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Infrared Thermography in Sports Activity

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1. Introduction

The origin of infrared thermography comes in 1800 when William Herschel discovered thermal radiation, the invisible light later called infrared, but only in the mid-sixties infrared thermography became a technique of temperature cartography. He proved that this radiation, called infrared, followed the same law as visible light. Later, this phenomenon was connected with the laws of Planck and Stefan. The first detectors for this type of radiation, based on the principle of the thermocouple and thermopile called, were developed around 1830. In 1970, the first cameras appeared for commercial. The first models were made up of a technology-based pyroelectric tube with an optical IR instead of the classical elements. Today, these concepts have been improved with new technologies in electronics and computing. Infrared acquisition systems can arrive at very high frame rates. The major argument is whether infrared thermography can determine thermal variations to enable sufficient quantitative analyses. The creation of computerized systems using complex statistical data analysis, which ensure high quality results, and the enhancement of thermal sensitivity have increased the development of technology of infrared thermography.

For years, infrared thermography has become a powerful investigation tool to inspect in many applications, from mechanical, electrical, military, to building and medical applications. Due to its non-intrusive feature (Kaminski et al 1999; Hoover et al, 2004; Wu et al, 2009; Hildebrandt et al, 2010), infrared thermography (IRT) can be defined as the science of analysis of data from non contact thermal imaging devices. Thermal imaging cameras detect radiation in the infrared range of the electromagnetic spectrum and produce images of that radiation, called thermograms. This method provides real-time, instantaneous visual images with measurements of surface temperatures over a greater distance.

Few studies using infrared thermography have been devoted to sports performance diagnostic and to sports pathology diagnostic .It is well known that sports activity induces a complex thermoregulation process where part of heat is given off by the skin of athletes. As not all the heat produced can be entirely given off, there follows a muscular heating resulting in an increase in the cutaneous temperature. In particular, the IRT method will enable, in the long term, to quantify the heat loss according to the swimming style, and to consider the muscular and energy outputs during the stroke.

A close examination of the literature shows that no study has been devoted to these problems. Though, for example, Brandt and Pichowski (1995) determined the temperature of a swimmer to be 33 °C after exercise, it was a local measurement only, therefore very partial, obtained by means of a thermocouple placed at the deltoid. In the same way, Huttunen et al. (2000) studied variations in the internal temperature of long distance swimmers in cold water. In no way did they study the cutaneous temperature. Whereas the technique of infrared thermography is usually used under thermal conditions of living (Jansky et al, 2003), no mention of its application to swimming or cycling can be found in the literature. The temperature of skin is a significant parameter, which conditions the evolution of physiological parameters such as, for example, the production of lactate or the heart rate (Mougios et al, 1993), which have a direct influence on the process of body thermoregulation.

Understanding spatial and temporal gradients in latent heat loss of the human body allows optimization for thermal comfort. Recently, De Bruyne et al. (2010) carried out a search thataims at quantifying transient spatial gradients in sweat production on a human head while cycling. The results of their research aims to enhance physiological insight of the sweating process and it can also help to develop sweating thermal manikins (Hsu et al, 2000; Davis et al 2001; Bruhwiler et al 2003; Bruhwiler et al, 2004) that behave more realistically to thermal changes (Bruhwiler et al, 2006; Buyan et al, 2006; Bogerd et al, 2008; Brühwiler et al, 2009). Latent heat loss of the human head has been quantified in many experiments. Few experiments tested the hypothesis that gradients in latent heat loss on a human head can be observed. However, in any case they have studied the distribution of skin temperature.

Infrared thermography allows for this distribution. But In the field of cycling, no application is mentioned in the literature.

The first medical application of infrared thermography for skin temperature measurement was in 1960. In 1980, the early detection of diseases was quickly developed. In the field of pathology diagnostic, applied to sports activity, the application of infrared thermography (IRT) has a long history (Jiang et al, 2005), mainly musculoskeletal trauma, pathologic processes such as pain in the lumbosacral region, intervertebral disc prolapse, spinal cord lesion, traumatic lesions, fractures, cardiovascular…

ALBERT et al. (1964) were the first to assess pain by infrared thermography. This technique is a diagnostic method providing information on the normal and abnormal sensory and nervous systems, trauma, or inflammation locally and globally. Infrared thermography shows physiological changes rather than anatomical changes and could be a new diagnostic tool to detect the pathology of the knee (Selfe et al, 2010).

However, interest in IRT is up today because of improved devices and methods of calculation. The special characteristic of IRT studies is that we can get additional information about the skin's thermal aspect and about the complex thermoregulatory process. IRT gives a possibility to evaluate the effect of the sporting activity and to detect possible trauma or dysfunctions, which cannot be shown by present conventional methods.

It can measure skin temperature over inflamed joints. This developing technology is used to detect thermal abnormalities characterized by a temperature increase or decrease found at the skin surface. The technique involves the detection of infrared radiation that can be directly correlated with the temperature distribution of a body region (Melnizky et al 1997).

The question is whether infrared thermography can accurately determine thermal variations to enable sufficient quantitative analyses. The purpose of this study is, on the one hand, to assess the usefulness of infrared thermography in sport activity and in sport medicine and, on the other hand, to show up to what point the cutaneous temperatures are influenced by the nature of activity.

2. Principle of IRT

Based on the measurement of infrared radiation of the body, infrared thermography is the most accessible technique to obtain images of the temperature profiling of a surface or a point. The principle of this technique is that every corps emits an amount of IR energy and the intensity of this IR radiation is a function of temperature.

Infrared thermography transforms the thermal energy, radiated from body in the infrared band of the electromagnetic spectrum (roughly 0.8 µm – 1000 µm in figure 1) into a visible image of that radiation, called a thermogram.

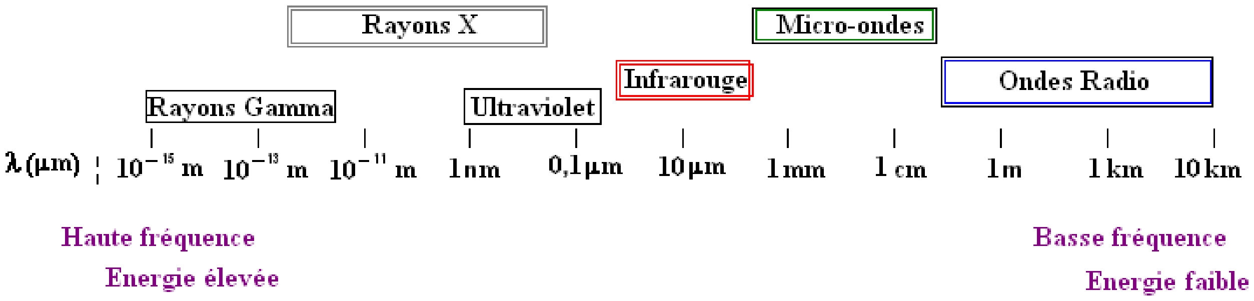


Fig. 1. Electromagnetic spectrum

The measuring range is restricted to infrared radiation classified into three categories:

- Near infrared of 0.75 µm – 1 µm
- Middle infrared of 1.5 µm - 4 µm
- Far infrared of 4 µm - 1000 µm

2.1 Fundamentals of thermal radiation

The radiation measured does not depend only on the body surface temperature but is also a function of the emissivity under measurement and on the environment. Emissivity is the relative ability of its surface to emit energy by radiation.

The total energy radiated per unit surface area of a black body per unit time is directly proportional to the fourth power of the black body's absolute temperature T.

2.1.1 Stephan-Boltzmann law

The equation for the radiation of an object is governed by Stefan–Boltzmann law (Schmidt et al, 1993; Gaussorgues, 1999):

$$R = \varepsilon.\sigma.T^4 \tag{1}$$

Where

R: radiation (W/m2),
T: temperature (K),
σ: Stefan–Boltzmann constant = 5.67 10^{-8} W/m^2 K^4
ε: emissivity

2.1.2 Black body

The radiation emitted by a body depends on its nature. The thermal emission is referred to the notion of the black body, defined as being able to completely absorb all incident radiation, regardless of its wavelength.

2.1.3 Planck's law

The characteristics of infrared radiation emitted by an object in terms of spectral radiant emittance are described by Planck’s law (Planck, 1901):

$$W(\lambda,T) = \frac{\overline{2\pi hc^2}}{\lambda^4}\left[\exp\left(\frac{hc}{\lambda kT}\right)-1\right]^{-1} Wcm^{-2}\mu m^{-1} \tag{2}$$

Where :

H = 6.6256 .10^{-34} Js : Planck's constant
K = 1.38054 .10^{-23} WsK^{-1} : Boltzmann's constant
C = 2.9979 .10^8 ms^{-1} : velocity of light in vacuum
μ: wavelength in μm
T: temperature in K

Human skin emits infrared radiation mainly in the wavelength range of 2–20 μm with an average peak of 9–10 μm (Steketee, 1973). 90% of the emitted infrared radiation in humans is between 8 and 15 μm (the emitted infrared in this case is based on Plank’s Law roughly). Human skin is a black body radiator with an emissivity factor of 0.98 (Steketee, 1973) and is therefore a perfect emitter of infrared radiation at room temperature

2.2 Passive and active thermography

The quality of thermal image depends on the variation in surface temperatures. Thermal images can be obtained under ambient conditions. Two types of schemes are deployed to make measurements by infrared thermography.

Passive thermography is essentially a qualitative or quantitative approach where the thermal model is available. It consists in testing a body or element whose surface temperatures are naturally different (often higher) than ambient.

However, in the case of the active thermography, an external stimulus is necessary to induce relevant thermal contrasts which are not available otherwise. Create a thermal gradient allows to highlight the presence of internal defects or simply define the thermophysical properties of material.

In this chapter, the accent is on the passive scheme.

3. Technical description of the infrared cameras

The Infrared cameras used in this investigation operate on the principle of high spatial resolution and highest sensitivity and accuracy. Tests were performed in by using two IR cameras: **FLIR-SC1000**, **CEDIP TITANIUM HD560M** coupled with thermographic software: **ThermaCAM Researcher** and **ALTAIR 5.50**.

3.1 FLIR-SC1000

The IR camera FLIR SC1000 has a range of temperature measurement between -40 ° C and 1500 ° C with an accuracy of ± 2% of measuring range (www.flirthermography.com).

Its 256x256 pixels format InSb focal plane array delivers respectively an outstanding 200 Hz frame rate while keeping extraordinary linearity and sensitivity figures, with high quantum efficiency (> 70%). The SC1000 has a sensitive to wavelengths from 3.4 to 5 µm ± 0.25 µm. It is equipped with a system of instant integration variable from 1 µs to 10ms and speed frame rate of up to 50 images / s in full speed.

The acquisition system is designed for ease-of-use, this real-time data; acquisition program communicates with and acquires data from numerous off-the-shelf and custom radiometric instruments. It transforms an image captured in the infrared according to the brightness of the object observed in a visible image. The heat maps are stored and processed in real time using the software "ThermaCAM Researcher" that allows:

- To deal with static images,
- To deal with video and infrared data in real time
- To process and analyze digital data at very high speed infrared.

3.2 CEDIP TITANIUM HD 560M

The IR camera CEDIP TITANIUM HD560M has a sensitive to wavelengths from 3.5 to 5 µm ± 0.25 µm (www.flirthermography.com). The focus of the camera is between 10 and 100 mm ± 0.5 mm, and the resolution of the camera is 640 × 512 features high quantum efficiency (> 70%). Thermal sensitivity was 0.04 °C per grayscale level over the physiological temperature range. Camera is equipped with a system integration instantaneous variable of 1µs to 10 ms and speed frame rate of up to 100 frames / s in full window.

The thermal image obtained was sent instantly to a portable computer connected to the camera, and it was immediately processed in real time using the software "ALTAIR 5.50" that allows:

- To deal with static images,
- Treat video and infrared data in real time,

3.3 Calibration and optimization of thermal resolution

Calibration of the infrared system by simulating real operating conditions must be performed, to take into account many variables.

The energy really emitted by the surface of body and detected by the infrared camera depends on the emissivity of the surface under measurement, on properties of body and on the environment. It is important not to take thermal cartographies in a too bright or when the body is exposed to other radiations.

For this, the choice of parameters of a system of infrared thermography as an instrument for measuring temperature must meet several compromises:

- Emissivity in the infrared and the spectral bands corresponding,
- Nature of the body,
- Ambient temperature,
- Temperature range in witch progress the body
- Objects parasites on the environment that can shine directly on the detector, or indirectly by reflection,
- Minimum and maximum distance linked to environmental constraints…

Thus, optimizing the thermal resolution is more than necessary. We must proceed step by step to get an optimal solution of the sizing system, by:

- Evaluating the spectral emissivity of the body,
- Evaluating the size of the body,
- Choosing the surface pupil and lens to obtain spatial resolution desired.
- Evaluating temperature range in witch progress the body…

4. Infrared thermography in sport

4.1 The influence of swimming type on the skin-temperature maps of a competitive swimmer from infrared thermography

This study aims, on the one hand, to highlight the feasibility and applicability of infrared thermography in swimming for the purpose of quantifying the influence of the swimming style on the cartographies of cutaneous temperatures of a swimmer.

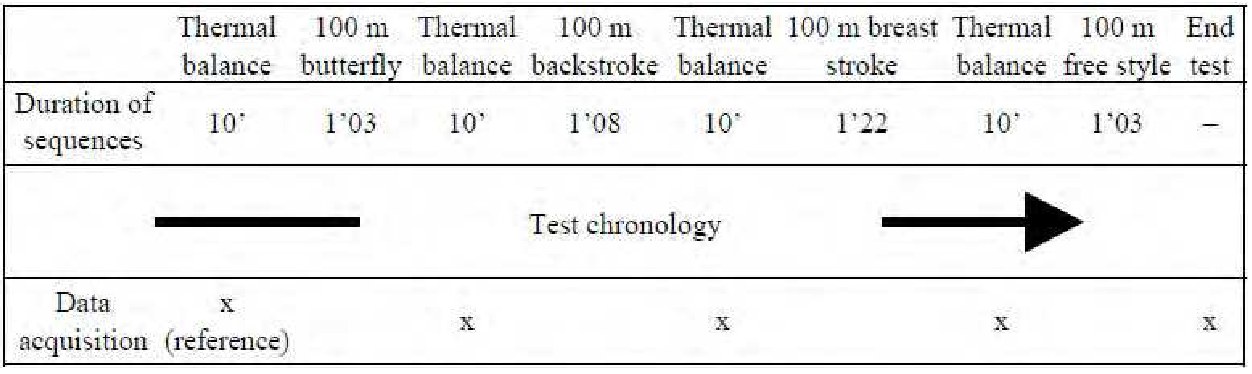
Whereas the infrared thermography is used under thermal conditions of living (Jansky et al, 2003), no mention of its application to swimming is found in the literature. The study was carried out in a swimming pool. The temperature of water in the pool is a significant parameter, which conditions the evolution of physiological parameters such as, for example, the production of lactate or the heart rate (Mougios et al, 1993) and which has a direct influence on the process of body thermoregulation. Swimming induces a complex thermoregulation process where part of heat is given off by the skin of a swimmer. As not all the heat produced can be entirely given off, there follows a muscular heating resulting in an increase in the cutaneous temperature. An analysis carried out by Robinson and Somers (1971) showed that in swimming, the optimal temperature of water for 20 minutes of freestyle must range between 21 and 33 °C, with an optimal breakeven point at 29 °C. This value is slightly higher than the one we measured at the time of the study in the swimming pool. The investigation being a preliminary study, only one male swimmer took part in it.

4.1.1 Protocol and method

The experimentation took place in a covered swimming pool of 25 m in length. The temperature of the water was 27 °C and that of the ambient air was 24 °C. The experimental protocol, summarized in Table 1, is defined as follows:

- At the beginning, the swimmer is immersed up to the neck in the static position for 10 minutes.
- At the end of this period, the swimmer leaves water and then is rapidly dried (water is opaque to infrared radiation).
- The following task was the first recordings of the body surface thermal maps, that constitute the thermal reference level of the swimmer at rest.
- Next, the swimmer executes his first 100 m butterfly, leaves water, is dried and then is subjected to a second set of thermal acquisitions that will provide the cartography of the body surface temperatures after the exercise.
- After that, the swimmer is immersed in water again. The duration between two swimming series is sufficiently long (10 minutes) to allow a return to the thermal balance of the swimmer.

This cycle is reproduced for the three other strokes. It is to be specified that the swimmer was subjected to a test during the period of recovery according to his training program, which explains the average results obtained during the test of a 4 × 100 m medley with a departure in water.



	Thermal balance	100 m butterfly	Thermal balance	100 m backstroke	Thermal balance	100 m breast stroke	Thermal balance	100 m free style	End test
Duration of sequences	10'	1'03	10'	1'08	10'	1'22	10'	1'03	–
				Test chronology					
Data acquisition	x (reference)		x		x		x		x

Table 1. Infrared thermography data acquisition

One subject participated in our experimentation. He is a swimmer of national level specialist in the 400 m medley who is training on average 10 to 12 hours per week. The principal anthropometric characteristics of the subject are summarized in the following table (Table 2):

	Age	Height (m)	Mass (kg)	Body fat (%)
Swimmer (man)	19	1.78	67	12.4

Table 2. Morphometric data for the swimmer

In order to better assess the influence of the swimming style on the muscular heating, the cutaneous surface was divided into closed polygonal surfaces A, B, ..., J, according to the distribution represented in Figure 2. The limb extremities and the joint regions, which represent poorly the contribution of the body thermoregulation process, were excluded from this geometrical body cutting. The body cutting used in our study allows for the elementary geometry approach adopted by YANAI (2001) for the swimmer representation to numerical simulation purposes.

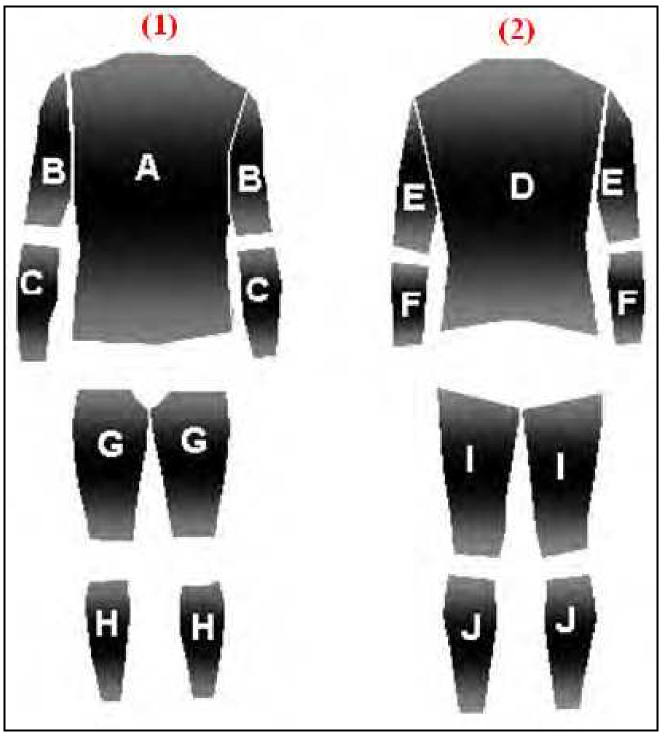


Fig. 2. Body zone definitions: frontal view (1) and dorsal view (2)

4.1.2 Reference temperature

Figure 3 presents infrared cartographies set at rest for the upper and lower limbs of the swimmer, after the swimmer had spent 10 minutes in the pool water at 27 ° C. From these

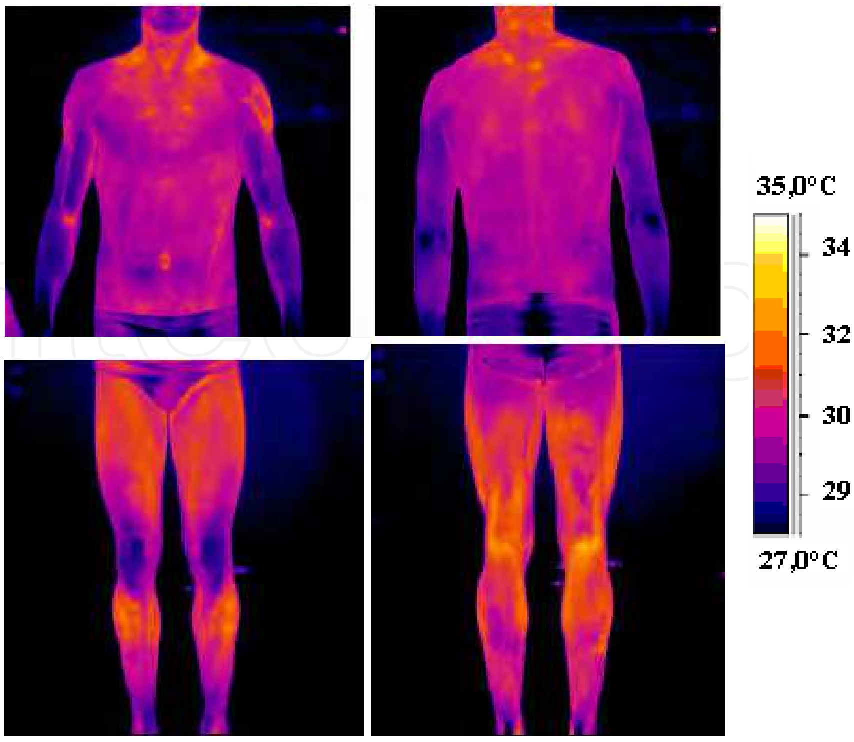


Fig. 3. Infrared cartographies of the upper and the lower limbs before effort

cartographies and using the software ThermaCAM Researcher, temperatures at rest were determined for areas A, B, C, D, E, F, G and H defined in Figure 2.

To quantify this distribution, let us introduce the histogram of the cutaneous temperature of the swimmer at rest shown in Figure 3. These temperatures constitute the case of reference of the study. There appear disparities in the distribution of the average temperatures of the zones; the highest temperatures correspond to the zones closest to the vital organs of the swimmer (abdomen, chest, back), whereas the lowest are those of the forearms of the swimmer. The maximum variation observed is about 1.7 °C.

4.1.3 Influence of the swimming style: Temperature after effort

Figures 4 and 5 show the various infrared cartographies established for the four styles and for the upper and lower limbs of the swimmer, after the swimmer had spent 10 minutes in the pool water at 27 ° C. Notable differences appear in the images, which allows us to predict a considerable influence of the swimming style on the distributions of the cutaneous temperature.

The average temperature difference (ΔT), defined as the difference between the temperature measured after effort and that measured at rest allows quantifying the influence of swimming style. The corresponding histograms are shown in Figure 6.

The histograms indicate that a significant increase in the cutaneous temperature is possible in accordance with the swimming style and the body zone considered. Indeed, it appears that the highest temperature is reached in the upper part of the body corresponding to zones A, B, C, D, E, F for the backstroke with 2.50 ± 0.10 ≤ ΔT ≤ 4.55 ± 0.10, whereas on the level of

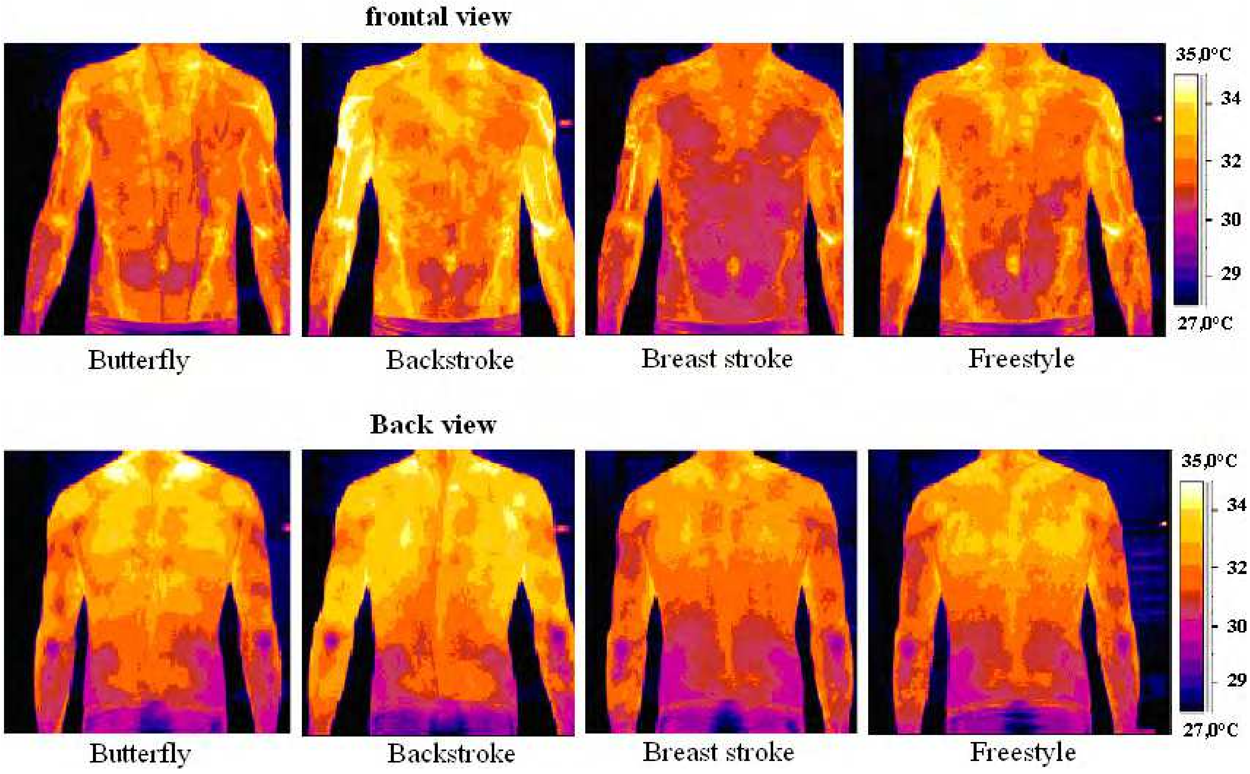
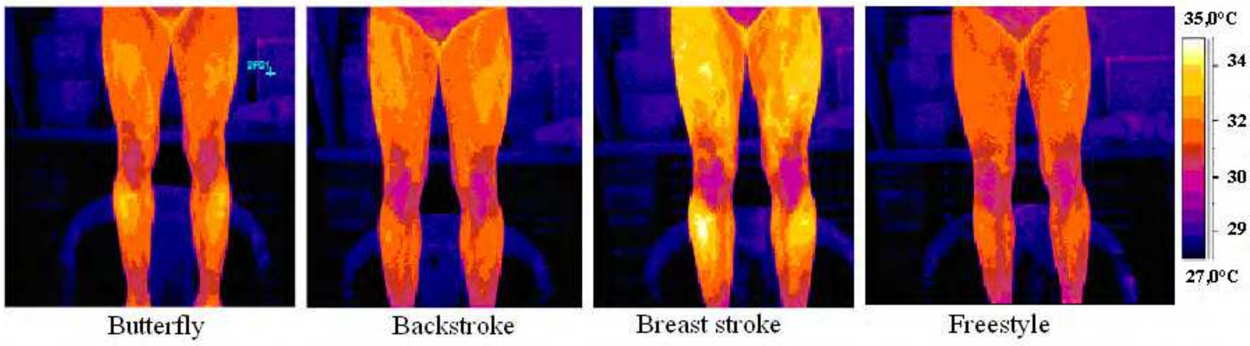


Fig. 4. Infrared cartographies of the trunk and the upper limbs

frontal view



Back view

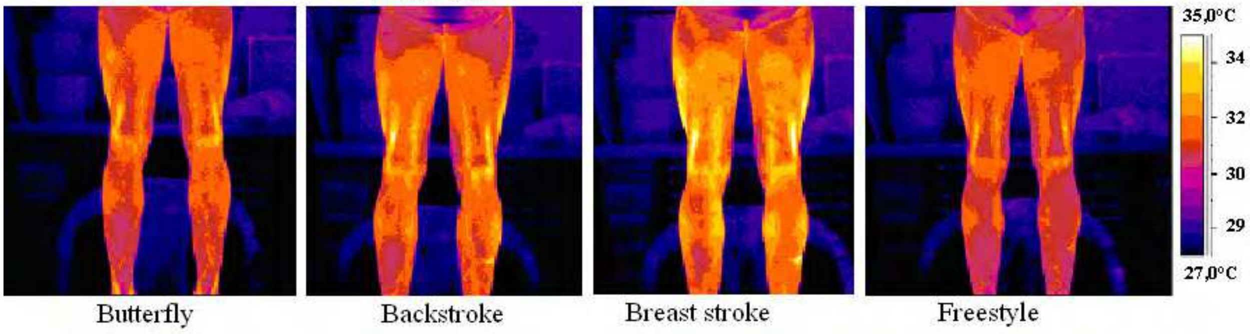


Fig. 5. Infrared cartographies of the lower limbs

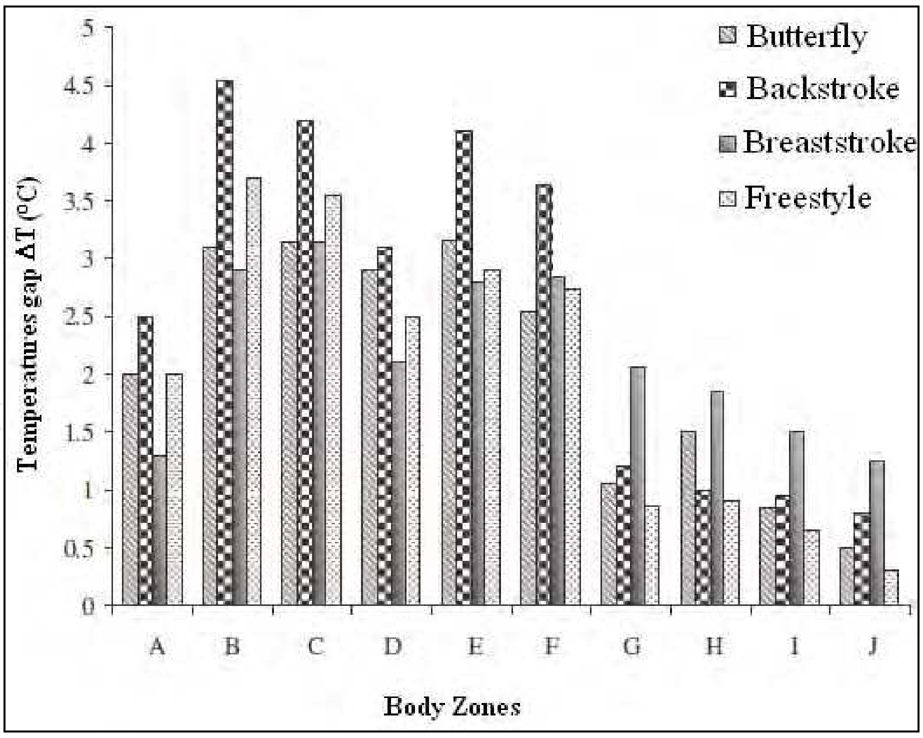
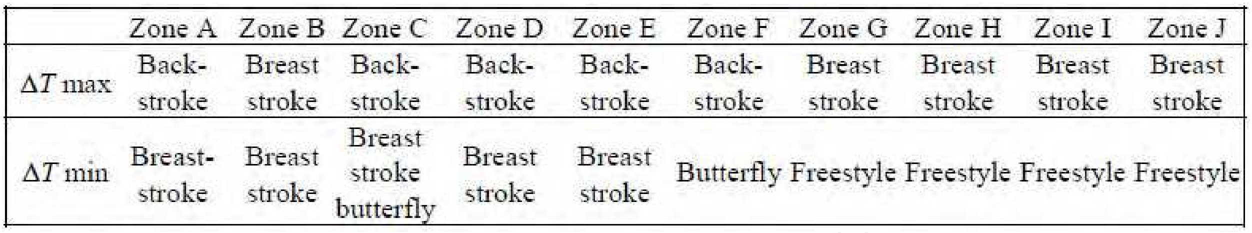


Fig. 6. Influence of the swimming style on the temperature gaps measured after effort and at rest

zones G, H, I, J, corresponding to the lower limbs, it is the breast stroke that generates the greatest increments in the cutaneous temperature, with 1.25 ± 0.10 ≤ ΔT ≤ 2.05 ± 0.10. On the contrary, freestyle induces the weakest variations in temperature on the lower limbs, with $0.30 \pm 0.10 \leq \Delta T \leq 0.90 \pm 0.10$.

Obviously, these results appear to be adequate with the intensity of the muscular activity related to the type of stroke. These are summarized in Table 3.



	Zone A	Zone B	Zone C	Zone D	Zone E	Zone F	Zone G	Zone H	Zone I	Zone J
ΔT max	Back-stroke	Breast stroke	Back-stroke	Back-stroke	Back-stroke	Back-stroke	Breast stroke	Breast stroke	Breast stroke	Breast stroke
ΔT min	Breast-stroke	Breast stroke	Breast stroke butterfly	Breast stroke	Breast stroke	Butterfly	Freestyle	Freestyle	Freestyle	Freestyle

Table 3. Distribution of temperature difference (ΔT) minimum and maximum in accordance with the swimming style and the body zone considered.

4.1.4 Global cutaneous temperature

After calculating all the average temperatures for all body areas previously defined for each swimming style, we were interested in defining a global average cutaneous temperature $\overline{T}_{\text{overall}}$ calculated over of the zones as a whole. It is given by the relation:

$$\overline{T}_{\text{overall}} = \frac{\sum_{i=A}^{j} T_i S_i}{\sum_{i=A}^{j} S_i} \tag{3}$$

Where Si is the number of pixels defining each polygonal zone, and Ti is the average temperature for each zone.

Table 4 contains the global temperatures obtained for the four styles. It is found that the highest skin temperature average determined in all selected zones corresponds to the case of swimming "backstroke". From an energy point of view, this swimming seems to be the most demanding, in our study. The lowest temperature corresponding to the case of swimming "Breaststroke" seems that of less expensive overall energy. The temperature difference induced by the practice of these two swimming is, in this case and according to the protocol established by 0.78 ° C ± 0.10.

	Butterfly	**Backstroke**	**Breast stroke**	**Freestyle**
$\overline{T}_{\text{overall}}$	31.73 ± 0.10	32.14 ± 0.10	31.43 ± 0.10	31.58 ± 0.10

Table 4. Overall cutaneous temperature values

The difference in global average temperature, calculated after every effort to swimming style is shown in figure 7.

We note that the temperature averaged over the entire surface cutaneous, compared to the position of rest, increased by 2.16 ° C for the butterfly swimming, 2.56 ° C for backstroke, 1.78 ° C for breaststroke and 2.00 ° C for the freestyle, after the test performed.

Holmer (1974) carried out experiments in the experimental pool of Stockholm. At a given speed, significant differences in energy expenditive were observed between the four swimming styles. Techniques with alternate locomotive cycles (crawl and backstroke) were more efficient than techniques with simultaneous cycles (butterfly and breaststroke).

Thereafter, these results were confirmed by Lavoie and Montpetit (1986). From the results of Table 4, one can note that the highest global average temperature corresponds to the backstroke case. This stroke seems to show, as for this study, the greatest expenditure of energy. The lowest temperature corresponds to the case of the breast stroke whose overall expenditure of energy seems to be the least. In the present case and according to the protocol drawn up, the temperature difference induced by the practice of these two strokes is 0.78 ± 0.10 °C. One should point out that by no means can our results be compared with those of Holmer (1974) and Lavoie & Monpetit (1986), which were established statistically on the basis of different experimental protocols.

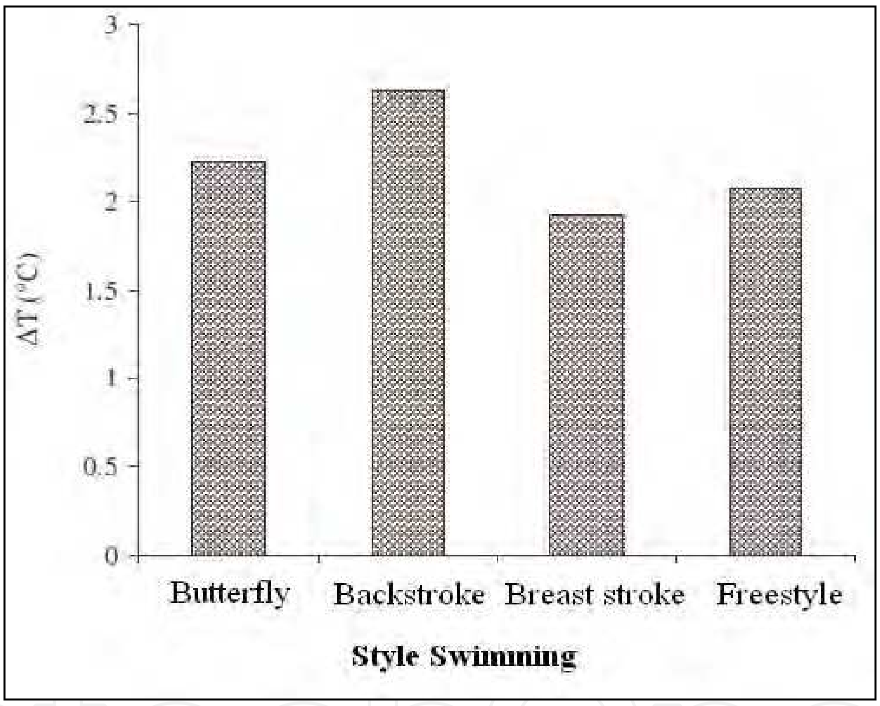


Fig. 7. Increase in mean body temperature after effort for the four swimming styles

A preliminary experimental study was undertaken, on the one hand, for studying the feasibility of using IR in the discipline of swimming and, on the other hand, for quantifying the influence of the type of stroke (within the framework of a well defined protocol) on the distributions of cutaneous temperatures. To the best of our knowledge, it is for the first time that such a study has been undertaken. In particular, this study shows significant variations in the cutaneous temperature according to the swimming styles. From the examination of infrared cartographies, one can note that the temperature, averaged over the whole body surface, is respectively increased by 2.16 °C for the butterfly, 2.56 °C for the backstroke, 1.78°C for the breast stroke and 2.00°C for the freestyle, after the practiced test.

One should recall that these conclusions cannot be considered as universal as far as only one subject, a male swimmer of national level, took part in this study. Nevertheless, the conclusions make us think of considering a statistical study that would also account for the initial temperature of the water in the swimming pool

4.2 On the use of thermography IR in cycling activities

Another possible use of thermography IR concerns the relationship analysis of both thermal and mechanical behaviors in the cycling technique of senior cyclists for example. The analysis of the driving force coupled with the acquisition of the skin surface temperature field of active legs can lead:

1. to highlight a systematic significant deficit of the force developed by one of the lower limbs,
2. to apprehend the mechanisms of muscular thermoregulation.

To fight against the different resistances to progress, the cyclist generates forces to the pedals during the pedaling motion. Pedaling results from actions of antagonistic muscle groups to mobilize the joints of the hip, knee and ankle, so as to achieve a full rotation of the crank around the bracket (Moussay et al, 2003). The use of footrests (pedal straps) or clipless pedals, however, allows the cyclist to generate a propulsive work even during the rise of the pedal. The use of the link shoe/pedal requires to describe the four phases in cycling.

The first phase of pedaling corresponds to a crank angle varying from 315 to 45°, generating what we can call a "dead pedaling zone". This is a transitional phase during which almost passive knee joints and hip are flexed.

The second phase of pedaling corresponds to a crank angle from 45 to 135°. This phase is the thrust phase during which the main driving pedaling efficiency is more important. During this phase, there is the extension of the lower limbs

The third phase is for a crank angle in the range 135-225°. This sector corresponds to the "bottom dead center". This is the transition between the pushing phase and the phase of the draw.

The fourth phase is a crank angle from 225 to 315°. In the area corresponding to the rise of the pedal, several scenarios are possible: 1) No action is taken on the pedal; the leg creates a resisting torque, 2) A driving force is created at the pedal to compensate some of all of the weight of the rising leg, 3) A driving force greater than the weight of the lower limb is created.

During Phases 1 and 3 it is anatomically difficult to have efficient propulsion.

The difference in performance between the 40 km cycling specialists against the clock is not entirely dependent on some physiological variables (Coyle et al, 1991). A study in which were measured: 1) The maximum oxygen consumption, 2) The lactic anaerobic threshold, 3) The use of muscle glycogen, 4) The type of muscle, 5) Enzyme activity, has allowed drawing the hypothesis that the cycling performance could be partially related to biomechanical factors related to individual pedaling technique (Coyle et al, 1991). Moreover, the experienced cyclists consume less oxygen per unit of power output, than cyclists of lower level (Coyle et al, 1992). It seems that these differences in oxygen consumption are not entirely due to physiological factors (muscle type), but also in biomechanical parameters (Coyle et al, 1991; Coyle et al, 1992; Kautz & Hull, 1995). It seems obvious that the physical potential of the athlete is a major parameter in the performance in cycling. However, it seems important to study how the energy generated by muscular contraction is converted into a propulsive energy on the pedal. The application of forces on the pedal is the last link in the conversion of metabolic energy into mechanical energy to drive the pedal.

During a competition on a very long time (eg Tour de France), a minimal improvement in motor efficiency of the athlete can make a difference in the way of performance. Indeed, a change in the pattern of pedaling can: 1) Change the distribution of work product, 2) Potentially reduce fatigue, 3) Increase the performance (Coyle et al, 1991).

A production of equivalent force on each pedal is also a factor in improving the efficiency of pedaling. The majority of elite cyclists has a "round and smooth" pedaling even though some may have an asymmetry greater than 10%. A population of cyclists are most vulnerable to these risks is the master population (50-60 years). In addition, this group of cyclists concerns the majority of practitioners. The purpose of this study is to study the biomechanics of cycling in masters cyclists during incremental test. At the same time acquiring a mapping of skin temperatures of active members will be conducted to better understand the mechanisms of thermoregulation muscle.

4.2.1 Materials and methods

Eleven masters cyclists (Table 5) performing tests of long distances (200 km) voluntarily participated in this study. Subjects were informed in detail of the study protocol, signed a letter of consent and could stop at any time if the wanted to abort the protocol.

Mechanical power and the pattern of pedaling (engine torque depending on the angle of the crank) were measured (200 Hz) using the system SRM Training System (scientific model,

Subjects		Age (years)	Distance traveled per year (km)	Height (cm)	Mass (kg)	Body fat (%)
Subject 1	B. P.	56	7000	172	79.1	18.7
Subject 2	C. J.-F.	47	4500	181	72.5	14.7
Subject 3	V. A.	53	5000	168	68.7	19.1
Subject 4	B. J.-M.	58	6000	176	66.4	13.9
Subject 5	B. J.	59	5500	170	72.6	21.3
Subject 6	M. B.	56	10000	178	74.7	18.9
Subject 7	B. J.-P.	51	7000	179	75.3	18.9
Subject 8	P. J.	57	14000	170	69.1	18.2
Subject 9	D. J.-P.	52	6000	169	68.2	18.6
Subject 10	R. R.	53	10000	180	70.6	15.3
Subject 11	T. J.-P.	47	8000	183	72.8	19
Average		53.5 ± 4.1	7545 ± 2815	175 ± 5	71.8 ± 3.7	17.9 ± 2.2

Table 5. Physiological parameters of the subjects

precision 0.5%, Germany). The validity of the SRM has been previously shown by Jones et al. (1998). The SRM system is a pedal equipped with 20 strain gauges that transmit data by induction to a control box located on the handlebars. Before each measurement, the SRM and the analysis software were calibrated according to manufacturer's recommendations. The SRM was mounted on a bicycle race (10.2 kg) equipped with clipless pedals. Before the start of each test, each cyclist has adjusted the bike to the position he usually uses. The tires were inflated to a pressure of 700 kPa.

Heart rate beat by beat (RR interval) was recorded during all experimental sessions using the Polar S810 heart rate monitor (Finland).

4.2.2 Protocol

The heart rate of subjects was recorded at rest for 5 minutes in a sitting position. Once the rider positioned on the bicycle, the skin temperature of the skin of the gastrocnemius muscle was measured. This temperature will be the reference temperature.

During exercise, cyclists had to perform an incremental progressive exercise on the bicycle in 18 minutes. The exercise was scheduled for external mechanical power of 100 W for 10 min, then the intensity increased in increments of 50 W for 3 min up to 200 W, then the last step was performed at 250 W for 2 min (Figure 8).

Once the exercise is performed, heart rate (standing) and skin temperature of the gastrocnemius muscles were measured over a period of 10 min.

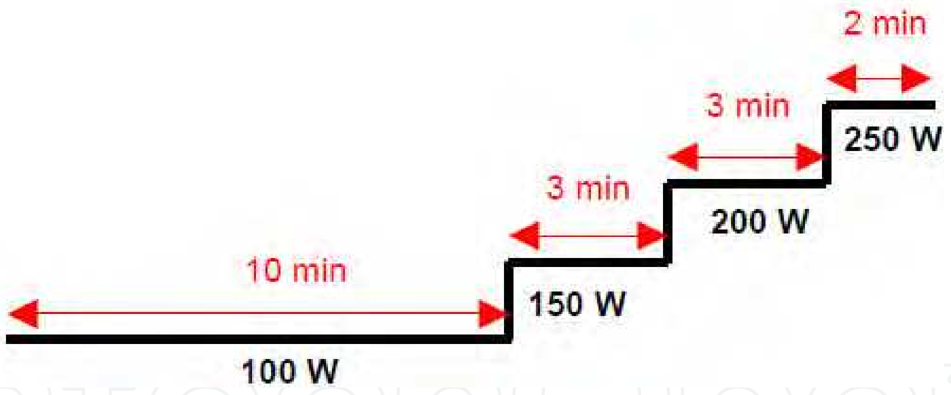


Fig. 8. Incremental bicycle exercise

4.2.3 Results

The objective of this preliminary study was to analyze in masters cyclists pedaling mechanics and to measure the skin temperature of the gastrocnemius muscle during incremental exercise.

Our results indicate (Table 6) that at a certain level of power (150 W) a significant difference (P <0.05) between the peak maximum of the right and left engine torques (+ 10% on the right limb).

Figure 9 shows an example of pedaling pattern on one of the subjects at the level at 150 W showing how the pedaling pattern becomes asymmetric. Using a mathematical model

Cycling Power (W)	Torque Max Peak Left (N.m)	Max Peak Right (N.m)	Min Peak Left (N.m)	Min Peak Right (N.m)
100	19.2 ± 3.7	21.8 ± 2.5	4.3 ± 1.5	4.6 ± 1.9
150	27.5 ± 2.9	* 34.8 ± 4.2	7.5 ± 1.2	7.7 ± 2.3
200	34.4 ± 4.7	* 42.9 ± 3.5	10.4 ± 3.5	11.0 ± 3.3
250	43.0 ± 2.6	* 52.5 ± 6.6	12.9 ± 3.4	14.2 ± 4.7

Table 6. Min and max values of the torque in left and right lower limbs for different power levels

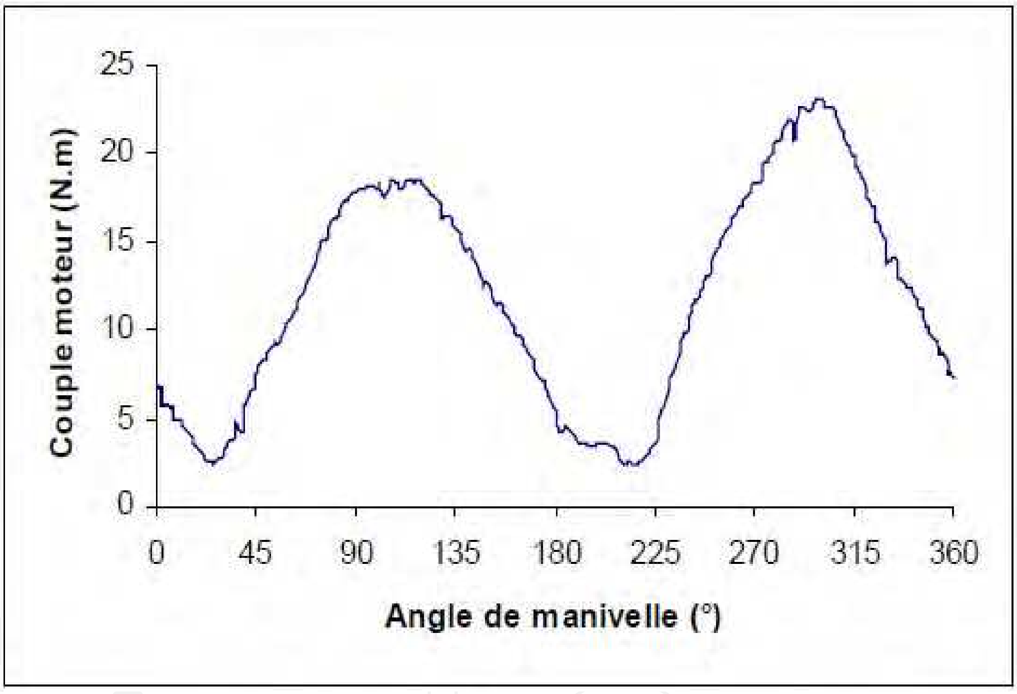


Fig. 9. Torque versus the crank angle for subject 1 at 150 W.

(Grappe et al, 1999), it is possible to estimate that a speed of 25 km/h on the flat (100 W) induces a symmetric pedaling while at 30 km/h (150 W) it becomes asymmetric. Cyclist masters of this study are specialized in long distance races (200 km or more) at a speed about 25 km/h. These results therefore suggest that cyclists have optimized their pedaling mechanics (kinetics and kinematics) only at the intensity they use most frequently. It is very likely that when the road profile is rugged, the power these riders develop is more than 100 W because this is a very low speed uphill (9 km/h on a 5% slope). This suggests that in each ascent the pedaling becomes asymmetric. These asymmetries may have several origins: 1). A marked muscle atrophy on one of the limbs, 2) A lesion of the motor command, or 3) An inappropriate gesture technique.

An imbalance in a pedal cycle repeated several thousand times may have negative effects especially in the cartilage of the knee and hip, and of course on performance. It is possible to improve the efficiency of the pedaling features, for example by performing exercises with feedback on the torque (Henke, 1998). In this way the rider can adjust itself the asymmetry.

Our study also highlight that the thermoregulatory mechanisms used by cyclists masters were variable among individuals. Even if a general trend, corresponding to the average curve of temperature, emerges, one can note the great variability of responses of the human body, and thus its adaptation from one subject to another (Figure 10).

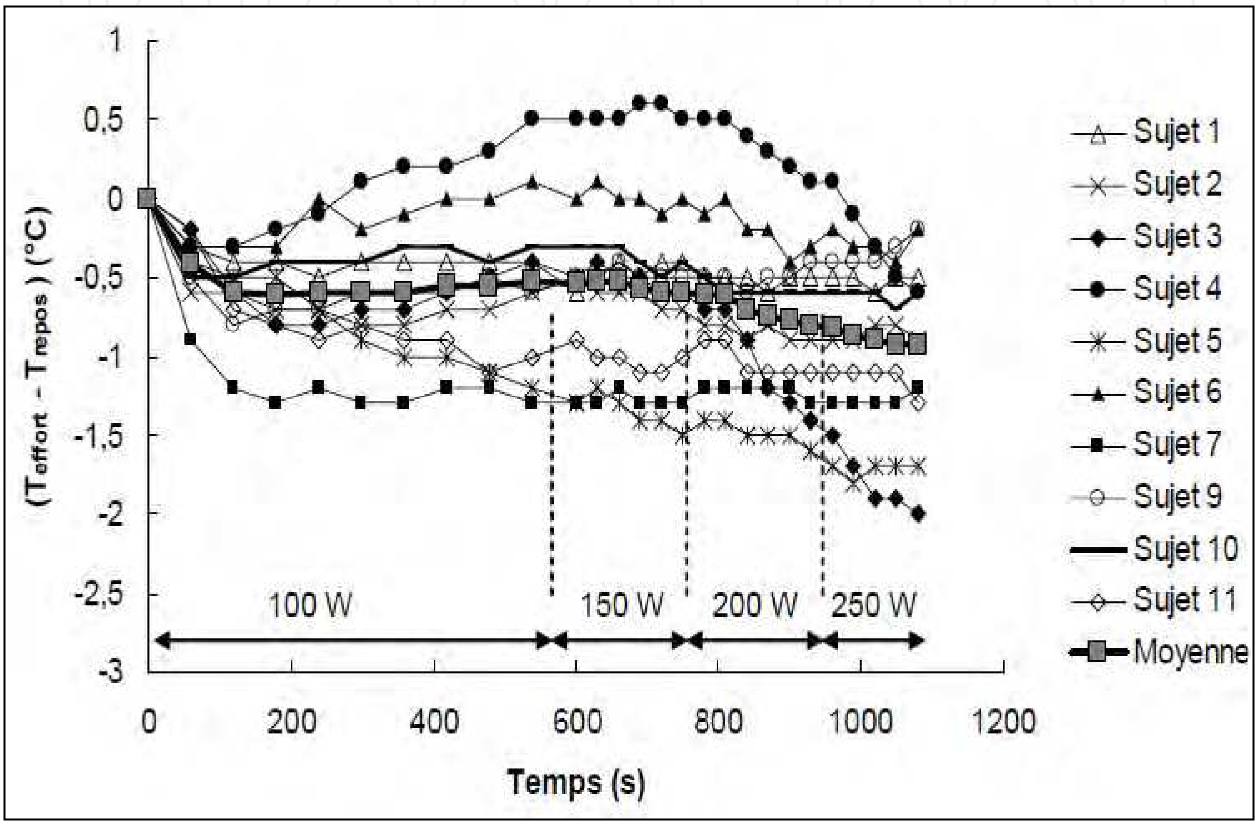


Fig. 10. Skin temperature evolution of the gastrocnemius muscles

For the majority of subjects (except subjects 4 and 6), calf skin temperature decreases with exercise intensity. The average temperature curve thus shows the levels for each power. This decrease in temperature can be related to mechanisms of heat removal employed by the human body. More the energy to evacuate is, the greater the temperature gradient across the fat must be high to allow the transfer by conduction. Then, this flow of heat must be transferred from the skin surface to the environment. During pedaling, and for low external mechanical powers, the thermal transfers are mainly convective, even if a share exchange radiation should not be overlooked. A contrario, if the exercise intensity increases, a sweating mechanism appears, allowing a much larger exchange by evaporation into the environment. The temperature difference between the surface of the skin and the air does not need to be as important as when only the convective heat exchange occurs. The cooling of the calf during the effort is clearly visible on maps of temperature in Figure 11. We also note that the cooling is not uniform over the entire surface of the skin. It will also differ from one individual to another.

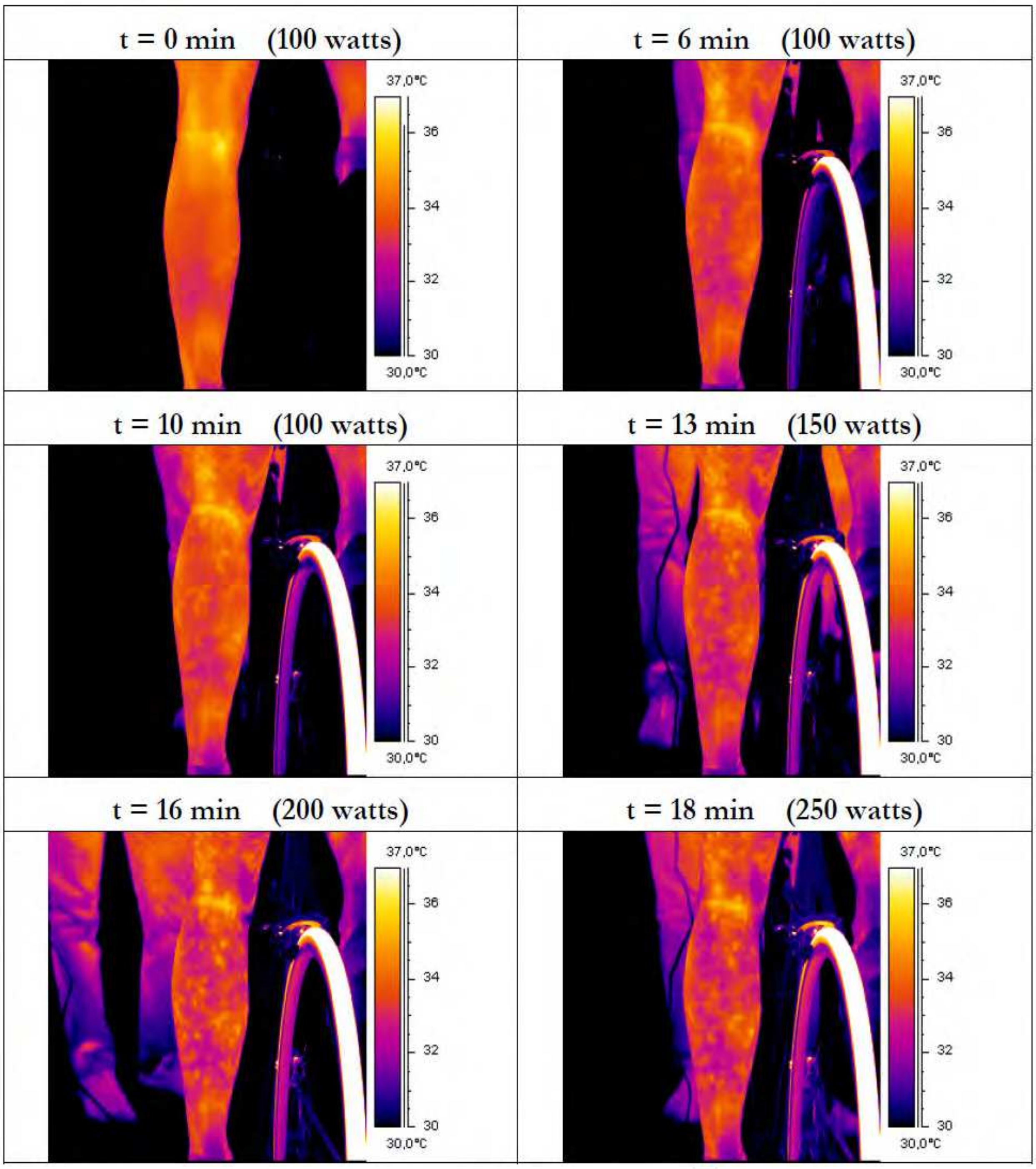


Fig. 11. Temperature maps of the calf during the protocol for subject 10

A thermomechanical analysis of Masters Cyclists pedaling was conducted in the laboratory. This preliminary study indicates that cyclists have an asymmetrical cycling from a relatively low level of power (100 W). Regarding thermoregulation during exercise, a gradual cooling of the calf as a function of external mechanical power is observed. This cooling is accompanied by strong inhomogeneities in the distribution of surface temperatures. These complex mechanisms of thermoregulation should be analyzed in future studies especially with regard to changes in heart rate and thickness of adipose tissue.

5. Infrared thermography and pathology diagnostic applied to sport activity

In this part, we aimed to study the feasibility of application of infrared thermography to detect osteoarthritis of the knee related to sport and to compare the distribution of skin temperature between participants with osteoarthritis and those without pathology. High performance training pushes the locomotor system to the edge of its anatomical and physiological limits. The knee is the most frequently affected joint in sports. Knee injuries are common in sports that involve jumping and abrupt direction changes such as football (Davidson & Laliotis, 1994). The need for further research in the field of injury prevention and management is crucial to counteract severe injuries.

Through its involvement in the activities of most humans, the knee is likely to be the seat to many diseases and injuries like osteoarthritis which is the participant of several clinical and scientific researches. Osteoarthritis is a degeneration of the cartilage without infection or special inflammation. This multi-factorial disease led to a more or less rapid destruction of cartilage that coats the ends of bones. Anatomically, this destruction is accompanied by a proliferation of bone under the cartilage. During cartilage destruction, small pieces of cartilage may break off and "float" in the articular pocket: then they trigger inflammatory attacks that result in mechanical hyper-secretion of fluid and swelling of the joint.

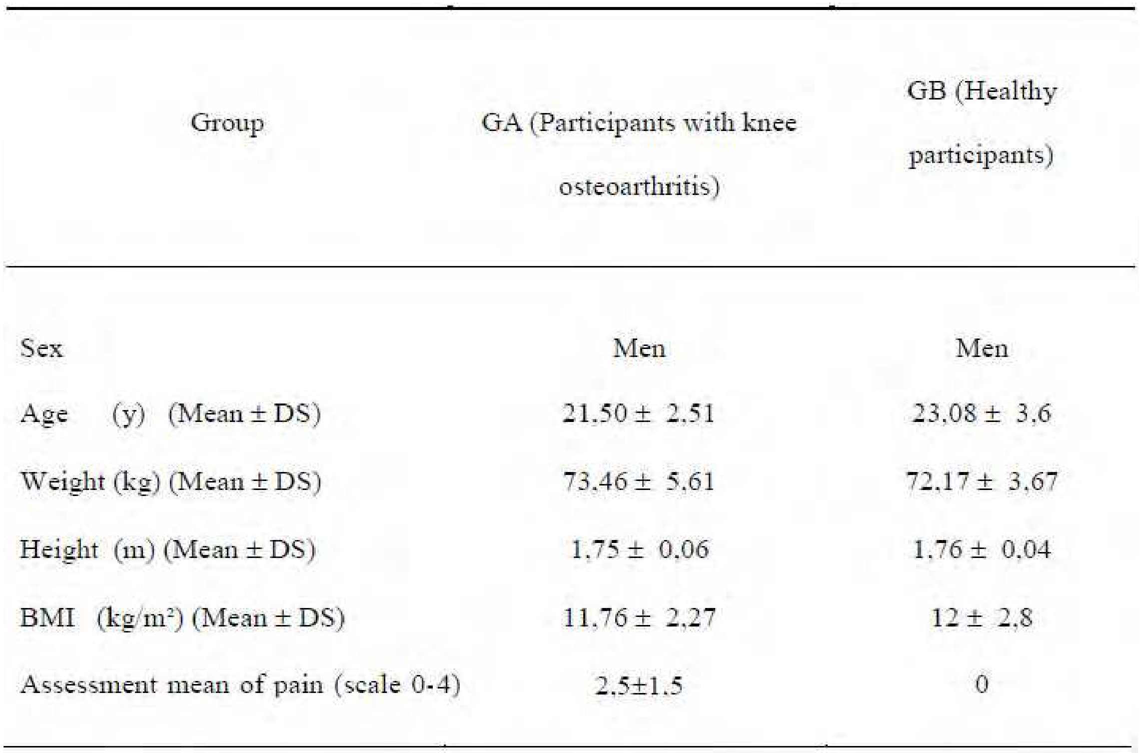
Horvath and Hollander (1949) measured the intra-articular temperature in patients with rheumatoid arthritis and noted that it could be used as a guide to the acuteness of inflammation. Bacon et al (1976) showed that measurement of mean skin temperature could be used as a measure of disease activity.

Infrared thermography is a diagnostic method providing information on the normal and abnormal sensory and nervous systems, trauma, or inflammation locally and globally. Infrared thermography shows physiological changes rather than anatomical changes and could be a new diagnostic tool to detect the pathology of the knee. The objective assessment of disease activity in OA is difficult. Many parameters are based on patients' symptoms, which may not give an accurate indication of the progress of the disease, and laboratory evaluation can be unhelpful.

The thermographic images have previously been used to examine anterior knee (Devereaux et al, 1986; Mangine et al 1987; Ben-Eliyahu, 1992). Ben-Eliyahu et al. (1992) investigated the clinical utility of infrared thermography in the detection of sympathetic dysautonomia in patients with patellofemoral pain syndrome. They have shown that the incidence of patellar thermal asymmetry was found to be statistically significant when tested by chi-2 analysis. More recently, the researches of Selfe et al. (2010) were aimed to investigate if palpation of the knee could classify patients into those with and those without cold knees and if this classification could be objectively validated using thermal imaging. They were unable to deduce a different response in skin temperature with cold stimuli between females whatever the initial temperature of knees is, namely cold and not. Self et al. (2010) concluded that further research was needed to assess the validity and reliability of the methods used to identify this subgroup of patients, to confirm the clinical profile.

5.1 Protocol and method

Ten participants with unilateral knee osteoarthritis (Men, between the ages of 17-26 years) and twelve reference participants without OA (Men, age range, 18-30 years) participated in this study (Table 7). For each participant, we reported the age, weight, height, body mass index (BMI), the dominant side, the existence of pain or other symptoms of functional knee.



Group	GA (Participants with knee osteoarthritis)	GB (Healthy participants)
Sex	Men	Men
Age (y) (Mean ± DS)	21.50 ± 2.51	23.08 ± 3.6
Weight (kg) (Mean ± DS)	73.46 ± 5.61	72.17 ± 3.67
Height (m) (Mean ± DS)	1.75 ± 0.06	1.76 ± 0.04
BMI (kg/m^2) (Mean ± DS)	11.76 ± 2.27	12 ± 2.8
Assessment mean of pain (scale 0-4)	2.5±1.5	0

Table 7. Characteristics of the participants by subgroups

Patients were excluded if they had other pain. To exclude other causes of knee pain, all patients underwent a thorough history taking, a physical evaluation, as well as standard and dynamic series of plain radiographs of femur, patella, and tibia. No medication or other additional conservative treatments were given after enrollment.

The assessment of pain was based on the simple verbal scale on a scale of 0 to 4 (0=none; 1=low; 2=moderate; 3=severe; 4= Maximum).

All tests were conducted at the University of Science and Technology of Physical Activities and Sports in Reims (France). The participants of two groups (with and without osteoarthritis of the knee) ran on a treadmill (slope 0%) during 5 minutes, at a fixed speed of 8 km/h.

The patients were asked to avoid smoking, alcohol, coffee, and exercise for at least 5 hours before testing. We checked each patient's body temperature to ensure that there was no one with extreme body temperature (below 36.4 °C or above 37.2 °C). Air temperature and relative humidity were recorded at the start of measurement periods. IRT has been carried out; using the IR camera CEDIP TITANIUM HD560M, in a room where the temperature was maintained at 18 °C ± 0.5 °C and the relative humidity was 60%. It is important to ensure that the patient was relaxed before imaging so that his emotional state will not influence the measurements.

Before the testing, the patient must wear a short to allow the taking of thermograms of the knees. 30 minutes were needed to balance the patient's body temperature with the environment before resuming testing.

The participants remained motionless and the recording was made in the anatomical position: the body upright, feet in the longitudinal axis of the leg, forearm supination and the palms facing forward. IR thermograms of right and left knees were taken before and after the race at a distance of 1.50 m:

- Before the effort: IR images were taken
- After effort, recordings were taken during 5 minutes.

According to Maly et al. (2002) in normal conditions, 71-91% of body weight is transmitted to the tibia-femoral junction and can reach 100% in the presence of osteoarthritis. Average temperatures were recorded in two areas of each knee (points: 1 to 4 for right knees, and points: 5 to 8 for left knees) as shown in Figure 12. For the healthy participants, the temperature was averaged from these eight points, while only four points were considered for a participant having pathology of the knee.

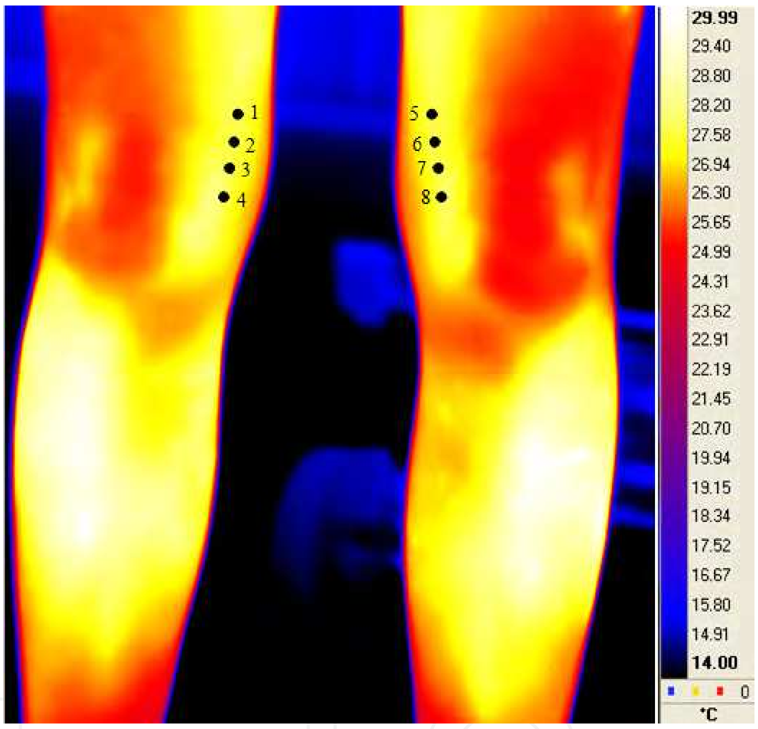


Fig. 12. Infrared thermography of right and left knees with the points selected for measuring the local temperature

5.2 Cartographies analysis

To ensure statistical conclusions, the temperature deduced from thermographic images is averaged over the study area and on all the participants of each group. It is recalled that 10 participants had knee osteoarthritis diseases while 12 participants were healthy. It is clearly shown in Fig. 13 that infrared thermography technique qualitatively enables highly visual estimate of such pathologies. For example in the case of a participant having osteoarthritis pathology in the right knee, the IR thermography in Fig. 13 reveals relevant disease by highlighting asymmetrical behavior in thermal color maps of both knees. It clearly appears by comparing a participant at rest with the same participant undergoing sporting activity that the more the knee is loaded, the more the warm thermal zone is extended. This is

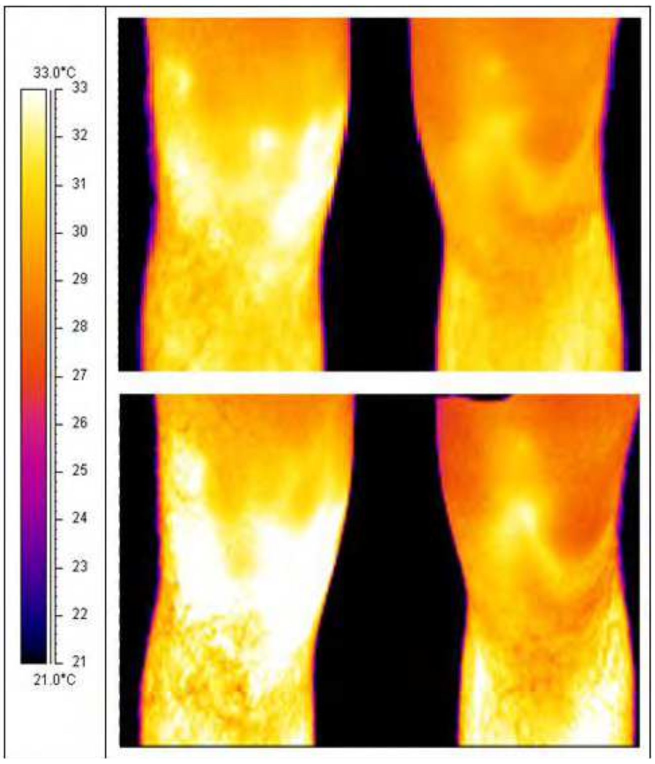


Fig. 13. Infrared thermography of right and left knees before and after race for a participant with right knee OA

probably due to the prompting of the knee, repetitive strain injury during the race increases inflammation in the knee and consequently the temperature of the skin. These findings have been observed in all participants of the GA group, while no temperature gradients appear between right and left knee thermal maps in healthy participants.

Qualitatively, and only from imagery examination, it seems that IR thermography as a simple and non-intrusive experimental device can be easily used as a powerful tool for rapid diagnosis of osteoarthritis of the knee.

5.3 Temperature distributions versus time

In Fig. 14 is represented the arithmetic average of the measured skin temperature in the knee area(s) versus time before and after the running protocol in place for both participant groups. At rest, significant differences occur depending on whether the knee is healthy or not. Thus we get an average measure of 25.83 °C in case of healthy knees while the presence of OA results in a 28.75 °C average temperature. This difference of almost 2 °C far exceeds the accuracy of the IR process, making it efficient for a reliable visual diagnosis of this disease.

After the race and whatever the participant group is, one observes a gap in the average temperature, namely about 1.15 °C for group with OA and 2.31 °C for healthy participants. This result is not paradoxical. It reflects only the fact that initially, at rest, the knee surface temperature was already high for this group of participants. During the acquisition time limited to five minutes, a similar behavior is observed in the temporal temperature evolution for both groups.

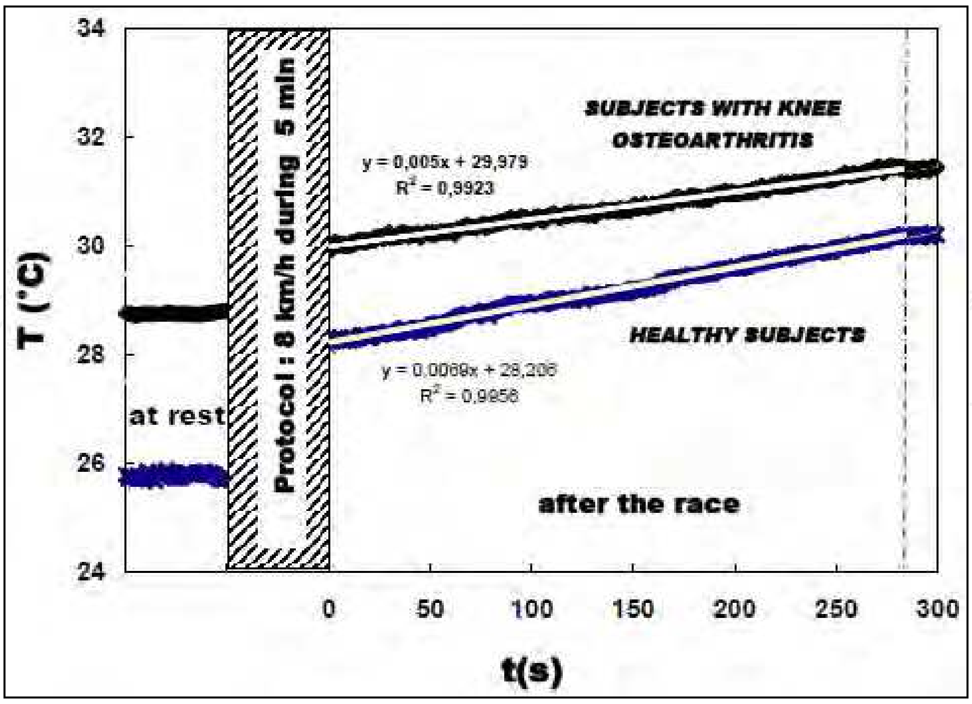


Fig. 14. Average temperature evolution versus time

One observes a perfect linear evolution (with a determination coefficient very close to the unit) of the temperature versus time during less than 5 minutes, followed by a tendency to an asymptotical behavior traducing the beginning of a relaxation thermal process. The slope of the linear regression is roughly the same order of magnitude whatever the group is. This means that there is no over-inflammation of the synovial fluid in OA after the race.

5.4 Relationship between pain intensity and the knee skin temperatures

It seems reasonable and interesting to answer the question of pain experienced by participants with OA, even if this question is based on a subjective analysis. Is there a relationship between the pain intensity and the knee temperature, itself being a feature of inflammation? Obviously, this study did not aim to establish a universal law but to draw a trend of feeling pain in participants with OA. In Fig. 15 is reported the pain intensity given by the participants versus the corresponding average temperature during the protocol. As a reference, is also reported the pain sensation in the case where participants are in rest. Although approximations are rough, these developments clearly show that the temperature can be regarded as a key parameter for evaluating pain. This reinforces the idea that the capture of temperature maps by infrared thermography as a diagnostic tool is certainly an interesting way to develop.

We measured surface temperature in normal and OA joints of the knee for 22 participants. IRT was performed in a room at constant temperatureduring experiments and patients were asked to follow strict instructions before examination. Many studies (Darton & Black 1990; Huygen et al, 2004; Varju et al, 2004; Zaproudina et al, 2009) have shown very good reproducibility of IRT in a temperature-controlled environment. The IRT was reliable to detect osteoarthritis of the knee by the way of distributions of skin temperature. In addition,

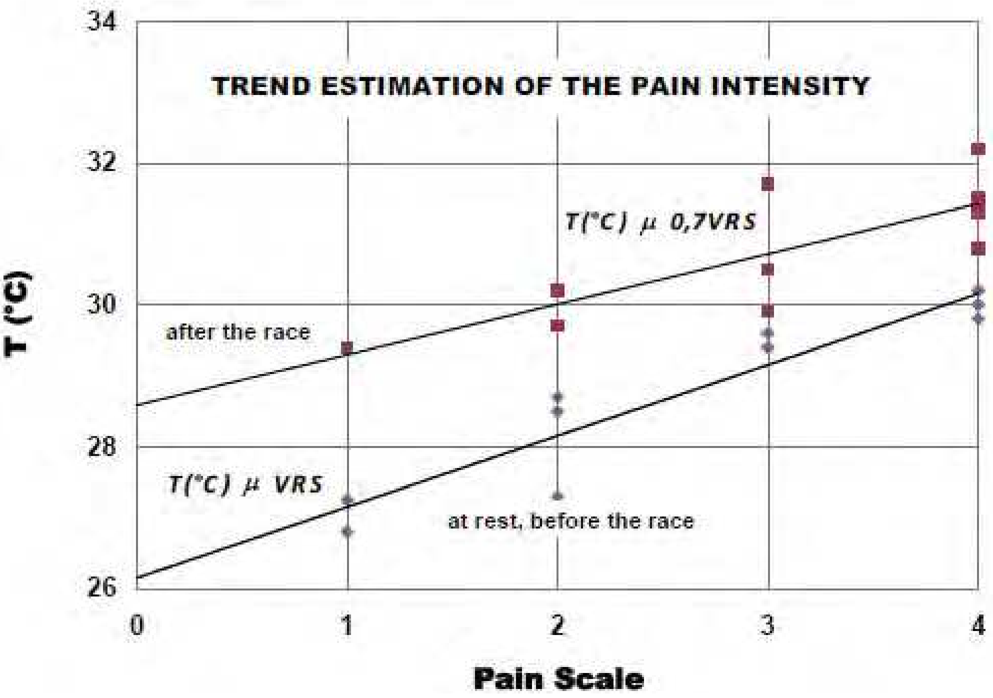


Fig. 15. Correlation between knee skin temperature and estimation of pain intensity

a correlation has been observed between knee skin temperature and the pain intensity due to OA.

Our study has demonstrated the stability of thermographic measurements over a very short period. It will be interesting to predict the disease progression of osteoarthritis and eventually determine a correlation between thermographic and radiographic images.

This study has shown that IRT appears to be a reliable diagnostic tool to detect quantifiable patterns of skin temperatures in participants with OA. It has been demonstrated that the temperature variation can be correlated with changes in pain intensity for the group GA that has osteoarthritis. We think that this non-intrusive technique enables to detect the early clinical manifestations of knee OA.

6. Conclusions

Due to its non-intrusive feature, infrared thermography (IRT) is a powerful investigation tool to be applied as well in sports performance diagnostic (due to the relationship between muscular energy and thermoregulation process) as in sports pathology diagnostic.

It is well known that sports activity induces a complex thermoregulation process where part of heat is given off by the skin of athletes. As not all the heat produced can be entirely given off, this follows a muscular heating resulting in an increase in the cutaneous temperature. For example, in sports activity, we have presented the usability of infrared thermography in swimming for the purpose of quantifying the influence of the swimming style on the cartographies of cutaneous temperatures of a swimmer similar analysis has concerned cycling activity. In particular, the IRT method will enable, in the long term, to quantify the heat loss according to the swimming style, and to consider the muscular and energy outputs during the stroke.

In the field of pathology diagnostic, applied to sports activity, the application of infrared thermography (IRT) has a long history in musculoskeletal trauma. Infrared thermography is a diagnostic method providing information on the normal and abnormal sensory and nervous systems, trauma, or local and global inflammation. Infrared thermography shows physiological changes rather than anatomical changes and could be a new diagnostic tool to detect the pathology of the knee. For example, IRT appears to be a reliable diagnostic tool to detect quantifiable patterns of skin temperatures in participants with knee osteoarthritis.

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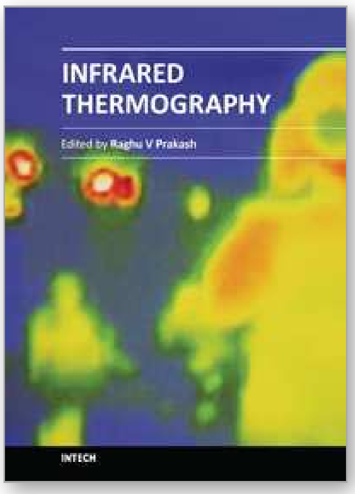

Infrared Thermography

Edited by Dr. Raghu V Prakash

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Infrared Thermography (IRT) is commonly as a NDE tool to identify damages and provide remedial action. The fields of application are vast, such as, materials science, life sciences and applied engineering. This book offers a collection of ten chapters with three major sections - relating to application of infrared thermography to study problems in materials science, agriculture, veterinary and sports fields as well as in engineering applications. Both mathematical modeling and experimental aspects of IRT are evenly discussed in this book. It is our sincere hope that the book meets the requirements of researchers in the domain and inspires more researchers to study IRT.

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