

Total body skin temperature of runners during treadmill exercise

A pilot study

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Abstract The aim of this study was to investigate the time evolution of total body skin temperature during running exercise on treadmill. A group of physically active subjects performed two different treadmill exercises, at graded load and at constant load, for a duration of 30 min, in a moderate indoor environment. Thermal maps of the anterior and posterior body regions were gathered, before, during and after the exercise, by means of infrared thermography. Skin temperature of total body was calculated as a combination of individual measurements taken over several body regions. Within the limits due to the relatively small size of the sample group, results typically show a fall in total body skin temperature during the early stages of treadmill exercise. As the exercise progresses, the dynamics of the skin temperature response is affected by the type of exercise, showing a further decrease during the graded load exercise and a slight increase during the constant load exercise. Regionally averaged skin temperatures were found to be lower than total body skin temperature over the most peripheral body regions less involved in running (upper limbs) and comparable with or higher than total body skin temperature over calves and thighs.

Keywords Skin temperature · Infrared thermography · Thermal imaging · Treadmill exercise

Introduction

In resting man, core temperature is maintained at a constant level (about 37 °C), regardless of external conditions, as a result of the balance between the metabolic heat production and the heat dissipation to the environment. During intense physical activity, metabolic rate can increase more than tenfold and this rate of heat production may be sustained for several hours [1, 2]. The increased rate of heat production associated with muscular work causes core temperature to rise. Even though core temperatures up to 40 °C may be reached during or after a long-distance running exercise [3], in order to maintain body temperature below tolerable limits (with a reduced capability of further body heat storage), heat dissipation must increase sufficiently to balance the increased rate of metabolic heat production.

The description of the dynamic energy balance of human body during exercise is facilitated by reference to a simple model of the human body, simulated by two concentric compartments representing the core and the skin of the body. The core and skin compartments exchange heat through direct contact and through the peripheral blood flow. At the onset of exercise, the larger demand of blood flow to oxygenate active muscles leads to a reduction of cutaneous blood flow (skin vasoconstriction). In the presence of a positive skin-to-environment temperature difference, skin vasoconstriction induces a skin temperature reduction 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 with a consequent increase in core temperature. At elevated internal temperatures, the central control organ for body thermoregulation (the hypothalamus) activates defense mechanisms consisting of heat dissipation, from the body to the environment, through skin vasodilation and sweating. During cutaneous

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vasodilation, blood flow to the skin increases by several fold; the warmer blood redirected from the body core to the surface (blood perfusion) substantially increases the heat transfer from the core to the periphery, leading to an increase in the skin temperature and a decrease in core temperature [4].

Well-trained and/or elite runners, able to tolerate high core temperature or to produce a reduced amount of metabolic heat by the oxidation process (as compared with less trained and/or recreational runners at the same running speed), may delay skin vasodilation without compromising the blood (and oxygen) supply to active muscles and sustain a great effort for the whole duration of the exercise. Conversely, runners whose increasing metabolic production induces, at a certain point of running exercise, a skin vasodilation may be forced to reduce their running speed due to the decreased supply of blood and oxygen to muscles.

Due to the aforementioned important implications, the knowledge of skin temperature during an intense activity like long-distance running can give useful information on the ability to sustain the required muscular work. Infrared thermography (IRT) is a noninvasive technique particularly suitable to precisely map the surface temperature of the body and its changes during exercise. The use of IRT to measure skin temperature in biomedical sciences is documented in the review papers by Ring and Ammer [5], Lahiri et al. [6] and Fernández-Cuevas et al. [7], but only few investigations (see, for instance, Clark et al. [8], Merla et al. [9], Fernández-Cuevas et al. [10] and the very recent paper by Fernandes et al. [11]) are devoted to thermal imaging of the body surface during running exercise. Recent experiments performed on cyclists [12, 13] even suggested the possibility to use thermal imaging as an indirect method to infer the level of training efficiency.

The main objective of this preliminary investigation was to evaluate the response of skin temperature to different types of running exercise on treadmill 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.

Materials and methods

Participants and procedures

Participants, six males and one female, whose physical characteristics are reported in Table 1, were physically active and well trained. All of them regularly trained from 3 to 5 sessions per week and were used to running in middle-distance and long-distance races. Some of the youngest

Table 1 Anthropometric characteristics of the subjects

No.	Sex	Age/years	Height/m	Mass/kg	BMI/kg m ⁻²
1	F	18	1.71	50.2	17.2
2	M	41	1.695	52.4	18.2
3	M	53	1.73	63.3	21.2
4	M	57	1.70	70.2	24.3
5	M	19	1.695	61.3	21.3
6	M	19	1.905	71.1	19.6
7	M	24	1.805	64.9	19.9

subjects took part in Italian youth and absolute championships in middle-distance track competitions (5000-m, 3000-m steeplechase), while the oldest ones regularly run half-marathon and marathon races with PB (personal best) under 1 h, 25 min and 3 h, respectively. All seven subjects were informed about the procedures of the investigation and gave their consent to participate in this research.

Since skin temperature is strongly affected by environmental conditions [2], a strict control of air temperature and humidity steadiness during experiments is required to exclude any connections between skin temperature changes over time and undesirable fluctuations of environmental variables. Treadmill running exercise was performed in an internal room properly equipped with a heating/cooling air-conditioning system able to guarantee steady values of air temperature and relative humidity with maximum fluctuations during each test of 0.5 °C and 4%, respectively. Nominal values of air temperature and relative humidity, measured by a digital weather station, were 22 °C and 60%, respectively, corresponding to a moderate indoor environment. The treadmill was set at zero inclination, and no airflow was present during the exercise. It is worth noting that a 1% treadmill inclination, to compensate the lack of air resistance, more accurately reflects the energetic cost of outdoor running at the same velocity [14]. In the opinion of this author, a closer representation of outdoor running should consider the presence of direct ventilation (with adjustable air velocity) rather than a prescribed treadmill grade in order to include the effects of both air resistance (without having to incline the treadmill) and convective heat transfer conditions occurring during outdoor running. Unfortunately, the laboratory room was not sufficiently large to host a system of fans adjusted so as to provide the same air velocity as the treadmill; thus, the basic condition of no forced ventilation (and no treadmill inclination) was set. During tests, the male subjects wore only shorts and running shoes, while the female subject wore footwear and a lightweight running kit consisting of bra and shorts. Each experiment was conducted at the same time of day (late morning) to avoid variation due to circadian rhythm of body temperature.

The study was designed to measure the skin temperature of subjects performing two different types of running exercise on treadmill: a graded load exercise and a constant load exercise. The two types of exercise have been designed with standardized velocity steps common to all subjects and not adjusted on the basis of individual characteristics. This choice was believed suitable to infer any possible interaction between the exercise-associated skin temperature changes and the level of physical efficiency or training of subjects. The graded and constant load exercise protocols are summarized in Table 2. After a 10-min acclimatization period, where the participants stood motionless, the running exercise started with a first 5-min warm-up period at the reduced treadmill velocity of 6 km h⁻¹. During the graded load exercise, from the warm-up initial value, the treadmill velocity was incremented by 1.5 km h⁻¹ every 5 min up to the maximum value of 13.5 km h⁻¹. During the constant load exercise, the treadmill velocity was set at 12 km h⁻¹ immediately after the warm-up period. The total running time for both sessions was 30 min. After the completion of each exercise, subjects stood motionless for a further 5-min rest period. All seven subjects performed the treadmill exercise with graded load. Four of them (No. 1 to No. 4 in Table 1) performed the treadmill exercise with constant load at a few days distance from the previous test.

During the experiments, the heart rate of subjects was continuously monitored by means of a standard ECG device. For all participants, the highest heart rate recorded was attained at the end of the each 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. The age-predicted maximal heart rate was estimated according to the formula reported by Nes et al. [15].

Thermal images acquisition and processing

Thermal images of subjects during running exercise were taken by using a digital infrared camera (FLIR T335,

320 × 240 pixels). All the measurements used for the evaluation of total body and regionally averaged surface temperatures were taken on the nude skin. Infrared emissivity of skin was set at 0.98, indicated as the standard choice by Fernández-Cuevas et al. [7]. The accuracy of infrared temperature measurements was assessed by a calibration test described in detail by Tanda [16, 17]. A sequence of 3–4 thermal images (within few seconds) of anterior and posterior body was typically acquired every 5 min throughout each exercise without interrupting the physical activity. In particular, the image series for the graded load exercise was taken after 4–4.5 min from the initiation of each speed step. The first image of each series has been typically employed to extract and process local temperature values. The remaining images of the series were used only in case of lack of information or image defects (i.e., blurred image) on a specific body region due to the subject movement.

After the collection of thermal images from each subject, the nude skin of the entire body has been divided into eighteen regions of interest (ROIs), as schematically indicated in Fig. 1, where each *i*th area is identified as Ar_{*i*}. Areas having the same number and concerning the right and left part of the same anatomical region (such as Ar10 and Ar10′) were grouped together during the thermal analysis. The definition of ROIs is a controversial issue that can affect the interpretation of results [18]. Guidelines and recommendations are provided in the literature in order to properly select the measurement region (see, for instance, Ammer [19]) and to evaluate the temperature representative of the specific area (see, for instance, Ludwig et al. [20]). The continuous variations in body positioning during exercise make it unfeasible to use templates or standard shapes for the placement of regions of interest. In this work, the ROI associated with a specific site of body surface was selected by the operator considering a representative area of each specific body region (for instance, the anterior calf or the scapula). The anatomical contour of each region was drawn by using a dedicated software program (Flir Reporter Professional©, Flir Systems); the effect of the movement can be inferred by comparing Fig. 1, where baseline ROIs are reported at rest, with Fig. 2, reporting the frontal view of one male and the female subject during treadmill exercise (only a few body regions are outlined in the figure for the sake of clarity).

The final temperature value of each region was evaluated as the arithmetic mean of all the pixels inside the ROI considered. Special care was taken to ensure that each specific body region was subjected to the same treatment for all the subjects and to minimize the operator dependency of the calculated average temperature inside a given ROI. In order to randomly assess the repeatability of skin temperature measurement over the same surface region, the

Table 2 Graded and constant load treadmill protocols

Time interval/min	Graded load Velocity/km h ⁻¹	Constant load Velocity/km h ⁻¹
Acclimatization (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 (5 min)	0	0

Fig. 1 Regions of interest (ROIs) in which regional average skin temperatures were calculated

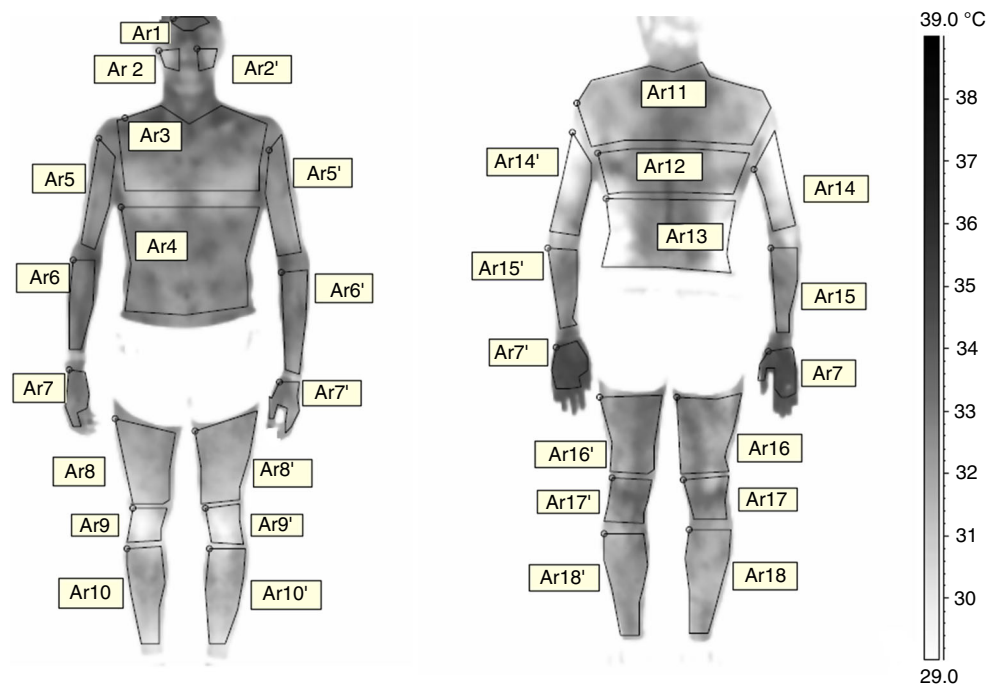
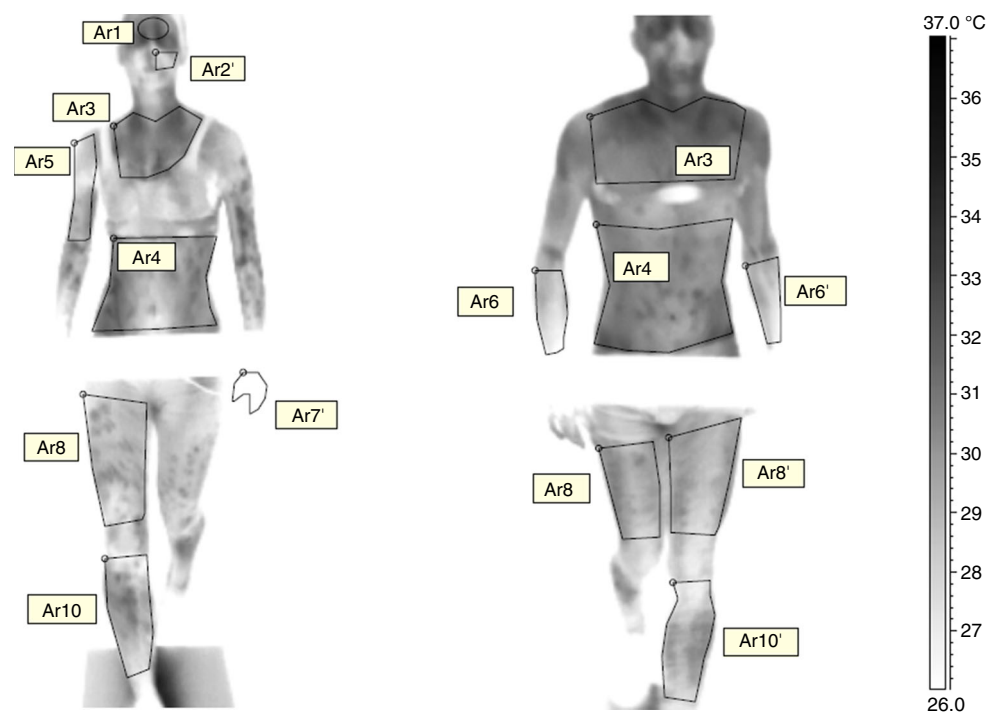


Fig. 2 Examples of ROIs from images of subjects during exercise



ROI selections of images taken for two representative subjects performing a graded load and a constant load exercise, respectively, have been repeated and processed by a second operator, and results, in terms of mean temperature of each ROI, have been compared according to the procedure suggested by Bland and Altman [21]. The statistical agreement (at 95% confidence interval) between two sets of 313 measurements over the same sites and two

different operators was 0.27 °C with slight differences related to the specific body region (0.25 °C over trunk, 0.27 °C over legs and 0.28 °C over arms); the temperature difference between the two sets of measurements dropped to only 0.17 °C when referred to the total body nude skin.

In principle, the true skin temperature of total body can be obtained by recording the skin temperature over an infinite number of measuring site. For practical reasons, the

mean skin temperature of the total body T_{sk} is typically estimated on the basis of a finite number of local (or regionally averaged) skin temperatures and the corresponding weighting factors. A survey of literature relationships, with a number of sites ranging from 3 to 15, was provided by Choi et al. [22]. Based on the investigation performed by Choi et al. for subjects at rest, a formula giving the mean, total body, skin temperature as the arithmetic mean of fourteen regionally averaged skin temperatures was believed to be the most accurate among literature relationships and was thus adopted to process IRT measurements by this author in previous works [16, 17]. With reference to Fig. 1, the fourteen ROIs subjected to regionally averaged temperature measurements were: cheek (Ar2–Ar2'), chest (Ar3), abdomen (Ar4), anterior forearm (Ar6–Ar6'), hand (Ar7–Ar7'), anterior thigh (Ar8–Ar8'), anterior calf (Ar10–Ar10'), scapula (Ar11), subscapula (Ar12), lumbar (Ar13), posterior upper arm (Ar14–Ar14'), posteromedial thigh (Ar16–Ar16'), posterolower thigh (Ar17–Ar17'), posterior calf (Ar18–Ar18'). Original formula reported by Choi et al. [22] included also the contribution of foot skin temperature, not considered here since its value can not be extracted from thermographic images of runners. For the female subject, skin measurements of chest (Ar3) and subscapula (Ar12), partially covered by garments, encompassed a reduced area as compared with that for male subjects and the same anatomical region. It follows that

$$T_{sk} = (T_{2-2'} + T_3 + T_4 + T_{6-6'} + T_{7-7'} + T_{8-8'} + T_{10-10'} + T_{11} + T_{12} + T_{13} + T_{14-14'} + T_{16-16'} + T_{17-17'} + T_{18-18'})/n \tag{1}$$

where $n = 14$ and the double subscript (for instance 2–2') stands for the mean between right and left side of the same anatomical region. Due to the impossibility to clearly distinguish the anterior and posterior sides of hands during exercise, it was decided to estimate the mean temperature of hands, $T_{7-7'}$, as the mean value over the ROIs Ar7 and Ar7' extracted from both the anterior and posterior views of the body (four ROIs).

In order to verify the reliability of Eq. (1) in providing an accurate estimation of the total body skin temperature, comparisons have been made with other relationships proposed for subjects during movement in recent literature papers by Fernandes et al. [11] and by Cholewka et al. [13] and based on eight and seven body regions, respectively. Since formula proposed in [13] includes foot skin temperature, not measured here, the weighting factors were slightly modified so as to give a sum equal to one. Figure 3 reports the distributions of total body skin temperature, for two representative subjects, No. 1 and No. 4, performing the graded load and the constant load exercise,

respectively, evaluated by using the three different formulas for T_{sk} . The symbols (closed and open circles) in the figure represent the total body skin temperature evaluated as the sum of each regional skin temperature multiplied by the respective ROI area (and normalized by the total body skin area). Even though a two-dimensional representation of a three-dimensional structure fails to precisely give the true area of each surface, this procedure was deemed to provide a total body skin temperature very close to the “true” value (and thus indicated as “true” value in the figure legend). Inspection of the figure reveals that the three simplified formulas are in good agreement with each another and with the true values. A statistical analysis showed that Eq. (1) follows more closely the true values (standard error of estimate SEE = 0.15 °C) as compared with the other two relationships (SEE = 0.17–0.26 °C).

Results

Figures 4 and 5 report representative thermographic images showing the skin temperature over the anterior and posterior parts of the body for the female subject and one of the male subjects. Infrared images were taken before, during and after the treadmill exercise with graded load. Figures show that, from the baseline distribution recorded before exercise, the skin temperature decreases as the exercise progresses. Inspection of the each sequence of images shows that the temperature reduction is not uniform over the body, being less pronounced over calves, thighs, neck, central posterior torso and cutaneous projections of liver and spleen. After the completion of exercise, skin

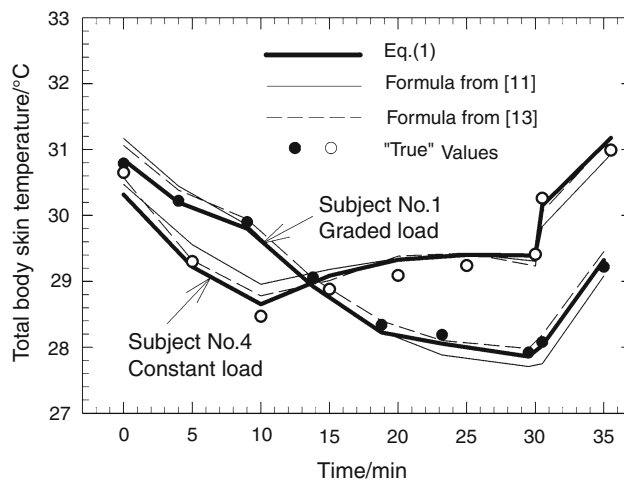


Fig. 3 Total body skin temperature distributions, evaluated as a combination of regionally averaged thermographic measurements by using Eq. (1) and different literature formulas, for two representative subjects performing two different types of exercises. Symbols identify “true” total body skin temperature values

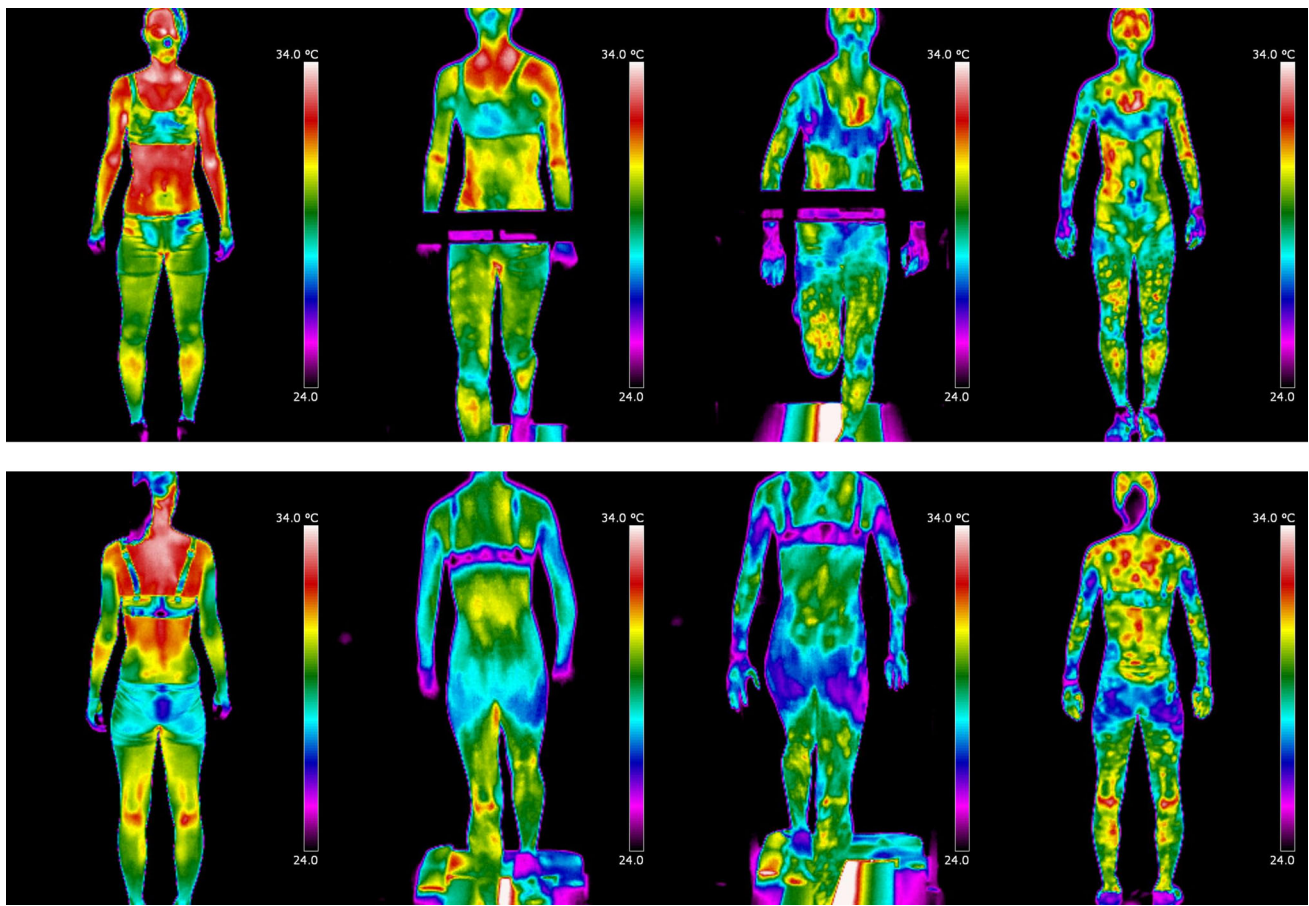


Fig. 4 Infrared thermal images of the anterior and posterior body for the female subject during graded load exercise. From *left to right*: before exercise, in the central stage of the exercise, before the end of exercise and during the motionless recovery from exercise

temperature exhibits a prompt rise during the motionless recovery with the occurrence of hyperthermal spots associated with skin vasodilation occurring at rest.

The variations over time of total body skin temperature during graded and constant load exercise, averaged among all the subjects (seven for the graded load exercise and four for the constant load exercise), are shown in Figs. 6 and 7, together with the respective time profiles of the treadmill velocity. Discrete experimental data collected at different time instants were connected by linear segments. The same figures report skin temperatures over calves, thighs and upper limbs (upper arms and forearms) averaged among the subjects participating in the graded and constant load exercise. All the plotted temperature data, together with the respective standard error of the mean (SEM), are summarized in Table 3. For each exercise, a one-way ANOVA for repeated measures (level of significance $\alpha = 0.05$) was used to analyze the total body skin temperature of subjects; pre-exercise skin temperature was found to be significantly reduced ($P < 0.05$) during the first 10 min from the exercise onset.

A direct comparison of the total body skin temperatures of each sample group performing the graded load or the constant load exercise can be inferred from Fig. 8. In this figure, the distribution of total body skin temperature for the graded load exercise for $N = 4$ was obtained by including in the average only the four subjects (out of seven) participating also in the constant load exercise. In this case, the comparison between the two temperature curves for $N = 4$ reflects the different response of the same sample group to the different exercise. Figure 8 reports also the SEM for each profile, indicated only on one side to improve the readability of the figure. During the graded load exercise, where the intensity of the physical effort is progressively increasing, the total body skin temperature tends to decrease over time, even though a nearly flat distribution in the central part of the exercise is noticed, regardless of the number of subjects (seven or four) included in the average. However, it should be observed that, for the central part of the graded load exercise, the standard error of the mean (SEM) is relatively large. In the case of constant load exercise, the total body skin

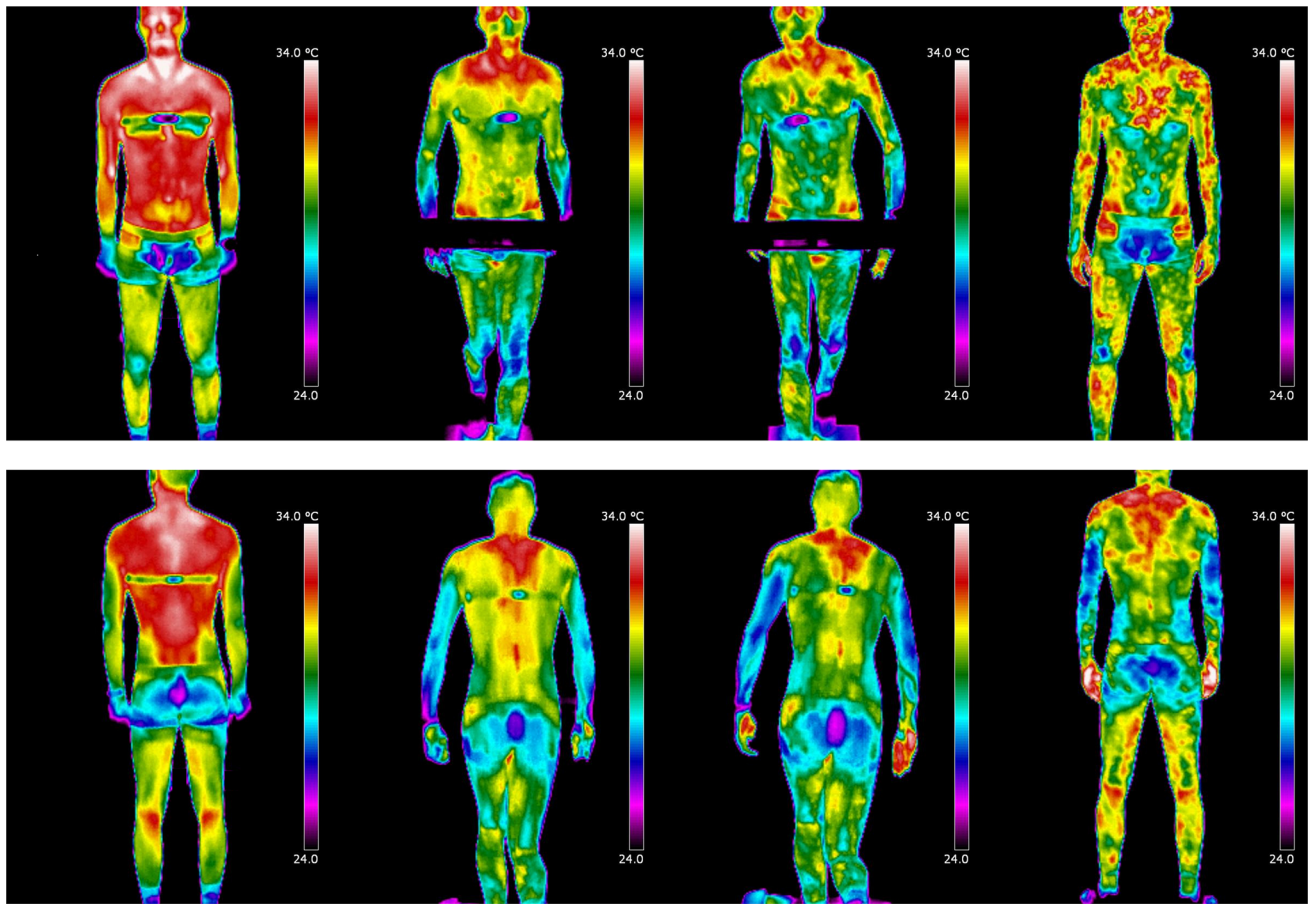


Fig. 5 Infrared thermal images of the anterior and posterior body for a representative male subject during graded load exercise. From *left to right*: before exercise, in the central stage of the exercise, before the end of exercise and during the motionless recovery from exercise

temperature, averaged among four subjects, still decreases after the onset of exercise up to the attainment of a minimum value; a slight increase in total body skin temperature over time is observed as the exercise progresses. A two-way ANOVA for repeated measures (level of significance $\alpha = 0.05$), applied to the same reduced group ($N = 4$) performing both types of exercise, was performed to test the diversity of the thermal response to the different exercises. Results provided evidence of a statistically significant difference between the two types of exercise ($P < 0.05$) about 10 min after the exercise onset (when a different treadmill velocity was set after the first 5-min warm-up period run at the same velocity) and at the end of the exercises.

Figures 6 and 7 also indicate interesting differences between total body and local skin temperature modifications. Inspection of the figures reveals that, for both types of exercise, the skin temperature decrease is more pronounced over the most peripheral regions (e.g., upper arms and forearms) less involved in running. Conversely, the skin over exercising muscle mass (e.g., calves and thighs) shows only a moderate reduction in temperature after the

onset of exercise and, in some compartments (thighs for graded load and calves for constant load), tends to be warmer than skin over the whole body as the exercise progresses.

Discussion

For all the investigated subjects, a fall in total body skin temperature during the initial stage of running exercise was recorded, regardless of the type of work (with graded or constant load). The origin of the skin temperature decrease during initial muscular work is still debated, with some studies attributing it to the cutaneous vasoconstriction [9, 23, 24] and others to sweat evaporation [12, 25]. The reduction of cutaneous blood flow due to the delivery of as much blood flow as possible to muscle for metabolic needs affects the skin temperature; at the same time, the sweat evaporation removes latent heat from the skin, locally reducing the skin temperature. The latter mechanism, controlled by the difference between the water vapor pressure at the skin and in the ambient temperature, is

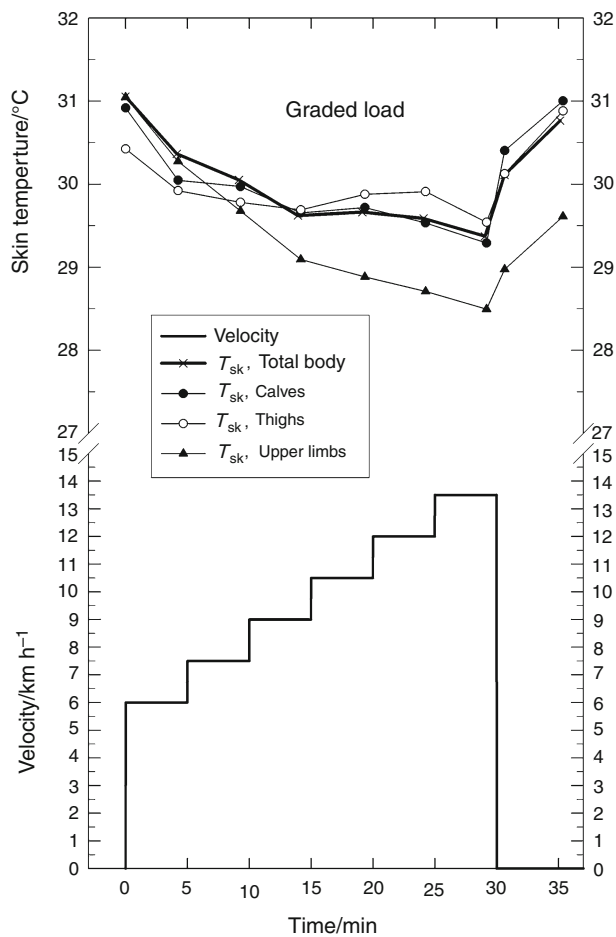


Fig. 6 Skin temperature distributions, averaged among the N subjects, over the total body, calves, thighs and upper limbs (upper arms and forearms) during the graded load exercise ($N = 7$). Treadmill velocity versus time is also plotted in the figure

largely affected by the ambient air temperature and relative humidity [26]. The role of sweat evaporation is expected to be remarkable when exercising in dry air conditions, and the sweating rate is significant. When experiments are performed under poorly controlled environmental conditions, with large variations in ambient air temperature and humidity, skin temperature response to exercise may be difficult to interpret. According to Torii et al. [24], when subjects exercised at identical work intensity and different climatic conditions, the decrease in skin temperature was almost equal although sweating rates were significantly higher at the higher ambient temperatures.

The reduction of skin temperature observed in the present study occurred immediately on starting to run, even during the first steps at moderately low velocities, without the appearance of sweat on the skin, and so it is likely to be related not to thermal factors like skin sweat evaporation but to skin vasoconstriction. The recorded progressive reduction of total body skin temperature (averaged among all the subjects) as the graded load exercise progresses

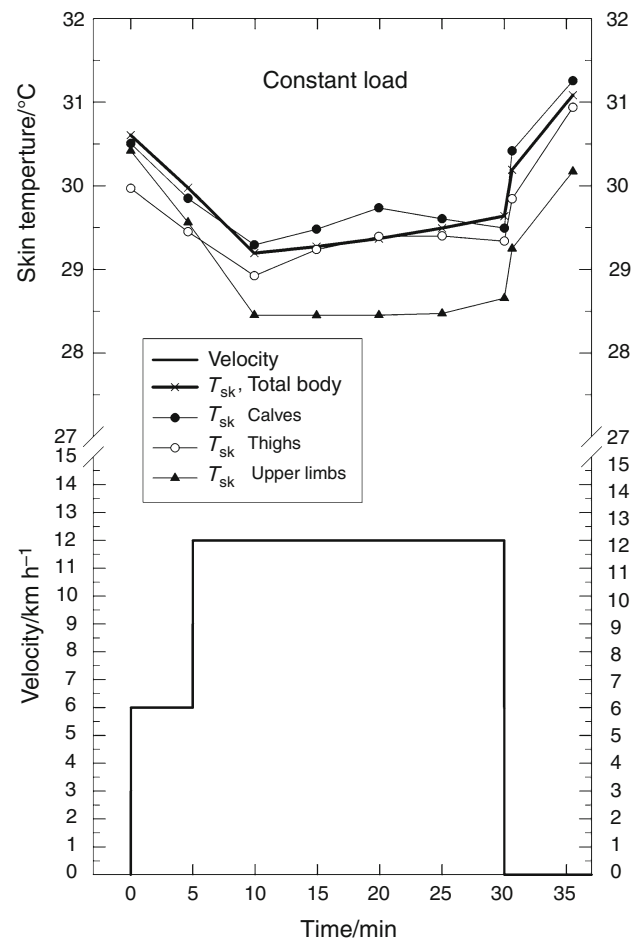


Fig. 7 Skin temperature distributions, averaged among the N subjects, over the total body, calves, thighs and upper limbs (upper arms and forearms) during the constant load exercise ($N = 4$). Treadmill velocity versus time is also plotted in the figure

(Fig. 6) is probably caused by the increasing demand for blood to the working organs and the consequent continuous stimulus to skin vasoconstriction. The same explanation was given by Merla et al. [9] to justify the continuous decrease in total body surface temperature during a graded running exercise under similar environmental conditions. Even if averaging the data among the subjects would lead to a loss of individual characteristics, it is observed that individual distributions of skin temperature (not reported for the sake of brevity) for the majority of participants were similar in shape to those averaged among the subjects.

The skin temperature decrease recorded, during graded load exercise, in the most peripheral regions not directly involved in running (upper limbs) and reported in Fig. 6 seems to support its association with the vasoconstriction effect rather than with the sweat evaporation effect, as the sweat rates from arms during running are typically lower than those from other parts of the body, such as forehead and torso [27]. The recorded skin temperatures over thighs

Table 3 Skin temperature values, averaged among the N subjects, during the graded load ($N = 7$) and the constant load ($N = 4$) exercise, with the respective values of the standard error of the mean, SEM. Values in bold refer to pre- and post-exercise phases

Time/min	Total body/°C	SEM/°C	Calves/°C	SEM/°C	Thighs/°C	SEM/°C	Upper limbs/°C	SEM/°C
Skin temperature, values averaged among N subjects performing graded load exercise ($N = 7$)								
0.0	31.06	0.23	30.92	0.14	30.43	0.30	31.05	0.27
4.1	30.36	0.21	30.05	0.13	29.92	0.22	30.27	0.19
9.2	30.05	0.19	29.97	0.08	29.78	0.19	29.68	0.25
13.9	29.62	0.22	29.65	0.15	29.69	0.20	29.09	0.22
19.1	29.66	0.30	29.72	0.25	29.88	0.31	28.88	0.31
24.1	29.59	0.26	29.53	0.21	29.91	0.29	28.71	0.28
29.1	29.37	0.30	29.29	0.24	29.54	0.38	28.50	0.33
30.6	30.11	0.35	30.40	0.30	30.12	0.47	28.97	0.39
35.1	30.76	0.28	31.00	0.18	30.88	0.36	29.61	0.37
Skin temperature, values averaged among N subjects performing constant load exercise ($N = 4$)								
0.0	30.61	0.10	30.51	0.30	29.97	0.24	30.42	0.16
4.6	29.98	0.23	29.85	0.19	29.45	0.23	29.56	0.16
9.9	29.20	0.35	29.29	0.30	28.92	0.18	28.45	0.36
14.9	29.27	0.33	29.48	0.29	29.24	0.33	28.45	0.37
19.9	29.37	0.23	29.74	0.23	29.39	0.26	28.45	0.22
25.0	29.49	0.22	29.61	0.24	29.40	0.34	28.47	0.15
30.0	29.64	0.20	29.49	0.27	29.34	0.41	28.66	0.11
30.6	30.19	0.23	30.42	0.26	29.84	0.42	29.25	0.24
35.5	31.08	0.24	31.26	0.24	30.94	0.29	30.17	0.31

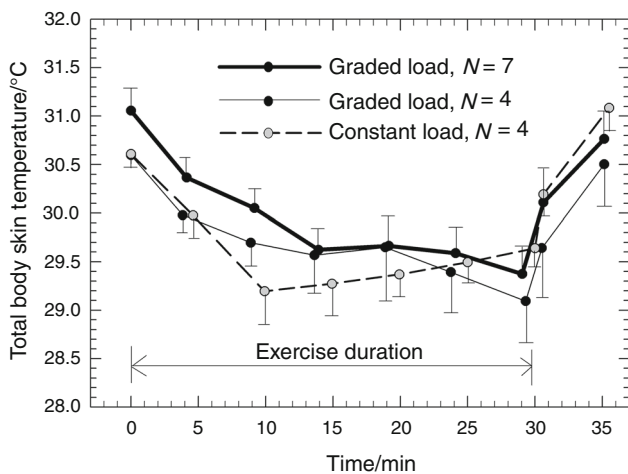


Fig. 8 Total body skin temperature distributions averaged among the N subjects during graded load exercise ($N = 4$ and 7) and constant load exercise ($N = 4$) with the standard error of the mean, SEM (SEM is reported only on one side of each curve to improve the readability of the figure)

and calves, averaged among all subjects performing the graded load exercise (Fig. 6), were slightly lower than that of the total body at the beginning of exercise, when the physical effort is light or moderate, while, at a certain point of exercise, when the load and the warm blood to muscles are increasing, the skin temperature over calves and thighs,

affected by thermal conduction from underlying muscles, becomes comparable with or higher than that of the total body.

Whereas a continuous increase in load intensity was found to produce further reductions in skin temperature, a relative minimum of skin temperature, followed by a little rise, was attained during a constant load running exercise, as documented in Fig. 7. The same circumstance was found by Tanda [17] for a group of four athletes, performing outdoor running at constant velocity, which exhibited a marked decrease of total body skin temperature during the first stage of exercise followed by a slight temperature increase during the rest of exercise. Fernandes et al. [11] investigated the skin temperature response to a moderate treadmill exercise with intermittent load (12 intervals of 5 min each at constant load with a passive interval of 1 min, with infrared images taken during the 1-min intervals) for a group of 12 active subjects. Results in terms of total body skin temperature were surprisingly very similar to those recorded in this study, i.e., a clear reduction during the first 10 min of exercise, followed by a slight rise up to the completion of exercise. Due to the mild exercise conditions considered in [11], the vasoconstrictor mechanism, activated at the beginning of exercise, ceases at a certain point because the demand for blood to active muscles is stable. At the same time, regional skin

temperature variations reported in [11] showed an increase of surface temperature over active muscles (thighs) during the exercise due to thermal conduction from muscles to the skin and this circumstance may have produced the little rise in total body skin temperature recorded after the attainment of the minimum value. A similar behavior, i.e., an initial descending trend followed by a light ascending trend of regional skin temperatures, was found by Nakayama et al. [23] (hands, thighs and legs) and by Zontak et al. [28] (hands) during a steady-load exercise on a bicycle ergometer. Authors interpreted the initial skin temperature decrease as the effect of cutaneous vasoconstriction and the subsequent increase as the effect of thermoregulatory vasodilation. The recorded variations of the total body, averaged among all subjects performing the constant load exercise and shown in Fig. 7, are affected by vasoconstriction at the beginning of exercise (increasing delivery of blood flow to the working muscles for metabolic needs); as the vasoconstrictor mechanism is reduced or suppressed (due to the steadiness of the working load), total body skin temperature reaches a quasi-steady-state condition, characterized by a little increase over time probably due to the combination of vasodilation (for thermoregulatory needs) and heat conduction from the muscles to the skin surface. The shape of the time distribution of skin temperature was the same for all the subjects participating in the present constant load exercise, 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 or body structure (affecting the core to skin thermal conductance), as documented in a parallel study [16], where comparisons between skin temperature modifications of two representative subjects are reported. It is argued that this diversity of the individual response to exercise may even reflect a different level of physical efficiency of the subjects; this circumstance however should be assessed by considering a larger cohort of athletes performing the same constant load exercise.

As recorded for the graded load exercise (Fig. 6), the skin temperature modifications over upper limbs follow, at a lower level, those of the total body skin temperature also for the constant load exercise (Fig. 7). In these nonactive regions, the action of skin vasoconstriction is visible during the first 10 min of exercise; then, a thermal steady state is reached, followed by a little rise at the end of exercise, probably indicating a redistribution of blood flow toward the skin (vasodilation). The response of skin temperature over calves and thighs to constant load exercise is similar to that previously commented for the graded load exercise. Skin temperature over the surface markings of active muscles increases, at a certain point, due to thermal conduction from underlying active muscles and decreases at

the end of exercise (when skin temperature over upper limbs increases) due to vasodilation.

The above considerations are summarized in Fig. 8, where the dynamics of the skin temperature response to the different type of exercise is clearly highlighted. The two curves obtained for the graded load exercise slightly differ due to the different population of the sample ($N = 7$ and 4), but their shape is similar, with the distribution for $N = 4$ being characterized by a larger SEM due to the lower number of athletes considered. To the author's knowledge, no further examples concerning the effect of the type of exercise on skin temperature are documented in the literature, except for the previously mentioned paper by Zontak et al. [28], where a similar response of skin temperature over hands was found during graded and constant load experiments on bicycle ergometer.

At the end of both types of exercise mean skin temperatures increase toward pre-exercise values. The infrared images taken during recovery (e.g., last images on the right-hand sides of Figs. 4 and 5, referring to the female subject and one male subject) showed the presence of hyperthermal spots (also observed by Merla et al. [9] and by Fernandes et al. [11]), probably due to peripheral vasodilation enabling a progressive transfer of warmer blood from the body core to the surface.

Concluding remarks

The response of the total body and regionally averaged skin temperature to running exercise on treadmill has been experimentally investigated for a group of active subjects using the infrared thermography. This study has demonstrated that infrared thermography is a reliable and noninvasive method able to provide surface temperature modifications of the body surface in a dynamic situation and that thermal imaging can be successfully adopted as a diagnostic tool during physical activity.

Two different types of exercise have been performed: with graded load and constant load. Tests have been conducted under strict control of indoor air temperature and humidity in a moderate indoor environment.

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). Graded load exercise led a progressive decrease in the total body skin temperature probably associated with the cutaneous vasoconstrictor response to exercise. Constant load exercise resulted in an initial decrease in the total body skin temperature, probably reflecting an initial vasoconstriction induced by exercise, followed by a little rise, in the central part of exercise,

probably associated with thermal conduction from warm muscles and vasodilation induced by thermoregulation.

This preliminary study, performed on a limited number of subjects, provides 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 evaluation of the physical efficiency and/or training level of athletes.

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