RESEARCH ARTICLE

Open Access

Thermoregulation during incremental exercise in masters cycling

Ahlem Arfaoui[1]✉, William Bertucci[1], Thierry Letellier[1] and Guillaume Polidori[2]

Abstract

This article follows a recently published work (Bertucci et al. 2012) on the effects of age on observed asymmetry during the mechanical process of pedaling for master cyclists and which concerns the majority of practitioners. The present work focuses first on the link that may exist between muscle mechanical imbalance and skin temperature imbalance. It is shown that the infrared thermography has not been able to confirm the mechanical asymmetries observed in the previous study. Moreover, a special attention has been paid on the possible relationship between the muscular skin temperature and the heart rate of subjects. Eleven male master cyclists were volunteers to take part in this study. The mapping of active members' skin temperatures (gastrocnemius muscle) during a graded exercise used the infrared thermography. The skin temperature of the calves decreased as the subjects started the exercise and during exercise. Skin temperature distribution presents hyperthermal spots due to the presence of perforator vessels which reach the surface of the skin. These spots have been highlighted during the exercise. Correlation was found between heart rate and skin temperature evolutions during incremental exercise. Similar trends in the evolution of these two parameters have been highlighted at the origin of each power level.

Keywords: thermography, incremental test, masters cyclists

✉**Contact email:***ahlem.arfaoui@univ-reims.fr* (A. Arfaoui)

[1]Biomechanics laboratory, [2]Thermomechanics laboratory, Research Group in Engineer's Sciences (GRESPI EA4694), University of Reims Champagne Ardenne, Moulin de la Housse, BP 1039, 51687 Reims cedex 2, France

Received: 28September 2013.Accepted:10April 2014.

Introduction

This article follows a recently published work (Bertucci et al. 2012) on the effects of age on observed asymmetry during the mechanical process of pedaling for master cyclists because this group of cyclists concerns the majority of practitioners. In particular, the conclusion of the previous study was that cyclists have a significant pedaling pattern asymmetry cycling from a relatively low level of power (100 W) to higher intensity (250 W). The purpose of the present analysis is to complete these last data and to have a precise idea on how the mechanisms of thermoregulation muscle occur from the infrared thermography tool. Especially, the present work focuses on the link that may exist between muscle mechanical imbalance and skin temperature imbalance, through the idea that muscles produce excess heat which must be dissipated. In addition, a special attention will be paid on the relationship between the muscular skin temperature and the heart rate of subjects. To our knowledge, no data in the literature deals with this type of study in cycling.

It is well known that muscular exercise leads to an increase in internal temperature and is accompanied by heat generation which represents the difference between the energy consumption and the mechanical energy. To maintain quasi-constant the internal temperature, the body must lose the heat generated during exercise. Thus, two evacuation processes are triggered namely: skin blood perfusion booth in the superficial and deep skin layers, and heat exchanges with surrounding environment via skin surface (Brengelmann et al. 1979; Chabanski 1993). In the last one, different mechanisms of thermolysis process occur in the thermoregulation one with the ambient medium: convection, evaporation, radiation, and conduction. It is now commonly accepted (Badza et al. 2012, Paulev and Zubiet 2000) that at rest and in the lower comfortable zone (20-26°C), heat is lost as follows: 60% through radiation, 25% through evaporation, 12% through air circulation (convection) and 3% through conduction (Gisolfi and Wenger 1984). During exercise, the most effective mechanism for the elimination of heat flux produced is sweating and evaporation of sweat from the body surface by convection. The thermoregulation process is highly dependent on the study conditions, whether "outdoor" or "indoor" ones. In a laboratory, the convection phenomenon mainly depends on the air that is mixed by moving the legs, while in exterior conditions, in addition to this mixing; one has to take into account the wind which may be present. This is the reason why, in order to overcome this, all experiments on all cyclists are taken under similar conditions, *e.g.* in a room.Skin layer represents a barrier between the inside of the body and the surrounding environment. It contains many thermal sensors that participate in the thermoregulatory control, and that affect the person's comfort.

The skin plays an important role in the metabolic processes, for this reason researchers have turned to infrared thermography which easily gives skin thermal maps. Thermography represents a non-invasive method that provides information about the skin's thermal aspect in a complex thermoregulatory process. Moreover, infrared thermography gives a possibility to evaluate the effect of the sporting activity and to analyse the impact of physiological and morphological factors on the dynamics of temperature changes (Chudecka and Lubkowska 2010).

Indeed, due to its non-intrusive feature (Clark et al. 1977; Hunold et al., 1992; Zontak et al. 1998; Kaminski et al. 2010; Merla et al. 2010; Hildebrandt et al. 2010), infrared thermography can be defined as a non-contact technique for measuring heat radiation on surface. 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 and video with measurements of surface temperatures over a large distance.

Torii et al. (1992) studies the skin temperature distribution of cycling men during initial muscular work. Eleven healthy men were selected to take part in a bicycle exercise at workloads of 50-150 W in a climatic chamber at ambient temperatures of 10-40°C (relative humidity 45-55%). They showed that increased work intensities reduced skin temperature. The results suggest that the fall in skin temperature during initial exercise was not due to increased evaporative cooling but to vasoconstriction (Johnson 1992; Kenney and Johnson 1992). The vasoconstriction is due to the muscular blood recruitment, prolonging exercise increases metabolic heat production and invokes thermal regulatory processes.

Indeed, Johnson et al. (1974) tried to determine whether skin is relatively vasoconstricted during upright exercise in the heat and to determine the roles of upright posture and exercise on the relationship of skin blood flow to internal temperature. They conclude that increasing blood flow was a result of competition between reflex vasoconstriction with muscular work. They suggested that skin is vasoconstricted during heat stress with exercise or upright posture and that the greatest effect occurs when these stresses are combined.

Merla et al. (2005) also used Infrared thermography to verify whether trained individuals have different skin thermoregulation from untrained ones during a graded exercise. They confirmed that ten professional footballers (training) have a better vasoconstriction capability during the initial phase of muscular work (Gray et al. 2002; Kenny et al. 2003; Krustrup et al. 2001) and a better capability to dissipate through the skin layers the metabolic heat that is produced during the muscular work (Racinais et al. 2005; Okasaki K et al. 2002). The process of thermoregulation is closely related to muscle activity and is a factor in endurance performance.

Abate et al. (2013) tried to determine if the thermoregulatory system that initiates heat loss mechanisms is different among trained and untrained subjects. Forty male volunteers participated to a standard warm up exercise divided in three steps (0-5 minutes at 100 Watt; 5-10 minutes at 130 Watt; and 10-15 minutes at 160 Watt). They showed that trained participants exhibited a temperature reduction in the third step, while no difference was observed in untrained participants. They noted a progressive increase in heart rate during exercise for trained and untrained subjects but more markedly in untrained subjects.

Focusing the analysis on master cyclists ineluctably leads to the questioning on the effect of age on the thermal responses in elderly subjects to muscular exercise. Indeed, many studies have examined the alterations of thermographic patterns during exercise and they assessed the possible thermographic profile changes associated to exercise in elderly subjects. Several researchers (Thomas et al. 1999; Minson et al. 1998; Ho et al. 1997; Hellon et al. 1956; Armstrong and Kenney 1993; Kenney 1988, 1997) compared the physiological responses of older people with those of younger people.

In 1997, Kenney showed that when older subjects are matched for VO_2max with young subjects and exercise at the same absolute and relative intensity, there are seldom differences in either central temperature or calculated heat storage (Kenney 1997).

In continuity, Ferreira el al. (2008) evaluated the thermographic changes associated with localized exercise in young and elderly subjects. Fourteen elderly subjects (12 women and 2 men) and fifteen young subjects (10 women and 5 men) participated in this study. They conclude that the elderly subjects presented lower resting temperature and slower heat dissipation compared to the young subjects. They confirmed that elderly and young subjects display similar capacity of heat production when submitted to localize low-intensity exercises.

The purpose of the present study is twofold:

- First, the idea of this work is to see if a tool such as infrared thermography is able to predict this type of muscle imbalance in the case of inherent asymmetric pedaling for the population of master cyclists.
- Secondly, a special attention will be paid on a possible relationship between the muscular skin temperature and the heart rate of subjects. We recall that at our knowledge, the literature does not seem to have been interested in this topic.

Materials and methods

Subjects

Eleven male master cyclists were volunteers to participate to this study. The experience of cycling of the subjects was 15 ± 11 years. Because the subjects are the same as those that have participated at a previous study (Bertucci et al. 2012) and for the sake of brevity, only the averaged data are given in table 1.

The subjects were asked to avoid smoking, alcohol, coffee within six hours before the exercise, (Stephenson and Kolka 1995; Pellaton et al. 2002) and to refrain from intense exercise for at least 24 hours before their participation in the study. Prior to testing and after having received full explanation about the nature and purpose of the study, the subjects gave written informed consent. The Ethical committee of the University of Reims approved of this study and the protocol used which was conducted in accordance with the ethical guidelines (Harriss and Atkinson 2009, 2014).

Materials

This study being the result of a recently published article (Bertucci et al, 2012) dedicated to cycling; we first recall all the material we used.

Mechanical power output and the pedaling pattern were measured (200 Hz) using the system SRM Training System (scientific model, precision 0.5%, Germany) like several previous studies (*e.g.* Bertucci et al. 2005, Carpes et al. 2007). The validity of the SRM has been previously shown by Jones et al. (1998). Before each test, the SRM was calibrated according to the manufacturer's recommendations (the zero power offset was reset although the setting of the zero offset does not substitute for a standardized calibration). However, the standardized calibration rig (*i.e.* the resetting of the SRM "frequency versus torque" slope) was performed just a few days before our first test day by the SRM manufacturer in Germany and resulted in an accuracy of ± 0.5% (manufacturer's proclamation). The SRM was mounted on a bicycle race equipped with clipless pedals. The rear wheel of the bicycle was fitted on the Basic Tacx ergometer (Tacx, Wassenar, Netherlands). Before the start of each test, each cyclist has adjusted his position. 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 (Polar, Kempele, Finland).

In order to access the skin thermal maps, body surface temperature can be evaluated and analyzed thanks to the use of an infrared camera which is a non-intrusive tool the use of which has found a wide application mainly in medicine and to a lesser degree in sports (Badza et al. 2012; Chudecka and Lubkowska 2012).

Unlike most studies in literature that use large areas of the human body to view maps of temperature, we have chosen to interest only a small area, namely calves, the role of which is crucial in cycling (Torri et al. 1992, Merla et al 2002, Abate et al. 2010).

Skin temperature of the gastrocnemius muscles was measured using an infrared thermal camera (Flir SC1000: 256×256 focal plane array, 200 Hz frame rate, quantum efficiency >70%. It is equipped with a system of instant integration variable from 1 μs to 10 ms., temperature measurement range between - 40 to 1500 ° C ± 2%) with infrared sensitive in the short range of wave lengths between 3and 5μm. The acquisition frequency of the camera is 50 Hz. The minimum detectable temperature difference is less than 0.1°C in the study temperature range.

The infrared camera was positioned on a tripod at a height of 0.5 m, and at a distance of 1.5 m behind the bicycle (Fig 1(a)). Infrared images were taken before, during and the end of the exercise while the subjects pedaled. This type of camera allows acquisitions even when the study area is moving. Average temperatures were recorded in the study areas surrounding the gastrocnemius as shown in Figure 2.

To define and individuate a region of interest, we have used thermally neutral markers placed surrounding the gastrocnemius as similarly used in Merla et al. (2010). The first thermal image was used as a reference for the other ones. Thermal images were taken every five seconds. As the movement of the legs is cyclic, the position of the calf is reproducible from one cycle to another. In such a way, it is thus easy to identify the calf area that will serve as study area from one cycle to another, and to avoid possible artifacts.

Unlike in Merla et al. (2010), it is not useful to use a recognition algorithm for the experiments and only one computer post-processing is sufficient to find the calf area of interest.

It should be noted that to ensure that all experiments have been made in the same experimental conditions the room temperature was maintained constant at 20 °C± 0.5 °C. Moreover, air temperature was systematically recorded at the start of each measurement period.

Protocol

The protocol is the same as the one used in the previous study by Bertucci et al. (2012). We briefly recall the content. The heart rate of subjects was recorded at rest for 5 minutes in a sitting position. Once the cyclist is positioned on the bicycle, the skin temperature of the gastrocnemius muscle on both lower limbs was measured. We recall that in order not to disturb the cycling pattern, thermal measurements have been taken during the motion; the thermal imaging was stable enough to allow this protocol. Indeed, the camera presents a rate of frames per second which is up to 50images /second in full speed mode. The temperature measured during the rest period was the reference temperature.

The cyclists had to perform an incremental progressive exercise during 18 minutes. The exercise was beginning at a power output of 100 W during 10 min, and then the intensity increased in increments of 50 W of 3 minutes each up to 200 W, then the last step was performed at 250 W for 2 min (Figure 3). The subjects could control their power output using the feedback on the SRM display.

Thirty minutes were needed to balance the body's temperature with the environment before resuming testing.

Statistical analysis

The data of the protocols were tested for normality and homogeneity of variance and turned out to be not normally distributed. Thus, the analysis of differences between the different power output intensities (*i.e.* temperature, heart rate) were assessed with paired (non-parametric) Wilcoxon tests. Significance was set at $p \leq 0.05$. Data are presented as mean values ± standard deviation. Spearman correlation coefficients were used to determine significant relationships between the cutaneous muscle temperature and the heart rate during the two parts of the tests (constant intensity at 100 W and from incremental part from 150 to 250W)

All the statistics were performed with Statsoft Statistica V7.1 software (Johannesburg, South Africa).

Table 1. Averaged physiological parameters of the eleven subjects

11 subjects	Age (years)	Distance travelled per year (km)	Height (cm)	Mass (kg)	Body fat (%)
Average	53.5 ± 4.1	7545 ± 2815	175 ± 5	71.8 ± 3.7	17.9 ± 2.2

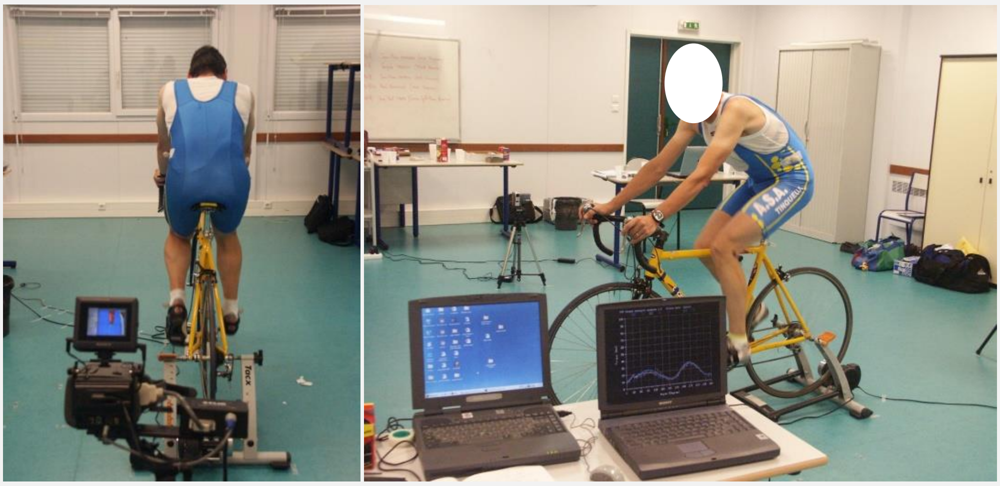

Fig 1(a) Fig 1(b)

Figure 1. The course of a test

Figure 2. Thermal explored area

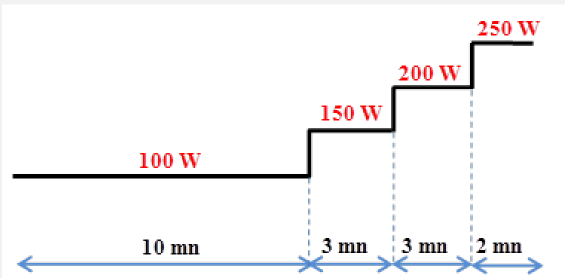

Figure 3. Description of the Incremental test.

Results

In figure 4 are represented the evolutions of average cutaneous temperatures in the left and right lower limb areas of the eleven cyclists. One may observe a similarity between both evolutions of temperatures on the left and right lower limbs. There is no significant difference between the left and right lower limb cutaneous temperatures.

The figure 5 shows an example of thermographic images during the incremental test. We represent in figure 6 the mean cutaneous temperature of the left lower limb at rest and at the end of each stage of the incremental test for the eleven master cyclists. This figure shows the significant decreasing of the muscle cutaneous temperature according to the power output level. There are significant differences between intensities of 150 and 200W ($p=0.016$) and between the rest condition and 250W ($p=0.005$). There is a tendency to be different between the rest condition and 100W ($p=0.08$). As for the inter-individual variability, the variation coefficients of the temperature (CV, %) were 1.35, 1.80, 2.26, 2.36 and 2.75 % for the rest, 100, 150, 200 and 250W conditions, respectively.

Figure 7 shows the evolution of heart rate and skin temperature during the cycling exercises. Three phases can be distinguished; the first corresponding to the three first minutes when the cutaneous temperature decreases, the second from the third to the twelfth minutes when the values are stabilized, and the last when the values increase significantly. Figure 7 shows

a significant relationship between the heart rate and the muscle cutaneous temperature during the stabilized phase of power output (100W) and during the incremental phase until 250W. The heart rate values increase significantly ($p<0.001$) according to the exercise intensity (104.6 ± 8.1, 121.9 ± 8.6, 139.6 ± 8.6 and 154.5 ± 9.3 bpm for 100, 150, 200 and 250W, respectively). There are differences ($p<0.01$) between the heart rate at 1) 100 vs 150W, 2) 150 vs 200W and 3) 200 vs 250W.
Figures 8(a) and 8(b) show a significant relationship between heart rate and the gastrocnemius cutaneous temperature during the stabilized phase of power output (100W) and during the incremental phase until 250W.

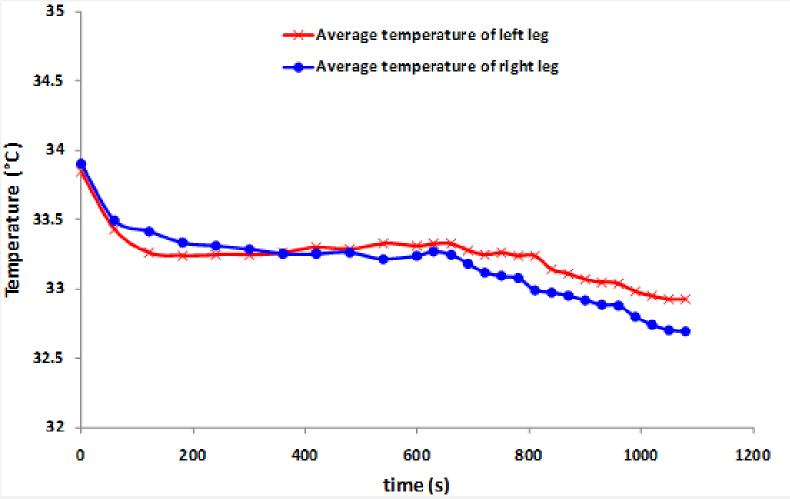

Figure 4. Distribution of average cutaneous temperatures in left and right gastrocnemius muscle areas during the cycling test.

Discussion

The aim of this preliminary study was to analyze the possible relationship between the muscular skin temperature of the gastrocnemius and the heart rate of master cyclists during incremental exercise.
The choice of gastrocnemius muscle as study area may be questionable. However, this selection has been guided by the fact that the gastrocnemius muscles are in their movement and at a given moment of their rotation cycle perfectly perpendicular to the camera axis, avoiding bias in the reliability of measurements.
One may notice that gastrocnemius infrared images and distribution of average cutaneous temperatures in left and right lower limbs areas (figure 4) did not reveal relevant muscular imbalance by highlighting

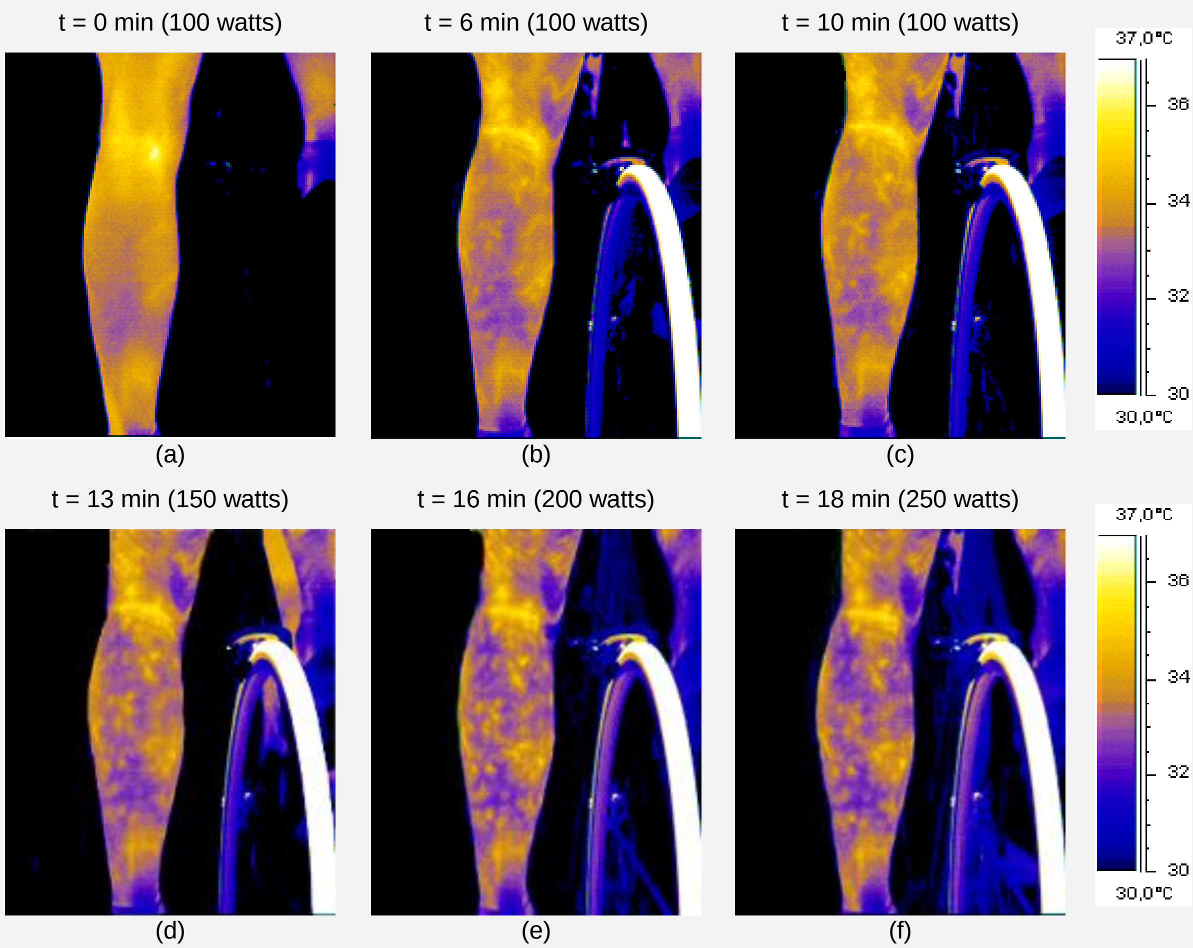

Figure 5. Example of thermal photography during the test.

asymmetrical behavior. Maybe the choice of another muscle in the cycling main muscle chain (*e.g.* quadriceps) could evidence the asymmetry in the pattern of pedaling. It is the reason why, for conciseness, only the left leg maps are presented in figure 2.

Concerning the thermographic analysis, the infrared images (figure 5) were taken during the different phases of the exercise: at a power output of 100 W (0 min; 6 min; 10 min), at 150 W (13 min) at 200 W (16 min) and at the power of 250 W (18 min; the end of exercise).
It is clear that at the beginning of the protocol, at t=0 (figure 5(a)); the temperature of the lower limb is perfectly homogeneous, excepted in the area immediately below the calf, which has a lower skin temperature. One may note that the skin temperature of the cyclist's left leg decreases during the exercise. This decrease was no longer homogeneous. Indeed, the relatively homogeneous temperature distribution at the beginning is replaced by a temperature pattern with distinctly warmer and cooler areas (Fig 5(b), 5(c), 5(d), 5(e), and 5(f)).
This observation is in accordance with the works of Merla et al. (2010) who studied cutaneous temperature variations in well-trained runners during graded treadmill exercise until reaching their individual maximal heart rate. They concluded that when performing graded exercise, the subject should favor vasoconstriction of the cutaneous vessels increasing the blood flow to muscles; it is the reason why the skin temperature decreases.

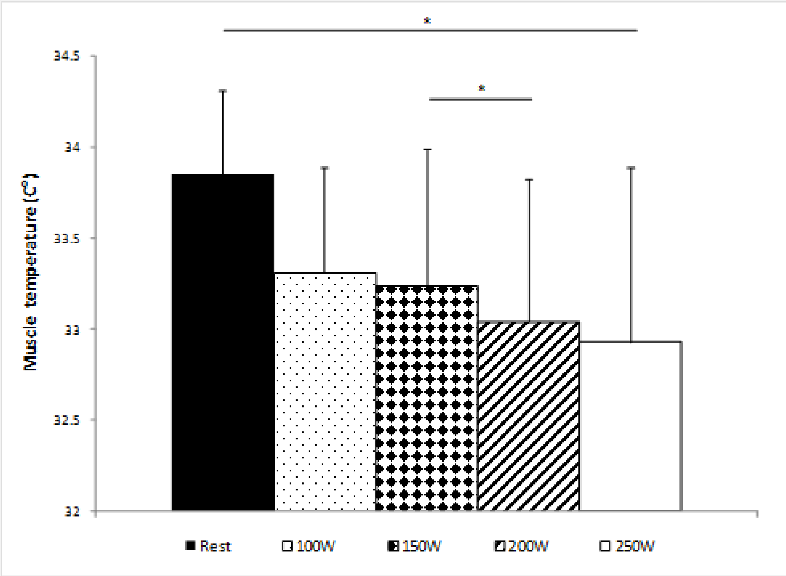

Figure 6. Average cutaneous temperature of the gastrocnemius muscle at rest and at the end of each stage of the incremental test. Error bars representing standard deviation.
*: Significant difference p<0.05

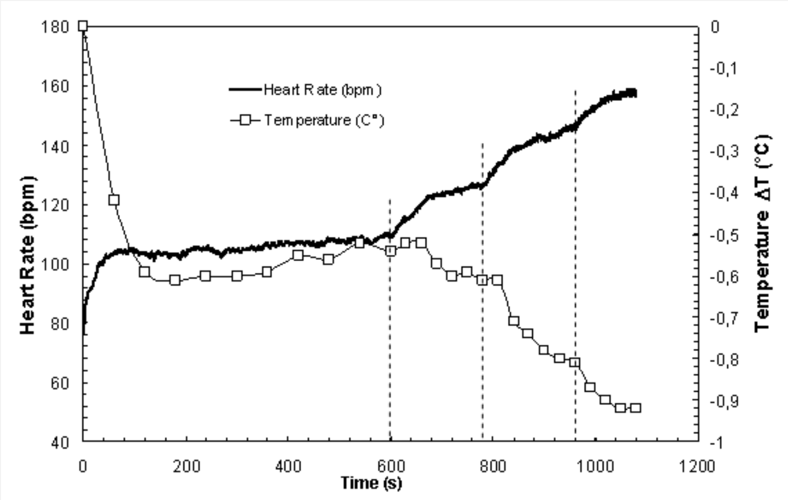

Figure 7. Evolution in time of heart rate and skin average temperature gradient.

Moreover, from a power of 150W, one can observe that the skin temperature distribution presents hyperthermal spots (Fig 5(d), 5(e), and 5(f)) due to the presence of perforator vessels which reach the surface of skin. The apparition of more elevated temperature spots (the number and arrangement of which seem to vary from one subject to another) has already been related in literature by Hunold et al. (1992), Vainer (2005). Nevertheless, contrary to the observation by Merla et al. (2010) who suggested that the presence of hyperthermal spots was due to muscle perforator vessels during baseline and recovery, but not during exercise, these spots have been highlighted during exercise in the present case.
To supplement the purely qualitative observations from thermographic images and corresponding colour codes, a more quantitative analysis was conducted. The curves in figure7 show the temporal evolution of heart rate and skin temperature during muscular effort. It should be recalled that the thermal results presented are obtained from an average over one leg of the eleven cyclists, the test area being defined in figure 2.
The temperature gradient ΔT presented in figure 7 corresponds to the difference between the measured temperature and the one at rest.
One may note at the early stages of the protocol that the skin temperature of the cyclist's calves drastically decreases. As already mentioned, this fall in skin temperature during initial exercise was not due to increased evaporative cooling but to vasoconstriction (Johnson 1992; Kenney and Johnson 1992; Merla et al. 2010), due to the muscular blood recruitment. This sharp drop is followed by a steady constant state, which then traduces a thermal equilibrium between inflow and heat dissipation at the skin up to 150W.
Prolonging exercise increases the metabolic heat production and invokes thermal regulatory processes. This results in a significant decay of the skin temperature in the form of regular levels. The decrease

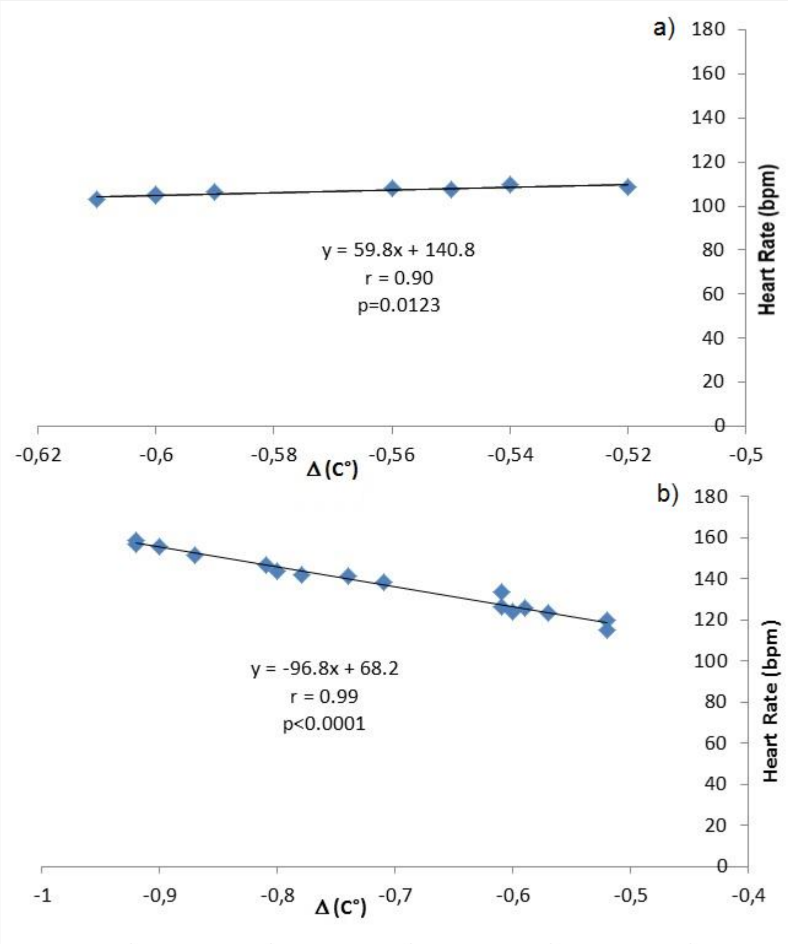

Figure 8. Linear regression between heart rate and gastrocnemius muscle temperature (ΔT : variation from the rest condition) during:
(a) the stabilized intensity (100W)
(b) the incremental exercise phase (150-250 W)

can also be partly a consequence of the convection heat. While pedaling, a continuous circulation of air flow is provided to the skin. The human body evacuates the heat flux with its environment much more than the rest phase and the skin surface is rapidly cooled. It seems difficult to distinguish if this decrease is due to vasoconstriction only or to the combination between vasoconstriction and convection (Kenney and Johnson 1992).

Comparing both the heart rate and the skin temperature evolutions shows that there is a strong relationship between these two parameters (Figures 8(a) and 8(b)). Indeed, in the same way that the coolant dissipates the heat of a combustion engine car, the blood has the vital function to dissipate the heat accumulated by the muscle during exercise. 80% of the blood flow is estimated to be devoted to the process of thermoregulation (Torii et al. 1992). It is easily seen that the higher the blood flow increases during the muscular effort, the more heat is removed and consequently the temperature of the skin decreases. Figures 6 and 7 show the decreasing of the temperature according to the level of intensity of the exercise.

A more detailed analysis shows that moving from are sting state to an exercise of a 100 W power is accompanied for the eleven subjects with an average increase in heart rate of about 30bpm. It is precisely this first phase which induces the strongest decrease in skin temperature since a mean difference of 0.6°C was recorded. In such a case, the vasoconstriction process is the main regime of heat dissipation. Thereafter, having considered in the protocol a first 100W power step during a long time, cyclists were able to stabilize their heart rate at 104.6 ± 8.1 bpm. One can see that this heart stabilization leads to a quasi-stationary thermal regime. From t=600s which corresponds to an increase of the power level by 50W steps from 100 W up to 250W, a similar trend is observed in the heart rate curve. During constant and incremental phases our results show a significant relationship between the muscular cutaneous temperature and the heart rate. This relationship confirms that the arterial blood flow is laid to the process of thermoregulation.

Indeed, the slope at the origin of the new effort seems to be significant and the curve seems to tend towards a stationary asymptotic state which is never reached during this temporal protocol due to the application of a higher power after 3minutes.

Similarly to the evolution of the heart rate versus the power exercise, the curve of temperature changes in reverse, showing a fundamental point in the process of thermoregulation in athletes, namely that we cannot separate heat dissipation and heart rate and therefore blood flow.

Conclusions

From the present analysis, the following conclusions have been drawn:

- Using a long first exercise stage allows the evidence of an asymptotic regime of thermal equilibrium at very moderate effort, appearing 2 min after the start of the protocol.
- The present analysis dealing with a cycling protocol confirms the study Merla et al.(2009) concerning the decrease in skin temperature during muscular exercise even if the muscle contraction type is different (concentric contraction only for pedaling while both eccentric and concentric for running).
- One can observe that the skin temperature distribution presents hyperthermal spots due to the presence of perforator vessels which reach the surface of the skin. These spots have been highlighted during pedaling exercise.
- The study of a relatively small area is sufficient to understand the dynamics of skin temperature.

Nevertheless, the infrared thermography has not been able to confirm the mechanical asymmetries observed in the previous study. Mechanical unbalance does not necessarily lead to a thermal imbalance. This is due to the thermal diffusion by conduction in muscle, which tends to standardize local temperature variations.

- A significant correlation was found between heart rate and skin temperature evolutions during graded exercise. Similar trends in the evolution of these two parameters have been highlighted at the origin of each power level.

Practical applications

The purpose of this experimentation was to better understand the mechanisms of thermoregulation muscle during the pedaling exercise of master cyclists which concerns the majority of practitioners.

Acknowledgment

The authors wish to thank all the cyclists who were involved in this study and their respective clubs (ASA Tinqueux, Cyclo-Club Rémois, Pédale-Rémoise).

References

1. Abate M, Di Carlo L, Di Donato L, Romani GL, Merla A. (2013) Comparison of cutaneous thermic response to a standardized warm up in trained and untrained individuals. JSports Med Phys Fitness. 53(2):209-15. PubMed PMID: 23584330.
2. Abate M, Di Carlo L, Romualdo SD, Ionta S, Ferretti A, Romani GL, Merla A. (2010) Postural adjustment in experimental leg length difference evaluated by means of thermal infrared imaging.Physiol Meas. 31(1): 35-43.
3. Atkinson G. (2003) Does size matter for sports performance researchers? Journal of Sports Sciences 21 (2): 73-74.
4. Armstrong CG, Kenney WL. (1993) Effects of age and acclimation on responses to passive heat exposure. Journal of Applied Physiology 75: 2162-2167
5. Badza V, Jovancevic V, Fratric F, Roglié G, Sudarov N. (2012) Possibilities of thermovision application in sport and sport rehabilitation. Vojnosanit Pregl 69(10): 904-907
6. Bertucci W, Arfaoui A, Polidori G. (2012) The pedaling biomechanics of master’s cyclists: a preliminary study. Journal of Science and Cycling 1(2): 42-46
7. Bertucci W, Grappe F, Girard A, Betik A, Rouillon JD. (2005) Effects on the crank torque profile when changing pedalling cadence in level ground and uphill road cycling. Journal of Biomechanics 38: 1003–1010.
8. Brengelmann GL, Johnson J. M, Hermansen L, Rowell LB. (1977) Altered control of skin blood flow during exercise at high internal temperature. Journal of Applied Physiology 43(5): 790-794.
9. Carpes FP, Rossato M, Faria IE, BolliMota C. (2007) Bilateral pedaling asymmetry during a simulated 40-km cycling time-trial. Journal of Sports Medicine and Physical Fitness 47:51-57.
10. Chabanski S. (1993) Spectral Analysis and Filtration of Dynamic Infra-red Images of the Human Body. Technion, Israel: MSc Research Thesis.
11. Chudecka M, Lubkowska A. (2010) Temperature changes of selected body’s surfaces of handball players in the course of training estimated by thermovision, and the study of the impact of physiological and morphological factors on the skin temperature. Journal of Thermal Biology, December: 35(8): 379-85.
12. Chudecka M, Lubkowska A. (2012) The use of thermal imaging to evaluate body temperature changes of athletes during training and a study on the impact of physiological and morphological factors on skin temperature. Human movement 13(1): 33-39
13. Clark RP, Mullan BJ, Pugh LG. (1977) Skin temperature during running - a study using infra-red colour thermography. The Journal of Physiology May 267(1): 53-62.
14. Coyle E, Feltner M, Kautz S, Hamilton M, Montain S, Baylor A, Abraham L, Petrek G. (1991) Physiological and biomechanical factors associated with elite endurance cycling performance. Medicine & Science in Sports & Exercise 23: 93-107.
15. Ferreira JJ, Mendonça LC, Nunes LA, Andrade Filho AC, Rebelatto JR, Salvini TF. (2008) Exercise-Associated Thermographic Changes in Young and Elderly Subjects. Annals of Biomedical Engineering, Vol. 36(8): 1420-1427
16. Gisolfi CV, Wenger CB 1984 Temperature regulation during exercise: old concepts, new ideas, Exercise and Sport Sciences Reviews 12: 339-72
17. Gray S. C, Devito G, Nimmo MA. (2002) Effect of active warm-up on metabolism prior to and during intense dynamic exercise. Medicine & Science in Sports & Exercise 34(12): 2091-6D.
18. Harriss DJ, Atkinson G. (2009) Ethical Standards in Sport and Exercise Science Research. International Journal of Sports Medicine 30: 701-702
19. Harriss DJ, Atkinson G. (2014) Ethical Standards in Sport and Exercise Science Research: 2014 Update. International Journal of Sports Medicine 34: 1025-1028
20. Hellon RF, Lind, AR, Weiner, JS. (1956) The physiological reactions of men of two age groups to a hot environment. The Journal of Physiology 133: 118-131.
21. 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
22. Ho CW, Beard JL, Farrell PA, Minson CT, Kenney WL. (1997) Age, fitness, and regional blood flow during exercise in the heat. Journal of Applied Physiology 82: 1126-1135.
23. Hunold S, Mietzsch E, Werner J. (1992) Thermographic studies on patterns of skin temperature after exercise. European Journal of Applied Physiology 65: 550-554.
24. Johnson JM, Rowell LB, Brengelmann GL. (1974) Modification of the skin blood flow-body temperature relationship by upright exercise. Journal of Applied Physiology 37 (6): 880-6.
25. Johnson JM. (1992) Exercise and the cutaneous circulation. Exercise and Sport Sciences Reviews 20: 59-97
26. Jones SM, Passfield L. (1998) Dynamic calibration of bicycle power measuring cranks. In: Haake SJ (ed). The Engineering of sport. Oxford: Blackwell Science: 265-274.
27. Kaminski A, Jouglar J, Volle C, Natalizio S, Vuillermoz PL, Laugier A. (1999) Non-destructive characterization of defects in devices using infrared thermography. Microelectronics Journal 30: 1137-1140
28. Kenney LW. (2001) Decreased cutaneous vasodilation in aged skin: mechanisms, consequences and

interventions. The Journal of Thermal Biology 26: 263-271.
29. Kenney WL, Johnson JM. (1992) Control of skin blood flow during exercise, Medicine & Science in Sports & Exercise 24(3): 303-312.
30. Kenney WL. (1988) Control of heat-induced vasodilation in relation to age. European Journal of Applied Physiology 57: 120-125.
31. Kenney WL. (1997) Thermoregulation at rest and during exercise in healthy older adults. Exercise and Sport Sciences Reviews 25: 41-76.
32. Kenny GP, Reardon FD, Zaleski W, Reardon ML, Haman F, Ducharme MB. (2003) Muscle temperature transients before, during, and after exercise measured using an intramuscular multisensor probe. Journal of Applied Physiology 94: 2350-2357.
33. Krustrup P, Gonzàlez-Alonso J, Quistorff B, Bangsbo J. (2001) Muscle heat production and anaerobic energy turnover during repeated intense dynamic exercise in humans. The Journal of Physiology 536(3): 947-956.
34. Mathews DK, Fox EL, Tanzi D. (1969) Physiological responses during exercise and recovery in a football uniform. Journal of Applied Physics 26(5): 611-615.
35. Merla A, Iodice P, Tangherlini A, De Michele G, Di Romualdo S, Saggini R, Romani GL. (2005) Monitoring skin temperature in trained and untrained subjects throughout thermal video. Conf. Proc. IEEE Eng. Med. Biol. Soc. 2: 1684-1686.
36. Merla A, Mattei P A, Di Donato L and Romani GL. (2010) Thermal imaging of cutaneous temperature modifications in runners during graded exercise. Annals of Biomedical Engineering38: 158–63
37. Merla A, Romano V, Zulli F., Saggini R, Di Donato L, Romani GL. (2002) Total body infrared imaging and postural disorders. In: Proceedings of the Second Joint EMBS/BMES Conference.
38. Minson, CT, Wladkowski, SL, Cardell, AF, Pawelczyk, JA, Kenney, WL. (1998) Age alters the cardiovascular response to direct passive heating. Journal of Applied Physiology 84: 1323-1332.
39. Okasaki K, Kamijo Y, Takeno Y, Okumoto T, Masuki S, Nose H. (2002) Effects of exercise training on thermoregulatory responses and blood volume in older men. Journal of Applied Physiology 93: 1630-1637.
40. Paulev PE & Zubieta G. (2000) [Thermoregulation, temperature and disorders, chapter 21] New Human Physiology. In: Copenhagen Medical Publishers.
41. Pellaton C., Kubli, S., Feihl, F. and Waeber B. Blunted vasodilatory responses in the cutaneous microcirculation of cigarette smokers. American Heart Journal 144(2): 269-274.
42. Racinais S, Blonc S, Hue O. (2005) Effects of active warm up and diurnal increase in temperature on muscular power. Medicine & Science in Sports & Exercise 37(12): 2134-2139.
43. Stephenson LA, Kolka MA. (1995) Increased skin blood flow and enhanced sensible heat loss in humans after nicotinic acid ingestion. Journal of Thermal Biology 20(5): 409–23.
44. Thomas CM, Pierzga JM, Kenney WL. (1999) Aerobic training and cutaneous vasodilation in young and older men. Journal of Applied Physiology 86: 1676-1686.
45. Torii M, Yamasaki M, Sasaki T, Nakayama H. (1992) Fall in skin temperature of exercising man. British journal of sports medicine 26(1): 29-32.
46. Vainer, BG. (2005) FPA-based infrared thermography as applied to the study of cutaneous perspiration and stimulated vascular response in humans. Phys Med Biol 50(23): R63-94.
47. Zontak A, Sideman S, Verbitsky O, Beyar R. (1998) Dynamic Thermography: Analysis of Hand Temperature During Exercise. Annals of Biomedical Engineering 26(6): 988-993.