FUNCTIONAL INFRARED IMAGING APPLIED TO THE STUDY OF THE SKIN THERMOREGULATION IN TRAINED AND UNTRAINED SUBJECTS

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Abstract: This study determined whether trained (Tr) and untrained (Untr) subjects differently control skin temperature (Tsk) during exercise. Ten Tr and eight Untr men performed load graded exercise until reaching volitional exhaustion. We recorded their oxygen consumption rate and monitored their thigh average skin temperature (Tav) by high resolution thermal imaging system. Tr and Untr Tav overlapped at rest and after recovery ($P > 0.05$). Tav decreased until reaching volitional exhaustion and increased during the recovery. Achieved minimum Tav was significantly different among groups($P < 0.01$). Tr and Untr Tav slopes were similar in the initial phase of the exercise (-0.21 ± 0.06 , -0.23 ± 0.07 °C/min; $P > 0.05$). Prolonging exercise caused Tr Tav slope change (-0. 98 ± 0.42 °C/min; $P < 0.01$). No Untr exhibited slope change. Tr Tav recovered faster than for Untr (0.71 ± 0.3, 0.39 ± 0.13 °C/min; $P < 0.01$). We conclude that Tr develop a specially devoted capability of controlling Tav to sustain actual oxygen consumption rate during intensive exercise, not present in Untr.

Introduction

While performing intense exercise at a given intensity (i.e., percent maximal oxygen uptake VO_{2max}), trained (Tr) subjects have a higher metabolic rate (i.e., higher oxygen uptake VO_2) and, then, produce more heat than do untrained (Untr) ones [1]. While Tr produce more heat, they achieve a core temperature similar to that of Untr subjects [2], thus suggesting that they are also able to dissipate the produced heat thanks a higher cutaneous blood flow level maintained during the exercise [1]. Skin thermoregulation is mainly controlled through cutaneous blood flow and heat exchange processes between inner tissues and the environment [3]. Therefore, it is reasonable to assume that skin temperature (Tsk) control and dynamics while performing physical activity might vary according to training levels [4]. So far, thermal infrared imaging has been proposed for Tsk monitoring during exercise [5, 6]. In particular, Zontak [5] has compared hand Tsk during graded versus constant load exercise in active healthy subjects, showing hand Tsk linearly decreased during the graded load exercise, while it remained stationary during constant load exercise. Merla et al [6] recorded thigh Tsk during mild graded load exercise (i.e., 65% maximal heart beat rate) on 35 healthy volunteers, reporting that subjects with higher oxygen uptake - indirectly estimated - exhibited also wider Tsk changes while performing the test. In this paper, we have used high-resolution thermal imaging to describe Tsk changes in Tr and Untr subjects during graded load exercise.

Materials and Methods

Subjects. 10 professional soccer players (Tr) and 8 active men not regularly performing exercise activity (Untr) were enrolled in the study. Both groups had similar mean age, weight, height, and surface area [7] [23.5 ± 1.2 vs. 22.8 ± 1.5 yrs, 70.2 ± 3.8 vs. 72.5 ± 5.1 kg, 1.78 ± 0.05 vs. 1.76 ± 0.03 m, 1.85 ± 0.4 vs. 1.94 ± 0.3 m^2]. No subject was taking drugs or medications effecting cardiovascular or thermoregulatory functions, neither was smoker or suffering for cardiovascular or pulmonary diseases or any orthopedic limitations to the exercising test.

Protocol and experimental design. Subjects performed a graded load exercise on a computerized treadmill (Proform 330 RT, Milan, Italy), at fixed slope. Exercise started with a 3.5 km/h speed walking for two minutes. Then, speed was further increased of 2 km/h every 2 minutes, until volitional exhaustion [2]. Room conditions were controlled and kept at 23-24 °C and 50 ± 5 % relative humidity, with no direct fan. Subjects observed standard preparatory rules for the thermal imaging measurements [8]. Paper markers were put on anatomical landmarks (reference points) to allow

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thermal images post-processing and reliable selection of regions of interest for Tsk measurements. Data recording started 1 minute prior the exercise (resting data) and continued, after the volitional exhaustion, until the complete recovery of the heart beat rate to resting values.

Thermal imaging measurements. High-resolution thermal video of the subjects' legs during the exercise were obtained by means of a 14-bit digital infrared camera (AEG 256 PtSi, AEG Aim Heilbronn, Germany; 256x256 Focal Plane Array; 3-5 μm spectral range; 0.1 K Noise Equivalent Temperature Differences (NETD); 31 Hz sampling rate; optics: germanium lens, f 50, f/1.5). Thermal images were acquired every second and, then, transferred to a workstation for the off-line processing. The image series were blackbody-calibrated and removal of artefacts on Tsk from sensors' response was performed. Image series were re-aligned and movement-corrected through a 3 parameters algorithm for rigid-body plane movement. Tsk was measured on the re-aligned series for both thighs on the region of interest delineated from the anterior projection of the trochanter to the insertion of the femoral quadriceps on the knee. Average both thigh Tsk (Tav) vs. time course was then obtained.

VO_{2max} Oxygen consumption rate was measured every 4 seconds (K4, Cosmed srl, Rome, Italy). VO_{2max} was defined as the peak value of the oxygen consumption rate along the exercise. Heart beat rate was recorded every 2 seconds with a standard ECG device (PowerLab ADInstruments, Sidney, Australia).

Statistics. Data are expressed as means ± SE. Data comparison between Tr and Untr were assessed by one-way ANOVA, the statistical significance of which was fixed at 0.05. Where significant group differences occurred, appropriate post hoc pairwise comparisons were performed by using Sheffé's Test with a significance level of 0.05.

Ethics. The Ethical Committee of the School of Medicine, Chieti-Pescara University approved the study. Participants signed informed consent before participating in this study.

Results

VO_{2max} and exercise performance. VO_{2max} achieved by Tr and Untr is reported in Table 1. It also reports maximal working load (speed achieved at volitional exhaustion), and graded load phase duration.

Thigh Tsk. Table 2 reports average Tav values at rest, its variation at volitional exhaustion, and at the end of the recovery time period for Tr and Untr groups. All Tr and Untr subjects have exhibited the same Tav dynamics, qualitatively consisting of: (1) initial decreasing during the graded load phase; (2) increasing during the recovery phase after the graded exercise (Figure 1).

Table 1. VO_{2max}, maximal speed achieved, and graded load phase lasting for Tr and Untr groups.

	VO_{2max} (ml/min Kg)	**Maximal speed** (Km/hr)	**Exercise Duration** (sec)
Untr(n= 8)	32.2 ± 5.1	9.7 ± 3. 2	510 ± 45
Tr (n= 10)	62.2 ± 2.4	14.3 ± 2.0	680 ± 20
ANOVA	P < 0.01	P < 0.01	P < 0.01

Table 2. Tav at rest, its variation at volitional exhaustion, and Tav at the end of the recovery time period for Tr and Untr groups.

	Tav at rest (°C)	**Tav variation at the volitional exhaustion** (°C)	**Tav at the end of recovery** (°C)
Untr(n= 8)	28.0 ± 1.2	-1.2 ± 0.6	27.6 ± 1.4
Tr (n= 10)	28.7 ± 0.7	-2.3 ± 0.6	28.2 ± 1.2
ANOVA	P > 0.05	P < 0.01	P > 0.05

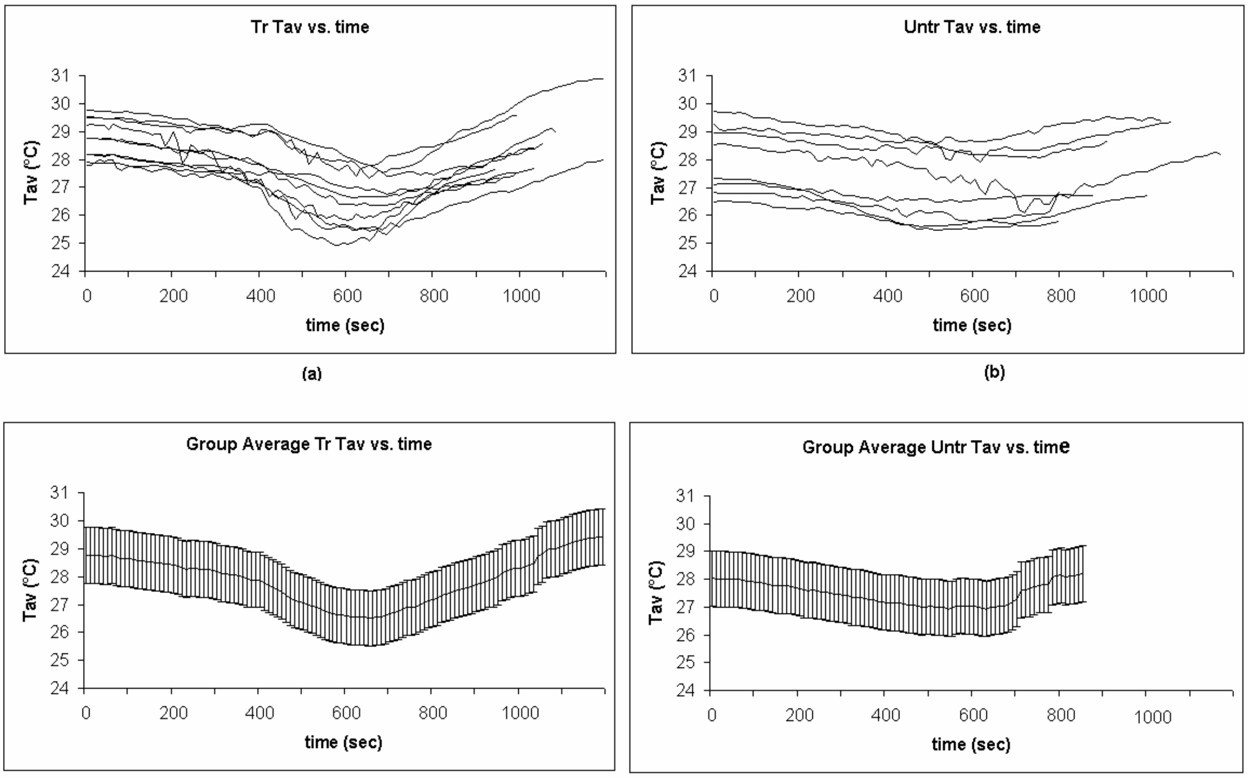
Individual and group Tav vs. time curves are plotted in Figure 1.

Both groups showed an exponential decay of Tav with the advancement of the graded exercise. Such a temperature decreasing lasted until reaching the volitional exhaustion.

On contrast with Untr Tav, Tr Tav exhibited a marked slope change across the graded load phase of the exercise. Once the volitional exhaustion was reached, Tav has exponentially recovered to baseline values. Given the features exhibited by Tav, its time course has been fitted as following:

1. Untr Tav vs. time curve with two single exponential curves, one for the graded load and one for the recovery phases, respectively;
2. Tr Tav vs. time curve during the graded load phase with two single exponential functions, respectively before and after the slope change time instant. Tav recovery curve was fitted with a single exponential function.

Best fit has been chosen according to standard Levenberg-Marquardt algorithm, thus obtaining Tav amplitude change (A) and the time constant (τ) as modeling parameters. Since A/τ ratio is related to the Tav variation rate along each exponential phase, we have decided to use A/τ ratio to compare Tr and Untr Tav dynamics.



(a) (b) (c) (d)

Fig. 1. Tav vs. time curves. (a) Tr individuals; (b) Untr individuals; (c) Tr group (mean ± SE) ; (d) Untr group (mean ± SE).

Table 3 shows A/τ ratio average values during graded load and recovery phases of the exercise for Tr and Untr groups. As earlier mentioned, we report two Tr Tav A/τ ratio values during the graded load phase of the exercise.

Table 3. A/τ average ratio during graded load and recovery phases of the exercise for Tr and Untr groups, respectively.

	graded load (°C/min)		**recovery** (°C/min)
Untr (n= 8)	-0.23 ± 0.07		0.39 ± 0.13
Tr (n= 10)	Before slope change	After slope change	0.71 ± 0.3
	-0.21 ± 0.06	-0. 98 ± 0.42	
ANOVA	$P > 0.05$	$P < 0.01$	$P < 0.01$

Discussion

Large haemodynamic changes involving multiple regulatory processes are associated to the physical exercise. Since exercise is closely connected to such haemodynamic changes and to heat generation within the body, marked alterations in thermoregulatory processes during exercise are expected, thus affecting dynamics of skin temperature.

In the present study, we have used high-resolution thermal imaging to describe how Tsk, and in particular Tav, varies in Tr and Untr individuals during graded load exercise

At rest Tav does not differ between Tr and Untr ($P > 0.05$). Performing the graded load exercise, both Tr and Untr individuals show a Tav decreasing that lasts until reaching the volitional exhaustion. Then, Tav increases during the recovery in both groups. At the end of the recovery, i.e. at the restoring of the at rest heart beat rate, Tr and Untr achieve similar final Tav ($P > 0.05$). Moreover, basal pre-exercise and final Tav overlap ($P < 0.01$).

Although Tav decreases in both groups, the A/τ ratio result similar only in the initial phase of the exercise (Tr -0.21 ± 0.06 °C/min, Untr -0.23 ± 0.07 °C/min; $P > 0.05$). In fact, while prolonging the exercise, Tr individuals exhibited a second more marked temperature drop, significantly faster than in the initial phase (A/τ = -0. 98 ± 0.42 °C/min; $P < 0.01$). No Untr individuals have exhibited such a slope change. The acceleration in Tav drop resulted in the lower Tav value at the volitional exhaustion. Since final Tav was the same for both groups, Tr individuals needed to activate Tav recovery processes more effectively than Untr ones. In fact, recovery A/τ ratios significantly differed in the two groups (Tr 0.71 ± 0.3 °C/min, Untr 0.39 ± 0.13 °C/min; $P < 0.01$).

Our data indicate that at rest Tav does not discriminate between Tr and Untr, while its dynamics (i.e. its variation with respect to the basal state) along the several phases of the exercise clearly highlights fundamental differences between the two groups. As the workload increase, Tr individuals seem to activate more effective and rapid thermal control processes.

Since Tsk, thus Tav, largely depends on the cutaneous blood flow [3], Tav dynamics reflected mostly cutaneous vasoconstriction and vasodilatation centrally controlled and sympathetically maintained [1].

Initial cutaneous vasoconstriction in regions proximal to the muscles directly involved in the exercise may also serve to reduce heat transport from muscle structures to surface tissue, thus helping the muscle to reach optimal working temperature [9]. Then, the loading level and the muscular mass involved in the exercise [9] in Tr individuals determine whether to increase cutaneous vasoconstriction to further supply blood to the muscle or to switch to thermoregulatory processes and vasodilatation to permit metabolic heat dispersion.

Once the volitional exhaustion has been reached, Tr Tav recovered to basal values faster than Untr.

Tav increasing rate represents the capability to redistribute blood from the muscle to the cutaneous layers, thus allowing peripheral thermal control.

Our results on Tav are in accord with the results of precedent study adopting similar protocols and loading schemes [5, 6].

Our results seem therefore to confirm a tight correlation between the training level and the capability of the cutaneous layers and of the muscle to exchange blood.

The main result of this study consists of having documented and modelled fundamentally different thermoregulatory processes at the cutaneous level in Tr and Untr, the former being able to effectively control haemodynamic resources to sustain intense exercise and to avoid over heating of muscular structures. Such a result may help into understanding regulatory processes during physical activity and their dependency on the muscular metabolism with training.

From the methodological point of view, this study presents an innovative way to investigate functional adjustment of skin thermoregulatory processes to physical activity and training. High resolution thermal imaging has allowed to study quantitatively and directly how skin temperature changes along exercise, thus permitting to find out specific behaviours discriminating Tr from Untr individuals undergoing graded load exercise.

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