

The use of infrared thermography to detect the skin temperature response to physical activity

This content has been downloaded from IOPscience. Please scroll down to see the full text.

2015 J. Phys.: Conf. Ser. 655 012062

(<http://iopscience.iop.org/1742-6596/655/1/012062>)

View [the table of contents for this issue](#), or go to the [journal homepage](#) for more

Download details:

IP Address: 130.251.67.77

This content was downloaded on 23/11/2015 at 07:00

Please note that [terms and conditions apply](#).

The use of infrared thermography to detect the skin temperature response to physical activity

G Tanda¹

DIME, Università degli Studi di Genova, Genova, Italy

E-mail: giovanni.tanda@unige.it

Abstract. Physical activity has a noticeable effect on skin blood flow and temperature. The thermal regulatory and hemodynamic processes during physical activity are controlled by two conflicting mechanisms: the skin vasoconstriction induced by the blood flow demand to active muscles and the skin vasodilation required by thermoregulation to increase warm blood flow and heat conduction to the skin. The time-evolution of skin temperature during exercise can give useful information about the adaptation of the subject as a function of specific type, intensity and duration of exercise. In this paper, infrared thermography is used to investigate the thermal response of skin temperature during running exercise on treadmill for a group of seven healthy and trained runners. Two different treadmill exercises are considered: a graded load exercise and a constant load exercise; for both exercises the duration was 30 minutes. Within the limits due to the relatively small size of the sample group, results typically indicate a fall in skin temperature during the initial stage of running exercise. As the exercise progresses, the dynamics of the skin temperature response depends on the type of exercise (graded versus constant load) and probably on the level of training of the subject.

1. Introduction

Human body temperature comprises the temperatures of the core and skin. The core temperature refers to the temperatures of the abdominal, thoracic and cranial cavities, the skin temperature refers to the temperatures of the skin and subcutaneous tissues. Core temperature is essentially the temperature of the blood in the circulation and is regulated by the brain, whereas skin temperature is influenced more by skin blood flow and environmental conditions [1].

The thermo-regulatory system of the human body is aimed at maintaining a constant core temperature against a wide range of environmental and/or physical work conditions. This constant temperature (about 37°C during rest) is the result of a balance between the metabolic heat production and the heat dissipation to the environment. During intense exercise, metabolic heat production can increase by 10- to 20 fold with respect to heat production at rest. Even if core temperature elevation up to 40°C may be tolerated during long-distance running races or training workouts, most of the extra metabolic heat has to be carried away from the body by conduction, convection, radiation and evaporation [2]. These heat transfer processes are mainly controlled by the skin temperature; indeed, the higher the temperature difference between the skin and the external environment, the higher the heat transfer rate dissipated to the environment. At the same time, intense physical activity activates

¹ To whom any correspondence should be addressed



compensatory vasoregulation through a reduction of blood flow in the skin compartment (skin vasoconstriction) and an increase demand of blood flow to active muscles. Therefore, the thermal regulatory and hemodynamic processes during physical activity are controlled by two conflicting mechanisms: the skin vasoconstriction induced by the blood flow demand to active muscles and the skin vasodilation required by thermoregulation to increase warm blood flow and heat conduction to the skin [3].

Consider the circulatory system model shown in Fig.1. The scheme on the left-hand, taken from Bejan's book [4], consists of three main parts: the heart, the pulmonary circulation, and the systemic circulation; blood is forced away from the heart to flow into the systemic and pulmonary circuits and then returns to the heart. In the right-hand picture, the system circulation has been here modified in order to split the cutaneous blood flow circulation from the internal body flow circulation.

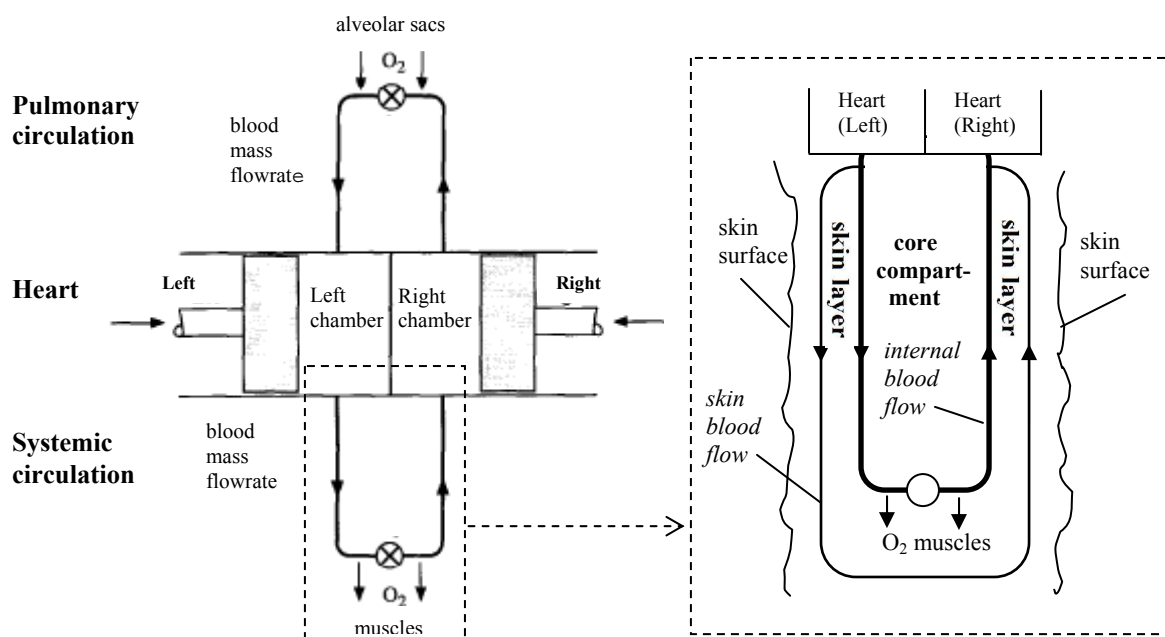


Figure 1. Simple scheme of circulatory system taken from [4] (left-hand) and implementation of the circulatory system by taking into account cutaneous blood circulation (right-hand).

The role of skin blood flow, vital to the human thermoregulatory control [5], can be inferred in combination with the energy balance of body during exercise shown in Figure 2. At the beginning of exercise, the increased oxygen supply to muscles implies a larger demand of blood flow to active muscles and thus a reduction of cutaneous blood flow (skin vasoconstriction). If the environmental air temperature and mean radiant temperature are lower than body temperature, skin vasoconstriction induces a reduction of the skin temperature due to the exposition to a cooler environment. At the same time, heat starts to accumulate into the body due the intense metabolic heat production, leading to an increase in core temperature. Beyond a “set-point temperature”, the hypothalamic thermoregulatory centers generate a “thermal command signal” to activate the heat loss response consisting in cutaneous vasodilation and sweating. Cutaneous vasodilation increases blood flow to the skin several-fold: the warmer blood redirected from the body core to the surface (blood perfusion) substantially increases the convective heat transfer from the core to the periphery; as a result the skin temperature tends to increase. Well trained and/or elite runners able to tolerate high core temperature or produce a reduced

amount of metabolic heat by the oxidation process (as compared with less trained and/or recreational runners) delay skin vasodilation without compromising the blood (and oxygen) supply to active muscles. In these conditions, they may sustain a great effort for the whole duration of the exercise. Conversely, runners whose increasing metabolic production, at a certain point, induces a cutaneous vasodilation will face a reduction in performance during the exercise due to decreased blood (and oxygen) supply to muscles.

It is apparent from above considerations that for exercising subjects the knowledge of skin temperature during an intense activity like long-distance running is of great importance to understand the sustainability of the required muscular work as well as to infer a possible association of the thermoregulatory response with the athletic performance. Modern thermal imaging devices like infrared thermography are particularly suitable to precisely map the cutaneous temperature distribution and its evolution during exercise. Infrared thermography has been widely used to visualize skin temperature in biomedical sciences (see, for instance, refs. [6,7]); however, a limited number of investigations [8-10] are devoted to dynamic thermographic imaging during running exercise. The time-evolution of skin temperature during running activity can give useful information about the adaptation of the subject as a function of specific type, intensity and duration of exercise. Moreover, recent studies performed on cyclists [11,12] suggested the possibility to use thermal imaging as an indirect method to evaluate the level of training efficiency.

The main purpose of this study was to evaluate the cutaneous temperature response to running exercise under controlled laboratory conditions, in order to gain an insight into the involved thermal regulatory and hemodynamic processes and to provide the basis for subsequent studies aimed at investigating the possible association between the skin temperature changes and the athletic performance.

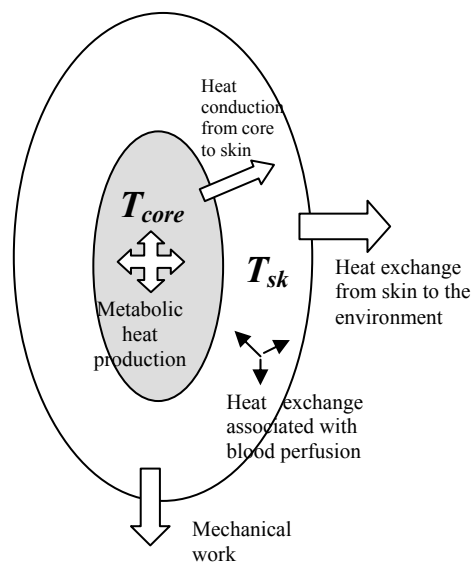


Figure 2. Energy balance during physical activity for core and skin compartments.

2. Materials and methods

The study was designed to measure the skin temperature response to different levels of physical activity, consisting of running exercise on a treadmill with graded or constant load.

2.1 Subjects

Seven healthy and active subjects (six males, one female) gave informed consent to participate in this investigation. All of them regularly trained from 3 to 5 sessions per week and were used to run in middle-distance and long-distance races. Some of them took part to Italian youth and absolute

championships in middle-distance track competitions (5000m, 3000m steeplechase), others regularly run half-marathons and marathons with PB (Personal Best) under 1hour, 25minutes and 3hours, respectively. Their age, weight, and height ranged from 18 to 57 years (mean: 33 years), from 50 to 71 kg (mean: 62 kg), and from 1.69 to 1.9 m (mean: 1.75 m), respectively. The body mass index was in the 17.2-24.3 kg/m² range (mean: 20.2 kg/m²).

2.2 Procedures

Treadmill running exercise was performed in an internal room with controlled air temperature and humidity conditions (temperature = 22°C±0.3°C, relative humidity 60%±2%, no direct ventilation). During tests, the athletes wore a light running kit or exercised bare-chested. Each experiment was conducted at the same time of day (late morning) to avoid variation due to circadian rhythm of body temperature.

Two different treadmill protocols were used: a graded load exercise and a constant load exercise. During the graded load exercise, from an initial value of 6 km/h the treadmill velocity was incremented by 1.5 km/h every 5 minutes up to the maximum value of 13.5 km/h. Throughout each step the speed was kept constant and thermal images of anterior and posterior body were typically taken after 4-4.5 minutes from the initiation of the respective speed step. The constant load exercise consisted of 25 min-running at the constant speed of 12 km/h, preceded by a warm-up period (5 min at 6 km/h) with thermal images (front and back of the body) typically taken every 5 minutes. The duration of both running sessions was 30 minutes. The standardized exercise programs are summarized in the scheme reported in Table 1.

For both protocols, the treadmill was set at zero inclination and no airflow was present during the exercise; heart rate was continuously monitored by means of a standard ECG device. Before each exercise, the participants stood motionless for a 10 minute acclimatisation period. At the end of each 30-minute exercise period, subjects stood motionless for a further 5-10 minute rest period.

All seven subjects performed the graded load treadmill test. Four of them performed the constant load test at a few days distance from the previous test. For each subject, the highest heart rate recorded during each exercise was reached at the end of the test. It ranged from 72% to 91% of respective age-predicted maximal heart rate for the graded load exercise and from 71% to 90% for the constant load exercise.

Table 1. Graded and constant load exercise scheme.

duration (min)	graded load	constant load
	velocity (km/h)	velocity (km/h)
acclimatisation (10 min)	0	0
0-5	6	6
5-10	7.5	12
10-15	9	12
15-20	10.5	12
20-25	12	12
25-30	13.5	12
recovery (10 min)	0	0

2.3 Estimation of total-body skin temperature

Thermal images of subjects during running exercise were taken by using a digital infrared camera (FLIR T335, Flir Systems Inc, USA, 320 x 240 pixels, Thermal sensitivity/NETD < 0.05°C). All the thermographic measurements were performed on the nude skin. Infrared emissivity of skin was set at

0.98 [7]; it is worth noting that the sweat, when present on the skin, does not significantly affect the surface emissivity as reported in [8].

The accuracy of infrared temperature measurements was assessed by a calibration test carried out by gradually heating an aluminium plate (110 mm × 150 mm × 8 mm) equipped with a plane heater on the back face and coated with a high-emissivity black paint on the frontal face. The calibration plate was surrounded, on lateral and bottom sides, by thermally insulating material (extruded polystyrene) to promote uniform temperature conditions. Ten fine-gauge, pre-calibrated, thermocouples, housed in small holes drilled in the material at different positions as close to the surface as possible, were used to measure the plate temperature and to verify the temperature uniformity. During the test, the plate was heated in order to reach a desired plate temperature, measured by the thermocouples, and the power was adjusted to maintain the equilibrium. At the steady state, the infrared image of the plate was captured and thermocouple readings were recorded. The maximum difference in temperature values given by thermocouples was 0.1°C, thus proving the high degree of temperature uniformity in the plate. This procedure was repeated for plate temperatures from 25 to 42°C. For an emissivity setting of 0.95 on the infrared camera, a typical agreement within 0.2°C was found between the temperatures detected by infrared camera and thermocouples.

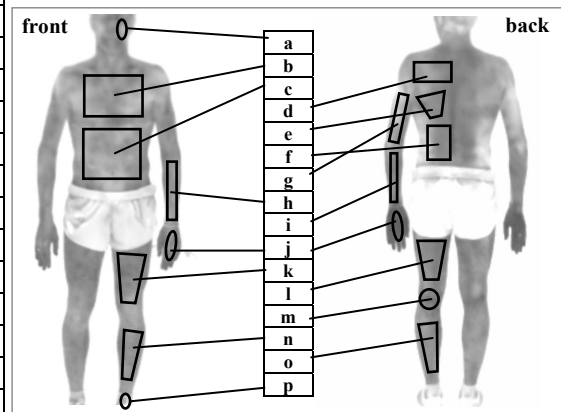
The major limitation of the total body, infrared thermal imaging is that each acquisition is a two-dimensional representation of a three-dimensional structure. Ideally, acquisitions would provide a three-dimensional representation of the surface temperature of the entire three-dimensional structure by using a multiple camera system and suitable post-processing techniques. This procedure largely increases cost and time to perform the investigation. In this study, the total body skin temperature was calculated by averaging the thermographic measurements over points encompassing a significant surface area of each region of interest (e.g., anterior thigh, abdomen, posterior calf, etc.). In order to minimize the errors associated with the calculation procedure of the total-body skin temperature, different literature relationships, proposed for the mean skin temperature evaluation, were considered. They are typically structured in the following form

$$T_{sk} = \left(\sum_{i=1}^n f_i T_{sk,i} \right) / f_0 \quad (1)$$

where T_{sk} is the calculated total-body mean skin temperature, $T_{sk,i}$ are local (or regionally averaged) skin temperatures, f_i are the corresponding weighting factors (with $f_0=1$, unless differently specified) and n is the number of skin temperature measurement sites. A survey of literature relationships is given in [13] where total-body skin temperature calculations were based on a number of skin locations n ranging from 3 to 15. Table 2 reports the weighting factors f_i (for each region of the body surface) and the value of f_0 to be used in Eq.(1) for four different formulas, based on $n=3, 8, 12$ and 15 . Each formula is named according to the notation introduced in [13]: the number of local skin temperature sites (8, 10, 12 or 15) is followed by a letter (W or U) indicating a weighted or unweighted (same weighting factor for all the skin sites) formula. The apices denote formulas (12W' and 15U') modified here to exclude the contribution of foot skin temperature, whose value can not be extracted from infrared thermographic images of runners. Some measurement sites were changed in [13] from those adopted in the original studies since accurate thermographic measurements revealed, for the new sites, a better agreement with the true mean skin temperature, measured for ten nude subjects as the arithmetic mean of local temperatures (from 10841 pixels) provided by infrared images of the total body surface. The individual sites subjected to local (or regionally averaged, as shown in the picture close to the table) temperature measurements were: cheek **a**, chest **b**, abdomen **c**, scapula **d**, subscapula **e**, lumbar **f**, posterior upper arm **g**, anterior forearm **h**, posterior forearm **i**, hand **j**, anterior thigh **k**, posteromedial thigh **l**, posterolower thigh **m**, anterior calf **n**, posterior calf **o**, foot **p**. Choi et al [13] found that formulas based on a number of at least eight locations ($n \geq 8$) were in close agreement (within $\pm 0.2^\circ\text{C}$) with the true mean skin temperature for 80 to 90% of the performed measurements on their subjects, staying at rest under ambient temperature conditions ranging from 4 to 40°C.

Table 2. Body surface regions (a→p), corresponding weighting factors f_i and value of f_0 used in the literature relationships: 3W ($n=3$), 8W ($n=8$), 12W ($n=12$), 15U ($n=15$). The apices denote formulas 12W' ($n=11$) and 15U' ($n=14$) modified here to exclude the contribution of the foot skin temperature. The measurement sites have been modified from the original ones according to Choi et al [13].

	3 W	8 W	12 W	15 U	12 W'	15 U'
a		0.07	0.07	0.0666	0.07	0.0666
b			0.0875	0.0666	0.0875	0.0666
c	0.5	0.175	0.0875	0.0666	0.0875	0.0666
d				0.0666		0.0666
e		0.175	0.0875	0.0666	0.0875	0.0666
f			0.0875	0.0666	0.0875	0.0666
g		0.07		0.0666		0.0666
h		0.07		0.0666		0.0666
i	0.14		0.14		0.14	
j		0.05	0.05	0.0666	0.05	0.0666
k		0.19	0.095	0.0666	0.095	0.0666
l			0.095	0.0666	0.095	0.0666
m				0.0666		0.0666
n			0.065	0.0666	0.065	0.0666
o	0.36	0.2	0.065	0.0666	0.065	0.0666
p			0.07	0.0666	/	/
f_0	1	1	1	1	0.93	0.9333



Despite their results were obtained for resting nude subjects, literature relationships implemented by Choi et al [13] were used in the present study to process the thermographic measurements performed on running subjects, due to the lack of specific formulas devoted to the mean skin temperature evaluation during exercise. Figure 3 shows the mean skin temperature, evaluated from the combination of regionally averaged thermographic measurements, for an athlete during a treadmill running exercise at constant load. Mean skin temperatures have been evaluated during the warm-up (0-5 minutes) following the acclimatisation period, the running period at constant velocity $V=12\text{km/h}$ (5-30 minutes), and the resting period (30-35 minutes). Inspection of figure shows that temperature distributions obtained by literature relationships have a common trend, except for results given by the relationship based on only three measurement points. Similar results were found by processing the individual measurements performed for a large cohort of athletes. Based on the suggestions reported in [13], the formula involving the largest number of measurement sites (15U', $n=14$) was deemed as the most accurate and thus was adopted to process the present thermographic measurements.

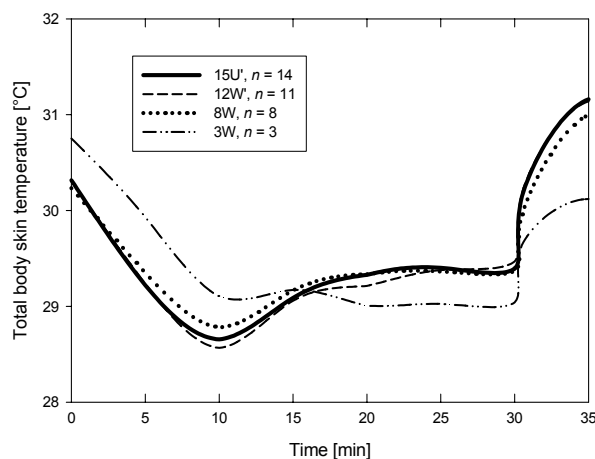


Figure 3. Mean skin temperature, evaluated as a combination of regionally averaged thermographic measurements by using different literature formulas, for a subject during a constant load treadmill exercise.

3. Results and discussion

Examples of thermographic images, with color-coded temperature maps, are presented in Figures 4 and 5. Each group of thermographic images has the same thermal scale in order to facilitate the comparison. Images, taken for three different subjects under conditions of graded load, show the typical skin temperature modifications on the front of the body during different phases of exercise.

Figure 4 shows the changes in temperature for the female athlete involved in this study: from the baseline distribution on left-hand side, the skin temperature decreases as the exercise progresses. Temperature reduction is not uniform over the body; it seems to be less pronounced over calves, neck and cutaneous projections of liver and spleen. A rapid increase in skin temperature is observed during motionless recovery from exercise (right-hand side); hyperthermal spots, probably associated with cutaneous vasodilation occurring at rest, are clearly visible. Similar features of skin temperature modifications for two male athletes during the grade load exercise are documented in Fig.5.

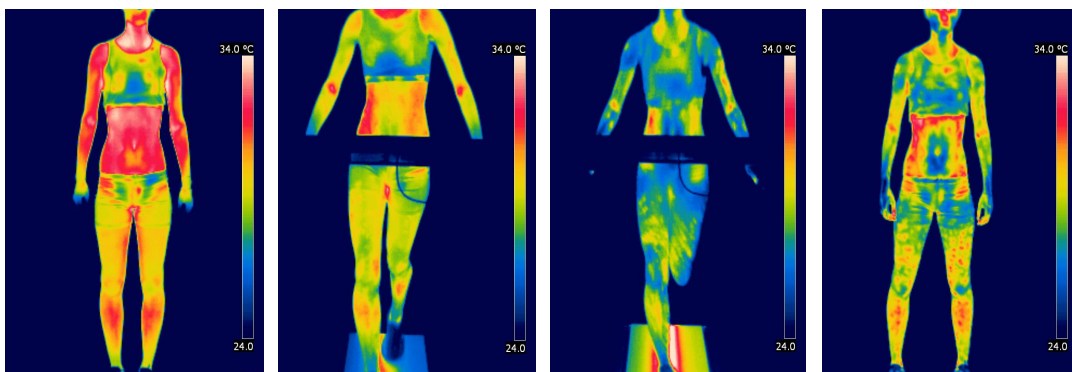


Figure 4. Infrared thermal images of the anterior body for an athlete during graded load exercise. From left to right: before exercise, after 15 min exercise period, after 29 min exercise period, immediately after the end of the exercise. The same thermal scale is adopted.

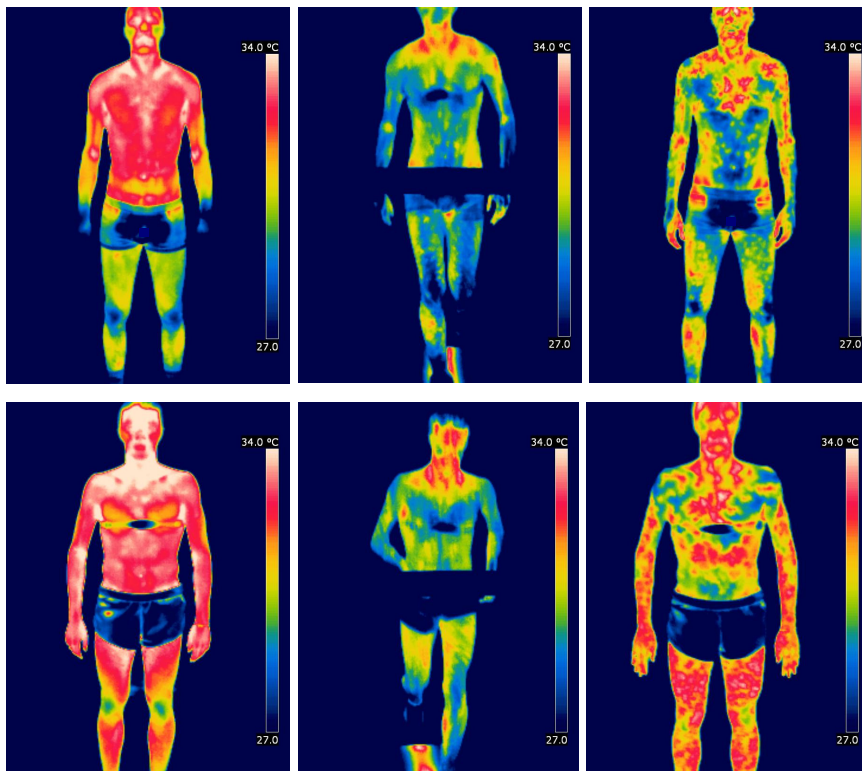


Figure 5. Infrared thermal images of the anterior body for two athletes during graded load exercise. From left to right: before exercise, after 15 min exercise period, immediately after the end of the exercise. The same thermal scale is adopted.

Total-body skin temperature distributions during graded and constant load exercise, averaged among all the subjects (7 for the graded load exercise, 4 for the constant load exercise), are shown in Figure 6. The skin temperature distribution for the graded load exercise, averaged only among the same four subjects participating in the constant load exercise, has been reported too. The same figure reports the velocity profiles set for the two treadmill protocols.

During the graded load exercise, where the load on the body is progressively increasing (and the blood demand to the working organs is increasing too), the mean skin temperature of the subjects decreases throughout the exercise. Time-distributions of skin temperature for the majority of the participants were similar in shape to that averaged among the subjects; thus individual data are not reported for the sake of brevity. The reduction of skin temperature occurs immediately on starting to run, even during the first steps at moderately low velocities, without the appearance of sweat on the skin and thus it is not related to thermal factors such as evaporation due to skin sweat. This finding is consistent with results found in [10] under similar experimental conditions: a continuous vasoconstrictor response, leading to a progressive reduction of blood flow in the tegumentary apparatus as the exercise intensity is increased, was deemed to justify the decrease in the mean skin temperature. The mean skin temperature distribution for a reduced group of subjects (4 out of 7, those participating in both treadmill protocols) has a similar trend but a different slope in the initial and final steps of exercise, while for both sample groups a nearly flat distribution in the central phase of exercise is noticed. These observations suggest the influence of individual characteristics (genetic and/or anthropometric and/or training factors) on the time-evolution of skin temperature during exercise. At the end of exercise, during recovery, mean skin temperatures increase toward pre-exercise values.

In the case of constant load exercise, the skin temperature, averaged among four subjects, still decreases at the beginning of the work due to the initial skin vasoconstriction and then attains a minimum value, followed by a little and gradual increase over time. It is argued that the initial decline and the subsequent slight rise in skin temperature is the net result of the competition between the vasoconstrictor response, which lasts as long as the exercise is continued, and the vasodilator response, induced by the increasing body temperature. All subjects exhibited the same time-distribution, but the start and the extent of the temperature rise during the last phase of exercise seem to be related to the individual grade of vasoregulation. No literature data are available, to the author's knowledge, for the dynamic response of skin temperature to a constant load running exercise; however, a behaviour similar to that here reported, i.e., an initial descending trend (reflecting vasoconstriction) followed by an ascending trend (reflecting vasodilation) of regional skin temperatures, was found in [14] (hands) and [15] (hands, thighs and legs) during a steady-load exercise on a bicycle ergometer.

Further information can be inferred from Figs.7-8, showing the regional skin temperature response to running exercise. Figure 7 reports, for the female athlete, the skin temperature distributions over total body, upper limbs (upper arms and forearms) and calves, for the graded load exercise. Inspection of the figure reveals that the skin temperature decrease is more pronounced over the most peripheral regions (e.g., upper limbs) less involved in running. Conversely, the skin over exercising muscle mass (e.g., calves) exhibits only a moderate reduction in temperature and tends to be warmer than skin over other structures as the exercise progresses; this result is probably related to the increasing delivery of blood flow to the working muscles for metabolic needs and to the heat conduction from the muscles to the skin surface.

Comparisons of total body and regionally averaged skin temperature distributions, for two athletes (one female and one male) under constant load exercise are reported in Figure 8. Solid lines represent the total body skin temperature distributions, whereas the dashed lines indicate the skin temperature over upper limbs (top) and calves (bottom). Different colours refer to different athletes. It can be inferred from Fig.8 that skin temperature over upper arms and forearms shows a time-evolution similar to that for total body but at a lower level, as outlined in the comment to Fig.7. Temperature of skin over active muscles (calves) decreases in a similar manner for both athletes; for one subject the

skin over calves is warmer than total body almost throughout the exercise, for the other subject the temperature of skin over calves starts from a lower value than total body and becomes higher in the second part of exercise. During the last part of the constant load exercise, skin temperature over calves decreases up to a value close to that registered for total body, probably due to skin vasodilation and the consequent reduction of warm blood flow to active muscles.

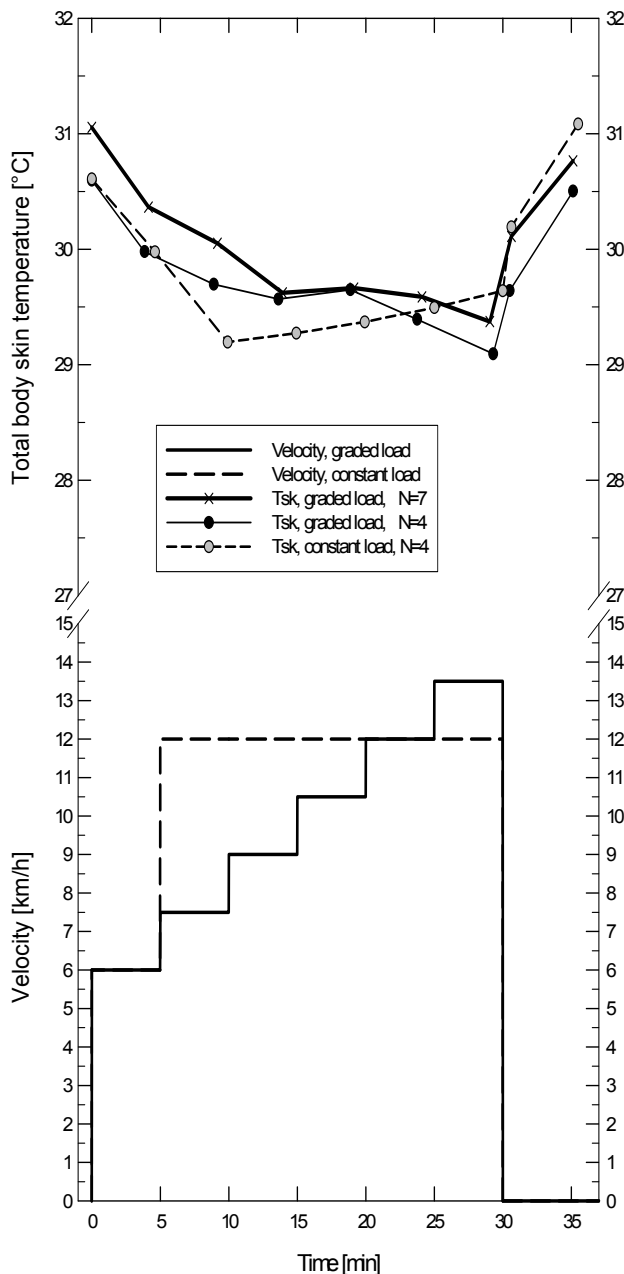


Figure 6. Total body skin temperature distributions averaged among the N subjects during graded and constant load exercise. Treadmill velocities versus time are reported too.

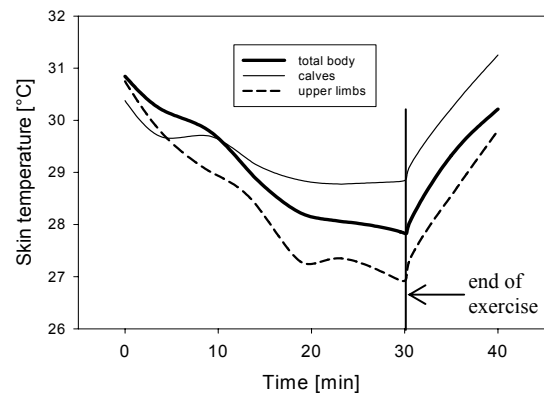


Figure 7. Distributions of the total-body skin temperature and the regionally averaged (over upper limbs and calves) skin temperature for an athlete during graded and constant load exercise

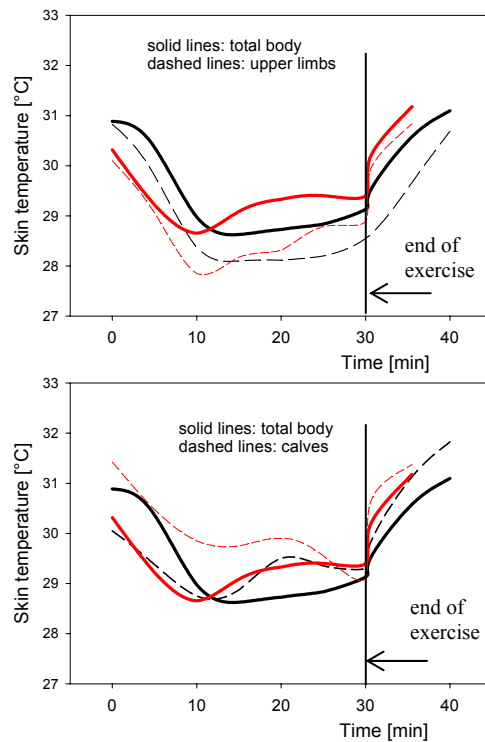


Figure 8. Distributions of the skin temperature over the total-body, over upper limbs (top) and over calves (bottom) for two athletes during constant load exercise. Different colours refer to different athletes.

4. Conclusions

Human thermoregulation during running exercise is ruled by a dynamic energy balance, involving environmental and physical work conditions, where the skin temperature represents the main variable controlling the heat exchanges at the body/environment interface. Infrared thermal imaging is currently the only method for real-time, non-invasive monitoring of cutaneous temperature.

In this work infrared thermography was used to visualize skin temperature of athletes during indoor treadmill running. For all the investigated subjects a fall in skin temperature during the initial stage of running exercise was recorded, regardless of the type of work (with graded or constant load). This skin temperature decrease is probably associated with the cutaneous vasoconstrictor response to exercise. A continuous increase in load intensity was found to produce further reductions in skin temperature; conversely, a relative minimum of skin temperature, followed by a little rise, was attained during a constant load running exercise, probably reflecting the competition between the vasoconstriction induced by exercise and vasodilation induced by thermoregulation. Hyperthermal spots were observed during the recovery following the running exercise, probably due to peripheral vasodilation enabling a progressive transfer of warmer blood from the body core to the surface.

This preliminary study, performed on a limited number of subjects, provided the basis upon which a subsequent massive investigation of skin temperature response to running exercise, according to specifically designed protocols and controlled laboratory conditions, could attempt to infer an indirect estimation of the physical efficiency and/or the training level of athletes.

References

- [1] Lim CL, Byrne C and Lee JKW 2008 Human thermoregulation and measurement of body temperature in exercise and clinical settings *Ann. Acad. Med. Singapore* **37** 347-353
- [2] Kenefick RW, Cheuvront SN and Sawka MN 2007 Thermoregulatory function during the marathon *Sports Med.* **37** 312-315
- [3] Johnson JM 1992 Exercise and the cutaneous circulation *Exercise Sport Sci. Rev.* **20** 59-97
- [4] Bejan A 2000 *Shape and Structure, from Engineering to Nature* (Cambridge Press)
- [5] Charkoudian N 2003 Skin blood flow in adult human thermoregulation: how it works, when it does not, and why *Mayo Clin. Proc.* **78** 603-612
- [6] Lahiri BB, Bagavathiappan S, Jayakumar T and Philip J 2012 Medical applications of infrared thermography: A review *Infrared Phys. Technol.* **55** 221–235
- [7] Fernández-Cuevas I, Bouzas Marins JC, Arnáiz Lastras J, Gómez Carmona PM, Piñonosa Cano S, García-Concepción MA and Sillero-Quintana M 2015 Classification of factors influencing the use of infrared thermography in humans: A review *Infrared Phys. Technol.* **71** 28-55
- [8] Clark RP, Mullan BJ and Pugh LGCE 1977 Skin temperature during running - A study using infra-red colour thermography *J. Physiol.* **267** 53-62
- [9] Roberts BC, Waller TM and Caine MP 2007 Thermoregulatory response to base-layer garments during treadmill exercise *Int. J. Sports Sci. Eng.* **1** 29-38
- [10] Merla A, Mattei PA, Di Donato L and Romani GL 2010 Thermal imaging of cutaneous temperature modifications in runners during graded exercise *Annals Biomed. Eng.* **38** 158–163
- [11] Akimov EB and Son'kin VD 2011 Skin temperature and lactate threshold during muscle work in athletes *Hum. Physiol.* **37** 621-628
- [12] Cholewka A, Kasprzyk T, Stanek A, Sieroń-Stołtny K and Drzazga Z 2015 May thermal imaging be useful in cyclist endurance tests? *J. Therm. Anal. Calorim.* (in press) DOI 10.1007/s10973-015-4662-5
- [13] Choi JK, Miki K, Sagawa S and Shiraki K 1997 Evaluation of mean skin temperature formulas by infrared thermography *Int. J. Biometeorol.* **41** 68–75
- [14] Zontak A, Sideman S, Verbitsky O and Beyar R 1998 Dynamic thermography: analysis of hand temperature during exercise *Annals Biomed. Eng.* **26** 988–993
- [15] Nakayama T, Ohnuki Y, and Niwa K 1977 Fall in skin temperature during exercise, *Jap. J. Physiol.* **27** 423-437