applied optics

Relationship between foot eversion and thermographic foot skin temperature after running

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Received 9 March 2017; revised 9 June 2017; accepted 9 June 2017; posted 12 June 2017 (Doc. ID 290357); published 0 MONTH 0000

The main instruments to assess foot eversion have some limitations (especially for field applications), and therefore it is necessary to explore new methods. The objective was to determine the relationship between foot eversion and skin temperature asymmetry of the foot sole (difference between medial and lateral side), using infrared thermography. Twenty-two runners performed a running test lasting 30 min. Skin temperature of the feet soles was measured by infrared thermography before and after running. Foot eversion during running was measured by kinematic analysis. Immediately after running, weak negative correlations were observed between thermal symmetry of the rearfoot and eversion at contact time, and between thermal symmetry of the entire plantar surface of the foot and maximum eversion during stance phase ($r = -0.3$ and $p = 0.04$ in both cases). Regarding temperature variations, weak correlations were also observed ($r = 0.4$ and $p < 0.05$). The weak correlations observed in this study suggest that skin temperature is not related to foot eversion. However, these results open interesting future lines of research.

OCIS codes: (100.0100) Image processing; (110.0110) Imaging systems; (170.0170) Medical optics and biotechnology; (040.6808) Thermal (uncooled) IR detectors, arrays and imaging; (330.4150) Motion detection.

https://doi.org/10.1364/AO.99.099999

1. INTRODUCTION

Extreme foot eversion (or foot pronation) during running has been associated with a higher probability of injury risk [1–4]. One of the main reasons of this association is its influence on the mechanics of the entire lower extremity [5–7]. In this sense, high values of foot eversion have been associated with internal tibial rotation, which is considered the genesis of the patella femoral pain and iliotibial band syndromes [5]. As a result of this relationship, shoe manufacturers have designed different motion control systems to control foot eversion [3]. To provide runners with information regarding the most adequate shoe for them or even the need of an orthosis, some sport shops and clinical sport centers have assessment methods of foot eversion in their facilities.

Research studies have used different methods to assess foot eversion such as kinematic analyses [1,5,7], biplane *x*-ray images [8,9], plantar pressure mapping [10,11], or diagnostic clinical tools such as the Foot Posture Index [3,12]. However, some of these methods are difficult to use in the field (e.g., sport shops) because they are expensive, the requirements for an adequate measurement cannot be guaranteed, or there is a lack of technical knowledge. With respect to simpler methods such as the Foot Posture Index, some studies observed a weak relationship between its values (obtained with the runner standing still) and the kinematics of the foot during walking and running [12,13]. Therefore, it is necessary to explore new methods that will allow researchers, biomechanists, and podiatrists to assess foot eversion in the field.

Recent studies have suggested a possible relationship between contact load and foot temperature [14,15]. This relationship could imply that the level of foot eversion has an effect on the thermal pattern of the foot sole. As a result, the assessment of the foot skin temperature could potentially be a method to estimate foot eversion. However, it is important to consider that skin temperature has a multifactorial dependence, as it can be the result of different thermoregulatory processes including blood flow, sweat rate, and heat production, as well as environmental factors such as environmental temperature, wind speed, and relative humidity [16–19]. Therefore, it would be plausible to hypothesize that, if there is a relationship between eversion and foot temperature, this relationship could be moderate at best.

1559-128X/17/240001-01 Journal © 2017 Optical Society of America

The objective of the study was to determine the relationship between the skin temperature of the foot sole, using infrared thermography, and foot eversion, using motion analysis, during running. It was hypothesized that both variables could present a moderate relationship, and therefore it would be possible to obtain an approximately value of foot eversion by the assessment of its thermal pattern.

2. METHODS

A. Participants

A priori analysis of power sample size was performed using the G*Power 3 software (University of Düsseldorf, Dusseldorf, Germany). To detect a moderate correlation equal to 0.6, a minimum sample size of 20 participants was estimated using a power of 90% and α error of 5%. Therefore, 22 runners (17 males and 5 females; age 34 ± 5 years, body mass 72.0 ± 12.9 kg, height 175.7 ± 7.3 cm; running training distance 36.6 ± 12.9 km/week) participated in this study and gave informed written consent. Inclusion criteria included no history of lower extremity injuries within the last six months, and a minimum running training distance of 15 km/week. The study procedures complied with the Declaration of Helsinki, and were approved by the university's ethics committee (approval number H1427706182089).

To reduce skin temperature variability [19,20] participants were asked to avoid the following: smoking and drinking alcohol at least 12 h before each test; sunbathing or being exposed to UV rays in the week before the test; applying body lotions and creams on the day of the test; performing high-intensity or exhaustive exercise at least 24 h before the test; and eating and drinking coffee or other stimulants during the 2 h prior to the test.

B. Protocol

Participants performed a pretest and a main test on different days, with a one-week separation between them. On the pretest, participants underwent a 5-min maximal effort run on a 400-m track to determine their individual maximal aerobic speed (MAS) [21,22]. MAS values obtained were 15.9 ± 1.9 km/h. In the main test one week later, participants ran at 1% slope on a treadmill (TechnogymSpA, Gambettola, Italy). They warmed up for 10 min at 60% of their MAS, and subsequently ran for 20 min at 80% of their MAS.

Participants performed the running test with their own footwear and socks to better reproduce the conditions that would exist in the target field environment (e.g., sport shops).

All tests were carried out in a moderate indoor environment: 22.9 ± 1.3°C and 44.4 ± 12.1% relative humidity. Skin temperature of the foot was measured before and after the running test, and foot eversion was registered throughout the running test.

C. Thermography Data Collection and Analysis

Skin temperature was measured using an infrared thermography camera with a size of the focal plane sensor array of 320 × 240, NETD of 50 mK at 30°C, and repeatability of the measurement of ±2% of the overall reading (FLIR E-60, Flir Systems Inc., Wilsonville, Oregon, USA). Before starting the experimental phase, a black body (BX-500 IR Infrared Calibrator, CEM, Shenzhen, China) was used to ensure a correct calibration of the camera. Thermal images of each participant were taken at three moments [19,23]: before the running test; immediately after the running test; and 10 min after the running test. To adapt to the room temperature, participants remained, with only their running shorts (without socks) on and seated with their legs up (the soles of their feet were not touching anything) for 10 min [20,24]. Then, thermal images of their feet soles were taken with the camera perpendicular to the soles from a distance of 1 m.

Measurements were taken in an area absent of sunlight which was 5 m away from electric light, electronic equipment, and people (except for the thermographer and the participant). An antireflective panel was placed behind the participants to minimize the influence of the infrared radiation reflected in the wall [25]. Reflected temperature was measured according to the standard method ISO 18434-1:2008 [26] and introduced into the camera setup. Air temperature and relative humidity were input into the camera setup for every thermographic measurement using a thermohygrometer with an accuracy of ±1°C for the air temperature and ±3% for the relative humidity (digital thermohygrometer, TFA Dostmann, Wertheim-Reicholzheim, Germany).

Four regions of interest (ROIs) were defined on each foot sole (Fig. 1). ROI length of the rearfoot was defined as 31% of the entire plantar surface of the foot [20]. Width of the medial and lateral ROIs was defined as 50% of the maximum width of the foot. The absolute mean temperature of each ROI was computed using a commercial software (Thermacam Researcher Pro 2.10 software, FLIR, Wilsonville, Oregon, USA). All images were processed using an emissivity factor of 0.98 to obtain skin surface temperatures [27].

In addition to the absolute temperature values, the following temperature variations were calculated [28]: ΔT (difference between the temperature immediately after and before the running test, expressed in °C), $\Delta T10$ (difference between the temperature 10 min after and before the running test, expressed in °C), and ΔTafter (difference between temperature 10 min after and immediately after the running test, expressed in °C).

Although thermal symmetry is usually defined as the degree of similarity between two ROIs mirrored across the human body's longitudinal axis [29], in the present study thermal symmetry was calculated and defined as the difference between the medial and lateral ROIs temperatures. Positive values corresponded to a higher temperature in the medial ROIs to make the associations with the foot eversion values easier. Thermal symmetries of temperature variations were also calculated.

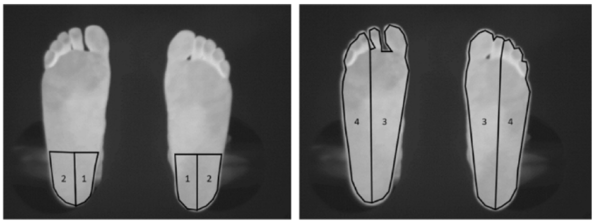

Fig. 1. Regions of interest (ROIs) defined: 1) medial rearfoot, 2) lateral rearfoot, 3) medial foot, and 4) lateral foot.

D. Kinematic Data Collection and Analysis

All kinematic procedures and analyses were performed by the same evaluator to reduce between-evaluators variability in marker placement. Clarke *et al.*'s bidimensional model of four markers [30] was used as in previous studies [31,32]. Foot eversion was calculated by the projected β angle between the two segments (calcaneus and leg) defined by the kinematic model [33] (Fig. 2). The foot eversion angle was calculated from an offset posture, considered as 0°, and it was measured having the athlete standing still [30]. Then, before the running test, reflective markers (diameter: 16 mm) were placed in both legs on the gastrocnemius (in the axial line of the leg, under the gastrocnemius bifurcation), on the Achilles tendon (at the height of the malleolus), and on the upper and lower side of the calcaneus (Fig. 2). Movements in the participants' frontal plane were captured at 125 Hz with a high-speed video camera (MotionScope, Redlake, MASD Inc., San Diego, USA) placed 1.5 m perpendicular to the motion plane and 0.5 m high. During the main part of the running tests (20 min at 80% MAS), kinematic data were recorded every 5 min for 5 s. Foot kinematics were captured with the camera software (Redlake MASD MotionScope, San Diego, USA) and analyzed using a motion analysis software (Kinescan/IBV System, Valencia, Spain). Before each measurement, optical distortion of the camera lens and calibration of the space were performed using a square object of known dimensions in which four space references were attached. Calibration was performed via 2D direct linear transformation using the motion analysis software. The spline smoothing method was used automatically in the motion analysis software [34].

Two variables were calculated from the kinematic data: the foot eversion at contact time (ECT) and the maximum eversion during stance phase (MES). Contact time was determined by an optical detection system synchronized with the kinematic camera. Since no significant effect of the measurement time was found on ETC and MES ($p > 0.05$ and ES < 0.8), the average of the five kinematic measurements throughout the 20 min of running was considered for the statistical analysis.

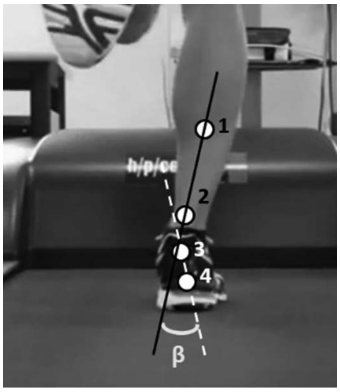

Fig. 2. Kinematic bidimensional model used to measure β angle of foot eversion during running with four markers—1) gastrocnemius, 2) Achilles, 3) upper calcaneus, and 4) lower calcaneus)—and two segments (leg segment shown by a black line and calcaneus segment by a white line).

E. Statistical Analysis

As both feet were assessed, 44 cases were used for the statistical analysis. Data were analyzed using SPSS Statistics 21.0 (IBM, Armonk, New York, New York, USA). Normality of the data was checked by the Kolmogorov–Smirnov test ($p > 0.05$). Repeated Measures ANOVAs were performed to assess the differences between medial and lateral ROIs in absolute temperatures and temperature variations of the rearfoot and foot ROIs. Ninety-five percent confidence intervals (95%CI) were calculated for the thermal symmetry values. A Pearson's correlation coefficient analysis was used to examine the relationships between the thermal symmetry values (absolute and variations of the rearfoot and the entire foot) and kinematic values (ECT and MES). Also, the correlation between thermal symmetries of ΔT and ΔTafter were calculated. Significant correlations ($p < 0.05$) were classified as weak ($0.2 < |r| < 0.5$), moderate ($0.5 \leq |r| < 0.8$), or strong ($|r| \geq 0.8$) [35]. Lineal regression analyses were performed for the significant correlations observed. Data are reported as mean ±SD. The effect size (ES) was computed with Cohen's d for each pair of comparisons and was classified as small (ES 0.2–0.5), moderate (ES 0.5–0.8) or large (ES > 0.8). Statistical significance was defined when $p < 0.05$.

3. RESULTS

With respect to the analysis of foot eversion, the values of ECT and MES were $-6.1 \pm 6.3°$ and $11.6 \pm 4.0°$, respectively.

Table 1 shows the absolute temperatures and temperature variations obtained in the running test, whereas Table 2 shows the thermal symmetry values observed. Although medial ROIs presented higher absolute temperatures than lateral ROIs ($p < 0.05$, Table 1), the effect size of these differences was small (ES < 0.5). Regarding temperature variations, similar results were observed at ΔT and $\Delta T10$ of the rearfoot. However, no differences were observed at ΔTafter of the rearfoot and in the temperature variations of the entire foot.

Figure 3 shows the regression analyses performed on the comparisons where significant correlations were observed. Weak negative correlations were observed in the moment "immediately after running" between thermal symmetry of the rearfoot and ETC values, and between thermal symmetry of the entire foot and MES values ($r = -0.3$ and $p = 0.04$ in both cases) [Fig. 3(A)]. Regarding temperature variations, positive weak correlations at ΔTafter were observed between thermal symmetry of the rearfoot and ETC values ($r = 0.4$ and $p = 0.01$), and between thermal symmetry of the entire foot and MES values ($r = 0.4$ and $p = 0.02$) [Fig. 3(B)]. With respect to the other bivariate relationships, no significant correlations were observed ($p > 0.05$).

The correlation between thermal symmetries at ΔT and ΔTafter was assessed to explain the relationships obtained above, resulting in a negative moderate correlation in the rearfoot ($r = -0.7$ and $p < 0.001$) and in the entire foot ($r = -0.5$ and $p < 0.001$).

4. DISCUSSION

The objective of the present study was to examine the relationship between the skin temperature of the foot sole and foot

Table 1. Average ± SD of the Absolute Temperatures and the Temperature Variations of the Medial and Lateral ROIs of the Rearfoot and the Entire Plantar Surface of the Foot[a]

	Rearfoot			Foot		
	Medial Average ± SD (°C)	Lateral Average ± SD (°C)	Med versus Lat p; ES	Medial Average ± SD (°C)	Lateral Average ± SD (°C)	Med versus Lat p; ES
Absolute temperatures						
Before running	27.7 ± 1.6	27.1 ± 1.8	$p < 0.001$; 0.3	27.2 ± 1.7	26.9 ± 1.8	$p < 0.001$; 0.2
Immediately after running	34.0 ± 1.2	33.8 ± 1.3	$p < 0.01$; 0.2	34.5 ± 1.2	34.2 ± 1.3	$p < 0.001$; 0.3
10 min after running	31.6 ± 1.5	31.5 ± 1.6	$p = 0.01$; 0.1	32.1 ± 1.4	31.7 ± 1.6	$p < 0.001$; 0.3
Temperature variations						
ΔT	6.4 ± 1.7	6.7 ± 2.0	$p < 0.001$; 0.2	7.3 ± 1.9	7.3 ± 2.0	$p = 0.54$; 0.0
$\Delta T10$	4.0 ± 2.0	4.4 ± 2.2	$p < 0.001$; 0.2	4.9 ± 2.0	4.8 ± 2.2	$p = 0.25$; 0.0
ΔTafter	–2.4 ± 1.5	–2.3 ± 1.5	$p = 0.34$; 0.0	–2.4 ± 1.4	–2.4 ± 1.6	$p = 0.53$; 0.0

[a] Differences between medial and lateral ROIs were assessed using the p values and the effect sizes (ES).

Table 2. Average ± SD and 95%CI of the Thermal Symmetry Values

	Rearfoot		Foot	
	Average ± SD (°C)	95%CI	Average ± SD (°C)	95%CI
Absolute temperatures				
Before running	0.5 ± 0.4	0.4, 0.7	0.3 ± 0.5	0.2, 0.4
Immediately after running	0.2 ± 0.5	0.1, 0.4	0.4 ± 0.4	0.2, 0.5
10 min after running	0.1 ± 0.4	0.0, 0.2	0.4 ± 0.4	0.3, 0.5
Temperature variations				
ΔT	–0.3 ± 0.5	–0.5, –0.2	0.1 ± 0.5	–0.1, 0.2
$\Delta T10$	–0.4 ± 0.4	–0.5, –0.3	0.1 ± 0.5	–0.1, 0.2
ΔTafter	–0.1 ± 0.5	–0.2, 0.1	0.1 ± 0.5	–0.1, 0.2

eversion during running. ETC values showed a weak negative relationship with the thermal symmetry of the rearfoot measured immediately after running, and a positive weak relationship with the rearfoot thermal asymmetry at ΔTafter. Similar results were found for MES values, which showed a weak negative relationship with the thermal symmetry of the foot measured immediately after running, and a positive weak relationship with the foot thermal asymmetry at ΔTafter.

It was hypothesized that the thermal symmetry (difference between medial and lateral side of the foot) could show a moderate correlation with foot eversion. The results of the study did not support this hypothesis because weak relationships were observed. Weak correlations could be explained by the multifactorial character of the skin temperature and the resulting greater thermal variability occurring during exercise. Although skin temperature could increase during foot contact [14,15], other factors such as the environmental temperature, human thermoregulation, and footwear insulation/breathability had been suggested to strongly affect foot temperature [14,20,36]. Environmental conditions could be controlled in a laboratory or in the target field environment (e.g., sport shops and clinical centers). However, physiological outcomes are also dependent on intrinsic factors such as age [37,38], sex [39,40], body composition [41], or level of physical fitness [23,42] that will inevitably increase the variability of the foot skin temperature. Extrinsic factors such as drinking and hydration, eating, or smoking could affect thermoregulation [43–45]. However, these factors were controlled in the present study and could be controlled in the field application by providing instructions to the participants. Additionally, when analyzing the thermal behavior of the feet, some physiological particularities need to be taken into account. Blood flow is rarely stable in the feet, because peripheral circulation is weak and depends strongly on the heat dissipation and heat conservation requirements of each situation [46–48]. Although blood flow could increase skin temperature during exercise [17], perspiration could result in the opposite effect [18,19]. Perspiration is produced mainly in the sole of the foot, where there are around $467\ \text{cm}^2$ of sweat glands that account for approximately 80% of the sweat glands of the entire foot [49]. Moreover, perspiration is also influenced by a number of intrinsic factors including age, sex, or physical fitness [50–52]. Finally, footwear and clothing also affect the heat dissipation and heat conservation processes [53]. The use of footwear could reduce the impact of eversion on skin temperature, first because footwear insulation could have a higher effect than eversion on skin temperature [20,36], and second because its use could also reduce the friction of the foot during the contact time [20], attenuating its effect on foot skin temperature. However, it is important to consider that if the runner is not used to barefoot running, this condition would alter his or her normal biomechanical patterns. In the present study, each participant performed the running test with his or her own footwear and socks, possibly increasing the thermal variability of the results. However, footwear and socks were

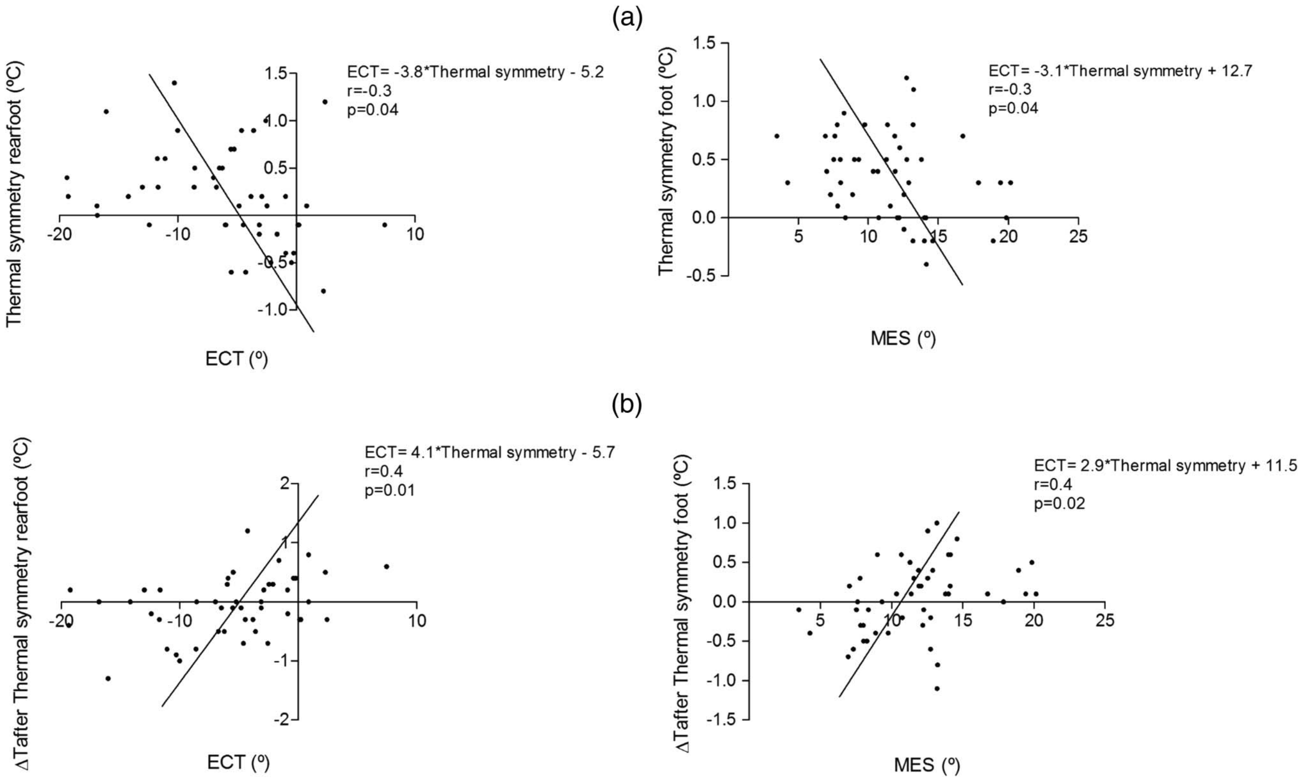

Fig. 3. Significant relationships observed between foot eversion variables (ECT, eversion at contact time; MES, maximum eversion during stance phase) and foot temperature variables (thermal symmetry of the rearfoot and the entire plantar surface of the foot, difference between medial and lateral side; ΔTafter thermal symmetry, thermal symmetry between medial and lateral side of the temperature variation between temperature 10 min after and immediately after the running test). (a) Relationships observed immediately after running. (b) Relationships observed at ΔTafter.

not controlled to better reproduce the conditions that would exist in the target field environment.

Skin temperature could be measured using different methods such as infrared thermography or thermocouples. Although each method presents both advantages and limitations [18,54], infrared thermography was used in the present study as it would be easier to use in a future target field environment. However, the weak correlations observed between foot eversion and foot temperature suggested that skin temperature alone is not related to foot eversion. Future studies should explore if infrared thermography combined with other assessment techniques (e.g., Foot Posture Index) can help to establish together the relationship with foot eversion during running.

Yavuz *et al.* [15] observed a moderate positive correlation between plantar pressure (shown by the peak shear stress) and the increase of foot temperature after walking ($r = 0.78$). Similarly, Shimazaki and Murata [14] observed at different velocities (from 3 to 12 km/h) that the regions with a greater increase of temperatures were associated with regions with high-contact loads (e.g., big toe and heel). However, the results of the regression analysis of our study showed an opposite effect to that observed in those previous studies [14,15]: an inverse relationship between foot eversion and thermal symmetry immediately after running. One possible explanation could be that the side of the foot experiencing less time of contact during the stance phase may be exposed to greater friction with the footwear, resulting in a greater increase of temperature. Another hypothesis could be that the side of the foot that experiences a greater time of contact may be facilitating heat loss by conduction. However, this heat loss is often considered negligible due to the lowly conductive surfaces that are in contact with the skin (in this case, the sock) [16]. As a result, it would be of great interest for future studies to investigate the causes of the correlations obtained in this study.

On the other hand, positive correlations were observed between foot eversion and thermal symmetry at ΔTafter. Previous studies [55,56] observed that during the recovery process after exercise, skin temperature tends to decrease to baseline values. These findings are in agreement with the results of the present study and are supported by the negative moderate correlations observed between thermal symmetries of ΔT and ΔTafter, meaning that regions with higher increases of skin temperature during exercise experience greater decreases during the recovery phase.

Although a protocol for thermographic analyses of the different regions of the human body was tried to be established (called the Glamorgan Protocol) [57], there is no agreement in the scientific literature as to the definition of the ROIs on the foot [58]. The Glamorgan protocol established two regions on the foot: the dorsal region and the sole of the foot [57]. In the present study, the ROIs of the entire sole of the foot and a subdivision of the rearfoot were assessed. This division of the foot was supported by the correlations observed. Foot eversion in the contact phase during running (shown by the ETC values) showed a relationship with the thermal symmetry of the rearfoot, while the maximum eversion during the stance phase (shown by the MES values) showed a relationship with the thermal symmetry of the entire sole of the foot. These logical associations support the idea that ROIs should be determined depending on the objectives as well as on the specific variables of the study.

The present work presents some limitations apart from those previously commented on (e.g., no control of footwear). The running pattern of the athletes (rearfoot, midfoot, forefoot) was not controlled and may influence the variability of the results. On the other hand, a 2D motion analysis system was used and could present more limited data than a 3D system. However, considering that the study was focused on the assessment of the applicability of infrared thermography on the field, and these limitations would also be present in these environments, these conditions may simulate better their field application and warrant the validity of the results.

5. CONCLUSIONS

The weak correlations observed in this study suggest that skin temperature is not related to foot eversion. However, these correlations open future lines of research such as the combination of infrared thermography with other assessment tools. Finally, further research aiming to explain the negative relationships observed in this study between foot eversion and thermal symmetry in the foot and rearfoot immediately after running is necessary.

2 **Funding.** Dirección General de Investigación Científica y Técnica (DGICT) (DEP2013-48420-P); Ministerio de Educación, Cultura y Deporte (MECD) (Doctoral Fellowship (FPU)).

Acknowledgment. We thank all the runners for their voluntary participation in this study. The work of Mr. Priego Quesada, Ms. Jimenez-Perez, and Dr. Lucas-Cuevas was funded by a doctoral fellowship (FPU) received from the Spanish Ministry of Education, Culture and Sport.

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Queries

1. AU: OSA policy requires many acronyms to be defined. In the sentence beginning “Calibration was performed” please confirm my definition of “DLT”.
2. AU: The funding information for this article has been generated using the information you provided to OSA at the time of article submission. Please check it carefully. If any information needs to be corrected or added, please provide the full name of the funding organization/institution as provided in the CrossRef Open Funder Registry (http://www.crossref.org/fundingdata/registry.html).