Chapter 10
Foot Temperature Assessment

Marina Gil-Calvo, Irene Jimenez-Perez, Pedro Pérez-Soriano and Jose Ignacio Priego Quesada

Abstract Thermographic studies of the foot can be very useful in 3 different ways: in preventing injury, in analyzing sporting technique and in assessing the effects of footwear and clothing. The aim of this chapter is to discuss several methodological points concerning the thermal analysis of the foot using infrared thermography, as well as to discuss how it can be applied to the science of sports, both in areas already researched and those as yet uninvestigated.

10.1 Introduction: Foot Anatomy and Physiology

To understand the possibilities that the analysis of foot temperature through infrared thermography presents to us, we first of all have to know the characteristics of that region of the body. The foot presents a very particular anatomy and physiology for a number of reasons. It has its own vascularization and thermoregulation, as it is one of the most peripheral regions of the body. Moreover, the feet support all the weight of an individual and are subject to considerable forces during physical exercise. We shall, therefore, now provide an introduction to the anatomic and thermophysiological structure of the foot.

M. Gil-Calvo (✉) · I. Jimenez-Perez · P. Pérez-Soriano · J.I. Priego Quesada
Research Group in Sport Biomechanics (GIBD), Department of Physical Education and Sports, University of Valencia, Valencia, Spain
e-mail: m.gil.gibd@gmail.com

I. Jimenez-Perez
e-mail: i.jimenez.gibd@gmail.com

P. Pérez-Soriano
e-mail: pedro.perez-soriano@uv.es

J.I. Priego Quesada
e-mail: j.priego.gibd@gmail.com

I. Jimenez-Perez · J.I. Priego Quesada
Biophysics and Medical Physics Group, Department of Physiology, University of Valencia, Valencia, Spain

J.I. Priego Quesada (ed.), *Application of Infrared Thermography in Sports Science*, Biological and Medical Physics, Biomedical Engineering,
DOI 10.1007/978-3-319-47410-6_10

The foot acts as a structural platform that is able to bear all the different loads and movements of the human body [1]. It consists of 28 bones (including the sesamoids) the movements of which are all interrelated [1]. Bone tissue behaves as a good heat sinks due to its porous structure and represents between 28 and 31% of the foot mass [2]. Furthermore, the bones of the foot are laid out in the form of longitudinal and cross-sectional arcs that provide greater support than other layouts would [3].

The structure of the foot is similar to that of the hand, but there are certain differences that allow it to support weight and adapt to different surfaces and speeds of locomotion. For that reason the big toe of the foot is less mobile but has a greater structural solidity [3].

There are two groups of muscles related with foot movement. On the one hand there are the extrinsic muscles of the foot which are located in the leg and exercise their action by pulling on the tendons that are inserted into the ankle and foot [3]. These are responsible for making the movements of dorsiflexion, plantar flexion, inversion and eversion of the foot [3]. These movements, especially eversion of the ankle, have been widely studied through biomechanics applied to sport, as they are the ones most associated with risk of injury [3, 4]. On the other hand are the intrinsic muscles of the foot. These muscles are responsible for the fine movements of the toes such as flexion, extension, adduction and abduction [3].

When the muscles are active, they can release great amounts of energy. In the foot, the extrinsic muscles, located in the leg, are responsible for bigger movements, so there is no great heat source within the foot and, therefore, the thermal energy generated comes from other sources [2]. This fact, together with the higher presence of the heat dispersal structures that the foot possesses (such as the sweat glands or bone tissue), actually facilitates heat loss in that region, so increasing susceptibility to injuries caused by cold [5].

Blood flow is rarely stable in the feet as the thermal changes affect many cutaneous blood vessels [6–8]. Blood supply to the foot comes from arteries that enter behind the malleolus and along the dorsal surface of the foot [9]. Medial plantar artery enters trough the medial malleolus, across the sole and provide blood to the intrinsic muscles of the foot, to the skin of the medial plantar region and to the medial three toes [9]. The external plantar artery feeds blood to the calcaneus and adjacent muscles, to the plantar tarsus and to the tarsometatarsal joints and the lateral zone of the sole of the foot [9]. In the dorsal zone are the medial and lateral tarsal arteries, the arcuate artery and the first dorsal metatarsal artery, which takes the blood to the first and second toes [9]. For their part, the second, third and fourth dorsal metatarsal arteries each supply blood to their own toe and the next one [9].

In the foot, moreover, the draining of the blood takes place from the toes towards the dorsal venous arch (nearer the surface) and the plantar venous arch (deeper) [9]. Venous return takes place through the tibial vein and the foot fascia, which mix with the blood from the dorsal surface before leaving the saphenous veins [2].

The normal state of the veins on the soles of the feet is that of vasoconstriction and consequently the accumulation of venous blood is minimum, a passive dilation of the veins being produced in hot situations [10, 11]. In contrast, there are mechanisms of active vasodilation in the dorsal region that are activated in hot situations [12], such as, for example, during exposure to heat or undertaking physical exercise, where vasodilation, blood flow and perspiration increase, as they are essential for dispersing heat [13, 14]. If, on the contrary, the human body cools down, vasoconstriction is activated, most of the blood flow going to the central areas of the body and reducing the arterial flow to the limbs [2]. In mountain sports where temperatures can be very low and, therefore, great vasoconstriction takes place, cases of foot amputation as a result of freezing are well known [15].

As commented on earlier, perspiration is one of the most important heat dissipating mechanisms in hot surroundings [14]. The sole of the foot has around 467 cm^2 of sweat glands, whereas the dorsal surface of the foot has only 119 cm^2, the sole, therefore, having an 80% concentration as opposed to 20% on the top [2]. Moreover, feet and hands lose more water than the rest of the body (2–4 times more) through the loss of transepidermal water. The dorsal surface of the foot loses $\sim$0.05 mg cm^{-2} min^{-1}, whereas the sole loses 0.10 mg cm^{-2} min^{-1} [16].

The foot plays a fundamental role in human thermoregulation as a thermal radiator whenever there is more than sufficient heat transported by the blood to these regions [17]. Thus, knowledge of foot temperature can help us to understand the effects that footwear and exercise have, both on risk and prevention of injuries, and on the sporting performance. Infrared thermography is now considered a valid and reliable technique when it comes to discovering the surface temperature of the skin, provided that the factors that may affect its measurement are controlled and an appropriate methodology to prevent errors of measurement is followed.

10.2 Methodological Aspects Related with Foot Temperature Assessment

As foot temperature is very unstable due to factors that will be explained later on, it is essential to be able to control a series of methodological aspects linked to the assessment of their temperature. That methodological control helps to minimize errors in measuring foot temperature, so increasing the validity and reliability of infrared thermography.

10.2.1 Advantages and Limitations of Infrared Thermography in Assessing Foot Temperature

Measuring foot surface temperature by means of infrared thermography brings with it a series of advantages and limitations. As mentioned earlier, infrared thermography is a quick, accurate, non-invasive and objective method for measuring foot surface temperature [18, 19]. One of the main advantages of infrared thermography is that the measurements are taken at a distance, in such a way that it allows us to see the distribution of temperature in a non-invasive manner and at no risk to the patients [20, 21]. These characteristics make thermography a highly recommended tool when it comes to assessing the temperature of any region of the body, including the soles of the feet.

Furthermore, by measuring the surface temperature of the soles of the feet, a great amount of information can be obtained on the physical, circulatory and thermoregulatory state of the individual being assessed. However, it is important to bear in mind that both skin temperature and limb temperature are very dependent on underlying circulation and the metabolic tissue rate [22]. This may involve inter-individual differences or differences caused by the influence of environmental conditions [23–25].

Similarly, the use of thermography enables us to define the location of the area where an inflammation and/or an injury has taken place [26]. The ability to detect injuries or inflammations through infrared thermography is because inflammatory response is characterized by an increase in the permeability of the blood vessels, which leads to an increased blood flow, so altering the body's heat pattern [26].

Despite that, the dynamic nature of foot temperature regulation and the variability of its reaction to the very same stimulus, with regard to the initial temperature has to be borne in mind [21, 27]. Here, there are multiple factors that make the temperature of the feet vary, such as environmental conditions, the moment of measuring and the physiological conditions of the region that is to be measured, so it is very complicated to establish a significant relationship between the foot and clinical diagnosis or sport intervention [28].

The main advantages as far as other injury-detecting instruments are concerned, such as magnetic resonances or scanners are that infrared thermography does not emit radiation, it works from a distance, it is portable and is low-cost [20, 29, 30]. Nevertheless, as far as foot temperature analysis goes, it has one clear limitation and that is that it is not possible to monitor foot temperature during the foot's daily activity. Being an imaging technique, it is necessary to undertake measurements in laboratory conditions and in most cases undressed and outside the foot's normal habitat, the shoe. This limitation is very evident in the sports setting where, when undertaking physical exercise, athletes usually have their feet covered by socks and footwear, which makes infrared thermography measurements on the soles of the feet, in a dynamic way, impossible.

Regarding sport sciences, thermographic analysis of the foot can offer numerous applications of great interest, as will be explained in this chapter. However, its use in this field is quite recent, so further studies are required that may help to clarify its potential. In the clinical field, the main limitation to thermography is the insufficiency of databases with which to diagnose any type of injury, as, to date, we can only detect the production or recovery from an inflammation and/or injury, but it is still not possible to diagnose it accurately. Currently, therefore, the best way of using thermography is in combination with other techniques, instead of as a replacement of them [29, 31]. By doing so, it can reveal physiological changes that appear before clinical signs appear and enable early diagnosis and intervention [26, 30, 32].

Moreover, on some occasions, it can provide relevant information on other physiological variables that conventional diagnosis techniques (such as magnetic resonance, scanners, etc.) do not take into account [30].

10.2.2 Reproducibility

One of the determinant aspects in measuring the temperature of the feet soles is the low reproducibility of measurements in that region. Skin temperature is more stable in the trunk than in the limbs, where there is high variability that seems to depend on endogenous factors, such as the sympathetic nervous system or the environmental temperature [33].

Furthermore, in the most distal regions of the human body, such as the feet, peripheral circulation is weaker and there is a constant struggle between the mechanisms of vasoconstriction and vasodilation that regulate the blood flow of the skin, so increasing the variability of skin surface temperature and reducing the reproducibility of thermographic measurements in that region [33]. It is for that reason, more important than ever, that we must be able of controlling any extrinsic factor (such as preventing alcohol, tobacco and medicinal intake or avoiding physical exercise before measuring, etc. as stated in Chap. 3 of this book) that may affect the infrared thermography measurements of the feet, so as to reduce the variability of measurements in these regions [33].

With regard to sports studies, where physical exercise is usually undertaken and temperature measured before and after, it would be interesting if future studies could compare the reproducibility of the variation in temperature (difference between pre- and post-exercise) with absolute temperatures. It is possible that, although the reproducibility of the foot is low [33], the effect of exercise may be more constant.

10.2.3 Thermal Imaging of the Feet

There seems to be a consensus about the position for taking thermographic images of the soles of the feet. The images are taken following a period of thermal equilibrium (or adaptation to room temperature), where the participant who is subject to thermal imaging, is positioned sat down with their legs extended (Fig. 10.1).

When the image is to be taken, it is recommendable to place a matt black anti-reflection panel behind the feet so as to minimize the effects of the reflected temperature of the surroundings, and to isolate the image of the foot sole and not capture other regions of the body such as the legs (Fig. 10.2a) [19, 34]. Nevertheless, it is important to bear in mind that the feet (together with the hands) are regions of the human body that present the highest values of radiant heat loss. Hence, these regions at rest (mainly the fingers and toes) usually present very

Fig. 10.1 Recommended position for thermal imaging of the soles of the feet

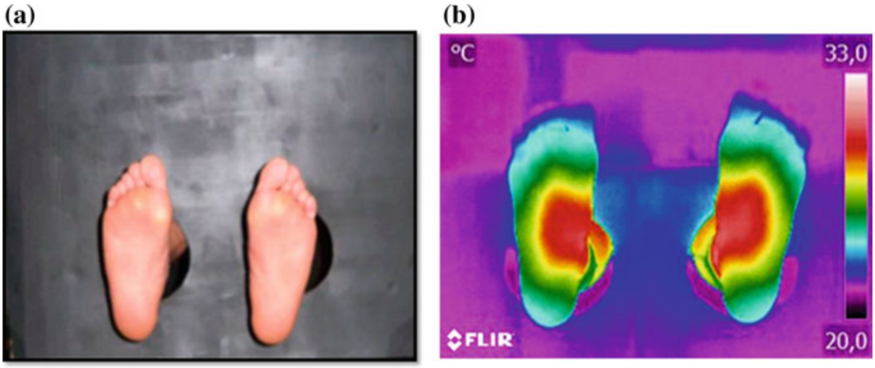

Fig. 10.2 **a** Anti-reflection panel behind the feet of a participant undergoing thermal imaging of the feet soles. **b** Example of a thermal image of toes that present temperatures similar to surrounding room temperature

similar temperatures to the surrounding room temperature where measuring takes place, and it is often complicated to visualize the fingers or toes as they are of such similar temperature to the surrounding temperature (Fig. 10.2b).

Most investigations have not reached an agreement on the time required for participants to remain in this position while adapting to the room. On the one hand, those studies where other regions of interest are measured in which the fact that the individual is seated may interfere, for example the posterior femoral zone, undertake a thermal adaptation period of between 15 and 20 min in anatomic position and once the thermal images of the body are taken, they seat the participant for a further 5 min before taking the thermal images of the feet soles [30, 33]. By doing so, they believe that this is sufficient time for thermal equilibrium to take place in those participants.

On the other hand, in studies that only focus on the soles of the feet, the participants remain in the seated position with their legs extended during the entire period of thermal adaptation [34, 35]. This period must be at least 10 min so as to adapt well to room conditions [29, 36], but it could be longer if the environmental conditions outside the room are of extreme cold or heat, as, in this case, the body needs a longer period to stabilize the temperature [33, 36].

10.2.4 Regions of Interest (ROIs)

Choosing the regions of interest (ROIs) for foot assessment depends on the aims of each investigation. It seems that there is no homogenous definition of ROIs for the foot that can serve for all studies.

Ammer [37] tried to establish a protocol for thermographic analysis of the different regions of the human body, which was called the *Glamorgan Protocol*. Within the 90 regions of interest in the entire body, it established two single regions on feet: the dorsal region and the sole of the foot (Fig. 10.3).

However, many authors do not follow the recommendations of this protocol when it comes to analyzing the sole of the foot, as, by doing so, one loses a large part of the information on what is happening in the different regions of the foot sole. Below we shall present several of the divisions that authors have undertaken both on the diabetic foot and in the medicine and physiology of sport, in an attempt to seek common ground between them.

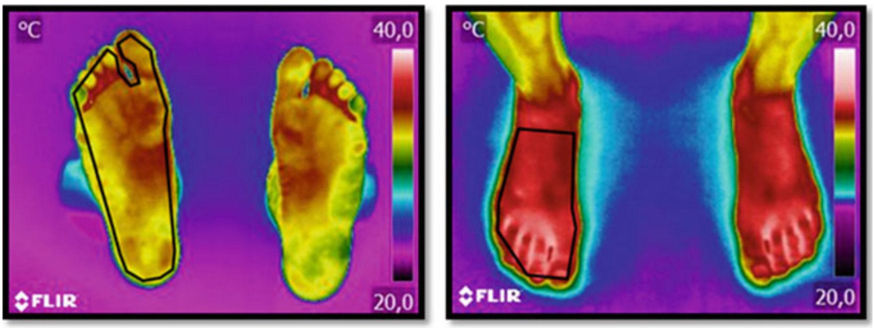

Fig. 10.3 Regions of Interest on the feet according to the Glamorgan Protocol [37]. The foot sole (*left*) and the dorsal region of the foot (*right*)

When studying diabetic foot ulcerations, there are two main ways of dividing the foot sole. On the one hand, some authors [20, 38, 39] opt for dividing the sole of the foot in an anatomic way, which varies depending on the aims of each study. The hallux (big toe), the lesser toes, the metatarsus (which can be separate or together) and the heel typically appear separated (Fig. 10.4). In some cases, moreover, divisions in the arch and the lateral zone of the midfoot appear [39, 40].

On the other hand, some studies [41–45] propose analyzing regions of the feet of diabetic subjects through the concept of angiosome, a region of the foot composed of the tissues irrigated by the same artery of origin [43, 46]. These authors divide the foot sole into 4 zones, in accordance with the medial plantar angiosomes proposed by Attinger et al. [47]: the angiosome of the medial plantar artery (MPA), the angiosome of the lateral plantar artery (LPA), the angiosome of the medial calcaneal artery (MCA) and the angiosome of the lateral calcaneal artery (LCA) (Fig. 10.5).

In the case of medicine and physiology, the division of the regions of interest on the foot sole is more structural. Zaproudina et al. [33] undertook a division of the soles of the feet into 9 regions of interest: the complete sole, three different regions of the arch and heel zone and each of the toes separately, so as to discover the reproducibility of this zone of the human body (Fig. 10.6).

In a recent study, and in the field of sport [34], it was proposed that the division of the regions should follow a commonly used division for analyzing plantar pressure when running: the forefoot (50% of the surface of the foot sole), midfoot (19% of the surface of the foot sole) and rearfoot (31% remainder of surface) (Fig. 10.7). The authors of this chapter would like to add to this division a further 5 regions of interest for future studies: complete foot sole, medial foot sole (50% inner surface of the foot sole), lateral foot sole (50% outer surface of the foot sole), medial rearfoot (50% inner rearfoot) and lateral rearfoot (50% outer rearfoot), as

Fig. 10.4 Example of anatomical division of the diabetic foot according to Sun et al. [39]

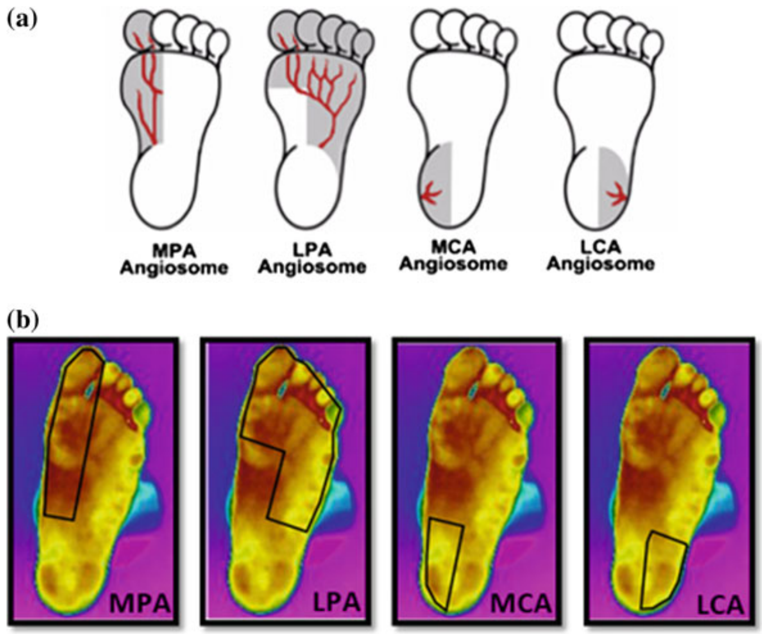

Fig. 10.5 Division of the thermographic image of the sole of the foot (**a**) according to the 4 angiosomes (**b**). Image A obtained from Nagase et al. [43]

Fig. 10.6 Structural division of the foot sole according to Zaproudina et al. [33]

shown in Fig. 10.7. This extra division will provide a deeper analysis of foot temperature with regard to exercise, as well as greater applicability in sport sciences, as will be explained in the following section.

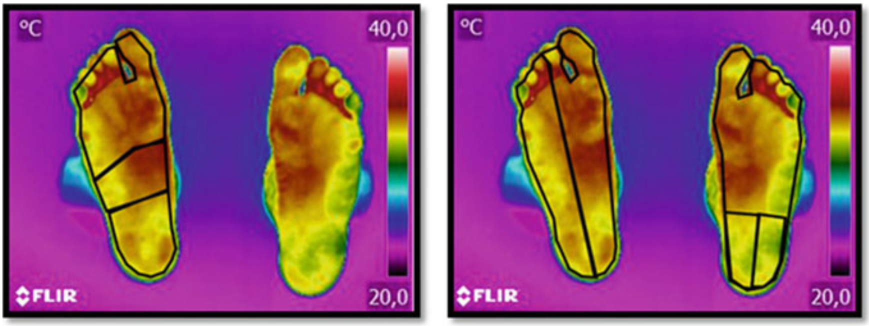

Fig. 10.7 Example of the division of the foot sole depending on the support provided while running according to Priego Quesada et al. [34] (*left*) and the five added region proposed by the authors of this chapter (*right*)

10.3 Applications of Thermographic Assessment of the Foot in Sports Sciences

The use of infrared thermal imaging in sport allows us to undertake rapid assessments, both quantitatively and qualitatively. Following up the thermal response of the sportsman or woman can provide relevant information on their health and on their performance, by contributing to the analysis of the sporting technique [48]. Furthermore, knowing foot temperature may help to understand the effects of footwear and sports equipment, which are also related with the performance and health of athletes [49, 50]. Hence, the following section focuses on the application of thermal imaging of the feet in terms of these three aspects: injury prevention, the analysis of sporting technique and the assessment of footwear and sports equipment.

10.3.1 Injury Prevention

Physical and sporting activity exposes its practitioners to great physical stress, so often producing injuries related to that activity [19, 51, 52]. Injuries are one of the main problems of athletes [48], and it is not only necessary to make a correct and appropriate diagnosis and treatment of injuries, but also to work on prevention, which will allow the sportsman or woman to undertake their sport in greater comfort, well-being and safety [53].

These injuries are accompanied by changes to body temperature. In some cases an increase in temperature (hyperthermia) occurs when there is an inflammation or some other process that leads to an increase in blood circulation, as in infections, tendonitis, bursitis, fractured bones, etc. Whereas a fall in temperature (hypothermia) occurs as a consequence of degenerative processes, a lower vascularization, arterial or venous occlusion, nerve damage, alterations in the autonomous nervous system, etc. [54, 55].

As the human body is bilateral and almost totally symmetrical in terms of its limbs, it may be said that it possesses bilateral symmetry in the surface temperature between two contralateral body zones [56, 57]. The differences of temperature found, therefore, between two opposite zones, called asymmetries, can serve as an indicator of pathologies or dysfunctions [57, 58].

Using this idea, the study of temperature asymmetries through infrared imaging has become a very valid method for use in the prevention, diagnosis and follow-up of an injury [29, 55]. Moreover, this technique allows us to study the temperature of the body surface during and after movement and, therefore, detect the changes produces by exercise [19, 59]. Nevertheless, it must not be used as a diagnosis tool, but as a technique that provides additional information, complementing other tests [31, 48].

According to some studies [60, 61], asymmetries greater than 0.38 ± 0.31 °C in the dorsal region of the foot, and 0.35 ± 0.27 °C on the sole; and 0.40 ± 0.30 °C both in the dorsal and sole, respectively, can be considered abnormal and be associated with an anatomical or physiological dysfunction.

However, a more recent study [57], with improvements both in applying the protocols and in the use of more modern and advanced thermographic cameras, found more accurate asymmetry values: 0.32 ± 0.18 °C for the dorsal region of the foot and 0.28 ± 0.13 °C for the sole; smaller values than those previously accepted for any area of the body in general (0.5 ± 0.3 °C). Moreover, this research recommended avoiding the view of the entire body when undertaking thermal imaging of the feet for specific studies on the asymmetries of the foot because this can reduce the accuracy of the measurement.

One of the factors to which several different injuries are associated, especially in running, are the high plantar loads to which the foot is subject [62]. It has been suggested that the increase in plantar pressures and friction in different regions of the foot may cause raised foot skin temperatures [17, 63, 64]. This supposition is based on the principle of energy conservation, where the mechanic energy produced by the repeated loads that the foot suffers in its interaction with the ground is transformed into thermal or calorific energy [17].

Hence, Shimazaki and Murata [17] found that the regions of the foot with the highest temperatures, the hallux and heel, coincided with the regions of the foot that have the highest contact loads when walking.

On the other hand, the studies of Yavuz and collaborators [64, 65] only reported a moderate lineal relationship between the increase of triaxial plantar loads and the increases of foot temperature as a consequence of walking. They claimed that the changes in foot temperature are produced, not only as a consequence of the plantar load but also blood circulation, the internal load and presence of kinetic friction in the interaction between the foot and the ground.

Another recent study [34] analyzed the relationship between static plantar pressure and the temperature of the feet soles, using thermography, following a 15 min run, with and without footwear. Although no correlations were found between the temperature and plantar pressure in any of the two conditions, they did find higher variations in temperature at the rearfoot in running without footwear, possibly as a consequence of a higher contact load, as the participants ran with a rearfoot striking pattern.

For their part, Taiar et al. [66] found higher increases of temperature in the heel than in the rest of the foot when walking; whereas during running, the temperature of the sole was higher than the complete foot. Thus they claimed that these results were due to the kinematic pattern differences between the two movements, walking vs running, and, therefore, the temperature rises are produced as a result of the specific movement that is undertaken.

To sum up, according to the above mentioned literature, although the evidence is not totally clear and still requires further investigation, it seems that the plantar temperature may be an alternative method for determining the loads or triaxial plantar shearing forces [17, 63, 64]; and, therefore, infrared thermography can provide a useful tool when it comes to assessing the mechanical stress to which the foot is subjected.

Associated with this idea, the authors of this chapter explored, using thermography, the ability of several insoles for reducing contact with ground loads. We analyzed the effect of two types of insoles (prefabricated and custom-made) on the surface temperature of the feet soles, after running, understanding that the use of insoles can reduce plantar pressures in several zones of the foot [67, 68]. Curiously enough, we did not find changes in plantar temperatures (Fig. 10.8), possibly explained by the period of adapting to the insoles where these changes may have taken place.

On the other hand, the study of Wrobel et al. [69] did find lower increases of temperature in diabetic subjects, both on the forefoot and midfoot after walking with an insole created to reduce shearing forces in comparison with a standard insole. In this study, therefore, thermography showed reductions of plantar temperature associated with lower plantar loads.

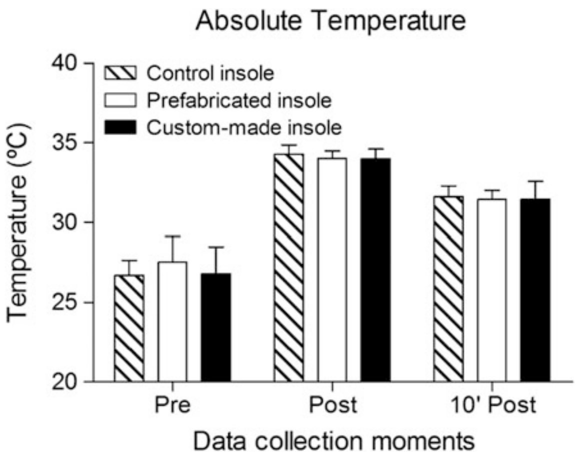

Fig. 10.8 Mean with 95% confidence Interval of the surface temperature of the feet soles at the three moments of measuring (the exercise consisted of a 20 min run)

As the case of Wrobel and collaborators [69] shows, infrared imaging is a very popular tool in the diagnosis and prevention of the diabetic foot [20, 31, 70, 71]. As mentioned before, its usefulness in assessment is evident and, especially, in the prevention of injuries related with physical activity [29, 48, 55], although its application to other injuries of the foot and foot sole, other than that of the diabetic foot, has yet to be fully studied.

To date, injuries related with the feet in which thermography has mostly been used for exploration, for changes in the temperature of the skin, are as follows:

- **Cutaneous injuries**:

When undertaking physical activity, the body is submitted to certain repeated loads that predispose the sportsman or woman to developing an injury. Due to the fact that the skin is the body's first line of defense, it is frequently exposed to the development of dermatological lesions [72]. In the feet, in particular, the friction and repeated pressure of the skin with the footwear or sock during exercise, together with the humidity and ventilation that the foot experiences, often causes traumas to the skin, such as abrasions, chafing, calluses, blisters, black heel or nail disorders [73–75].

Among these lesions, chafing and blisters on the feet and soles are frequent in almost all sports [73, 76]; but they mostly appear in running and especially in long-distance runners [75, 77]. According to a Mailler and Adams' review of dermatological lesions in marathons [77], the most common lesions discovered on the feet were blisters (0.2–39%), followed by chafing (0.4–16%).

Although these lesions seldom hinder the athletes from continuing their activity, they can be very painful, so restricting the normal functioning of the foot and altering the biomechanics of the lower limbs, and, hence, reducing the sporting performance and increasing the risk of injury [73, 78].

During chafing, repeated friction leads to reddening and peeling of the skin [74], whereas during blistering, friction leads to the separation of the layers of the epidermis causing local acute inflammation and the infiltration of liquid into the area [76]. This inflammation can promote an increase in the temperature of the skin, which along with the generation of a point of access, are the main indicators of the formation of blisters on the foot [72, 79]. Thus the studies of Hashmi et al. [72] and Kirkham et al. [80] investigated, using infrared imaging, the thermal changes in the skin of the foot due to friction in order to describe and quantify the physiological responses that take place in the skin of the foot before, during and after the formation of a blister. They arrived at the conclusion that thermal imaging can be of great use in evaluating the scope of the traumatically damaged skin of the foot, both for blisters [72, 81] and other pathologies and injuries whose main characteristic is inflammation and consequently an increase in temperature in the damaged area [82].

Chafing, blisters, calluses, cuts and all types of foot injuries are especially dangerous in people who suffer from diabetes mellitus, given that their complication can lead to the development of an ulcer, which if not treated in time can increase the risk of amputation [71, 82, 83].

Diabetes mellitus is a metabolic disease that is characterized by the presence of hyperglycemia caused by a lack of insulin [54]. It is one of the pandemics of the 21st century and its prevalence is in continuous growth: according to the *International Diabetes Federation* it is estimated that there are around 415 million people suffering from diabetes throughout the world and that this number will increase to more than 642 million in the year 2040 [84].

Among the various complications that this disease brings with it is what is called the diabetic foot, the main cause of which is a reduction in blood supply (vascular disorder) and loss of sensitivity (neuropathy) [70]. These factors, together with the repeated stress that the foot suffers in contact with the ground can lead to the appearance of a diabetic ulcer [85, 86], very common for this disease (it arises in 15–25% of diabetic cases) [87]. Areas with probability of ulceration are associated with local increases in skin temperature due to inflammation and the enzymatic autolysis of the tissue [88, 89]. Thus, checking the diabetic patient's foot temperature is very useful for the early identification of this lesion and would contribute to reducing its incidence [31, 43].

Again, infrared imaging has become one of the methods with the greatest potential for assessing and diagnosing the diabetic foot [20, 70, 71, 90]. Indeed, it is a very popular technique among researchers focusing on the foot and diabetic ulcers. According to several recent studies, it has been proposed as an accurate indicator of diabetes, even better than blood sugar measurements [70], and it seems to be a good substitute for measuring inflammation [82, 85]. Its already mentioned advantages as a non-invasive and non-contact technique, in comparison with other techniques, such as dermal thermometers or liquid crystal thermography [20, 31, 71], benefit the assessment of the diagnosis of the diabetic foot, as it allows us to obtain a full representation of temperature distribution in the plantar and dorsal regions [83], including the medial arch, or of feet with deformities [31]; it creates no undesired pressures or the transmission of pathological organisms [43]; and its high resolution allows the detection of temperature differences, often without the need to apply image processing algorithms [31]. However, it must be stated that its use must always be as a complementary method to other techniques in medical assessment [29, 31].

The study of diabetic foot temperature by thermography has allowed us to relate certain temperatures with the risk of developing complications of the diabetic foot, such as neuropathic ulcer, Charcot anthropathy and other complaints [83, 91]. Here, Sun and collaborators [92] found that diabetic patients in a situation of risk have a significantly higher mean temperature of the foot (30.2 ± 1.3 °C) in comparison with healthy subjects (26.8 ± 1.8 °C). On the other hand, Bagavathiappan et al. [40] found that patients with diabetic neuropathy show a higher mean temperature of the foot (32–35 °C) than patients without neuropathy (27–30 °C).

Similarly, most investigations use asymmetry analyses with thermography by comparing the temperature of the damaged limb with the contralateral limb as control in order to determine the risk of diabetic complication [20, 71, 91]. In particular, van Netten et al. [93] found a difference of temperature of 2.2 °C between two contralateral points as the maximum cut-off value for the detection of these complications. Curiously, this value is the same as that found in previous clinical studies that used cutaneous thermometry [85, 88, 94, 95].

Along these same lines, different authors [41–45] proposed asymmetry analysis on the feet of diabetics by analyzing the differences of temperature between the 4 contralateral angiosomes proposed by Attinger et al. [47], described earlier in Sect. 10.2.4 of this chapter.

Nevertheless, some authors [39, 92] are against diagnosis by asymmetries in systemic diseases that affect both limbs and propose standardizing the absolute temperature of the foot sole with respect to the temperature of the forehead. They take the temperature of the forehead as standard index, given that they claim that this is positively correlated with common central temperatures, is devoid of derivations from thermoregulatory flow and of countercurrent mechanisms that could significantly alter skin temperature [28], and finally because this temperature varies little.

Finally, other studies use more complex methods based on automated detection through the analysis of infrared thermal images, using algorithms, to identify the risk of ulceration [71, 82, 83, 96].

- **Bone injuries**:

The validity of infrared thermal imaging as a diagnostic tool for fractures due to stress has been conclusively shown as a result of the inflammatory process that accompanies them [54]. According to Goodman et al. [97] thermography can provide an accurate and non-invasive way of distinguishing a fracture from stress from other injuries with similar pain symptoms among runners. Besides its application in the follow-up on recovery from the injury, it allows the sportsman/woman to take up his or her activity again in the shortest and safest period of time.

However, its use has been little studied despite the fact that these injuries are produced quite frequently as a consequence of doing sport, especially in the metatarsals [98]. Thus, DiBenedetto [99], in 2002, used thermography to evaluate the risk of suffering a fracture by stress in the foot during basic military training. More recently, Niehof and collaborators [100] reported that this technique can be useful for complementing the diagnosis of complex regional pain syndrome (chronic pain that often compromises a limb, possibly as a consequence of a dysfunction of the nervous system) in patients with fractures in the feet, taking thermographic recordings in the dorsal and plantar regions of the feet.

- **Muscular injuries**:

Muscular injuries, among which are muscle cramps, contractures, strains and contusions are the most frequent injuries among sportsmen/women after osteoarticular injuries [101]. Generally, they have an important inflammatory component that is easily detectable by a local thermal variation [102], so they can be assessed by means of measuring temperature through infrared thermography technique, as several studies have shown [102–105].

The detection of muscular pain from delayed onset muscle soreness (DOMS) has even been investigated with this technique [106]. However, the study of muscular injuries produced in the feet using thermography is still inexistent, when it may be of great interest in such common sporting injuries as plantar fasciitis [53].

We have only been able to find one study [30] concerned with the assessment of muscular injury (low back pain) using thermal imaging on the feet soles. Curiously this investigation found a correlation between temperature changes in the plantar surface of the feet and the intensity of low back pain, due to the fact that the salient innervation of the low back region transports information to the soles of the feet by means of the sympathetic system.

- **Joint injuries**:

Foot sprains usually occur in the midfoot and the first metatarsophalangeal joint, but are not very common amongst sportsmen/women, whereas ankle sprains, closely related with the foot, are among the most common injuries in sport [107, 108].

Even so, there have been few scientific investigations into the application of infrared imaging in the study of any type of ankle joint injury [109] and even less of the foot. According to current literature, Oliveira et al. [109] was the first to use this technique in the assessment of an ankle sprain with the aim of studying its potential as a complementary tool for diagnosing degrees of this injury.

In Fig. 10.9, the image on the right shows an injured foot from judo, with a sprain of the anterior talofibular ligament, and the image on the right the contralateral healthy foot, showing the regions involved in this injury according to Oliveira et al. [109]. Clearly there is a difference of 1.4 °C in temperature in the affected region, the greatest temperature value being found at the uninjured extremity. This is due to the fact that the image of the injury was taken more than 48 h after the injury taking place, so, at that moment, the injury was already in the recovery process. Hence, the inflammatory component, due to the immediate

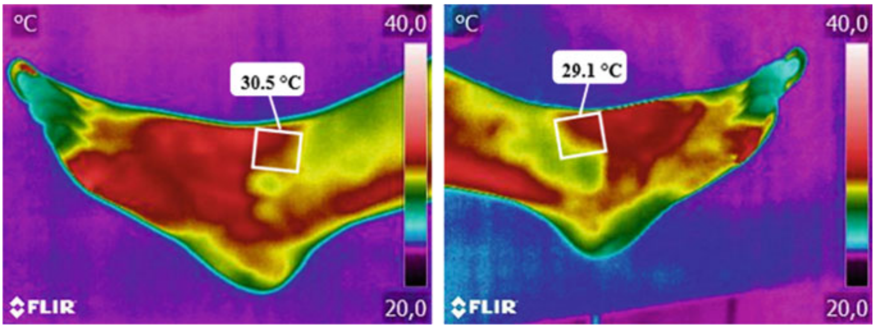

Fig. 10.9 Comparison of asymmetries between the right foot with sprain of the anterior talofibular ligament (*right*) and the healthy left foot (*left*), showing the mean temperature of the affected region

incidence of the injury, had already disappeared, but one can observe a lack of blood flow to the distal zone of the injured foot, associated with a fall in the overall temperature of that extremity, which suggests a hypothermia of the right foot, due to an already known and diagnosed pathology.

Another investigation [110] applied thermography in the assessment of a sprain, this time to the knee, to explore the possible effects of a type of manual therapy in the treatment of a complete rupture of the anterior crossed ligament. Curiously the surface temperature of the skin was measured, both of the knee and the feet and, although no significant changes were found in the temperature of the feet following treatment, it was interesting that the temperature of the feet before treatment was always lower on the injured side in comparison with the healthy side, whereas the temperature in the knee region was always higher on the injured side.

- **Vascular injuries**:

Lastly, hardly related to physical activity and sport, Staffa and collaborators [35] assessed the effect of percutaneous transluminal angioplasty using thermography of the feet and indicated the possibility of using thermal imaging as a means of early detection of the appearance of ischemic disorders of the foot, such as the diabetic foot, previously treated, or the Raynaud phenomenon.

In fact, the Raynaud phenomenon has for a long time been evaluated using infrared thermography [111–115], being especially focused on the hands [116, 117].

It is characterized by the manifestation of episodic vasospasms in the fingers and toes as a consequence of exposure to cold temperatures or strong emotions [118]. During these vascular spasms a narrowing of the blood vessels takes place which reduces the blood supply to the fingers and toes and produces a drastic reduction in temperature [113, 118].

Specifically, the study of Lim et al. [117] identified, through measuring the gradient of foot temperature using infrared thermography, a difference of temperature equal to or greater than 3.11 °C between the dorsal of the foot and the big toe, as the cut-off value that may indicate the presence of this disease (Fig. 10.10)

Both Lim et al. [117] and Tse et al. [115] reported that this technique can be very useful in diagnosing this phenomenon in the foot. Indeed, Tse et al. [115] claim that infrared thermography provides a more accurate and objective method than traditional physical exploration undertaken by health professionals by identifying the asymmetries of skin temperature related with the Raynaud phenomenon.

10.3.2 Determining the Pattern of Running

Sporting specialization can affect the normal thermal patterns in healthy athletes [119], causing thermal asymmetries that are specific to a particular sport, such as the forearm in tennis players, the tibialis anterior in football players, the arm in

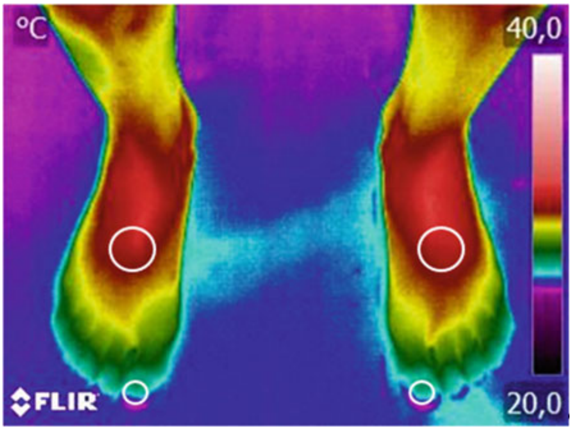

Fig. 10.10 Adaptation of the method used by Lim et al. [117] for measuring temperature gradients, comparing the dorsal of the foot with the big toe

volleyball and basketball players or the grasping forearm of a judo practitioner [54]. It is, therefore, important to know the thermal pattern commonly presented by the participants of a sport and the individual thermal patterns of the sportsman or woman in particular, before assessing the thermal asymmetries and venturing a possible injury [54].

Likewise, the execution of a sports technique, depending on the sport and the characteristics of the individual, can present certain thermal patterns, so it may be suggested that infrared thermography can be of great use to coaches, providing them with valuable information on the muscular activity undertaken and the technique employed as well as contributing to their improvement in training [120].

With this idea, and in relation with the foot region, the authors of this chapter undertook a preliminary study, the aim of which was to analyze the relationship between the temperature of the skin surface on the foot sole and the eversion of the ankle in running in order to determine whether infrared thermography could be a quick and simple tool for predicting the degree of ankle eversion in runners [121].

As Fig. 10.11 shows, there is a positive correlation between the symmetries of temperature variation (temperature difference between the medial side and the lateral side of the foot as a result of running) and the maximum ankle eversion during stance phase (MAE), but not with the eversion in first contact of the foot with the ground. So, finally it was concluded that in neutral pronator runners (with maximum eversion values of between 7 and 15°) the higher the temperatures observed in the internal region of the foot, the greater the degree of eversion.

Hence, it was suggested that thermography has great potential for predicting the foot type contact during running (pronation-supination), although further research is required to evaluate runners with different support patterns so as to be able to corroborate the findings.

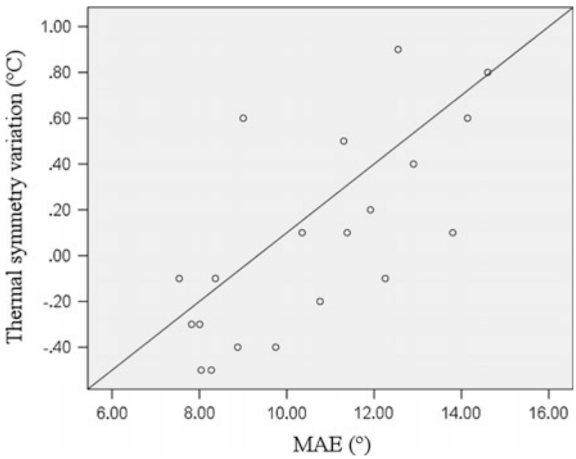

Fig. 10.11 Correlation between the maximum ankle eversion during stance phase (MAE) and the variation of the thermal symmetry of the plantar temperature (difference in temperature variation due to running between the medial and lateral sides of the foot) r = 0.7, $p = 0.001$

Along the same lines, the following image (Fig. 10.12) suggests that both the type of running contact (pronation-supination) and the running foot strike pattern of an athlete (forefoot, midfoot and rearfoot) could be studied by evaluating the temperatures of the soles of the trainers following exercise, simply by taking thermographic images.

This idea lacks scientific evidence, as there is no literature on it. Similarly research using thermography in other subjects that could also be interesting for the evaluation of this technique, such as the study of lateral dominance, the use of one extremity more than another, or the greater application of load on one foot rather than the other, and not only in running, but also in any sport where the foot comes into contact with the ground.

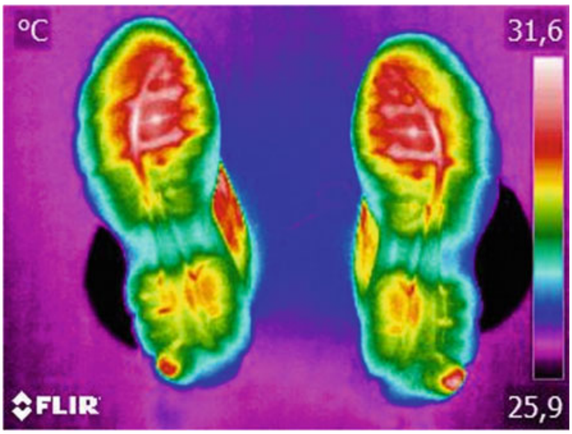

Fig. 10.12 Thermographic image of the soles of an athlete's footwear 10 min after running that could predict the type of foot contact (pronation-supination) due to the differences in temperature between regions

10.3.3 Determining the Effect of Footwear and Textiles on the Foot

Sports equipment significantly influences the sporting performance of the athlete in terms of the possible development or prevention of an injury [50, 122]. Specifically, the sports shoe plays an important role in these two aspects in a great number of sports where the interaction of the foot and the ground predominates.

Currently the sports market offers a huge selection when it comes to choosing specific footwear as there are many types of wide ranging characteristics that differ both in structure and functionality, and in style [123]. Hence, the sportsman or woman must choose footwear bearing in mind the architecture of their feet, their sport mechanics and the specific demands of their sports modality, as those characteristics will reduce the risk of injury and increase performance [124].

Moreover, thermal comfort is another characteristic that has to be taken into account in the design and choice of footwear, as it has great repercussions on general comfort while exercise is being undertaken and is also associated with improvement in sporting performance [125–127]. The thermal properties related with thermoregulation and thermal comfort are breathability and thermal insulation [125, 126]. Consequently, footwear that allows good breathability during exercise or that in very cold situations and adverse climatology are insulating and impermeable will favor the thermal comfort of the athlete [49, 125].

Another garment that has an influence on the microclimate created inside the shoe and directly affects the thermoregulation of the foot during sport is the sock. However, there are very few studies on the effect of socks, despite the fact that new textiles and fabrics have been designed to improve thermal equilibrium and to provide greater thermal comfort to the user [128].

In this sense, thermographic information on the foot can be very useful for the functional design of both footwear and socks; for the evaluation of the thermal properties that these garments offer to sportsmen and women, and also for observing the thermoregulation of the foot depending on the type of shoe or sock in the sports context [129].

In fact, according to the review published by Banerjee et al. [130], various applications of infrared thermography have already been reported in the textile industry, such as measuring the thermal properties of textile materials, measuring dryness and the transport of heat and humidity, analyzing the mechanical properties or the comfort of the garment, where this technique can play a crucial role in the future.

- **Breathability and sweat**:

As mentioned previously, the foot functions as a thermal radiator, of great importance to human thermoregulation. So, when the feet are inside footwear for long periods of time, the temperature and humidity within the footwear tends to increase [17], and can begin to cause discomfort and irritation and even provoke the development of an lesion or bacterial infection. This fact is especially so in summer and in warm and humid regions, as Kinoshita and Bates found in their study [131], temperatures on the sole of the footwear greater than 50 °C being recorded during a 40 min run on a summer's day.

The zones that are furthest away from the opening of the shoe and sock, i.e., the toes, receive less air movement (less ventilation), so their temperature will be highest [128].

These high foot and footwear temperatures, together with restrictions to ventilation as a consequence of the closed shoe, cause a high production of sweat by the foot aimed at trying to maintain body temperature around 37 °C [128].

It has been shown that the foot produces great amounts of sweat in comparison to the rest of the body [132], as it has a dense region of eccrine sweat glands. These glands are distributed all over the body, but are mostly concentrated on the palms of the hand, feet soles and forehead. They possess an innervation of the sympathetic nervous system and their secretion is commonly called sweat, so contributing to heat loss through evaporation [17]. Sometimes the feet and footwear produce bad smells due to the proliferation of bacteria resulting from excessive humidity derived from sweat in that area.

Nevertheless, in a study the aim of which was to describe the production of foot sweat during exercise, in this case running, a greater amount of sweat secretion was observed in the dorsal of the foot than in the plantar zone [133], even when there is a higher number of sweat glands in feet soles [2]. Moreover, it was also found that the use of footwear limits the increase in sweat production as running intensity increases [133].

Thus a particularly important factor both for the comfort of sportsmen and women's feet and for the appropriate maintenance of heat dynamics during exercise is that the footwear or sock presents suitable properties of heat dissipation through convection and conduction currents between the feet and the fabric and improves breathability, i.e., the elimination of sweat through evaporation [14, 123]. For its part, the sock is fundamental for maintaining the climate of the foot, given that it transports the sweat from the foot to the upper part of the shoe so that it evaporates better [123].

Thermal analysis of the sports shoe using infrared thermal imaging can, therefore, be very useful in identifying the areas that provide the greatest breathability to the athlete and help him or her to choose the footwear that facilitates thermoregulation, as shown in Fig. 10.13.

As can be seen in the next figure (Fig. 10.13), the specific running shoe presents higher temperatures to that of the mountain shoe. This is due to the fact that the running shoe is more breathable and less insulated, so facilitating the flow of temperature from the foot to the outside of the shoe. This method of analyzing footwear could become a very interesting field of research. As can be observed, the terms insulation and breathability are closely linked, so the characteristic of insulation will now be explained.

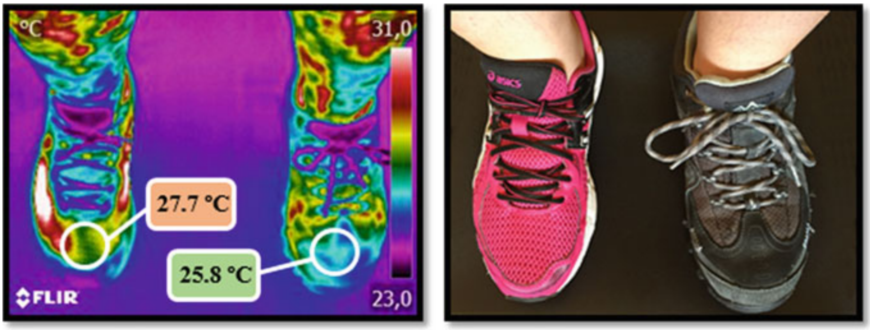

Fig. 10.13 Thermographic images of the dorsal views of the feet with two different sports shoe after undertaking a 10 min run: a specific running sports shoe (*left*): and a trail sports shoe (*right*). Mean temperatures of the regions within the circumferences are shown

- **Insulation**:

During exercise the feet remain hot. However, during inactivity the temperature of the feet falls rapidly [49]. One of the properties of footwear that helps to reduce heat loss is thermal insulation, the importance of which is accentuated when physical activity is undertaken at low temperatures or in cold and humid regions [134].

Insulation can be increased through garments or materials added to the footwear that provide local insulation, such as on the toes and heels, whose effects are clearly notable on the mean temperatures of the skin [49]. However, wearing a thick pair of socks in a tight shoe can produce the opposite effect, increasing the accumulation of humidity and so reducing the insulation of the footwear by up to 45% [134, 135].

The thermal insulation of footwear and socks can be assessed through two methodologies: directly on the feet of human beings [136], or using a thermal foot model [49, 137]. The main drawback of which is that it cannot contemplate the conditions and changes that are produced during a specific sports practice, and the alterations caused in the physiology of the foot of the user as a consequence of that practice.

To date, there have been two investigations carried out on human beings that have reported increases in temperature in certain regions of the foot, during walking and running, probably as a result of the effect of footwear insulation [17, 34], respectively.

The latter, of Priego Quesada et al. [34], used, as the skin measuring technique, infrared thermography, the main advantage of which is that it does not interfere in the behavior of the athlete when in use, nor does it effect the thermoregulation of the foot as it is non-invasive. Other methods can be invasive, such as incorporating sensors on the surface of the skin of the foot, which was used by Shimazaki and Murata [17]. However, the main drawback of the infrared thermography method is that the measurements have to be taken in static positions and without footwear and socks, as it is not possible to undertake then while running in a real situation. In this sense, surface sensors have a clear advantage.

On the other hand, in various studies the aim of which was to compare foot temperature with the use of different models of footwear and socks during running, the conclusion was reached that the perception of foot temperature by the user may differ from the real physiological temperature of the foot [123, 128]. Thus, it may be said that, when determining how a shoe or sock affects the physiological temperature of the foot, the study has to be undertaken through techniques that provide more precise information than the subjective perception of the user. Infrared thermography does this, providing speed and simplicity to the assessment. We cannot, however, ignore the perceptions of the user, given that they will be the ones to determine thermal comfort and, consequently, the performance of the athlete [128].

10.4 Conclusions

As explained in this chapter, the thermographic analysis of the foot in sport sciences presents numerous and interesting applications. These applications range from the prevention of injuries and the analysis of the effects of sporting technique on foot temperature to the evaluation of sports equipment (footwear, insoles and socks). Infrared thermography, therefore, can provide vital information for the athlete on how to improve his or her performance and on reducing the possibilities of injury. Nevertheless, evidence is scarce in these fields and future studies are required to analyze the hypothetical potential of infrared thermography dealt with in this chapter. Methodologically, there are also issues that need to be addressed. An analysis needs to be made of which determination of the regions of interest on the foot can be of assistance to each of the different applications. Moreover, studying the reproducibility of the foot temperature variation as a result of exercise is an aspect that must be investigated. In conclusion, thermography in the analysis of the foot in sport sciences presents great potential, although there is at present little literature that has gone into any depth on those applications.

References

1. Nordin M, Frankel VH (2001) Basic biomechanics of the musculoskeletal system. Lippincott Williams & Wilkins
2. Taylor NA, Machado-Moreira CA, van den Heuvel AM, Caldwell JN (2014) Hands and feet: physiological insulators, radiators and evaporators. Eur J Appl Physiol 114:2037–2060
3. Thibodeau GA, Patton KT (2007) Anatomía y fisiología. Elsevier España
4. Hreljac A (2004) Impact and overuse injuries in runners. Med Sci Sports Exerc 845–849. doi:10.1249/01.MSS.0000126803.66636.DD
5. Golden FSC, Francis TJR, Gallimore D, Pethybridge R (2013) Lessons from history: morbidity of cold injury in the Royal Marines during the Falklands Conflict of 1982. Extreme Physiol Med 2:23. doi:10.1186/2046-7648-2-23
6. Johnson JM, Kellogg DL (2010) Local thermal control of the human cutaneous circulation. J Appl Physiol Bethesda Md 1985 109:1229–1238. doi:10.1152/japplphysiol.00407.2010

7. Pérgola PE, Kellogg DL, Johnson JM et al (1993) Role of sympathetic nerves in the vascular effects of local temperature in human forearm skin. Am J Physiol 265:H785–792
8. Taylor WF, Johnson JM, O'Leary D, Park MK (1984) Effect of high local temperature on reflex cutaneous vasodilation. J Appl Physiol 57:191–196
9. Standring S (2015) Gray's anatomy: the anatomical basis of clinical practice. Elsevier Health Sciences
10. Blair DA, Glover WE, Roddie IC (1960) Vasomotor fibres to skin in the upper arm, calf and thigh. J Physiol 153:232–238
11. Roddie IC (2011) Circulation to skin and adipose tissue. Comprehensive physiology. Ed. American physiological society. doi:10.1002/cphy.cp020310
12. Johnson JM, Pérgola PE, Liao FK, et al (1995) Skin of the dorsal aspect of human hands and fingers possesses an active vasodilator system. J Appl Physiol Bethesda Md 1985 78:948–954
13. Charkoudian N (2003) Skin blood flow in adult human thermoregulation: how it works, when it does not, and why. Mayo Clin Proc 78:603–612. doi:10.4065/78.5.603
14. Chicharro JL, Vaquero AF (2006) Fisiología del ejercicio/Physiology of Exercise. Ed. Médica Panamericana
15. Morrison SA, Gorjanc J, Mekjavic IB (2014) Mount Everest and Makalu cold injury amputation: 40 years on. High Altitude Med Biol 15:78–83. doi:10.1089/ham.2013.1069
16. Taylor NA, Machado-Moreira CA (2013) Regional variations in transepidermal water loss, eccrine sweat gland density, sweat secretion rates and electrolyte composition in resting and exercising humans. Extreme Physiol Med 2:4. doi:10.1186/2046-7648-2-4
17. Shimazaki Y, Murata M (2015) Effect of gait on formation of thermal environment inside footwear. Appl Ergon 49:55–62. doi:10.1016/j.apergo.2015.01.007
18. de Andrade Fernandes A, dos Santos Amorim PR, Brito CJ et al (2014) Measuring skin temperature before, during and after exercise: a comparison of thermocouples and infrared thermography. Physiol Meas 35:189
19. Hildebrandt C, Zeilberger K, Ring EFJ, Raschner C (2012) The application of medical infrared thermography in sports medicine. Ultrasound 10:2
20. Mendes R, Sousa N, Almeida A et al (2015) Thermography: a technique for assessing the risk of developing diabetic foot disorders. Postgrad Med J 91:538. doi:10.1136/postgradmedj-2015-133441
21. Wasner G, Schattschneider J, Baron R (2002) Skin temperature side differences–a diagnostic tool for CRPS? Pain 98:19–26
22. Berry RJ, Kennedy AD, Scott SL et al (2003) Daily variation in the udder surface temperature of dairy cows measured by infrared thermography: potential for mastitis detection. Can J Anim Sci 83:687–693. doi:10.4141/A03-012
23. Alsaaod M, Büscher W (2012) Detection of hoof lesions using digital infrared thermography in dairy cows. J Dairy Sci 95:735–742. doi:10.3168/jds.2011-4762
24. Bowers S, Gandy S, Anderson B et al (2009) Assessment of pregnancy in the late-gestation mare using digital infrared thermography. Theriogenology 72:372–377
25. Nikkhah A, Plaizier JC, Einarson MS et al (2005) Short communication: infrared thermography and visual examination of hooves of dairy cows in two stages of lactation. J Dairy Sci 88:2749–2753. doi:10.3168/jds.S0022-0302(05)72954-4
26. Alsaaod M, Schaefer AL, Büscher W, Steiner A (2015) The role of infrared thermography as a non-invasive tool for the detection of lameness in cattle. Sensors 15:14513–14525
27. Oberle J, Elam M, Karlsson T, Wallin BG (1988) Temperature-dependent interaction between vasoconstrictor and vasodilator mechanisms in human skin. Acta Physiol Scand 132:459–469. doi:10.1111/j.1748-1716.1988.tb08353.x
28. Kakuta N, Yokoyama S, Mabuchi K (2002) Human thermal models for evaluating infrared images. Eng Med Biol Mag IEEE 21:65–72
29. Sillero-Quintana M, Fernández-Jaén T, Fernández-Cuevas I et al (2015) Infrared thermography as a support tool for screening and early diagnosis in emergencies. J Med Imaging Health Inform 5:1223–1228

30. Zaproudina N, Ming Z, Hänninen OO (2006) Plantar infrared thermography measurements and low back pain intensity. J Manipulative Physiol Ther 29:219–223
31. Sousa P, Felizardo V, Oliveira D et al (2015) A review of thermal methods and technologies for diabetic foot assessment. Expert Rev Med Devices 12:439–448. doi:10.1586/17434440.2015.1032251
32. Schaefer AL, Cook NJ, Luzi F, et al (2013) Heat generation and the role of infrared thermography in pathological conditions. Thermography Curr Status Adv Livestock Anim Vet Med 69–78
33. Zaproudina N, Varmavuo V, Airaksinen O, Närhi M (2008) Reproducibility of infrared thermography measurements in healthy individuals. Physiol Meas 29:515. doi:10.1088/0967-3334/29/4/007
34. Priego Quesada JIP, Kunzler MR, da Rocha ES et al (2015) Plantar pressure and foot temperature responses to acute barefoot and shod running. Hum Mov 16:142–148. doi:10.1515/humo-2015-0040
35. Staffa E, Bernard V, Kubicek L, et al (2016) Infrared thermography as option for evaluating the treatment effect of percutaneous transluminal angioplasty by patients with peripheral arterial disease. Vascular. doi:10.1177/1708538116640444
36. Marins JCB, Moreira DG, Cano SP et al (2014) Time required to stabilize thermographic images at rest. Infrared Phys Technol 65:30–35. doi:10.1016/j.infrared.2014.02.008
37. Ammer K (2008) The Glamorgan Protocol for recording and evaluation of thermal images of the human body. Thermol Int 18:125–144
38. Hall M, Shurr DG, Zimmerman MB, Saltzman CL (2004) Plantar foot surface temperatures with use of insoles. Iowa Orthop J 24:72–75
39. Sun P-C, Jao S-HE, Cheng C-K (2005) Assessing foot temperature using infrared thermography. Foot Ankle Int 26:847–853. doi:10.1177/107110070502601010
40. Bagavathiappan S, Philip J, Jayakumar T et al (2010) Correlation between plantar foot temperature and diabetic neuropathy: a case study by using an infrared thermal imaging technique. J Diabetes Sci Technol 4:1386–1392. doi:10.1177/193229681000400613
41. Bharara M, Boulger E, Grewal GS, et al (2014) Applications of angiosome classification model for monitoring disease progression in the diabetic feet. In: Proceedings of the 2014 summer simulation multiconference society for computer simulation international, p 34
42. Mori T, Nagase T, Takehara K et al (2013) Morphological pattern classification system for plantar thermography of patients with diabetes. J Diabetes Sci Technol 7:1102–1112. doi:10.1177/193229681300700502
43. Nagase T, Sanada H, Takehara K et al (2011) Variations of plantar thermographic patterns in normal controls and non-ulcer diabetic patients: novel classification using angiosome concept. J Plast Reconstr Aesthetic Surg 64:860–866
44. Peregrina-Barreto H, Morales-Hernández LA, Rangel-Magdaleno JJ, Vázquez-Rodríguez PD (2013) Thermal image processing for quantitative determination of temperature variations in plantar angiosomes. In: 2013 IEEE international instrumentation measurement technology conference I2MTC, pp 816–820
45. Peregrina-Barreto H, Morales-Hernandez LA, Rangel-Magdaleno JJ, et al (2014) Quantitative estimation of temperature variations in plantar angiosomes: a study case for diabetic foot. Comput Math Methods Med. doi:10.1155/2014/585306
46. Taylor GI, Palmer JH (1987) The vascular territories (angiosomes) of the body: experimental study and clinical applications. Br J Plast Surg 40:113–141
47. Attinger CE, Evans KK, Bulan E et al (2006) Angiosomes of the foot and ankle and clinical implications for limb salvage: reconstruction, incisions, and revascularization. Plast Reconstr Surg 117:261S–293S
48. Marins JCB, Fernández-Cuevas I, Arnaiz-Lastras J, et al (2015) Aplicaciones de la termografía infrarroja en el deporte: Una revisión. Rev. Int. Med. Cienc. Act. Física Deporte
49. Kuklane K (2004) The use of footwear insulation values measured on a thermal foot model. Int J Occup Saf Ergon 10:79–86

50. Morey G, Mademli L (2015) El calzado deportivo. In: Perez-Soriano P, Llana-Belloch S, Biomecánica básica aplicada a la actividad física y el deporte. Ed. Paidotribo. pp 351–362
51. Dekker R, Kingma J, Groothoff JW et al (2000) Measurement of severity of sports injuries: an epidemiological study. Clin Rehabil 14:651–656
52. Zwerver J (Hans) (2015) Sports injuries. In: Glaudemans AWJM, Dierckx RAJO, Gielen JLMA, Zwerver J (Hans) (eds) Nucl. Med. Radiol. Imaging Sports Inj. Springer Berlin Heidelberg, pp 49–67
53. Sobhani S, Dekker R, Postema K, Dijkstra PU (2013) Epidemiology of ankle and foot overuse injuries in sports: a systematic review. Scand J Med Sci Sports 23:669–686
54. Fernández-Cuevas I, Bouzas Marins JC, Arnáiz Lastras J et al (2015) Classification of factors influencing the use of infrared thermography in humans: A review. Infrared Phys Technol 71:28–55. doi:10.1016/j.infrared.2015.02.007
55. Hildebrandt C, Raschner C, Ammer K (2010) An overview of recent application of medical infrared thermography in sports medicine in Austria. Sensors 10:4700–4715
56. Vardasca R (2008) Symmetry of temperature distribution in the upper and lower extremities. Thermol Int 18:154–155
57. Vardasca R, Ring F, Plassmann P, Jones C (2012) Thermal symmetry of the upper and lower extremities in healthy subjects. Thermol Int 22:53–60
58. Vardasca R, Ring EFJ, Plassmann P, Jones CD (2007) Thermal symmetry on extremities of normal subjects. In: Conference in precedings of the first research student workshop on the faculty of advanced technology. University of Glamorgan, pp 19–24
59. Hardaker NJ, Moss AD, Richards J, et al (2007) The relationship between skin surface temperature measured via non-contact thermal imaging and intra-muscular temperature of the rectus femoris muscle. Studies 13:17
60. Niu HH, Lui PW, Hu JS, et al (2001) Thermal symmetry of skin temperature: normative data of normal subjects in Taiwan. Zhonghua Yi Xue Za Zhi Chin Med J Free China Ed 64:459–468
61. Uematsu S, Edwin DH, Jankel WR et al (1988) Quantification of thermal asymmetry: Part 1: normal values and reproducibility. J Neurosurg 69:552–555
62. Chuckpaiwong B, Nunley JA, Mall NA, Queen RM (2008) The effect of foot type on in-shoe plantar pressure during walking and running. Gait Posture 28:405–411
63. Brand PW (2003) Tenderizing the Foot. Foot Ankle Int 24:457–461. doi:10.1177/107110070302400602
64. Yavuz M, Brem RW, Davis BL et al (2014) Temperature as a predictive tool for plantar triaxial loading. J Biomech 47:3767–3770
65. Yavuz M, Delvadia N, Atves J, et al (2013) Biomechanical value of temperature in assessing plantar loading. Am Soc Biomech. Communication in the 37th annual meeting of the American Society of Biomechanics, Omaha, NE
66. Taiar R, Rebay M, Vannozzi G, et al (2008) Evolution of the in-shoe temperature during walking and running. Bio Eng Biomed Med 601–89
67. Lee Y-C, Lin G, Wang M-JJ (2012) Evaluating insole design with joint motion, plantar pressure and rating of perceived exertion measures. Work 41:1114–1117
68. Lucas-Cuevas AG, Pérez-Soriano P, Llana-Belloch S et al (2014) Effect of custom-made and prefabricated insoles on plantar loading parameters during running with and without fatigue. J Sports Sci 32:1712–1721. doi:10.1080/02640414.2014.915422
69. Wrobel JS, Ammanath P, Le T et al (2014) A novel shear reduction insole effect on the thermal response to walking stress, balance, and gait. J Diabetes Sci Technol 8:1151–1156
70. Lahiri BB, Bagavathiappan S, Jayakumar T, Philip J (2012) Medical applications of infrared thermography: a review. Infrared Phys Technol 55:221–235
71. Liu C, van Netten JJ, van Baal JG et al (2015) Automatic detection of diabetic foot complications with infrared thermography by asymmetric analysis. J Biomed Opt 20:026003. doi:10.1117/1.JBO.20.2.026003

72. Hashmi F, Richards BS, Forghany S et al (2013) The formation of friction blisters on the foot: The development of a laboratory-based blister creation model. Skin Res Technol 19: e479–e489. doi:10.1111/j.1600-0846.2012.00669.x
73. Basler RSW, Hunzeker CM, Garcia MA, Dexter W (2004) Athletic Skin Injuries. Phys Sportsmed 32:33–40. doi:10.3810/psm.2004.05.304
74. Helm MF, Helm TN, Bergfeld FW (2012) Skin problems in the long-distance runner 2500 years after the Battle of Marathon. Int J Dermatol 51:263–270
75. Purim KSM, Leite N, Purim KSM, Leite N (2014) Sports-related dermatoses among road runners in Southern Brazil. An Bras Dermatol 89:587–592. doi:10.1590/abd1806-4841.20142792
76. Honsik KA, Romeo MW, Hawley CJ et al (2007) Sideline skin and wound care for acute injuries. Curr Sports Med Rep 6:147–154
77. Mailler EA, Adams BB (2004) The wear and tear of 26.2: dermatological injuries reported on marathon day. Br J Sports Med 38:498–501. doi:10.1136/bjsm.2004.011874
78. Van Tiggelen D, Wickes S, Coorevits P et al (2009) Sock systems to prevent foot blisters and the impact on overuse injuries of the knee joint. Mil Med 174:183–189. doi:10.7205/MILMED-D-01-8508
79. Reynolds K, Darrigrand A, Roberts D et al (1995) Effects of an antiperspirant with emollients on foot-sweat accumulation and blister formation while walking in the heat. J Am Acad Dermatol 33:626–630. doi:10.1016/0190-9622(95)91283-5
80. Kirkham S, Lam S, Nester C, Hashmi F (2014) The effect of hydration on the risk of friction blister formation on the heel of the foot. Skin Res Technol 20:246–253. doi:10.1111/srt.12136
81. Hashmi F, Kirkham S, Nester C, Lam S The effect of topical anti blister products on the risk of friction blister formation on the foot. J Tissue Viability. doi:10.1016/j.jtv.2016.04.002
82. Liu C, van der Heijden F, Klein ME, et al (2013) Infrared dermal thermography on diabetic feet soles to predict ulcerations: a case study. In: SPIE BiOS. International society for optics and photonics, pp 85720N–85720N
83. Hernandez-Contreras D, Peregrina-Barreto H, Rangel-Magdaleno J et al (2015) Automatic classification of thermal patterns in diabetic foot based on morphological pattern spectrum. Infrared Phys Technol 73:149–157. doi:10.1016/j.infrared.2015.09.022
84. International Diabetes Federation (2015) IDF diabetes atlas, 7th edn. International Diabetes Federation, Brussels, Belgium
85. Armstrong DG, Holtz-Neiderer K, Wendel C et al (2007) Skin temperature monitoring reduces the risk for diabetic foot ulceration in high-risk patients. Am J Med 120:1042–1046. doi:10.1016/j.amjmed.2007.06.028
86. Lavery LA, Armstrong DG, Vela SA et al (1998) Practical criteria for screening patients at high risk for diabetic foot ulceration. Arch Int Med 158:157–162
87. Boulton AJ, Vileikyte L, Ragnarson-Tennvall G, Apelqvist J (2005) The global burden of diabetic foot disease. Lancet 366:1719–1724. doi:10.1016/S0140-6736(05)67698-2
88. Armstrong DG, Lavery LA, Liswood PJ et al (1997) Infrared dermal thermometry for the high-risk diabetic foot. Phys Ther 77:169–175
89. Lavery LA, Higgins KR, Lanctot DR et al (2004) Home monitoring of foot skin temperatures to prevent ulceration. Diabetes Care 27:2642–2647. doi:10.2337/diacare.27.11.2642
90. Balbinot LF, Canani LH, Robinson CC et al (2012) Plantar thermography is useful in the early diagnosis of diabetic neuropathy. Clinics 67:1419–1425
91. van Netten JJ, Prijs M, van Baal JG et al (2014) Diagnostic values for skin temperature assessment to detect diabetes-related foot complications. Diabetes Technol Ther 16:714–721. doi:10.1089/dia.2014.0052
92. Sun P-C, Lin H-D, Jao S-HE et al (2006) Relationship of skin temperature to sympathetic dysfunction in diabetic at-risk feet. Diabetes Res Clin Pract 73:41–46. doi:10.1016/j.diabres.2005.12.012

93. van Netten JJ, Jannink MJA, Hijmans JM et al (2010) Long-term use of custom-made orthopedic shoes: 1.5-year follow-up study. J Rehabil Res Dev 47:643. doi:10.1682/JRRD.2010.03.0040
94. Armstrong DG, Lavery LA, Wunderlich RP, Boulton AJM (2003) Skin temperatures as a one-time screening tool do not predict future diabetic foot complications. J Am Podiatr Med Assoc 93:443–447. doi:10.7547/87507315-93-6-443
95. Armstrong DG, Lipsky BA, Polis AB, Abramson MA (2006) Does dermal thermometry predict clinical outcome in diabetic foot infection? Analysis of data from the SIDESTEP* trial. Int Wound J 3:302–307. doi:10.1111/j.1742-481X.2006.00269.x
96. van Netten JJ, van Baal JG, Liu C et al (2013) Infrared thermal imaging for automated detection of diabetic foot complications. J Diabetes Sci Technol 7:1122–1129
97. Goodman PH, Heaslet MW, Pagliano JW, Rubin BD (1985) Stress fracture diagnosis by computer-assisted thermography. Phys Sportsmed 13:114–132
98. Laird RC (2015) Acute forefoot and midfoot injuries. Clin Podiatr Med Surg 32:231–238
99. DiBenedetto M (2002) Foot evaluation by infrared imaging. Mil Med 167:384
100. Niehof SP, Beerthuizen A, Huygen FJ, Zijlstra FJ (2008) Using skin surface temperature to differentiate between complex regional pain syndrome type 1 patients after a fracture and control patients with various complaints after a fracture. Anesth Analg 106:270–277
101. Schmitt M, Guillot Y (1984) Thermography and muscular injuries in sports medicine. In: Recent advances medical thermology. Springer, pp 439–445
102. Bandeira F, Neves EB, de Moura MAM, Nohama P (2014) A termografia no apoio ao diagnóstico de lesão muscular no esporte. Rev Bras Med Esporte 20:59–64
103. Bandeira F, de Moura MAM, de Souza MA et al (2012) Pode a termografia auxiliar no diagnóstico de lesões musculares em atletas de futebol? Rev Bras Med Esporte 18:246–251
104. Barcelos EZ, Caminhas WM, Ribeiro E et al (2014) A combined method for segmentation and registration for an advanced and progressive evaluation of thermal images. Sensors 14:21950–21967. doi:10.3390/s141121950
105. Morales Ríos M, Medina Chacón E, Carnevali Fernández Á, Orozco Guillén E (2011) Termografía infrarroja y el estudio de riesgos de lesiones músculo esqueléticas. Rev Ing Ind 55–67
106. Al-Nakhli HH, Petrofsky JS, Laymon MS, Berk LS (2012) The use of thermal infra-red imaging to detect delayed onset muscle soreness. J Vis Exp. doi:10.3791/3551
107. Doherty C, Delahunt E, Caulfield B et al (2014) The incidence and prevalence of ankle sprain injury: a systematic review and meta-analysis of prospective epidemiological studies. Sports Med 44:123–140
108. Tenforde AS, Yin A, Hunt KJ (2016) Foot and ankle injuries in runners. Phys Med Rehabil Clin N Am 27:121–137
109. Oliveira J, Vardasca R, Pimenta M et al (2016) Use of infrared thermography for the diagnosis and grading of sprained ankle injuries. Infrared Phys Technol 76:530–541
110. Litscher G, Ofner M, Litscher D, others (2013) Manual Khalifa therapy in patients with completely ruptured anterior cruciate ligament in the knee: first preliminary results from thermal imaging. North Am J Med Sci 5:473
111. Ammer K (1996) Diagnosis of raynaud's phenomenon by thermography. Skin Res Technol 2:182–185
112. Cherkas LF, Carter L, Spector TD et al (2003) Use of thermographic criteria to identify Raynaud's phenomenon in a population setting. J Rheumatol 30:720–722
113. Ring F (2016) The Herschel heritage to medical thermography. J Imaging 2:13
114. Saito S, Ishii T, Kamogawa Y et al (2016) Extracorporeal shock wave therapy for digital ulcers of systemic sclerosis: a phase 2 pilot study. Tohoku J Exp Med 238:39–47
115. Tse J, Rand C, Carroll M, et al (2015) Determining peripheral skin temperature: subjective versus objective measurements. Acta Paediatr 105:126–131. doi:10.1111/apa.13283
116. Chlebicka I, Matusiak U, Maj J et al (2013) Freezing fingers syndrome, primary and secondary Raynaud's phenomenon: characteristic features with hand thermography. Acta Derm Venereol 93:428–432

117. Lim MJ, Kwon SR, Jung K-H et al (2014) Digital thermography of the fingers and toes in Raynaud's phenomenon. J Korean Med Sci 29:502–506
118. Block JA, Sequeira W (2001) Raynaud's phenomenon. Lancet 357:2042–2048
119. Tauchmannova H, Gabrhel J, Cibak M (1993) Thermographic findings in different sports, their value in the prevention of soft tissue injuries. Themol Osterr 3:91–95
120. Chudecka M, Lubkowska A, Leźnicka K, Krupecki K (2015) The use of thermal imaging in the evaluation of the symmetry of muscle activity in various types of exercises (symmetrical and asymmetrical). J Hum Kinet 49:141–147
121. Gil-Calvo M, Jimenez-Perez I, Priego Quesada JI, et al (2016) Could skin temperature predict ankle eversion after running? Book Abstract. 21st Annual Congress European College Sport Science. Vienna, Austria
122. Stefanyshyn DJ, Wannop JW (2015) Biomechanics research and sport equipment development. Sports Eng 18:191–202. doi:10.1007/s12283-015-0183-5
123. Barkley RM, Bumgarner MR, Poss EM, Senchina DS (2011) Physiological versus perceived foot temperature, and perceived comfort, during treadmill running in shoes and socks of various constructions. Am J Undergrad Res 10:7–14
124. Yamashita MH (2005) Evaluation and selection of shoe wear and orthoses for the runner. Phys Med Rehabil Clin N Am 16:801–829
125. Covill D, Guan ZW, Bailey M, Raval H (2011) Development of thermal models of footwear using finite element analysis. Proc Inst Mech Eng [H] 225:268–281. doi:10.1243/09544119JEIM860
126. Fan J, Tsang HW (2008) Effect of clothing thermal properties on the thermal comfort sensation during active sports. Text Res J 78:111–118
127. Luo G, Stergiou P, Worobets J et al (2009) Improved footwear comfort reduces oxygen consumption during running. Footwear Sci 1:25–29
128. Purvis A, Tunstall H (2004) Effects of sock type on foot skin temperature and thermal demand during exercise. Ergonomics 47:1657–1668. doi:10.1080/00140130412331290880
129. Shen WW, Gu YD, Bull AM (2013) Characteristic of foot surface temperature variety during continual low-intensity exercise. Biotechnol Indian J 7:352–356
130. Banerjee D, Chattopadhyay SK, Tuli S (2013) Infrared thermography in material research–a review of textile applications. Indian J Fiber Text Res 38:427–437
131. Kinoshita H, Bates BT (1996) The effect of environmental temperature on the properties of running shoes. J Appl Biomech 12:258–268
132. Park SJ, Tamura T (1992) Distribution of evaporation rate on human body surface. Ann Physiol Anthropol 11:593–609
133. Smith CJ, Machado-Moreira CA, Plant G et al (2013) Design data for footwear: sweating distribution on the human foot. Int J Cloth Sci Technol 25:43–58
134. Kuklane K, Geng Q, Holmér I (1998) Effect of footwear insulation on thermal responses in the cold. Int J Occup Saf Ergon 4:137–152
135. Kuklane K, Gavhed D, Fredriksson K (2001) A field study in dairy farms: thermal condition of feet. Int J Ind Ergon 27:367–373
136. Kuklane K, Afanasieva R, Burmistrova O et al (1999) Determination of heat loss from the feet and insulation of the footwear. Int J Occup Saf Ergon 5:465–476. doi:10.1080/10803548.1999.11076432
137. Kuklane K, Ueno S, Sawada S-I, Holmér I (2009) Testing cold protection according to EN ISO 20344: is there any professional footwear that does not pass? Ann Occup Hyg 53:63–68. doi:10.1093/annhyg/men074