Thermography for skin temperature evaluation during dynamic exercise, a case study on an incremental maximal test in elite male cyclists

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Received 15 July 2016; revised 21 September 2016; accepted 21 September 2016; posted 23 September 2016 (Doc. ID 270699); published 0 MONTH 0000

The use of thermal imaging in monitoring the dynamic of skin temperature during prolonged physical exercise is central to assessing the athletes' ability to dissipate heat from the skin surface to the environment. In this study, seven elite cyclists completed an incremental maximal cycling test to evaluate their skin temperature response under controlled-environment conditions. Thermal images have been analyzed using a method based on maxima detection (T_{max}). Data confirmed a reduction in skin temperature due to vasoconstriction during the exercise, followed by a temperature increment after exhaustion. A characteristic hot-spotted thermal pattern was found over the skin surface in all subjects. This research confirmed also the notable ability by highly trained cyclists to modify skin temperature during an incremental muscular effort. This study gives additional contributions in the understanding the capability of the T_{max} method applied to thermoregulation and physiological processes.

OCIS codes: (100.0100) Image processing; (170.0170) Medical optics and biotechnology; (040.6808) Thermal (uncooled) IR detectors, arrays and imaging.

http://dx.doi.org/10.1364/AO.99.099999

1. INTRODUCTION

Since the development of the first image detectors for infrared thermal radiation, thermography has been considered a unique method of nondestructive diagnostics on the human body [1]. Infrared thermography (IRT) has also been widely used in biomedical studies to evaluate both skin temperature without contact and human thermoregulation mechanisms [2].

Largely, the direction of heat transfer is from the underlying tissues toward the skin. Any variations in blood flow determine patterns of thermal contrast detectable on the bare human skin. The dimensions of these patterns give rise to a corresponding variation in the rate at which energy is dissipated through long-wave IR radiation (8–12 μm).

IRT is nowadays an increasingly popular method for skin temperature evaluation in athletic activities with a noncontact approach. During continued physical activity, muscular exercise causes an excessive metabolic production of heat that the body has to remove to avoid an excessive increase of the internal temperature. Through an activation of vasoconstriction and vasodilatation mechanisms, blood flow is drained from core districts to the skin, which plays an important role in thermoregulation [3]. Here, the heat is dissipated by means of several mechanisms: irradiation, sweating (and evaporation), convection, and respiration [4,5]. Some of them are in conflict because cooling down of skin by evaporation causes a decrease of irradiation toward the environment [6]. On the other side, a colder area on the skin contributes to cooling down blood in superficial capillary vessels by convection even if the rate of heat dissipation strongly depends on the thermal conductivity of skin itself. Fat skin is supposed to reduce the effectiveness of this mechanism [7]. Models of thermoregulation were definitely proposed by Stolwijk [5] and Tanabe [6], even if on manikins or using contact probes for the temperature measurements.

Hence, in the sport science the study of the ability to dissipate heat, related to the skin temperature, is crucial to sustain muscular efforts until the end of the exercise [4].

The aim of this study was to obtain a single temperature value representative for each subject while also evaluating temperature distributions on thighs during a maximal incremental exercise in elite cyclists under controlled-environment

Table 1. Subjects' Anthropometric and Physiological Characteristics

Subj.	Age (y)	Height (m)	Body Mass (kg)	Body Fat (%)	VO^2_{max} (ml kg^{-1} min^{-1})
1	21	1.78	74.0	7.70	69.90
2	23	1.81	71.0	4.60	66.70
3	19	1.81	79.0	7.80	65.30
4	20	1.73	66.0	9.00	75.50
5	22	1.80	74.0	11.20	64.50
6	18	1.71	62.5	9.20	64.70
7	19	1.79	64.5	11.00	61.60
Mean value ± SD	20.3 ± 1.8	70.14 ± 6.00	1.77 ± 0.03	8.64 ± 2.25	66.89 ± 4.55

conditions. Considering previous works [8,9], two experimental considerations were made: first, in order to be as close as possible to the real agonistic performance, we studied the effects of an increasing and controlled work for a selected group of highly professional athletes in their actual training condition. Second, a specific experimental setting was designed for the thermal image acquisition.

Our goal was not to obtain a subject's global temperature, taking into account the reference points suggested by literature [5,6], because we consider these measurements as perturbative of the athlete's performance and affected by inevitable experimental errors. Our aim was actually to compare different methods of thermal imaging analysis in addition of what was studied in previous works on agonistic versus untrained females in a calf rise exercise and on trained males in a squat exercise [10,11]. To perform this comparison, we evaluated results obtained from analysis of thermal images recorded on a well-defined anatomic region using different methods (T_{roi} and T_{max}) described in Section 2. We hypothesized that the T_{max} method based on threshold criterion should be equivalent to the T_{roi} in describing dynamics of skin temperature during physical exercise but more accurate and less operator dependent [10].

2. MATERIALS AND METHODS

Seven male elite cyclists participated voluntarily in the study. All subjects were selected for similar anthropometric characteristics as shown in Table 1. They were also instructed to avoid high-intensity or strenuous physical activity 24 h prior to testing. Subjects were deeply informed of the procedures before their participation, and a written informed consent was signed by them.

All measurements were performed in the laboratory of MAPEI Sport Research Center with a controlled environmental temperature and humidity (22–23°C and 50 ± 5% RH), natural and fluorescent lighting, and no direct ventilation.

Each subject was asked to perform the following protocol exercise (Fig. 1): before the incremental cycling test, subjects rested for 10 min in order to acclimatize the body skin with the temperature of the room. During thermal image acquisitions, subjects were asked to stay upright with leg extended toward the floor in a sitting position on the cycle ergometer (Fig. 2). Spectral emissivity was set to 0.98 as generally used for human skin [2].

After 10 min of warm up performed with a constant load of 100 W, subjects completed an incremental maximal cycling test assessing maximal oxygen uptake and maximal power output. Each participant started at a workload of 100 W with an increase of 25 W every minute until exhaustion. Pedaling cadence was kept constant throughout the test in a range between 80 and 90 rpm. Time to exhaustion point corresponded with the cyclist's incapacity to maintain a cadence of 80 rpm for almost 5 s. Maximal power output coincided with the workload at the same time.

The thermal camera (AVIO TVS700 micro bolometer uncooled detector) was placed on a tripod in front of the subjects perpendicularly to the tights (Fig. 2) in order to reduce perspective distortions. Two images were recorded interspersed by 10 s at each specific time point: *basal* (at rest or pre-warm-up), *warm up end* (pre-exercise), and after the incremental

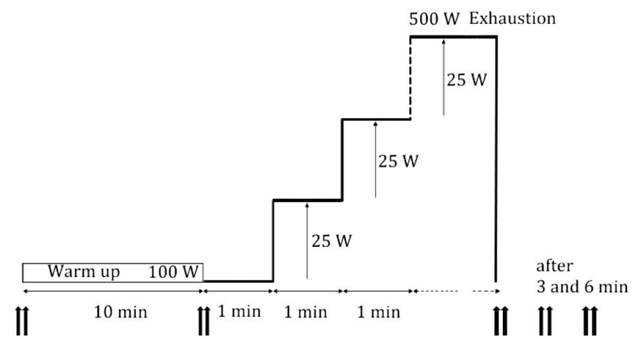

Fig. 1. Protocol of the training followed by the athlete in laboratory. After the warm-up, each step was of 25 W per minute until exhaustion. Arrows in bold represents the time of thermal shoots.

Fig. 2. Experimental setting during the thermal image acquisition. The subject was asked to stay upright with legs extended toward the floor in a sitting position on the cycle ergometer.

training, *exhaustion*, and 3 min and 6 min after the exhaustion. The bold arrows in Fig. 1 represent thermal image shots.

The thermal images were analyzed using the T_{max} method, which was recently proposed for high load exercise [11]. The method consists in giving to each region of interest (ROI) a temperature value as the average of the five highest temperatures detected within the ROI. The average is done over an area of 5 × 5 pixels around the hottest one as shown in Fig. 3. In this way the results are representative of the same number of pixels on each thigh, resulting into a more representative sampling of the warmest areas of the thighs (see [10,11] for more details).

For all the subjects, after calculating the T_{max} values of the left and the right thigh, we averaged them to obtain one representative temperature value per each subject. All values are representative of the most important cutaneous areas for heat dissipation.

Data normal distribution was verified by a Shapiro–Wilk test, and all data (mean ± SD) met the assumption of normality. A one-way analysis of variance for repeated measures was used to compare skin temperature dynamics among the time points. Partial eta squared (Part η_2) was used to estimate the magnitude of the difference within each group, and the thresholds for small, moderate, and large effects were defined as 0.01, 0.06, and 0.14, respectively.

Overall analysis was performed using IBM SPSS Statistics (v. 21, New York, United States), and an alpha threshold of $p < 0.05$ was set to identify statistical significance.

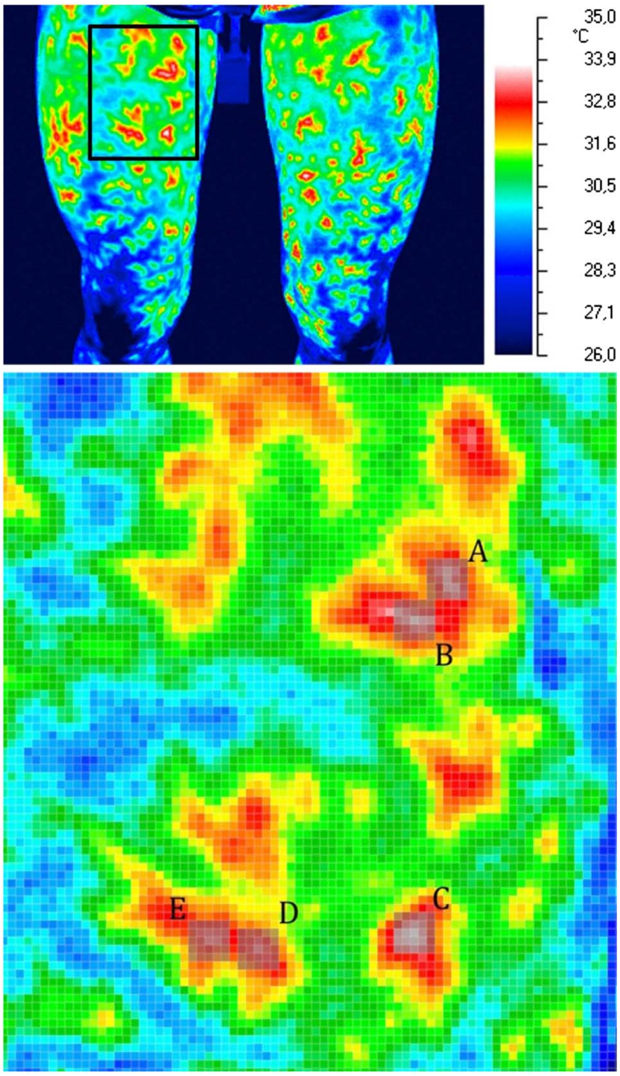

Fig. 3. Thermal image after exhaustion and magnification of the rectangular area (ROI). Inside the ROI magnification, the gray squares of 5 × 5 pixels are centered on one of the five hottest pixels found automatically by the thermal analysis software.

3. RESULTS AND DISCUSSION

The sequence of thermal images of one subject is shown in Fig. 4, starting from rest condition before warm up, and up to 6 min after the exhaustion. It illustrates the changes of temperature distribution on thighs during and after the protocol training.

The graphic in Fig. 5 shows the temperatures differences calculated with respect to the ones recorded during 10 min of the basal condition (rest) of the seven subjects; they are plotted for the five representative time points before and after the training.

We want to stress that the T_{max} method in this specific case allows us to obtain values of temperature representative of the blood in the cutaneous vessels. It is directly influenced by the heat produced in the muscles of the thigh. The temperature evolution of the muscular districts involved in this work is then monitored by these hot spots.

After the end of the exercise we observed a characteristic hot-spotted pattern in all subjects (Fig. 3, upper panel). This pattern has been already reported in thermographic analyses on dogs and horses over a treadmill [12] and in squat exercise for humans [11]. The similarity could be explained by the type of effort (e.g., incremental maximal effort) but not by the type of exercise (e.g., running or cycling). In fact, similar texture in thermal images has been found for different exercises such as running tasks [9,13,14]. This characteristic thermal pattern has a strong influence on the skin temperature measurements of a specific body area. In these cases, usually a non-Gaussian thermal distribution inside a selected ROI is present, and it is clear that the method based on averaging pixel temperatures over the whole ROI (T_{roi}) cannot be applied for a reliable analysis of these subjects [10,11].

On the other hand, the T_{max} method does not evaluate the average of the all thermal profiles but only considers the temperature of the maxima. This implies that the non-Gaussian distribution of pixel values is not so critical. Moreover, this method is applied on the same number of pixels per image.

This ensures the same statistical weight per each ROI considered on the skin surface. The average time course of skin temperature is shown in Fig. 6. During incremental exercise, skin temperature decreased substantially from 32.50 ± 0.67°C to 30.87 ± 0.73°C ($P = 0.002$; Part $\eta_2 = 0.937$) between baseline and exhaustion time points.

In the recovery time, after 3 min, skin temperature increased significantly ($P < 0.01$) from the exhaustion time point, returning similar to basal values and remaining constant after 6 min from the end of the exercise.

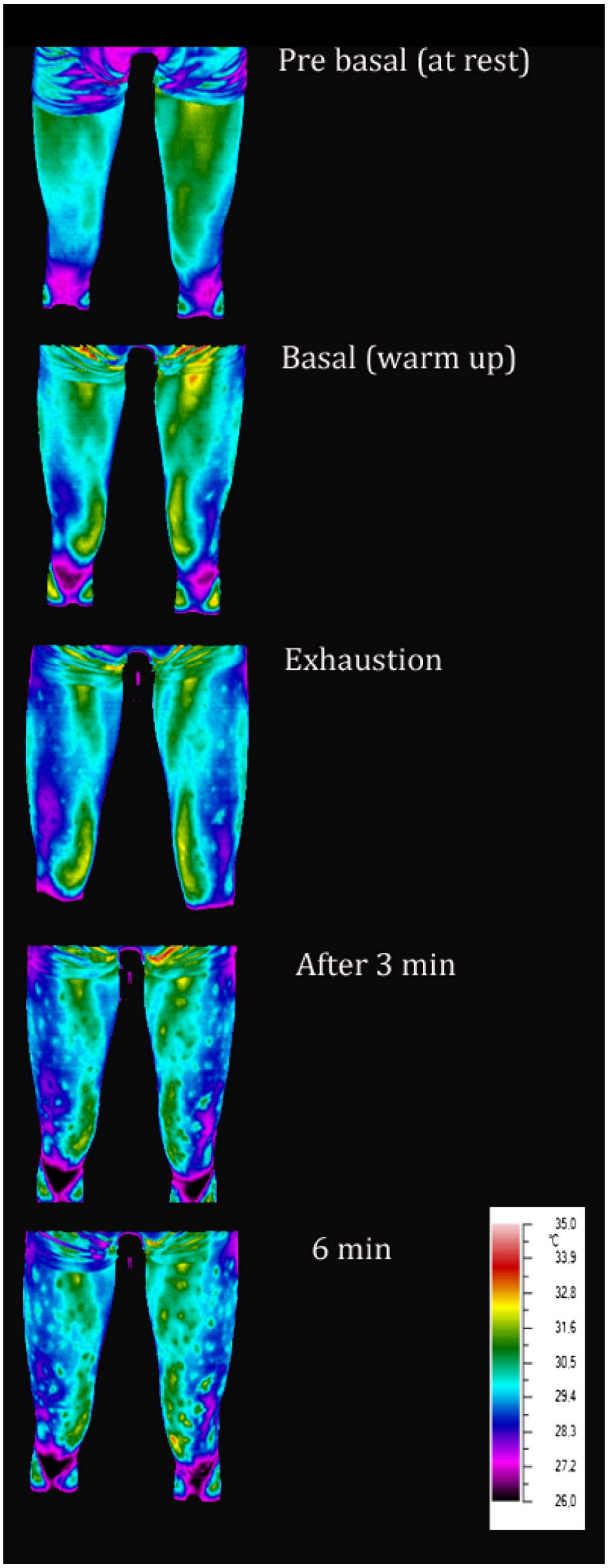

Fig. 4. Thermal images of a representative subject shot at different conditions before and after the incremental training. (spectral emissivity for skin at 8–12 μm set at 0.98).

This clear up and down behavior of skin temperature was also observed by other authors [9,14]. However, to date, this is the first study that has investigated the skin temperature

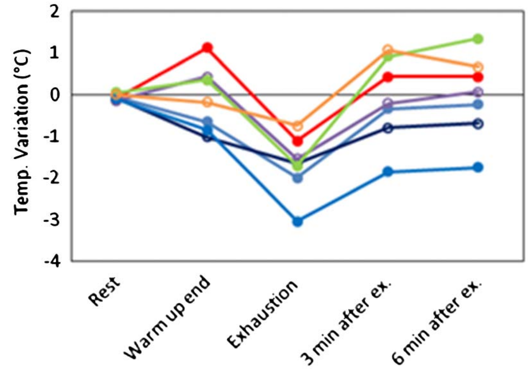

Fig. 5. Temperature variation with respect to average basal temperature in seven subject at the five most representative times before and after the training. Errors range in the order of +0.2°C.

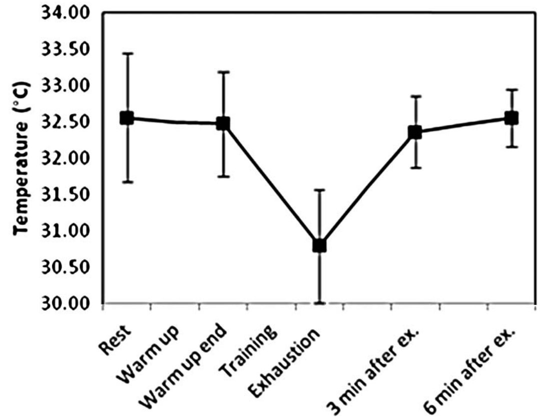

Fig. 6. Skin temperature (average) dynamics among different time points. $P < 0.05$, exhaustion versus basal; $P < 0.01$ exhaustion versus after 3 min and after 6 min.

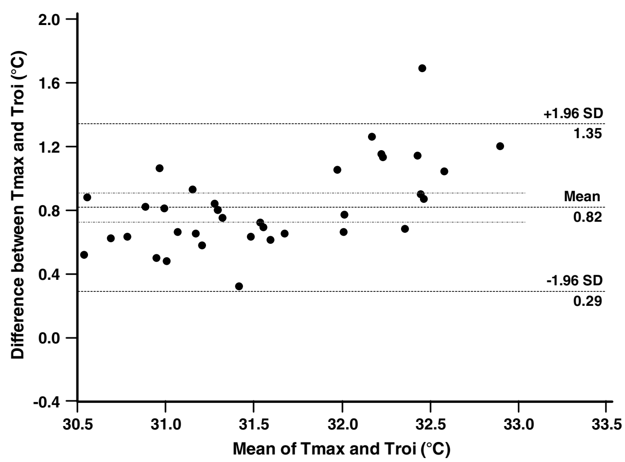

Fig. 7. Bland and Altman analysis for temperature values measured with the T_{max} method and T_{roi} method on small areas inside the thermal images of thighs. This distribution demonstrated, as expected, a quite constant bias [0.8°C] and relatively low standard deviations. Only a little increase in skin temperature difference for higher values of mean temperature can be observed.

dynamics using the T_{max} method during an incremental exercise. With regard to the literature, our findings showed a greater efficiency of vasoconstriction and vasodilation processes in removing heat from the core to the skin layers of highly trained subjects.

In order to compare data obtained with the T_{max} method with a reference method in widespread use in the analysis of thermal images, we used a Bland and Altman analysis on a set of data obtained by basal and exhaustion thermography. Temperature values were measured with the T_{max} method and T_{roi} method on small areas (about 1000 pixels) of both left and right thighs. The distribution (see Fig. 7) demonstrated, as expected, a quite constant bias [0.8°C], and relatively low standard deviations. However, for higher values of mean skin temperature we observed a little increase in the difference of skin temperature measured with the two methods.

4. CONCLUSION

In this work, thermal images have been analyzed using a method based on maxima detection (T_{max}). The results contribute to better characterize this method in skin temperature detection as particularly useful when a non-Gaussian distribution of temperature is found such as in high load physical exercise. The method based on automatic detection of highest values of temperature is useful when nonhomogenous distribution of temperature is found.

In our trial, the skin temperature dynamic of muscle quadriceps showed an explicit decrease during an incremental maximal exercise and a subsequent rapid recovery immediately after exhaustion. This behavior reflects a remarkable ability to dissipate metabolic heat through the cutaneous surface by highly trained cyclists. This can be explained by the effect of vasoconstriction/vasodilatation mechanisms.

This research confirmed the ability by highly trained cyclists to modify skin temperature during an incremental muscular effort.

Furthermore, an interesting finding of this work was the characteristic hot-spotted thermal pattern over the skin surface in all subjects.

Finally, this study suggests additional contributions in the understanding the applicability of the T_{max} method in the study of thermoregulation and physiological processes. In particular, it could be promising in the study of physical activities or pathologies characterized by discontinuous thermal patterns over the skin surface.

Acknowledgment. According to the declaration of Helsinki, the study was approved by the Ethical Committee of the Università degli Studi di Milano. Subjects were deeply informed of the procedures before their participation, and a written informed consent was signed by them. Human Performance Laboratory, MAPEI Sport Research Centre, Olgiate Olona (VA), Italy, Dott. Davide Bugini of CNST—IIT at Polimi di Milano, Italy.

REFERENCES

1. R. Barnes, “Diagnostic thermography,” Appl. Opt. **7**, 1673–1685 (1968).
2. E. F. J. Ring and K. Ammer, “Infrared thermal imaging in medicine,” Physiol. Meas. **33**, R33–R46 (2012).
3. Z. J. Schlader, B. G. Perry, M. R. C. Jusoh, L. D. Hodges, S. R. Stannard, and T. Mündel, “Human temperature regulation when given the opportunity to behave,” Eur. J. Appl. Physiol. **113**, 1291–1301 (2013).
4. M. Torii, M. Yamasaki, T. Sasaki, and H. Nakayama, “Fall in skin temperature of exercising man,” Br. J. Sports Med. **26**, 29–32 (1992).
5. J. A. J. Stolwijk, “A mathematical model of physiological temperature regulation in man,” NASA, CR-1855 (1971).
6. S. I. Tanabe, K. Kobayashi, J. Nakano, Y. Ozeki, and M. Konishi, “Evaluation of thermal comfort using combined multi-node thermoregulation (65MN) and radiation models and computational fluid dynamics (CFD),” Energy Build. **34**, 637–646.
7. K. McLellan, J. S. Petrofsky, G. Bains, G. Zimmerman, M. Prowse, and S. Lee, “The effects of skin moisture and subcutaneous fat thickness on the ability of the skin to dissipate heat in young and old subjects, with and without diabetes, at three environmental room temperatures,” Med. Eng. Phys. **31**, 165–172 (2009).
8. J. I. Priego Quesada, F. P. Carpes, R. R. Bini, R. Salvador Palmer, P. Pérez-Soriano, and R. M. Cibrián Ortiz de Anda, “Relationship between skin temperature and muscle activation during incremental cycle exercise,” J. Therm. Biol. **48**, 28–35 (2015).
9. A. Merla, P. A. Mattei, L. Di Donato, and G. L. Romani, “Thermal imaging of cutaneous temperature modifications in runners during graded exercise,” Ann. Biomed. Eng. **38**, 158–163 (2014).
10. N. Ludwig, D. Formenti, M. Gargano, and G. Alberti, “Skin temperature evaluation by infrared thermography: comparison of image analysis methods,” Infrared Phys Technol. **62**, 1–6 (2014).
11. D. Formenti, N. Ludwig, A. Trecroci, M. Gargano, G. Michielon, A. Caumo, and G. Alberti, “Dynamics of thermographic skin temperature response during squat exercise at two different speeds,” J. Therm. Biol. **59**, 58–63 (2016).
12. V. Redaelli, N. Ludwig, L. N. Costa, L. Crosta, J. Riva, and F. Luzi, “Potential application of thermography (IRT) in animal production and for animal welfare: a case report of working dogs,” Annali dell’Istituto superiore di sanità **50**, 147–152.
13. W. Bertucci, A. Arfaoui, L. Janson, and G. Polidori, “Relationship between the gross efficiency and muscular skin temperature of lower limb in cycling: a preliminary study,” Comput. Methods Biomech. Biomed. Eng. **16**, 114–115 (2013).
14. A. Arfaoui, W. Bertucci, T. Letellier, and G. Polidori, “Thermoregulation during incremental exercise in masters cycling,” J. Sci. Cycling **3**, 33–41, 2014.

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