearing the same socks (Kalenji KipRun, Decathlon SA, Villeneuve-d'Ascq, France). However, runners wore their own running footwear, in order to introduce no further change to their customary running conditions and to make the simulated clinical field conditions more realistic (Priego Quesada *et al.*, 2015; Lewinson, Worobets and Stefanyshyn, 2016). All runners used traditional running shoes with a similar drop (8-10 mm). Thermographic images were taken one minute before and one minute after this laboratory test, and plantar pressure data were measured at the end of the test.

2.3. Plantar pressure

Plantar pressure was measured using the F-Scan® in-shoe pressure measurement system (v7.50; Tekscan Inc, Massachusetts, USA), at 200 Hz, placed inside the dominant foot footwear. Dominance was determined by the question "If you would shoot a ball on a target, which leg would you use to shoot?" (van Melick *et al.*, 2017). Plantar pressure was recorded in the last minute of the 30-minute run, over 15 seconds, taking an average of 20 steps. Mean peak plantar pressure was measured in three regions: rearfoot, midfoot and forefoot (Burns *et al.*, 2005; Priego Quesada *et al.*, 2015). The rearfoot was computed as 31% of the total foot length, from the heel. The midfoot was then defined as 19%, from the rearfoot, and finally, the forefoot was calculated as 50% of the total foot length, from the midfoot to the longest toe. For each participant, plantar pressure data from each foot region were normalized by dividing by the individual body mass of the participant (Castro *et al.*, 2013). Then, the percentage represented by the plantar pressure of each region with respect to total plantar pressure (sum of the three regions) was calculated (García-Pérez *et al.*, 2013).

2.4. Infrared thermography

Thermographic images of the sole of the dominant foot and footwear outsole were taken using an infrared camera (Flir E60bx, Flir Systems Inc., Oregon, USA) with a resolution of 320 x 240 pixels, with noise equivalent temperature difference (NETD) < 0.05°C, and measurement uncertainty of ±2°C or 2%. Images were collected just one minute before the test run, after 10 min adaptation to the thermal environment of the laboratory (Gil-Calvo *et al.*, 2017), and one minute immediately after the test. The 10 min adaptation period and thermographic measurements were carried out with the participants sitting down with their legs in a horizontal position and with the camera lens parallel to the soles from a distance of 1 m, and barefoot in the case of the sole of the foot image. Before the test, the sole of the foot image was taken first and then the footwear outsole image, and vice versa after the test. The infrared camera was turned on 10 minutes before taking measurements in order to ensure its electronic stabilization. In addition, thermographic images were collected in an area absent of sunlight, 5 m away from electronic equipment, electric light, and people (except for the thermographer and the participant). Air temperature [20.9 (1.0)°C] and relative humidity [39.0 (6.0)%] were controlled using an air conditioning unit, monitored with a weather station (Digital thermos-hygrometer, TFA Dostmann, Wertheim-Reicholzheim, Germany) and input into the camera setup. Likewise, reflected temperature was measured according to the standard method ISO 18434-1:2008 (ISO, 2008) and introduced into the camera setup. Moreover, the TISEM checklist was used to control all environmental, individual and technical factors that could affect thermographic measurements (Moreira *et al.*, 2017). Before starting the running test, a black body target (BX-500 IR Infrared Calibrator, CEM, Shenzhen, China) was used to ensure the correct calibration of the camera. In addition, an antireflective panel was placed behind the participant to minimize the influence of infrared radiation reflected from the wall (Hildebrandt *et al.*, 2012).

Images were analyzed using commercial software (ThermaCAM Researcher Pro 2.10 software, Flir Systems Inc., Oregon, USA). Sole of the foot images were processed using an emissivity factor of 0.98 to obtain skin surface temperatures (Steketee, 1973). Furthermore, before starting the study, the overall emissivity of the footwear outsole was determined experimentally with 15 different footwear running models and found to be 0.97 (0.01). This emissivity was recorded by warming each footwear sole, fitted with a piece of adhesive tape with a known emissivity of 0.95 (tape 0554 0051, Testo, S.A., Spain) (**Fig 1A**). By feeding this emissivity value into the camera, the temperature of the footwear outsole with the adhesive tape was determined. The emissivity of the camera was then modified until the footwear outsole without the tape showed the same temperature as the outsole with the tape of known emissivity (Priego Quesada, Salvador Palmer and Cibrián Ortiz de Anda, 2017). This experimental procedure was repeated three times per footwear in order to obtain a robust average.

The mean values of temperature were extracted from images of three regions of interest (ROIs) corresponding to the forefoot, midfoot and rearfoot (**Fig 1B**). ROIs of sole of the foot and footwear outsole were determined in the same way as for plantar pressure analysis (50%, 19%, and 31% of the foot length, respectively). The variables studied were: post-run absolute temperature (measured immediately after the test) and temperature variation. Temperature variation was calculated as the difference between the temperature immediately after and before the running test, expressed in °C. Temperature before running was only used to calculate temperature variation, and was not taken into account in the study analysis. From each foot region, post-run absolute temperatures and temperature variations were converted to percentage of the whole foot temperature (sum of the temperature of the three regions), as was the plantar pressure percentage.

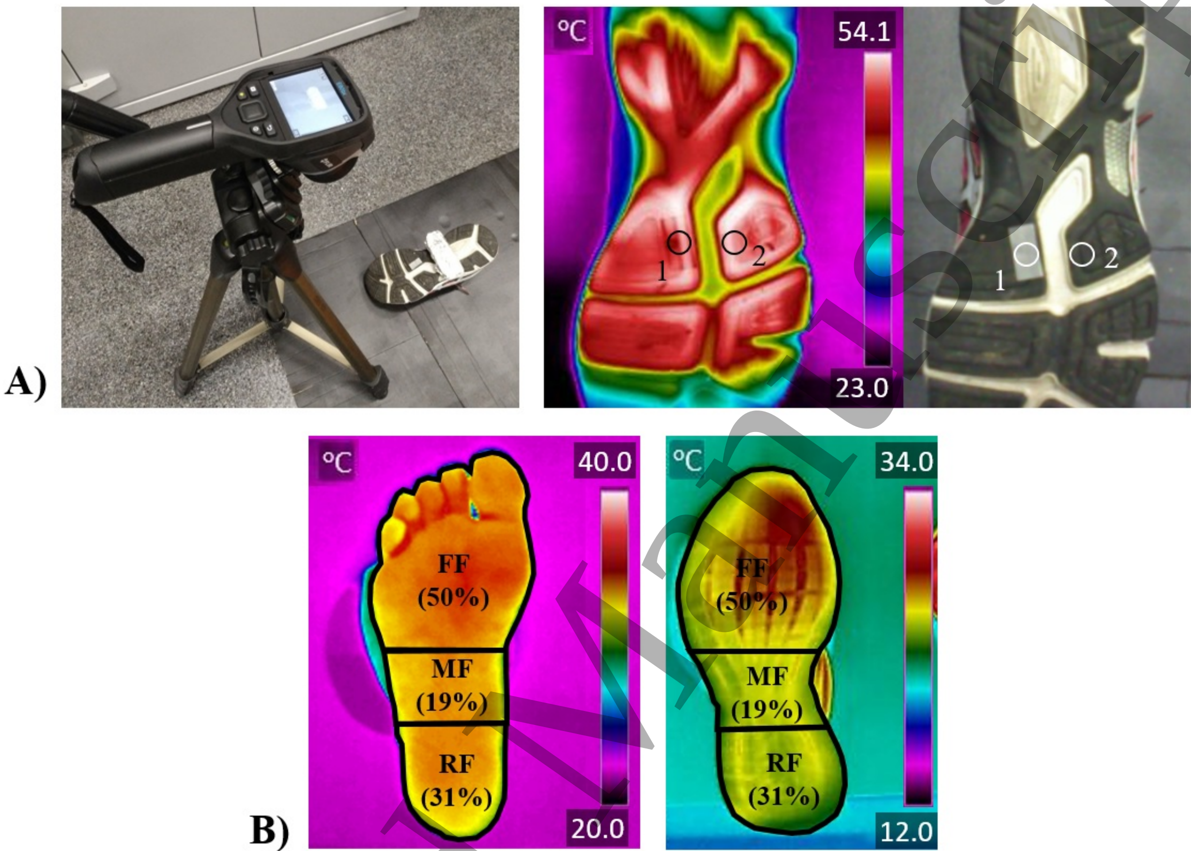

Fig 1 A) Process to determine footwear outsole emissivity: taking thermographic image to determine the emissivity of the footwear outsole (left) and image of an outsole with two marks: 1) with a piece of adhesive tape with known emissivity, and 2) without tape, to calculate the emissivity when the temperature of the mark with tape is reached (right). B) ROIs delimitation in the sole of the foot and in the footwear outsole: forefoot (FF), midfoot (MF) and rearfoot (RF).

2.5.Statistical analysis

SPSS software (v.23.0, IBM, Armonk, USA) was used for statistical analysis. Shapiro-Wilk test was used to confirm the normality distribution of the data ($P > 0.05$). Data are reported as means and with 95% confidence intervals (95% CI). An ANOVA with repeated measures was then applied to analyze the differences between foot regions (intra-subject factor) and between sexes (inter-subject factor), for each variable of plantar pressure and temperature (both sole of the foot and footwear outsole). For the significant ANOVA model ($P < 0.05$), the post-hoc Bonferroni correction test was carried out. Significance level was set at α=0.05. Pearson correlation coefficient was used to examine the relationship between plantar pressure and temperature, and the relationship between the temperature of the footwear outsole and the temperature of the sole of the foot, for each foot region (forefoot, midfoot and rearfoot). Statistical significance of correlations was defined at $P < 0.05$ and was classified as weak ($0.2 < |r| < 0.5$), moderate ($0.5 \leq |r| < 0.8$), or strong ($|r| \geq 0.8$) (O'Rourke, Hatcher and Stepanski, 2005) for all analyses. In addition, stepwise multiple linear regressions were performed using as predicting variables, the plantar pressure measurements (plantar pressure and plantar pressure percentage in the three regions assessed), and, as inputs of the models, the temperature measurements (sole of the foot and footwear outsole temperatures) and individual characteristics measurements (age, sex, physical fitness level (VO2/kg), type of foot and test speed). For the models obtained, the coefficient of each variable of the equation, the percentage of the variance explained by the model (R^2) and the significance value of the model were provided.

3. Results

Results showed higher plantar pressure values in forefoot and lower values in midfoot (**Fig 2**). Similar results were observed in sole of the foot temperature variation (after-before), whereas in post-run sole of the foot temperature there were no differences between forefoot and midfoot ($P > 0.05$), but lower values were found in rearfoot ($P < 0.001$). Moreover, in all footwear outsole temperature parameters, the highest values were also found in forefoot, with lower values presented in rearfoot (**Fig 3**).

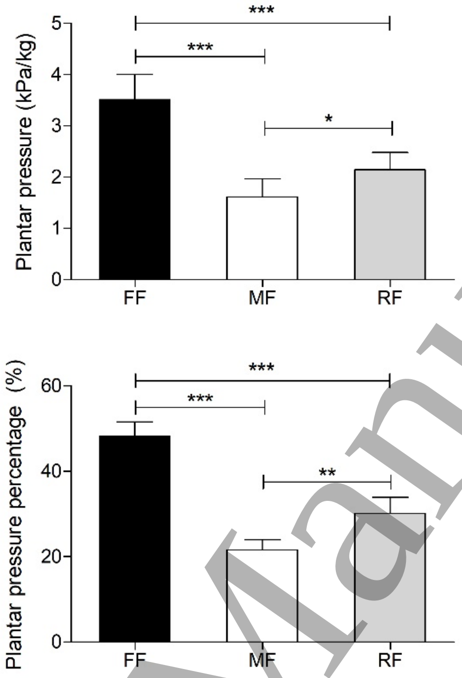

Fig 2 Differences (mean and 95% CI) between the three foot regions (FF: forefoot, MF: midfoot, RF: rearfoot) in plantar pressure (above) and percentage of plantar pressure (below) during the prolonged run. Significant differences at $P < 0.05$ (*), $P < 0.01$ (**) and $P < 0.001$ (***).

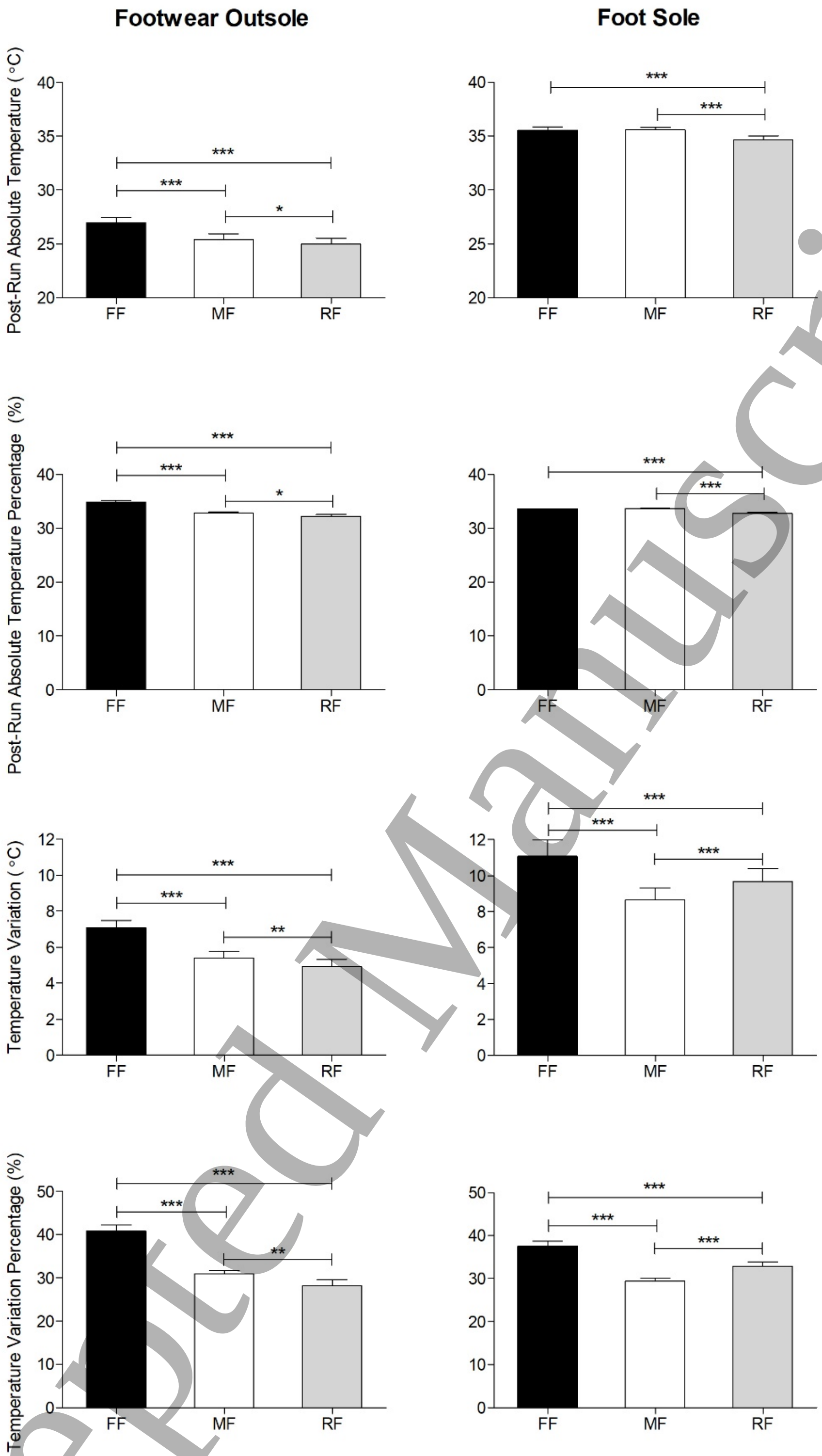

Fig 3 Differences (mean and 95% CI) between the three foot regions (FF: forefoot, MF: midfoot, RF: rearfoot) in footwear outsole temperature variables (left) and sole of the foot temperature variables (right). Significant differences at $P < 0.05$ (*), $P < 0.01$ (**) and $P < 0.001$ (***).

No differences were observed between sexes in plantar pressure parameters. However, females presented lower values in post-run footwear outsole absolute temperature, in the three regions analyzed, compared to males (forefoot: 26.3 vs 28.0°C, $P < 0.001$; midfoot: 24.8 vs 26.3°C, $P = 0.002$; rearfoot: 24.5 vs 25.7°C, $P = 0.033$, respectively). In addition, females presented higher temperature variations in the sole of the foot, also in all regions, compared to males (forefoot: 12.3 vs 9.8°C, $P = 0.004$; midfoot: 9.3 vs 8.0°C, $P = 0.047$; rearfoot: 10.7 vs 8.7°C, $P = 0.003$, respectively).

A moderately correlation between footwear outsole temperature and sole of the foot temperature was found, specifically in rearfoot. Also, a weak correlation was observed in the post-run absolute temperature percentage in forefoot (Table 1).

In addition, no significant correlation ($P > 0.05$) was observed between plantar pressure and temperature parameters (both footwear and sole of the foot). However, a moderately significant correlation between plantar pressure percentage and temperature percentages (both footwear outsole and sole of the foot) were found in forefoot and rearfoot, but not in forefoot sole of the foot temperature variation percentage (Table 2). Furthermore, the correlation coefficient was always greater with footwear outsole than with sole of the foot. The scatterplots of the significant correlations are shown in **Fig 4**.

Finally, the multiple linear regression (Table 3) indicated that plantar pressure percentage was positively related with post-run footwear outsole absolute temperature percentage in forefoot and rearfoot ($P < 0.01$). However, no variable was related with the plantar pressure variable ($P > 0.05$). In addition, neither the sole of the foot temperature nor any of the individual characteristics analyzed were related with plantar pressure parameters ($P > 0.05$).

Table 1. Correlation coefficients between footwear outsole and sole of the foot temperatures in the three foot regions (FF: forefoot, MF: midfoot, RF: rearfoot).

		Foot Sole		
		Post-Run Absolute Temperature		
Footwear Outsole		FF	MF	RF
Post-Run Absolute Temperature	*r*	0.09	0.18	**0.41**
	P	0.69	0.40	**0.04**
		Temperature Variation		
Temperature Variation	*r*	0.29	0.32	0.11
	P	0.19	0.14	0.63
		Post-Run Absolute Temperature Percentage		
Post-Run Absolute Temperature Percentage	*r*	**0.41**	0.13	**0.61**
	P	**0.04**	0.55	**<0.01**
		Temperature Variation Percentage		
Temperature Variation Percentage	*r*	0.37	-0.03	**0.52**
	P	0.08	0.90	**0.01**

Table 2. Correlation coefficients between plantar pressure and temperature in the three foot regions (FF: forefoot, MF: midfoot, RF: rearfoot).

		Post-Run Absolute Temperature						Temperature Variation					
		Footwear Outsole			Foot Sole			Footwear Outsole			Foot Sole		
		FF	MF	RF	FF	MF	RF	FF	MF	RF	FF	MF	RF
Plantar Pressure	*r*	0.11	-0.05	0.37	-0.09	-0.14	0.27	0.06	-0.16	0.20	-0.05	-0.01	-0.06
	P	0.61	0.80	0.07	0.63	0.46	0.16	0.76	0.46	0.35	0.82	0.98	0.75
		Post-Run Absolute Temperature Percentage						Temperature Variation Percentage					
Plantar Pressure Percentage (%)	*r*	**0.58**	0.20	**0.72**	**0.40**	0.19	**0.61**	**0.52**	0.156	**0.73**	0.27	-0.04	**0.57**
	P	**<0.01**	0.35	**<0.01**	**0.03**	0.33	**<0.01**	**<0.01**	0.44	**<0.01**	0.17	0.83	**<0.01**

Table 3. Multivariate stepwise regression analyses between plantar pressure parameters and temperature parameters and individual characteristics measures (age, sex, physical fitness level, type of foot and test speed), in each foot region (FF: forefoot, MF: midfoot, RF: rearfoot).

Regression models obtained			
Region of interest	**Variable**	**Coefficient [CI95%]**	**R^2 (p-value)**
Plantar Pressure Percentage (%)			
FF	Constant	-199.01 [-354.46, -43.54]	0.33 (0.003)
	Post-Run Absolute Temperature Percentage on Footwear Outsole	7.10 [2.63, 11.55]	
MF	No variable was included		
RF	Constant	-302.52 [-443.40, -161.64]	0.52 (<0.001)
	Post-Run Absolute Temperature Percentage on Footwear Outsole	10.30 [5.94, 14.66]	

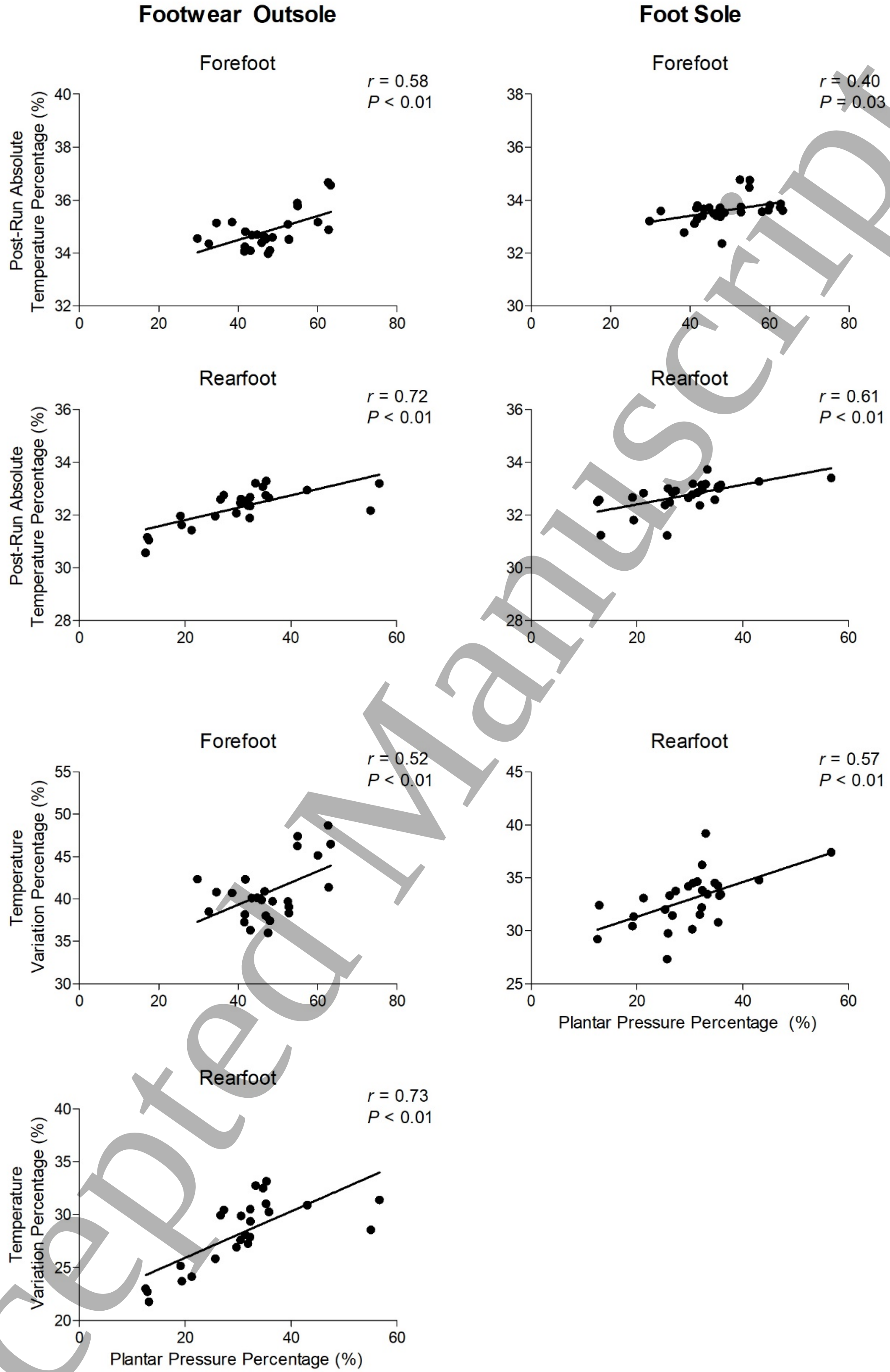

Fig 4 Significant correlations observed between plantar pressure and footwear outsole temperature variables (left) and sole of the foot temperature variables (right).

4. Discussion

The purpose of the study was to see whether plantar pressure during a prolonged run could be related to plantar temperature, either of the sole of the foot or the footwear outsole. The main result was that plantar pressure percentage may be related through a moderate correlation with temperature percentage in forefoot and rearfoot, and with a stronger relationship with the footwear outsole temperature than with the sole of the foot temperature.

4.1.Relationship between plantar pressure and temperature

Several studies have investigated the existence of a relationship between plantar load and foot plantar temperature, in order to find a simple technique that explains/predicts plantar load (Yavuz *et al.*, 2014; Priego Quesada *et al.*, 2015; Shimazaki and Murata, 2015; Reddy *et al.*, 2017; El-Nahas *et al.*, 2018; Wang *et al.*, 2018). Hence, Shimazaki and Murata (2015) observed that high-temperature-rise regions such as the hallux and heel coincided with regions with high-contact loads, which suggested a relationship between temperature rise and contact load. Likewise, Wang et al. (2018) assumed that vertical plantar pressure was related to plantar temperature, since they observed that toe and forefoot had higher rises in temperature and higher plantar pressure correspondingly. For their part, the work of Yavuz et al. (2014) was only able to establish a moderate linear relationship (r = 0.78) between plantar pressure (shown by the peak shear stress) and the increase in foot temperature, after walking 10 minutes at low speed. Also, El-Nahas et al. (2018) established a correlation between plantar pressure distribution and plantar temperature changes measured by smart socks during walking, but between non-corresponding regions. In contrast, other studies (Priego Quesada *et al.*, 2015; Reddy *et al.*, 2017) found that correlations between sole of the foot temperature and plantar pressure were not significant. In short, the literature shows that, in some cases, the relationships suggested have not been statistically verified, or the correlations found have only been weak. In the present study, moderate correlations between plantar pressure and plantar temperature have been observed, both in the sole of the foot and in the footwear outsole. Three main reasons may have caused greater plantar pressures in our study, thus explaining discrepancies between our results and previous studies. Some studies (Yavuz *et al.*, 2014; Shimazaki and Murata, 2015; Reddy *et al.*, 2017; El-Nahas *et al.*, 2018) used walking protocols and we analyzed running. The intensity and duration of running were higher than in previous studies (Priego Quesada *et al.*, 2015; Wang *et al.*, 2018). Furthermore, dynamic plantar pressures have been analyzed, unlike previous studies that only evaluated static pressures (Yavuz *et al.*, 2014; Priego Quesada *et al.*, 2015; El-Nahas *et al.*, 2018; Wang *et al.*, 2018).

Regarding the regions analyzed, correlations have been established specifically in forefoot and rearfoot. The lack of a relationship in midfoot could be explained by the fact that the arch region is more susceptible to modifications depending on the type of foot. Specifically, in this study, the vast majority of participants showed a normal (23%), normal/cavus (23%) or cavus (47%) foot. This type of foot, with a higher arch, presents less plantar load due to having less contact with the ground (Burns *et al.*, 2005; Anbarian and Esmaeili, 2016), as has also been seen in this study. Also, and in line with other running studies (Willems, De Ridder and Roosen, 2012; Anbarian and Esmaeili, 2016; Escamilla-Martínez *et al.*, 2020), the greatest loads were observed in the forefoot and rearfoot regions due to their importance in the initial contact and propulsion phases of running gait (Escamilla-Martínez *et al.*, 2020).

Just as foot temperature is influenced by intrinsic factors, plantar pressures are also subject to individual characteristics such as age, sex (Demirbüken *et al.*, 2019), foot type (Burns *et al.*, 2005), physical fitness level (Chow, Chen and Wang, 2018) or running speed (Peng *et al.*, 2020). However, the regression analysis for explaining plantar pressure did not include any of these aspects in the model, so these factors do not influence the explanation of plantar pressure.

4.2.Sole of the foot or footwear outsole temperature

In the present study, it was hypothesized that plantar pressure would be related to footwear outsole temperature, but not to the sole of the foot temperature. The results of this study largely supported this hypothesis. Pearson's correlation analysis showed a moderate correlation between plantar pressure percentage and the percentages of the temperature variables (post-run absolute temperature percentage and temperature variation percentage), both on the sole of the foot and the footwear outsole, and in forefoot and rearfoot. However, the correlation was always stronger with the footwear outsole than with the sole of the foot (r = 0.52-0.73 vs r = 0.40-0.61, respectively). Furthermore, the stepwise regression analysis selected only the post-run absolute temperature percentage of the footwear outsole to explain plantar pressure percentage in forefoot and rearfoot. The lower association between plantar pressure and sole of the foot temperature could be explained by the foot's own characteristics: 1) Particular thermoregulation (Taylor *et al.*, 2014), 2) Multifactorial dependence of foot temperature (West *et al.*, 2019) and 3) Thermal variability during exercise (Formenti, Merla and Quesada, 2017).

The foot has small muscle groups, a large amount of bone tissue and a large number of sweat glands that are mostly concentrated on the sole, so facilitating perspiration and heat loss in this region (Taylor *et al.*, 2014; Gil-Calvo *et al.*, 2017). Blood flow is rarely stable in the feet, because peripheral circulation is weak and strongly depends on the heat dissipation and heat conservation requirements of each situation (Zaproudina *et al.*, 2008). Although blood flow could increase skin temperature during exercise (Formenti, Merla and Quesada, 2017), perspiration could have the opposite effect (Priego Quesada *et al.*, 2016). In addition, the foot has the ability to alter its vasoconstriction/vasodilation state very quickly according to thermal needs, so the reproducibility of surface temperature measurements in this region is low (Taylor *et al.*, 2014; Gil-Calvo *et al.*, 2017).

The foot shows greater increases in skin temperature after exercise (~5 - 10°C) than more proximal regions of the body (~1 - 5°C) (Formenti, Merla and Quesada, 2017; Gil-Calvo *et al.*, 2019). Many factors can influence plantar temperature changes during exercise: mechanical forces acting on the plantar surface (friction and pressure), blood flow, intrinsic muscle activity, viscoelastic heat generation by fat or other tissues (Yavuz *et al.*, 2014), environmental temperature, human thermoregulation, footwear insulation/breathability (Kuklane, 2004; Shimazaki and Murata, 2015; West *et al.*, 2019), intrinsic factors (age, sex, body composition, level of physical fitness,…) (Formenti *et al.*, 2013; Chudecka, Lubkowska and Kempińska-Podhorodecka, 2014; Chudecka and Lubkowska, 2015) and extrinsic factors (hydration, eating, smoking,…) (Moreira *et al.*, 2017). It is, therefore, possible that footwear outsole temperature offers a better correlation with plantar pressure given that it is more stable, not influenced by so many factors, and depends solely on the heat transfer mechanism (West *et al.*, 2019). On a practical level, it is interesting that the footwear outsole temperature has a better relationship with plantar pressure than the temperature of the sole of the foot, since it is easier to measure during running and avoids the runner having to take off the footwear every time an evaluation is made.

Pearson's correlation analysis also shows a relationship, although moderate, between sole of the foot temperature and footwear outsole temperature, especially in rearfoot. However, this relationship may not only be stronger due to the thermoregulatory mechanisms of the foot, but also because footwear microclimate and socks may affect the processes of heat dissipation and heat conservation (West *et al.*, 2019). The use of footwear could not only isolate the foot without allowing heat dissipation, but also reduce the friction of the foot during contact (Kuklane, 2004; Priego Quesada *et al.*, 2015; West *et al.*, 2019).

Regarding sole of the foot temperature, parameters of post-run absolute temperature showed higher values in forefoot and midfoot, with no differences between them. Rearfoot lower temperatures after the run could be due to the fat pad of the heel, which has an insulation capacity resulting in impairment of heat dissipation (Yavuz *et al.*, 2014). On the other hand, temperature variations showed a greater increase in forefoot, as it is the most distal area (comprising hallux and toes) that begins with much lower temperatures. The next region with the highest increase of temperature was the rearfoot, also possibly because it started with lower temperatures due to its greater fat tissue, and finally the midfoot.

Similarly, footwear temperature presented its highest values in forefoot, then in midfoot and finally in rearfoot, with less differences between these last two regions. Likewise, temperature variations showed this same distribution, since the three regions of the footwear outsoles started from the same initial temperature. One explanation for this distribution could be provided by the usual distribution of the materials of the running shoes. Cushioning systems usually predominate in midfoot and rearfoot (Escamilla-Martínez *et al.*, 2020), which may create an insulating effect. However, this idea is speculation, as each participant used their own footwear, and no control of the characteristics of the materials was undertaken.

Lastly, in relation to the comparison between sexes, females showed higher temperature variations in the sole of the foot in all regions, which could be explained by having lower baseline surface temperatures as the study by Jimenez-Perez *et al.* (2020) found. These lower baseline temperatures could be a consequence of lower blood circulation in the peripheral areas (Barnes, 2017) and a higher percentage of fat and lower lean mass compared to males

(Salamunes, Stadnik and Neves, 2017). In addition, females presented lower values in post-run footwear outsole absolute temperature compared to males, possibly also due to the lower basal temperatures of females that may have caused less heat transfer between the foot and the footwear outsole during much of the running time. Another possible speculation to this result is the fact that females generally weigh less than males (Atwater, 1990), and may have exerted less friction between the footwear and the treadmill.

4.3.Limitations and further research

The main limitation of the study is that the design and materials of the participants' footwear were not controlled, possibly increasing the thermal variability of the results. However, participants used their own footwear in order not to modify their running pattern (Priego Quesada *et al.*, 2015; Lewinson, Worobets and Stefanyshyn, 2016) and to simulate an applied situation. In addition, the time of use of the footwear and socks could also increase this variability, since it is possible that the wear of the sole can alter the friction that the footwear exerts against the ground (Sun *et al.*, 2020; Beschorner *et al.*, 2021). It would be interesting for future lines of research to control these aspects. Similarly, the foot strike pattern was not controlled either, and the participants presented different types of foot. Nevertheless, the analysis carried out made comparisons and relationships paired to minimize the influence of all these factors. It would, therefore, be interesting for future studies to investigate these relationships focusing on a single type of foot, delimiting more regions of interest or forming groups according to shoe type. The running protocol of the present study was, however, decided upon in order to simulate the most customary training of a recreational runner (MacLean, Van Emmerik and Hamill, 2010). Nevertheless, future studies should analyze the relationships proposed here in different running protocols, such as intermittent running, of much longer duration or sprints.

5. Conclusions

The present study shows a moderate relationship between plantar pressure distribution and plantar temperature distribution, both on the sole of the foot and on the footwear outsole, especially in the forefoot and rearfoot regions. However, only footwear outsole temperature may be better related to plantar pressure distributions in the forefoot and rearfoot. The midfoot is the most sensitive and variable region to analyze, as it does not seem to have any relationship with plantar pressure. This study may be considered as preliminary research to test alternative techniques for assessing plantar pressure stress. According to the results, it is still too early to suggest the use of footwear outsole temperature as a substitute for plantar pressure, given that future studies are required to replicate this study with standardized footwear, and test different footwear outsole materials to determine that this relationship exists in all cases.

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Declaration of interest statement

The authors declare that they have no conflicts of interest.

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