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Monitoring Skin Thermal Response to Training with Infrared Thermography

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ABSTRACT

There is no doubt that core or central temperature has a direct relationship with exercise intensity. However, local temperature responses, specifically the acute temperature effects of workouts on joints and muscles, and the temperature changes that take place during the recovery process, have not yet been well described. Infrared thermography (IRT) is a safe, non-invasive and low-cost technique that makes it possible to measure specific local thermal responses to exercise. The authors used IRT to observe changes in skin temperature related to muscle and joint activity of both the upper and lower limbs during, immediately after and up to eight hours after strength and aerobic training. They found that the use of IRT may provide important information on local metabolic activity generated by training and adaptations related to the reestablishment of initial skin temperature post training, which can indicate whether the athlete has recovered enough to be able to effectively train or compete again. If this finding can be confirmed, IRT would be a practical tool for monitoring athletes' training.

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Introduction

The physiological effects of training are reasonably well established in terms of hormonal[1,2,] morphological[3], bone[4], neural[5], or cardiovascular[6] responses, or with regard to the type of training[7]. However, local temperature responses, specifically the acute effects of workouts on joints and muscles, and the changes that take place during the recovery process, have not yet been well described.

There is no doubt that core or central temperature has a direct relationship with exercise intensity[8,9] . Some studies have focused on measuring central thermal response by using gastrointestinal capsules (ingestible sensors) or by taking rectal, oesophageal or tympanic temperature during and after exercise[9-13]. These have reported different temperature responses in certain regions of the body, such as the joints, compared to the central temperature[14] caused by redistribution of blood flow via hypothalamic thermal control[15]. The temperature response from each part of the body can also vary in the recovery period, as the trained muscular regions and joints involved in the movement have a higher metabolic activity with faster energetic and tissue recovery facilitated by increased blood supply[2,16].

Infrared Thermography (IRT)[17] is a safe, non-invasive and low-cost technique that makes it possible to rapidly record the irradiated energy released from the body[18]. It has recently been proved that a high-resolution thermal image can provide interesting information about the complex thermoregulation system of the body[19]. The development of fast and easy IRT monitoring tools allows us to obtain general and local thermal profiles of humans, including their main body regions of interest (ROI), and to provide interesting information on physiological responses after exercise.

The influence of physical activity on skin temperature (Tsk)[24] and the validity of the assessment of Tsk distributions by thermography[19] are well known, but there is a lack of studies about the long term evolution of Tsk after moderate intensity strength or aerobic training. Therefore, it seems quite interesting to study the long-term thermal behaviour of the skin after exercise as a reflection of the responses of the structures underneath it. Moreover, analysis of local thermal response may provide the technical team (practitioners, physical therapist and coaches) with important information on the recovery status of the athlete and his/her capacity to continue training at a given level of intensity.

It is well-known that core temperature gradually decreases after conclusion of an extended period of exercise[8,25]. However, to our knowledge, there is no research about local and specific thermal responses of joints and muscles temperatures just after exercise and during the recovery process.

Therefore, the purpose of the study is to use IRT to determine the evolution of Tsk for muscles and joints after aerobic and strength training in order to understand better the impact of physical activity on the thermoregulatory system and metabolism. We hypothesize that the temperature response of the skin over eight hours post workout will be different in the joints than in the muscles, and different for aerobic training and strength training.

Methods

Subjects

A total of fifteen physically active university students from the Technical University of Madrid (Age: 21.44 ± 2.64 years; Height: 1.78 ± 0.04m; Weight: 73.2 ± 7.6kg; BMI: 23.05 ± 1.56) reporting that they exercise at least three times per week volunteered for this study. The participants reported no physical limitations or diseases, and declared no consumption of medicines, drugs, alcohol or tobacco. They were asked to refrain from a list of activities 24 hours prior to the test.

The Ethics Committee of the Technical University of Madrid approved the study plan, following the principles outlined by the Word Medical Assembly Declaration of Helsinki.

Training and establishment of working load intensity parameters

The participants chosen for the study signed a consent form informing them about the aims, procedures and risks involved in the investigation. They also answered questions pertaining to a history of their injuries, strength training experience, and other personal details. Measurements for height (m) and weight (kg) as well as their capacity and limitations with the assigned exercises were recorded. Participants were familiarised with the appropriate technique of the exercises (rhythm and coordination) as well as the thermography machine (IRT).

During the morning of the study, participants recorded their individual resting heart rate (RHR). This value was used to calculate their maximal heart rate (MHR) with use of the Whaley formula[26]. Based on the formula, 60% and 75% of their MHR-RHR was calculated, establishing the heart rate limits for the study. With the limits established, participants performed a trial run for 45 minutes on the treadmill, familiarising them with the aerobic portion of the study.

With regards to the strength training component, two exercises for major muscle groups - bench press (BP) and crossed pulleys (CP) for the chest; leg press (LP) and leg extension (LE) for the thigh - were chosen. All participants completed a one repetition maximum (1RM) test for each exercise in two separate sessions. The 1RM test, was measured based on the principles described by BAECHLE & EARLE[27]. Each participant warmed up for five minutes on a cycle ergometer. The 1RM protocol consisted of a warm-up phase followed by five progressive lifts, with the work load increased systematically until only one repetition with the proper technique and a rhythm of 2:2 (2 seconds eccentric and 2 seconds concentric) could be performed. To prevent muscular fatigue, a maximum of five sets were used to determine 1 RM[28]. Table 1 summarises the maximal strength values achieved.

Strength training session protocol

After the familiarisation process, the strength training portion of the study was started. Participants performed a five-minute warm-up on the bicycle followed by five minutes of general stretching targeting the muscles involved in the selected exercises. Before each lift, six to ten repetitions with a light weight were performed to establish proper technique and rhythm of execution (cadence 2:2). All participants performed four sets of ten repetitions at 70% of 1RM, with a rest period of 90 seconds between sets and three minutes between exercises.

Monitoring during the exercise provided real-time feedback about the speed and range of movement of each exercise. Participants performed two main exercises (BP and LP), followed by two ancillary exercises (CP and LE). Upon the completion of the last exercise, thermogram measurements were conducted two minutes post, followed by a ten-minute passive stretching session of the muscles used in the exercises.

Table 1: Averaged maximal strength results

	1RM	1RM/kg
BP: Bench press (session 1)	76.36±9.44	0.79±0.10
CP: Crossed pulleys (session 2)	26.07±6.01	0.27±0.06
LE: Leg extension (session 1)	107.86±14.24	1.11±0.15
LP: Leg Press (session 2)	180.57±28.25	1.86±0.29

Resistance training session protocol

Similarly to the strength portion of the study, participants warmed up for five minutes prior to a 45-minute treadmill run at a moderate intensity (60-75% HR). The intensity of the exercise was measured using the Borg scale of perceived exertion (from 6 to 20).

Before and after each run, participants were weighed to establish a dehydration level. A calculation of the measured loss was performed giving a value for the amount of water needed to be consumed post exercise. With regards to ingestion of food, participants were allowed their normal daily intake during the supervised eight-hour period post-exercise. Water consumption was calculated to at least 150% of the weight lost due to dehydration[29].

General and thermographic protocol

Participants were asked to maintain normal eating and resting habits, but were instructed to desist from any exercise for at least 24 hours before the trial. Each trial session began between 08:30 and 11:30. Participants were requested to remain in their underwear for a minimum of 15 minutes in order to achieve a thermal balance with their surroundings, before baseline skin temperatures were recorded. The average temperature for the room was maintained at 20.6 ± 0.7°C with a humidity reading of 44.0 ± 3.2%.

During the workouts participants wore shorts, T-shirt and training shoes. They were instructed to consume the minimal amount of water during and immediately after exercise[29]. With the room temperature kept at a constant temperature (18.5°C and 21.0°C), participants were monitored for eight hours post-trial. They were asked to abstain from having a shower, but were allowed to wear comfortable clothing. During the monitoring period they remained seated, partaking in passive activities (i.e. reading, studying or playing computer games). The only time they were allowed to leave the room was to eat between 13:30 and 15:30.

Ten series of four thermograms (Anterior and Posterior of the Upper and Lower body: AU, AL, PU, PL) were registered before the exercise (BE), immediately after exercise (IAE) and once an hour post-workout ("A+1" to "A+8"). Temperature data from the selected regions of interest (ROI) were obtained from 72 anatomical regions based on criteria set out by GOMEZ CARMONA et al[30] (see Figure 1). The selected ROI were: pectoral (PEC), dorsal (DOR) deltoids (DEL), biceps brachii (BIB), triceps brachii (TRB), quadriceps (QUA) and Hamstring (HAM) muscles and 2) the elbow (ELB) and knee (KNE) joints bilaterally (left and right), when applicable, in the frontal (F) and dorsal (D) views. In addition, during the resistance training, the abdominal (ABD) region was considered. Tympanic temperature readings were taken twice during each thermal assessment.

The thermographic protocol for this study was in agreement with the guidelines of the European Association of Thermology concerning the participants, camera and environmental conditions[31], ensuring the recording of images of the highest quality.

Equipment

Thermograms were recorded using the 335 FLIR infrared camera (FLIR Systems, Sweden), with data extracted by Termotracker software (Pemagroup, Spain). Tympanic temperature was recorded with a ThermoScan® PRO-4000 (BRAUN, Germany). The environmental conditions were controlled by a BAR-908-HG portable weather station (Oregon Scientific, USA).

The machines used for the strength training protocol were: leg extension (X Pression - Panatta, Italy); leg press (Free Weight); Smith machine (X Pression - Panatta, Italy); cable station with bar (X Pression - Panatta, Italy). For the initial assessment, experimental trial and the aerobic training test, the Runner Advance "E" (Panatta, Italy) treadmill and the RS400 heart rate monitor (Polar, Finland) were used.

Statistical analyses

Average and standard deviations for the Tsk of the selected ROI were derived from the thermograms using the Termotracker software

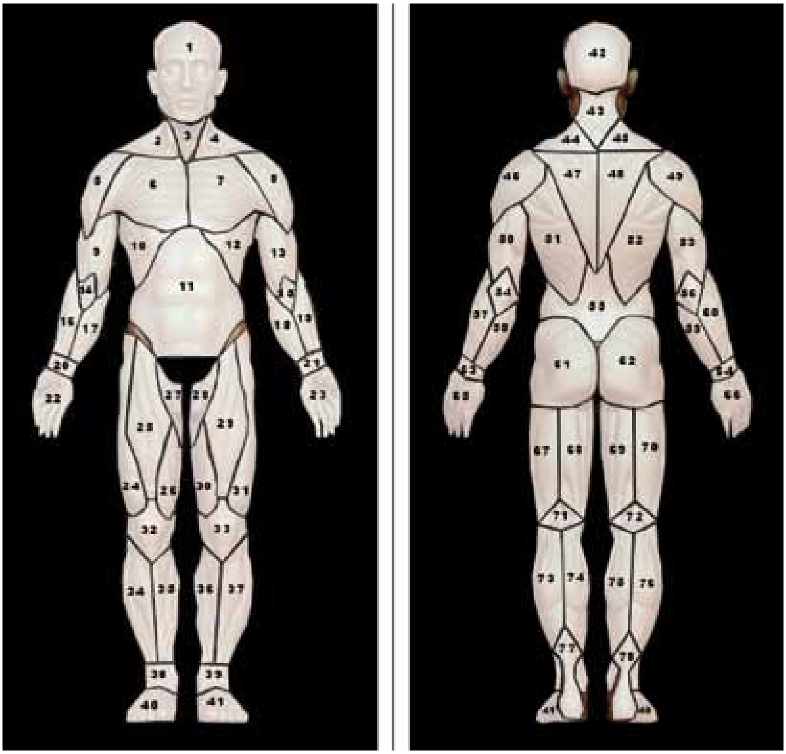

Figure 1: Body area templates use for Thermgraphy recording of local temperatures

(Pemagroup, Spain). To find any significant differences between each muscle and joint ROI as well as tympanic temperature reading, descriptive and multivariate analysis of repeated measure tests by the data collection moment with additional Tukey post hoc tests were carried out over time. To perform analysis of the data, statistical significance was established at $p<0.05$ using the SPSS software (version 15.0).

Results

Effects of strength training on skin temperature

A summary of the averaged Tsk and the standard deviations for each muscle ROI in the ten conditions: baseline before exercise (BE), immediately after the strength training (IAE) and during the eight hours of recovery ("A1" to "A8") is presented in Table 2. Additionally, significant differences for the multivariate analysis of repeated measures test for Tsk by data collection moment and the results of the post hoc Tukey analysis among different moments during recording of Tsk are also presented. Furthermore, Table 3 shows the relation of Tsk to the articular regions and tympanic temperatures.

From Table 2 we concluded that the Tsk_{IAE} is lower or similar than Tsk_{BE} in all the muscle ROIs. In turn, differences regarding thermal responses related to muscle activity in the selected exercises (agonist, synergist or antagonist) for both the upper and lower limbs are shown.

The thermal response of the skin of the articular regions (elbows and knee) was also different when considering either the upper or lower limbs (Table 3). In the upper limb, the strength exercises affected the anterior differently from the posterior part of the elbow with regards to Tsk. However, the Tsk response of the knee to the strength training exercise did not reflect a significant decrement in most areas.

Table 2: Averaged temperatures (±) standard deviations and repeated measurements multivariable analysis for each considered muscular ROI along the data collection process. (STRENGTH TRAINING)

ROI		BE	IAE	RECOVERY POST EXERCISE								P	*Post hoc Tukey*		
				A+1 (1)	A+2 (2)	A+3 (3)	A+4 (4)	A+5 (5)	A+6 (6)	A+7 (7)	A+8 (8)		Dif. BE – IAE P<0.05? (Δ?)	Dif. BE-A+n (only *p*<0.05)	Dif. IAE-A+n (only *p*<0.05)
Deltoids (DEL)	F R	31.98 ± 0.65	31.57 ± 0.83	32.18 ± 0.54	32.28 ± 0.45	32.32 ± 0.61	32.45 ± 0.49	32.53 ± 0.58	32.53 ± 0.48	32.29 ± 0.40	32.38 ± 0.46	0.000	p=0.18 (↓≈0.4)	4,5,6,8 (⇑)	1,2,3,4,5,6,7,8 (⇑)
	F L	32.03 ± 0.66	31.66 ± 0.86	32.27 ± 0.54	32.26 ± 0.43	32.30 ± 0.56	32.42 ± 0.54	32.46 ± 0.64	32.54 ± 0.52	32.27 ± 0.46	32.36 ± 0.59	0.000	p=0.19 (↓≈0.4)	4,5,6 (⇑)	1,2,3,4,5,6,7,8 (⇑)
	D R	30.94 ±0.83	29.96 ± 1.23	30.95 ± 0.80	31.18 ± 0.66	31.39 ± 0.67	31.35 ± 0.67	31.38 ± 0.76	31.53 ± 0.73	31.28 ± 0.68	31.32 ± 0.64	0.001	Yes (↓≈1.0)	3,4,5,6 (⇑)	1,2,3,4,5,6,7,8 (⇑)
	D L	30.91 ± 0.86	29.91 ± 1.28	30.97 ± 0.77	31.10 ± 0.78	31.22 ± 0.70	31.39 ± 0.69	31.36 ± 0.77	31.51 ± 0.65	31.26 ± 0.62	31.29 ± 0.75	0.005	Yes (↓≈1.0)	4,5,6 (⇑)	1,2,3,4,5,6,7,8 (⇑)
Pectoral (PEC)	F R	31.78 ± 0.54	31.04 ± 1.12	31.95 ± 0.48	32.15 ± 0.53	32.27 ± 0.56	32.46 ± 0.46	32.48 ± 0.60	32.56 ± 0.48	32.32 ± 0.49	32.39 ± 0.58	0.000	Yes (↓≈0.7)	2,3,4,5,6,7,8 (⇑)	1,2,3,4,5,6,7,8 (⇑)
	F L	31.75 ± 0.58	31.08 ± 1.09	31.95 ± 0.55	32.13 ± 0.54	32.25 ± 0.52	32.48 ± 0.47	32.47 ± 0.61	32.60 ± 0.48	32.35 ± 0.49	32.36 ± 0.58	0.000	p=0.06 (↓≈0.7)	2,3,4,5,6,7,8 (⇑)	1,2,3,4,5,6,7,8 (⇑)
Dorsal (DOR)	D R	31.12 ± 0.66	29.35 ± 1.15	31.25 ± 0.64	31.42 ± 0.71	31.63 ± 0.59	31.72 ± 0.54	31.67 ± 0.67	31.85 ± 0.75	31.61 ± 0.59	31.74 ± 0.71	0.000	Yes (↓≈1.8)	3,4,5,6,7,8 (⇑)	1,2,3,4,5,6,7,8 (⇑)
	D L	31.19 ± 0.66	29.44 ± 1.20	31.34 ± 0.59	31.51 ± 0.72	31.61 ± 0.56	31.77 ± 049	31.78 ± 0.66	31.91 ± 0.71	31.68 ± 0.56	31.79 ± 0.69	0.000	Yes (↓≈1.8)	3,4,5,6,7,8 (⇑)	1,2,3,4,5,6,7,8 (⇑)
Biceps Braquii (BIB)	F R	31.52 ± 0.66	31.47 ±0.70	31.67 ± 0.50	31.63 ± 0.74	31.76 ± 0.52	31.72 ± 0.69	31.81 ± 0.70	31.93 ± 0.63	31.75 ± 0.56	31.84 ± 0.64	0.204	p=0.85 (→≈0.05)	6 (⇑)	-
	F L	31.46 ± 0.70	31.48 ± 0.65	31.66 ± 0.58	31.48 ± 0.83	31.62 ± 0.67	31.73 ± 0.82	31.76 ± 0.77	31.90 ± 0.76	31.65 ± 0.68	31.73 ± 0.71	0.238	p=0.94 (→≈0.02)	6 (⇑)	-
Triceps Braquii (TRB)	D R	29.32 ± 0.97	29.09 ± 0.76	29.51 ± 0.69	29.50 ± 0.79	29.71 ± 0.71	29.80 ± 0.76	29.90 ± 0.86	30.06 ± 0.79	29.90 ± 0.79	29.99 ± 0.77	0.002	p=0.36 (↓≈0.2)	3,4,5,6,8 (⇑)	1,3,4,5,6,7,8 (⇑)
	D L	29.27 ± 0.99	29.16 ± 0.76	29.43 ± 0.70	29.31 ± 0.91	29.45 ± 0.76	29.69 ± 0.83	29.80 ± 0.91	29.92 ± 0.84	29.81 ± 0.87	29.92 ± 0.86	0.010	p=0.70 (↓≈0.1)	6,8 (⇑)	5,6,7,8 (⇑)
Quadri-ceps (QUA)	F R	29.68 ± 0.77	29.67 ± 1.01	30.20 ± 0.63	29.86 ± 0.52	30.10 ± 0.74	30.23 ± 0.53	30.35 ± 0.88	30.38 ± 0.62	30.30 ± 0.78	30.06 ± 0.67	0.029	p=0.95 (→≈0.01)	1,3,4,5,6,7,8 (⇑)	1,6 (⇑)
	F L	29.56 ± 0.76	29.63 ± 0.96	30.12 ± 0.56	29.76 ± 0.51	29.99 ± 0.73	30.12 ± 0.53	30.16 ± 0.83	30.21 ± 0.61	30.17 ± 0.74	29.96 ± 0.66	0.048	p=0.82 (→≈0.07)	1,3,4,5,6,7,8 (⇑)	1 (⇑)
Hamstring (HAM)	D R	30.23 ± 0.93	28.65 ± 1.06	30.62 ± 0.71	30.81 ± 0.72	31.15 ± 0.85	31.26 ±0.68	31.51 ± 0.62	30.47 ± 0.65	31.43 ± 0.85	30.90 ± 0.71	0.000	Yes (↓≈1.6)	2,3,4,5,6,7,8 (⇑)	1,2,3,4,5,6,7,8 (⇑)
	D L	30.25 ± 1.04	28.68 ± 1.09	30.66 ± 0.74	30.82 ± 0.75	31.21 ± 0.94	31.34 ± 0.69	31.58 ± 0.67	31.50 ± 0.64	31.42 ± 0.82	30.90 ±0.71	0.000	Yes (↓≈1.6)	2,3,4,5,6,7,8 (⇑)	1,2,3,4,5,6,7,8 (⇑)

ROI = Regions of Interest; F = Frontal; D = Dorsal; R = Right; L = Left; BE = Before exercise; IAE= Immediately After Exercise;
A+n = Number of hours after training; (X) = Codes for significant differences in the post hoc Tukey test during resting.

Table 3: Averaged temperatures (±) standard deviations and repeated measurements multivariable analysis for each considered articular ROI and tympanic temperature along the data collection process. (STRENGTH TRAINING)

ROI		BE	IAE	RECOVERY POST EXERCISE								P	Post hoc Tukey		
				A+1 (1)	A+2 (2)	A+3 (3)	A+4 (4)	A+5 (5)	A+6 (6)	A+7 (7)	A+8 (8)		Dif. BE – IAE P<0.05? (Δ?)	Dif BE-A+n *(only p<0.05)*	Dif IAE-A+n *(only p<0.05)*
Elbow (ELB)	F R	31.82 ± 0.71	31.86 ± 0.52	31.98 ± 0.57	31.82 ± 0.87	31.93 ± 0.55	31.97 ± 0.75	32.06 ± 0.67	32.19 ± 0.57	31.97 ± 0.59	32.10 ± 0.63	0.316	p=0.87 (→≈0.04)	6 (⇑)	-
	F L	31.77 ± 0.67	31.75 ± 0.5	31.98 ± 0.52	31.67 ± 0.76	31.83 ± 0.70	31.90 ± 0.84	32.02 ± 0.71	32.17 ± 0.62	31.96 ± 0.57	32.00 ± 0.64	0.160	p=0.92 (→≈0.07)	6 (⇑)	-
	D R	28.95 ± 0.80	29.61 ± 0.69	29.25 ± 0.75	29.04 ± 0.66	29.23 ± 0.81	29.26 ± 0.69	29.42 ± 0.74	29.56 ± 0.52	29.26 ± 0.65	29.42 ± 0.77	0.103	Yes (↑≈0.6)	6 (⇑)	2 (⇓)
	D L	28.92 ± 1.00	29.67 ± 0.66	29.11 ± 0.81	28.73 ± 0.98	28.87 ± 0.99	29.08 ± 0.82	29.00 ± 0.98	29.26 ± 0.83	29.06 ± 0.87	29.20 ± 0.97	0.082	Yes (↑≈0.7)	-	1,2,3 (⇓)
Knee (KNE)	F R	28.31 ± 1.13	27.61 ± 1.23	28.44 ± 0.62	28.10 ± 0.94	28.31 ± 0.90	28.65 ± 1.01	28.59 ± 1.10	28.58 ± 1.15	28.40 ± 1.09	28.32 ± 1.01	0.113	p=0.11 (↓≈0.7)	-	1,4,6 (⇑)
	F L	28.31 ± 1.24	27.43 ± 1.01	28.49 ± 0.62	28.14 ± 0.81	28.43 ± 1.02	28.75 ± 1.14	28.64 ± 1.25	28.60 ± 1.23	28.40 ±1.27	28.34 ± 1.20	0.019	Yes (↓≈0.9)	-	1,2,3,4,5,6,7,8 (⇑)
	D R	31.00 ± 0.68	29.01 ± 0.91	30.79 ± 0.66	30.93 ± 0.80	31.28 ± 0.56	31.28 ± 0.76	31.25 ± 0.79	31.22 ± 0.76	31.25 ± 0.73	30.99 ± 0.67	0.000	Yes (↓≈2.0)	3,4,6 (⇑)	1,2,3,4,5,6,7,8 (⇑)
	D L	31.15 ± 0.79	29.33 ± 0.81	31.03 ± 0.63	31.13 ± 0.66	31.50 ± 0.57	31.56 ± 0.73	31.46 ± 0.76	31.39 ± 0.79	31.38 ± 0.71	31.10 ± 0.71	0.000	Yes (↓≈1.8)	3,4,5,6 (⇑)	1,2,3,4,5,6,7,8 (⇑)
Timpanic Temperature		36.66 ± 0.29	36.76 ± 0.21	36.57 ± 0.22	36.50 ± 0.29	36.64 ± 0.34	36.66 ± 0.26	36.68 ± 0.23	36.80 ± 0.27	36.72 ± 0.36	36.69 ± 0.30	0.012	p=0.21 (↑≈0.1)	2 (⇓)	1,2 (⇓)

ROI = Regions of Interest; F = Frontal; D = Dorsal; R = Right; L = Left; BE = Before exercise; IAE= Immediately After Exercise;
*A+n = Number of hours after training; (X) = Codes for significant differences in the post hoc Tukey test during resting. (*p=0.06)*

Effects of resistance training on skin temperature.

Similarly to the strength training data, Tables 4 and 5 present a summary of the muscle, joint Tsk and tympanic temperature at rest (BE), immediately after aerobic exercise (IAE) and during the eight-hour recovery period ("A1" to "A8"). Multivariate analysis of repeated measures test and post hoc Tukey analysis for the Tsk among the different recording moments are presented in these tables.

In most of the selected ROIs, the upper limb Tsk_{IAE} is lower than the Tsk_{BE} with significance being achieved only in the anterior part of the deltoids (See Table 4). In contrast, the triceps brachii Tsk_{IAE} is higher than the Tsk_{BE}. Concerning the lower limb muscles, the IAE temperature remained constant or showed a slight increase but was of no significance.

The results for the joints were heterogeneous (Table 5) with significant increments of Tsk shown in the posterior part of the elbows and anterior part of the knees. However, non-significant measures of Tsk were recorded IAE compared with the BE baselines. Within Table 5, an increase in IAE of the tympanic temperatures are shown but were not significant. With regards to the abdominal area there was a sharp decrease in temperature IAE.

Discussion

Thermographic recordings present a complex physiological response of the skin to different training load, involving the skeletal muscle (metabolism), the cardiovascular system (blood flow), neural system (central and local) and adrenergic system[32,33]. In this study, therrmographic data indicated that the skin response was specific for the muscle group and selected joints evaluated over time for different training loads.

Short-term effects of training on skin temperature.

Among the 16 evaluated muscle ROIs, a reduction of Tsk occurred in 75% of cases immediately after strength training, ranging from 0.1°C to 1.6°C. Significance ($p<0, 05$) was demonstrated only in the posterior deltoid (R & L), pectoral (R), dorsal (R & L) and hamstring (R & L) (see Table 2). Comparing strength to aerobic training (Table 4), there was a reduction of the Tsk in 63% of the analysed ROIs post 45-minute run. The change in range was from 0.3°C to 0.8°C. However, a significant difference ($p<0.05$) was only observed in the right anterior shoulder.

The thermal response to strength training was heterogenic in the joints (Table 3) with a significant rise ($p<0.05$) in the back part of the elbow (R & L) and a reduction in the knee joint. Significance was observed in the left anterior and both the left and right posterior part ($p<0.05$), with an average decrease of up to 2.0°C. The response to aerobic versus strength training in the joints was different with a slight and non-significant decrease on the anterior and posterior regions of the elbow and knee joints, respectively. The temperature change was between 0.3°C and 0.5°C, with a heightened and significant increase on the posterior region of the elbow and the anterior region of the knee ($p<0.05$), ranging between 1.2°C and 2.7°C.

From the data collected the muscle areas of Tsk were lower than the initial IAE temperature with a pronounced decrease in the strength training protocol. With regards to the elbow or knee joints, a greater decrease in temperature was observed in the knee post strength training. The mean difference was approximately 2.0°C in the posterior. However, after aerobic training the temperature was reduced between 0.4°C – 0.5°C with the higher readings recorded in IAE of the posterior region of the elbow (between 1.0°C – 2.7°C) and anterior part of the knee (between 1.2°C – 1.5°C).

Skin cooling has been shown to occur during both running[16,34] and exercise with a cycle ergometer[35]. However, the reduction of temperature after strength training has yet to be investigated. Using IRT, Merla et al[21] showed

Table 4: Averaged temperatures (±) standard deviations and repeated measurements multivariable analysis for each considered muscular ROI along the data collection process (RESISTANCE TRAINING)

ROI		BE	IAE	RECOVERY POST EXERCISE								P	Post hoc Tukey		
				A+1 (1)	A+2 (2)	A+3 (3)	A+4 (4)	A+5 (5)	A+6 (6)	A+7 (7)	A+8 (8)		Dif. BE – IAE P<0.05? (Δ?)	Dif. BE-A+n *(only p<0.05)*	Dif. IAE-A+n *(only p<0.05)*
Deltoids (DEL)	FR	31.62 ±0.55	30.80 ±1.08	32.06 ±0.55	32.03 ±0.72	32.24 ±0.68	32.20 ±0.77	32.26 ±0.42	32.40 ±0.51	32.29 ±0.49	32.28 ±0.55	0.000	Yes (↓0.8)	1,3,4,5, 6,7,8(↑)	1,2,3,4,5,6,7,8(↑)
	FL	31.69 ±0.49	30.94 ±1.15	32.13 ±0.54	32.06 ±0.69	32.25 ±0.52	32.17 ±0.71	32.27 ±0.42	32.29 ±0.50	32.36 ±0.50	32.30 ±0.56	0.000	0.069 (↓0.7)	1,3,4,5, 6,7,8(↑)	1,2,3,4,5,6,7,8(↑)
	DR	30.90 ±0.67	30.48 ±1.44	31.28 ±0.67	31.26 ±0.79	31.43 ±0.88	31.48 ±0.73	31.38 ±0.66	31.49 ±0.52	31.31 ±0.66	31.41 ±0.74	0.031	0.420 (↓0.4)	3,4,5, 6(↑)	1,4,6(↑)
	DL	30.84 ±0.67	30.67 ±1.28	31.22 ±0.73	31.14 ±0.88	31.33 ±0.86	31.37 ±0.80	31.34 ±0.62	31.39 ±0.52	31.21 ±0.60	31.32 ±0.81	0.112	0.785 (↓0.2)	3,4,5,6(↑)	4(↑)
Pectoral (PEC)	FR	31.38 ±0.54	30.67 ±1.40	31.87 ±0.59	32.08 ±0.72	32.21 ±0.69	32.21 ±0.88	32.28 ±0.47	32.28 ±0.60	32.30 ±0.54	32.25 ±0.70	0.000	0.128 (↓0.7)	1,2,3,4,5, 6,7,8(↑)	1,2,3,4,5,6,7,8(↑)
	FL	31.37 ±0.55	30.80 ±1.29	31.90 ±0.61	32.12 ±0.68	32.24 ±0.65	32.21 ±0.87	32.27 ±0.47	32.30 ±0.61	32.35 ±0.50	32.28 ±0.66	0.000	0.208 (↓0.6)	1,2,3,4,5, 6,7,8(↑)	1,2,3,4,5,6,7,8(↑)
Dorsal (DOR)	DR	31.07 ±0.65	30.70 ±1.62	31.39 ±0.56	31.50 ±0.74	31.85 ±0.62	31.75 ±0.79	31.70 ±0.36	31.75 ±0.39	31.66 ±0.50	31.81 ±0.62	0.020	0.550 (↓0.4)	3,4,5, 6,7,8(↑)	4,6,8(↑)
	DL	31.15 ±0.61	30.86 ±1.49	31.46 ±0.55	31.57 ±0.70	31.92 ±0.60	31.81 ±0.82	31.77 ±0.36	31.82 ±0.43	31.74 ±0.51	31.85 ±0.59	0.018	0.650 (↓0.3)	3,4,5, 6,7,8(↑)	4,6,8(↑)
Biceps Braquii (BIB)	FR	31.34 ±0.60	30.60 ±1.31	31.59 ±0.58	31.42 ±0.80	31.71 ±0.64	31.67 ±0.72	31.70 ±0.46	31.77 ±0.49	31.77 ±0.49	31.78 ±0.51	0.006	0.165 (↓0.7)	6,7,8(↑)	6,7,8(↑)
	FL	31.39 ±0.45	30.61 ±1.20	31.67 ±0.56	31.48 ±0.78	31.70 ±0.66	31.63 ±0.66	31.70 ±0.46	31.76 ±0.44	31.82 ±0.44	31.78 ±0.46	0.003	0.064 (↓0.8)	1,2,3,4,5 ,6,7,8(↑)	1,2,3,4,5,6,7,8(↑)
Triceps Braquii (TRB)	DR	29.08 ±0.71	30.05 ±1.70	29.76 ±0.96	29.51 ±1.07	29.69 ±1.02	29.61 ±1.08	29.76 ±0.86	29.90 ±0.89	29.82 ±0.98	29.92 ±1.14	0.164	0.057 (↑1.0)	1,3,5, 6,7,8(↓)	---
	DL	29.04 ±0.62	30.45 ±1.60	29.75 ±1.12	29.47 ±1.18	29.62 ±1.08	29.55 ±1.09	29.58 ±0.88	29.63 ±0.85	29.61 ±0.82	29.73 ±1.05	0.013	Yes (↑1.4)	1,3, 6,7,8(↓)	1,2,4,5,7(↓)
Quadri-ceps (QUA)	FR	29.59 ±0.56	29.77 ±1.31	30.39 ±0.57	30.15 ±0.62	29.94 ±0.70	30.09 ±0.68	30.11 ±0.75	30.17 ±0.56	30.20 ±0.64	30.10 ±0.58	0.088	0.741 (↑0.2)	1,2,4,5, 6,7,8(↑)	4(↑)
	FL	29.44 ±0.53	29.77 ±1.28	30.33 ±0.61	30.04 ±0.56	29.88 ±0.69	30.04 ±0.62	30.04 ±0.70	30.07 ±0.52	30.07 ±0.64	29.98 ±0.54	0.086	0.446 (↑0.3)	1,2,4,5, 6,7,8(↑)	---
Hams-tring (HAM)	DR	29.60 ±0.50	29.84 ±1.66	30.57 ±0.63	30.83 ±0.86	30.72 ±0.59	30.69 ±0.88	30.94 ±0.83	30.28 ±2.04	30.88 ±0.68	30.56 ±0.89	0.021	0.650 (↑0.2)	1,2,3,4,5 ,7,8(↑)	2,3,4,5,7(↑)
	DL	29.72 ±0.54	29.69 ±1.67	30.50 ±0.67	30.87 ±0.86	30.74 ±0.62	30.74 ±0.83	31.04 ±0.78	30.37 ±1.99	30.99 ±0.73	30.63 ±0.84	0.013	0.746 (→0.0)	1,2,3,4,5,7,8(↑)	1,2,3,4,5,7,8(↑)

ROI = Regions of Interest; F = Frontal; D = Dorsal; R = Right; L = Left; BE = Before exercise; IAE= Immediately After Exercise; A+n = Number of hours after training; (X) = Codes for significant differences in the post hoc Tukey test during resting.

Table 5: Averaged temperatures (±) standard deviations and repeated measurements multivariable analysis for each considered articular ROI and tympanic temperature along the data collection process (RESISTANCE TRAINING)

ROI		BE	IAE	RECOVERY POST EXERCISE								P	*Post hoc Tukey*		
				A+1 (1)	A+2 (2)	A+3 (3)	A+4 (4)	A+5 (5)	A+6 (6)	A+7 (7)	A+8 (8)		Dif. BE – IAE P<0.05? (Δ?)	Dif BE-A+n *(only p<0.05)*	Dif IAE-A+n *(only p<0.05)*
Elbow (ELB)	FR	31.70 ±0.49	31.35 ±0.83	32.03 ±0.46	31.84 ±0.54	31.99 ±0.61	31.84 ±0.64	32.04 ±0.44	32.13 ±0.44	32.06 ±0.47	32.04 ±0.41	0.000	0.267 (↓0.3)	1,5,6(↑)	1,2,3,4, 5,7,8(↑)
	FL	31.66 ±0.39	31.35 ±0.85	32.01 ±0.55	31.76 ±0.72	31.90 ±0.66	31.79 ±0.71	32.00 ±0.52	32.05 ±0.44	32.04 ±0.43	31.94 ±0.42	0.000	0.320 (↓0.3)	6,7(↑)	1,5,6, 7,8(↑)
	DR	28.77 ±0.78	30.89 ±1.71	29.50 ±1.12	29.10 ±1.29	29.09 ±1.16	29.26 ±1.09	29.28 ±0.88	29.44 ±0.84	29.30 ±1.14	29.27 ±1.02	0.001	Yes (↑2.1)	6(↑)	1,2,3,4, 5,6,7,8(↓)
	DL	28.75 ±0.68	31.43 ±1.58	29.43 ±1.32	28.78 ±1.29	28.95 ±0.90	29.11 ±1.20	29.18 ±0.78	29.13 ±0.74	29.10 ±0.80	29.11 ±0.97	0.000	Yes (↑2.7)	1(↑)	1,2,3,4, 5,6,7,8(↓)
Knee (KNE)	FR	28.30 ±0.70	29.81 ±1.31	29.39 ±1.01	28.46 ±1.08	28.31 ±1.15	28.60 ±1.26	28.53 ±1.28	28.54 ±1.15	28.44 ±1.21	28.55 ±0.97	0.000	Yes (↑-1.5)	1(↑)	2,3,4, 5,6,7,8(↓)
	FL	28.31 ±0.75	29.53 ±1.36	29.39 ±1.07	28.51 ±1.14	28.42 ±1.26	28.68 ±1.34	28.55 ±1.36	28.53 ±1.20	28.36 ±1.24	28.51 ±1.17	0.005	Yes (↑1.2)	1(↑)	2,3,5,6, 7,8(↓)
	DR	30.40 ±0.52	29.96 ±1.21	30.99 ±0.58	30.80 ±0.74	31.01 ±0.63	31.04 ±0.59	30.90 ±0.66	30.33 ±1.78	30.77 ±0.53	30.92 ±0.49	0.023	0.141 (↓0.4)	1,2,3,4, 5,7,8(↑)	1,2,3,4, 5,7,8(↑)
	DL	30.55 ±0.58	30.05 ±1.17	31.16 ±0.58	31.04 ±0.78	31.15 ±0.73	31.18 ±0.67	30.99 ±0.68	30.40 ±1.76	30.95 ±0.60	31.00 ±0.52	0.015	0.106 (↓0.5)	1,2,3,4, 5,7,8(↑)	1,2,3,4, 5,7,8(↑)
Timpanic Tem-perature		36.62 ±0.28	36.91 ±0.43	36.62 ±0.25	36.59 ±0.27	36.60 ±0.21	36.67 ±0.25	36.72 ±0.28	36.77 ±0.26	36.76 ±0.24	36.68 ±0.26	0.028	0.069 (↑0.3)	---	1,2,3, 4,5(↓)
Abdominal		31.17 ±0.65	29.69 ±1.64	31.77 ±0.64	31.94 ±0.86	32.09 ±0.79	32.12 ±0.97	32.14 ±0.61	32.10 ±0.65	32.16 ±0.62	32.10 ±0.72	0.000	Yes (↓1.5)	1,2,3,4,5 ,6,7,8(↑)	1,2,3,4, 5,6,7,8(↑)

ROI = Regions of Interest; F = Frontal; D = Dorsal; R = Right; L = Left; BE = Before exercise; IAE= Immediately After Exercise;
A+n = Number of hours after training; (X) = Codes for significant differences in the post hoc Tukey test during resting.

a reduction in Tsk in response to a gradual increase of running intensity over 12 minutes in the forearms (5.2°C), the trunk (3.0°C), and the quadriceps (4.6°C). The two training protocols of this study produced similar results, but with less magnitude in the case of the strength training. At this point we have to consider that the characteristics of the efforts were quite different. In our study, the duration of the exercises exceeded 30 minutes versus 12 minutes in the studies of MERLA et al[21]. The observed acute Tsk reduction IAE may be partially compensated by heat conduction mechanisms: the sweat created, as a result of blood flowing from the muscle to the skin, releases excess heat from the muscle.

The thermal gradient between the skin and blood accounts for evaporation of sweat. This mechanism cools the blood, maintaining the internal temperature at an acceptable level[14,32]. The tympanic temperature measurements of this study validated this argument as they were significantly higher than the skin temperature IAE.

The internal temperature of the body can be influenced by exercise intensity[8,9]. Regulation of blood temperature, pressure and metabolic activity by the hypothalamus protects the body from dangerous increases in core temperature. Active central and peripheral vasoconstriction and vasodilation mechanisms in the body ensure that blood flows from the muscle to the skin. Under extreme conditions, six to eight l/min of blood may flow[32] in an attempt to cool the skin. In addition, the stimulation of sweat glands and the reduction of the temperature of blood by convection, the relationship of ambient air temperature to the skin[19,36] ensures that temperature of the body is maintained at a safe and constant level. The radiated skin temperature in response to the aforementioned mechanisms can be captured by IRT[19, 36].

The displacement of blood flow from the skin to regions of active muscle assists in the reduction of body temperature obtained IAE, during short-term exercise[21]. During moderate intense running, blood flows from the abdominal region to other muscles providing nutrients and a cooling effect. The measurement for Tsk in the abdominal region indicates a decrease in blood flow when analysed.

Interval strength training promotes a specific local thermal adjustment in contrast to a continuous run, with running imposing a neural vasodilation reflex in the skin[32]. The redistribution of blood from the skin to the active muscle region is inhibited by an increased need for internal heat loss. This inhibition is caused by thermal stress in response to extremely high air temperatures, or by a large internal heat production for a prolonged period of high intensity exercise. Nonetheless, these phenomena were not seen in this study.

Tympanic temperature is an indicator of internal body temperature. A study by MEIR et al[13] indicated that tympanic temperature accounted for a significant increase of 0.34°C compared to the resting condition at the end of a rugby match. This rise was greater than the value for strength training (0.11°C), but similar to the data after aerobic training (0.29°C), in the present study. In turn, the data collected in this study indicates a direct relationship between the increment of internal temperature with the intensity and duration of exercise.

Skin temperature during recovery

Changes of Tsk during the eight hours of recovery in the ROI for both strength and aerobic training increased when compared to the initial temperature BE and IAE (Tables 2 and 4). However, Tsk increases for the joints did not present with any significant changes. Though a sharp temperature increase in the anterior region of the knee post aerobic training was seen, this value was similar to the rest value two hours post 40-minute run (Tables 3 and 4).The use of IRT in research evaluating Tsk response during recovery post strength training is sparse. This limitation prevents the comparison of our data to other material. However, the rise in Tsk in several regions of the body post running has been shown by MERLA et al.[35].

In general, the highest recorded temperatures occurred four to six hours and six to nine hours post strength and aerobic training, respectively. An interesting response was noticed concerning maximal Tsk values recorded IAE and two hours post training for the anterior part of the knee and posterior part of the elbow. The values obtained in these areas were quite similar to the resting conditions.

After the exercise there is a new metabolic condition, demanding specific thermal adjustments including a redistribution of blood flow. Furthermore, it is known that during the recovery period the internal oesophageal temperature remains elevated indicating an increased metabolic activity[37]. After the completion of the exercise, activation of the mechanisms for releasing the metabolic and mechanic heat produced during the training period and their long term effects is still necessary. Kenny et al[14] established that 53% of heat stored during 60 minutes of cycling at 70 W was lost in 60 minutes of recovery. Therefore, the increase in skin temperatures during the recovery period may be attributed to the activation of the above mentioned mechanism.

Exercise produces an increase of nitric oxide (NO) in the blood, an important vasodilator of the cutaneous arteriole. Given the need for a local metabolic heat loss, NO promotes the vasodilation in the exercised regions through a mechanism called the prolonged plateau nitric oxide vasodilation mechanism[33]. The result is an increase in blood supply causing an elevation of local temperature, which can be measured by thermal imagers.

Increases in Tsk during the recovery of the joints and muscle, may be influenced by other mechanisms such as glycogen resynthesis[16] or adaptive mechanisms of hypertrophy[2]. The heat generated by these mechanisms occurs in the anatomical structures just under the skin.

The thermal profile obtained during the eight-hour recovery period can be influenced by environmental conditions (≈ 20.6°C and 44% RH), creating a thermal gradient between the skin and environment[38]. In cases of extremely hot environmental conditions (≈ 38°C and ≈ 70% RH in tropical areas) it is possible that this response would be different.

It is difficult to establish the effect of circadian variation of temperature on the results of this study. A study by ARNETT[41] indicated that swim training in the morning eliminated the effect of daily variation in body temperature, with MORRIS et al[36] concluding that Tsk during recovery after exercise (70% VO_2 max for 30 min) did not vary significantly. However, it is interesting to note that in this study, the highest temperature recorded for the ROI was approximately six hours post-exercise, which is similar to peak temperatures recorded by circadian rhythm studies[42].

In this study, the thermal measurements recorded for the 24 ROI in relation to Tsk were different before, during and after both strength and aerobic training. The results were influenced by the type of training (strength vs aerobic), the characteristics of the collected samples as well as the environmental conditions (room temperature). The constant monitoring of the body with regards to the aforementioned influences, is a very complex endeavour involving the synergy between the hypothalamus and other multiple sensors[15]. This feedback loop provides a constant monitoring of the internal temperature, maintaining a safe range for the proper function of the body. Factors that may influence this "safe" temperature range are: age[25,32,41], gender[25], level of fitness[12,42], hydration[10,32], clothing[43], circadian rhythm[40], type of training, as well as environmental conditions[34].

The specificity of local thermal responses to exercise requires further study to enhance the basic knowledge, particularly in high-performance competitive sport, where the athlete's recovery actions and the assimilation of training loads, are essential for the intervention of physical therapists and trainers.

Conclusions

Considering the ROI, Tsk presents specific responses in relation to strength and aerobic training. The main changes in Tsk observed in muscle (chest and thigh) were a reduction in temperature immediately post exercise versus the initial values, and a progressive increase during the eight hour recovery period with Tsk peaking approximately six hours post exercise. This value during the recovery period was never higher than 1°C compared to the initial resting values. The impact of exercise on Tsk with regards to the joints (knee and elbow) was lower and more heterogeneous with the local temperatures increasing or decreasing moderately in the ROI after strength training. However, the effects were more relevant after aerobic training in both the anterior part of the knee and posterior part of the elbow; with the recovery lasting only one or two hours. Therefore, use of IRT may provide important information on local adaptations in response to re-establishing the initial skin temperature post training. This may indicate whether the athlete has recovered enough to effectively train or compete again. If this theory is proven, IRT would be a practical and easy tool for monitoring the athletes' training.

Recommendations

Use of thermography may prove to be a valuable tool for trainers. By evaluating the local metabolic activity generated by the workout, and the subsequent return to baseline Tsk, a decision can be made when the athlete can resume training. In addition, therapists may use thermography as a tool for monitoring individual effects of techniques on their patients. In turn, the absence of differences in temperature between paired ROIs may indicate a balanced condition thereby minimising the possibility of injury.

The use of thermography on a regular basis during the training will create a thermal profile of the athlete, with special attention given to regions (muscle and joint) exposed to a higher training load or greater risk of injury. Increments of Tsk in these regions may be a strong indicator of an incomplete recovery. This information may help trainers control, decrease or abandon the training until Tsk returns to baseline levels.

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