Heat transfer in athletic shoes during the running

M. REBAY[1], A. ARFAOUI[2], A. LEOPOL[3], J. PERIN[3] AND R. TAIAR[3]

[1] *Laboratoire de thermomécanique, UTAP, faculté des sciences, B.P. 1039, 51687 Reims,* FRANCE

[2] *Laboratoire LETTM, faculté des sciences de Tunis, 2092 Manar II, TUNISIA*

[3] *Laboratoire d'Analyse des Contraintes Mécaniques, UFR STAPS, BP 1036, 51687 Reims, FRANCE*

Abstract - Regarding a conception of a new running shoe, a primary study of the foot heating during the running constitutes an important step for the thermal comfort optimisation and augmentation of the athletic performances. In order to evaluate the local heating and to determine the zones of maximum friction, we present here the temperature and the plantar pressure measurements during the running of an athlete with low and high speeds. The temperatures are measured in time by miniature thermocouples on 3 points on the sole of the foot : the heel, the plantar-arch and the plenty toes. Furthermore, cartographies of plantar pressure on the whole right foot sole are obtained by the use of Zebris platform of force.

Key-words : walking, running, biomechanics, shoes, heat transfer, plantar pressure

1. Introduction

The human body is a homoeothermic, it must maintain its temperature at the value close to 37°C. He controls his temperature thanks to all their active metabolic organisms. When it produces a prolonged muscular effort, important sweat losses appear, that allowed him to evacuate the heat produced during the effort in order to maintain its temperature between two crucial limits, 34 and 40°C. The mechanical output of the muscles for human body is very weak, with about 75 to 80% of the spent energy transformed into heat. With such a rate, internal temperature could reach high values, therefore, organism could not survive in the absence of regulating mechanisms. Heat transfer by evaporation of sweat intervenes essentially in the capacity of the body to maintain its internal temperature under maximum levels about 39 to 40 °C, even in hot environment and during a long time of exercises. Sweat is constituted by water and salt, its evaporation on the surface of the skin allows evacuating of energy produced by the body (approximately 580 kcal per litre of evaporated sweat) [1].

Thermal comfort is generally associated to a neutral thermal feeling or quasi-neutral of all the body. This feeling depends on the temperature of the body, which depends as well on the environmental factors (temperature of the air, relative humidity, air velocity...), as on personal factors (metabolism and clothing). The physiological processes contribute to maintain the temperature and the humidity at the skin surface below a limiting value. Comfort seems to be reached when the temperatures of the body are maintained constant with a minimal physiological regulating effort [2 - 7].

The experiments reported by Zotterman [3] showed the rise in temperature under various phases of heating and cooling of the skin body. The study was interested to the evolution of the intensity of the hot and the cold feeling during these phases. The skin, initially at 25°C, is initially heated until 35°C at a rate of 0,45°C/min. The feeling passes from cold to hot at the temperature 29°C. The skin is then cooled until 25°C at -0,87°C/min rate, a cold feeling then appears at temperature close to 30°C. This temperature caused during the first phase (heating) a hot feeling. It had been concluded that, according to whether the skin is being heated or cooled, the same temperature causes in a case a feeling of heat and in another case a feeling of cold. In other words, the feeling depends as well on the temperature as of direction of the heat flux, entering or outgoing of the skin.

The heat exchanged between the foot and the ground through the shoe is also important in the mechanisms of thermal regulation. In fact, the foot is the only contact point between the human body and the ground. Only few papers dealt with heat transfer in foot. In the paper of Bergquist and Holmer [7], a cold protective footwear have been tested with regard to their resistance to dry heat loss (i.e. the insulation) with a new electrically heated foot model. The model simulated 'walking' movements in order to provide a more realistic simulation of wear conditions. Thermal insulation of shoes with and without a steel toe cap was tested.

The study presented here deals with the local heating and the plantar pressures of the foot of a runner during exercise. In our knowledge, there is no paper in literature that concerned with the heat transfer between the runner feet and the shoes in real conditions.

2. Heat transfer from a shoe

The shoe provides mechanical and thermal protections of the foot. Their importance varies accordingly to the design of the shoes. Indeed, the shoe evacuates the heat generated in the foot when walking or training. The three mainly heat transfer modes are present : conduction through the various soles, convection and radiation from the surfaces of the shoe. The convection caused by the ventilation of the openings, and also by evaporation, is the principal mode of heat transfer between the foot and the ambient air. The properties of insulation of shoes depend on their form, their structure, and the materials which constitute their various layers [4].

The human foot is a complex articular body formed by a variable framework of bones, cartilage and by several muscles responsible of the quality of the support and the kinetics of its movement (fig. 1). Let us note that during the movement, the foot is interdependent of the lower limb, which implying the knee and the hip. During the movement, the foot passes by 2 positions of stability: the VFE (Valgus Flexion Rotation Externe) and the VRI (Varus Flexion Rotation Interne) positions (fig. 2. a and b). Its local heating depends on the zones of maximum contact with the sole in these two positions.

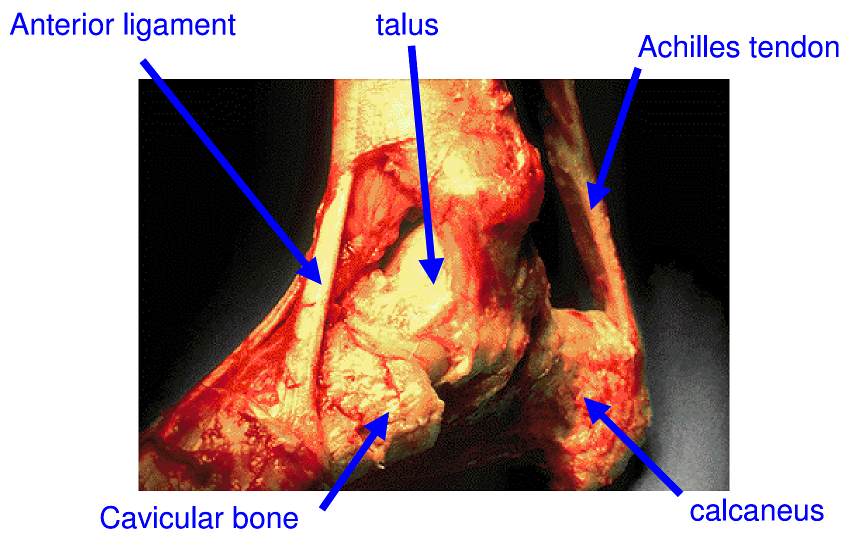
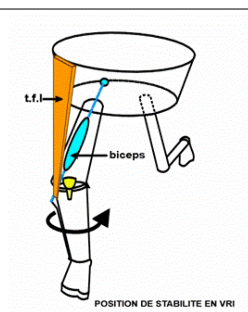


Fig. 1. The instep articular



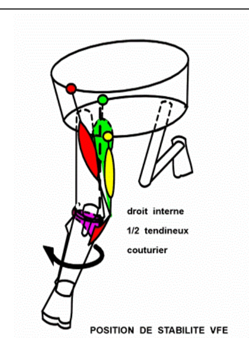


Fig. 2a. VRI Stability Position	Fig. 2b. VFE Stability Position

3. Protocol of the tests

Due to the stress on the lower limb and foot during running, injuries and complaints are quite common. It is very important to wear the right foot shoes. Different sports can require slightly different types of training shoe. Running shoes generally have a slightly raised heel, with plenty of cushioning for stability. They will also have a toe box that is large enough to accommodate the pressure on the forefoot and give the toes plenty of space to spread out during the stride. The covering should be a light mesh-like material which allows the foot to breathe. Limiting the heating and local friction between the foot and the shoes is very important way to give neutral thermal sensitivity for the runner.

The objective of this study is to define and test a measurement method in order to evaluate the temperature elevation in foot and the plantar pressures evolutions during training. This study would allow characterizing the local heating and friction on the sole of the foot for different shoes material and different running speed. It is a first step in defining a comparison method to test several shoes with different running conditions (physiology of the runner, air-humidity and temperature, speed…), that is the next step that should be done for the characterisation. Especially, the method of evaluation will be used in order to optimise new running shoes, by choosing their material and design.

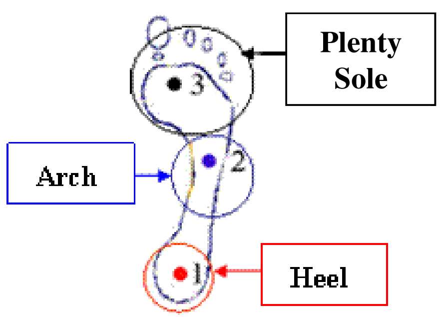


Fig. 3a. Locations of the temperature sensors

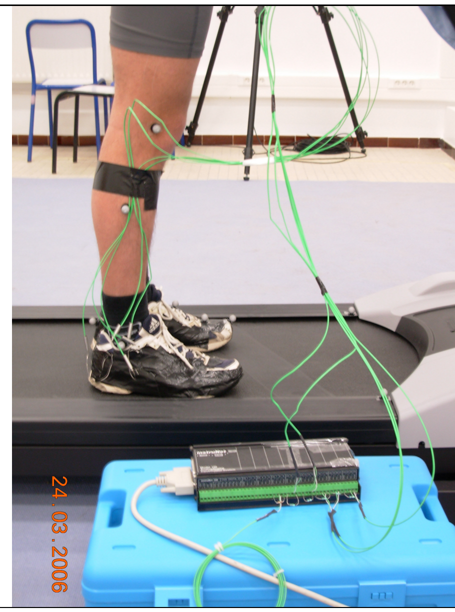


Fig. 3b. Photography of experimental set-up

We carried out two tests with two different speed of run of a 28 years old male athlete. In the first test, the athlete threads the pair of shoes and standing-up in static position during 2 minutes. Then, it is placed on the treadmill and running at a fixed speed of 4 km/h during 4 minutes (corresponding to a fast walking). Lastly, it is replaced again in standing-up position during 4 other minutes. The measurement of temperature in time at different positions allows the follow-up the complete evolution of the temperature field during the three phases: standing-up, exercise and recovery phase by standing-up again. In the second test, the subject carries out the same protocol as in test 1. However, the speed of the treadmill was fixed equal to 16 km/h (corresponding to a fast run).

During these tests, we recorded the temperature in 3 different zones from the lower face of the foot: the toes plenty, the arch and the heel. The internal shoe length is 26.9cm. The first thermocouple is placed at 5.5cm from the end of the shoe, the second is at 16.2cm and the third one is located at 24.7cm from the end. (fig. 3 a).

The temperature measurements are given by 3 K-thermocouples (Chromel-Alumel), with 0.25 mm in diameter, introduced between the insole and the outsole, on the median axis of the shoe. The thermocouples are connected to a high speed acquisition station (INET 200) (fig. 3 b). Temperatures are recorded at 2 seconds sample rate.

Simultaneously to the temperature measurements, a cinematic study of the whole inferior limb is also conducted. Several infra-red sensors (the subject was equipped by Vicon markers), enables us to save trajectories of different parts of the inferior limb. Such measurements are primordially to determine dynamics of the movement of the whole leg during the tests. These measurements are not presented here, nevertheless, they helped us in the interpretation of the change of the maximum zone of heating in the foot according to the speed of the runner.

4. Results and discussions

4.1. Temperatures in the first 2 minutes standing-up

Let us note on figure 4 that the temperatures recorded in the 3 zones of the foot in standing-up position are not equal. Indeed, the temperature on the heel is about 22.2°C, whereas, it is about 23.3°C on the plenty sole and 24.65°C on the arch of the foot. The contact zones of the foot with the sole (heel and plenty sole) are therefore colder than the arch of the foot. That can be explained by the heat diffusion in the zones of contact with the sole. Indeed, the hollow of the plantar-arch is not a fulcrum of the foot, it is thus not in direct contact with the sole. It should be noted that the 3 temperatures remain practically constant throughout these 2 minutes.

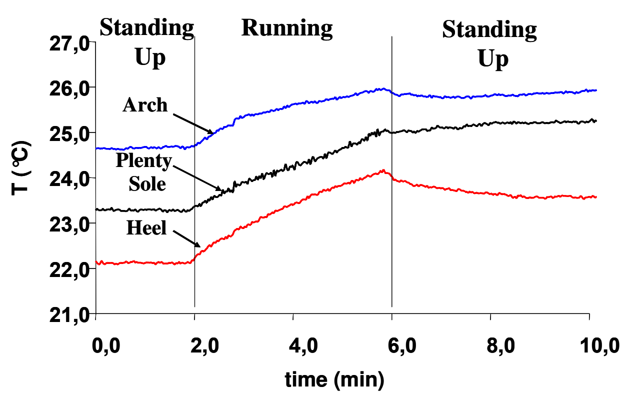


Fig. 4. Temperature evolutions in test with low speed

4.2. Temperature evolutions throughout the 4 minutes running

Graph 5 represents the temperature elevation of the 3 zones during the first test (4 km/h). The most important rise in temperature is observed on the heel. Indeed, after 4 minutes, the temperature of the heel increases of approximately 2 °C, whereas the increase is less than 1.6 °C on the plenty sole and 1.2°C on the foot arch.

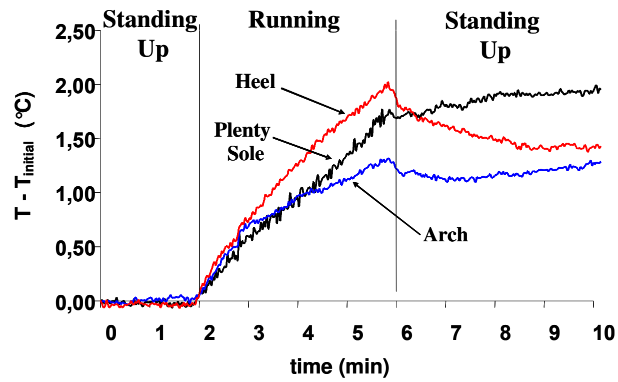


Fig. 5. Temperature elevation in low speed running test

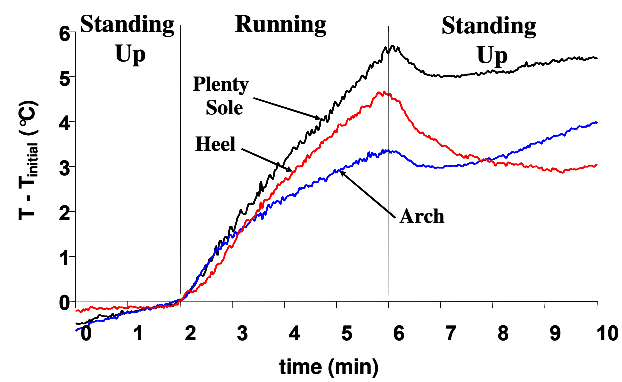


Fig. 6. Temperature elevation in high speed running test

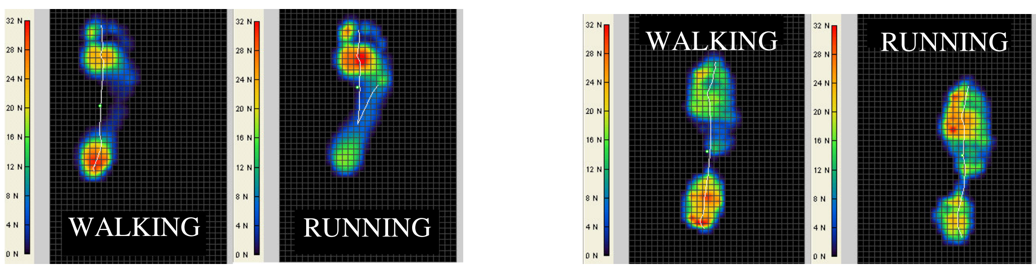
In test 2, corresponding to high speed running (16 km/h), the temperature augmentation is about 6°C on the plenty sole and 4.5°C on the heel (Figure 6). Therefore, contrary to low speed running test, the heating is more important on the plenty sole than on the heel.

It is important to note that the plantar arch has always the lowest temperature elevation in both tests (approximately 3°C).

Running is a complex and coordinated process that involves the entire body. It is executed as a sequence of strides, which alternate between the two legs. Each leg's stride can be roughly divided into three phases: support, drive, and recovery. Support and drive occur when the foot is in contact with the ground. Leg recovery phase occurs when the foot is off the ground. Since only one foot is on the ground at a time in running, one leg is always in recovery, while the other goes through support and drive. Then, briefly, as the runner leaps through the air, both legs are in recovery.

The change of location of maximum plantar pressure in support an drive phases is responsible of the observed difference of the maximum heating zones between the two tests. In low speed running test, the heel have more important contribution than the plenty sole in the reception of the foot on the ground during the support phase. In fact, the foot is in contact with the ground and supports the body against gravity. The body's center of mass is typically somewhere in the lower abdominal area between the hips. The supporting foot touches ground slightly ahead of the point that lies directly below body's center of mass. The knee joint is at its greatest extension just prior to the support phase; when contact is made with the ground, the knee joint begins to flex.

However, since the change of the posture of the of the runner body varies accordingly with its speed, the temperature elevation is more important on the plenty sole than on the heel in the second test (with high speed). During high speed run, the body is slightly leaning forwards, therefore, the plenty sole of the foot ensures the reception and the drive (pushing the body to do next stride). The heel doesn't practically touch the ground in this test.



(a) (b)

Fig. 7. Plantar Pressures without (a) and with (b) shoes

We measured the temporal evolutions of the plantar pressure distribution during both tests by means of the Zebris platform of force (Figure 7). Two situations are tested : with and without (bare feet) shoes. It is observed on Figure 7 that, with or without wearing shoes, the highest pressure is located under the heel in test 1 (fast walking). It is situated under the plenty toes when the runner goes faster (test 2). The zones of high pressure involve more friction between the foot and the sole of the shoe, increasing therefore, locally, the production of energy.

By comparing the three measured temperatures, one can notice that they increase in test 2 with high speed more than in test 1 with low speed. The greatest elevation recorded by the sensors is close to 5.4°C in test 2 against 2°C in test 1. Indeed, in high speed running, the high stride frequency increases the friction of foot with the sole, producing by consequent more heat emission.

4.3. Recorded Temperatures in second standing-up phase

Between the 6^{th} and the 10^{th} minutes of each test, the runner is held standing on these two feet during 4 minutes of recovery after the effort. There temperatures were recorded during this phase since it is important to quantify the capacity of a shoe to evacuate heat during the effort and also during the standing phase.

Figures 5 and 6 show that, for the two tests, the temperature on the plenty toes and on the arch decrease slightly in time, they reach a minimum value at approximately one minute after stopping the run, then, they increase again. However, the temperature of the heel has a monotonous variation, it decreases throughout the 4 minutes in the two tests under the effect of the release heat by conduction of the foot towards the ground through the various soles of the shoe. In standing position, the plantar pressure measurements with the Zebris platform showed that, due to the support of the body by the heel, the pressure is the highest under the heel.

5. Conclusion

By the measurement of the evolutions in time of temperature and plantar pressure at different locations during the running exercise, it was shown that the method used would be able to characterise the local heating and friction encountered in the sportive shoes. The obtained results have been allowed to show that the local heating on the plenty sole varies according to the speed of run and to the supporting zones of the body during the exercise. The increase in the temperature is more important on the heel during running with low speed. However, the most important elevation of temperature is located at the plenty toes when running with high speed. The change of the maximum local heating is due to the modification of the kinetics of the movement when the speed of the run changes, which induces a changing in the friction zones between the foot plant and the insole of the shoes.

It is important to note the difference of the temperature evolution during the standing phase after 4 minutes exercise (recovery phase of the runner). The heat is evacuated more easily through the sole under the heel than from the arch or the plenty toes of the foot.

A parametric study of the change of temperature, humidity and reaction of the metabolism (complaints of the skin, discomfort…) according to material and to the design of the shoe is in hand. It should allow a complete characterisation of the interaction shoe-foot in various situations of physical exercises.

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