



Body surface profile in ambient and hot temperatures during a rectangular test in race walker champions of the World Cup in Oman 2022

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ABSTRACT

There is current interest in infrared thermography as a method to assess changes in body surface temperature to determine thermoregulatory mechanisms, especially in endurance sports. The aim of this study was to evaluate the effect of two environmental temperatures (17 and 28°C) on body surface temperature in different anterior and posterior aspects of the body during a rectangular test in international walkers of the Spanish National Team. Three international walkers performed a rectangular test, where body temperature was measured at rest, and after the 5th, 10th and 15th run using an infrared thermographic camera in room temperatures at 17 and 28°C. In addition, oxygen consumption was measured simultaneously. ANOVA detected a group $\times$ time interaction in the chest and abdomen (right and left), left back and right calf ($p < 0.05$), with a trend in the right hamstring ($p = 0.053$) when comparing 17°C and 28°C. ANOVA detected no significant group $\times$ time interaction ($p = 0.853$) but there was a significant group effect ($p = 0.022$). The eleven degrees increase in ambient temperature (17 to 28°C) produces changes in almost all anatomical zones, but not homogeneously in international walkers during a rectangular test. This indicates that metabolic and blood flow changes are different depending on the anatomical zone measured.

1. Introduction

Thermoregulation is largely affected by environmental temperature and humidity and is one of the factors that can alter performance in endurance competitions (Périard et al., 2021; Rojas-Valverde et al., 2021). In addition, the state of hydration and its dynamics during exercise (i.e. body water loss) through increased sweating may limit the rise in core temperature and the development of fatigue under heat stress (Périard et al., 2021). Therefore, optimization of programming an athlete's preparation for success in professional competitions under hot and humid conditions is crucial for high-performance (Périard et al., 2015). Thus, assessing thermoregulatory response before, during and after exercise is extremely important to understand more precisely how an individual athlete responds to different environmental conditions (i.e., cold and hot) (Périard et al., 2015).

Physiological or autonomic control of temperature functions through thermogenic and thermolytic responses are independent of conscious

voluntary behavior (Périard et al., 2015). These mechanisms include control of metabolic heat generation (i.e. shivering), vasomotor function (i.e., conduction of heat flow through redistribution of blood from the core to the skin) and sudomotor function (i.e., sweating) (Périard et al., 2015).

In fact, numerous studies have focused on fluid loss, one of the main thermoregulatory responses to exercise that is responsible for cooling the skin at the surface level, releasing internal heat generated by cellular and tissue metabolic change and exchanging biochemical elements (Baker, 2017; Gerrett et al., 2018; Shiohara et al., 2016). Under heat stress, the cardiovascular system is probably the major limiting factor in exercise performance by redirecting blood from the brain and muscles to the skin (Périard et al., 2016). Furthermore, improved evaporative cooling of the skin reduces cardiovascular strain and delays fatigue during heat stress (Périard et al., 2016).

Galloway et al. (Galloway and Maughan, 1997) evaluated the effects of increased ambient temperature (4, 11, 11, 21 and 31 °C) with 70%

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relative humidity (RH) on performance, body temperature and biochemical parameters in recreationally-active subjects in a test to exhaustion. This author found that, with increasing ambient temperature, there was a parallel increase in mean rectal, chest, upper arm, thigh and calf skin temperature (Galloway and Maughan, 1997). In addition, he found that, with increasing temperature, there was an increase in sweat rate coupled with a decrease in oxygen consumption and a decrease in performance (time to exhaustion at an intensity of 70% of $\text{VO}_{2\text{MAX}}$) (Galloway and Maughan, 1997). This shows that a $\sim 10^\circ\text{C}$ change in ambient temperature is sufficient to generate heat stress in the human organism leading to biochemical and metabolic alterations.

Specifically, in a sample of elite athletes where a condition of norm temperature ($15.9 \pm 1.2^\circ\text{C}$, RH $55 \pm 6\%$) and heat ($31.6 \pm 1.0^\circ\text{C}$, RH $74 \pm 5\%$) were evaluated, performance and temperature variables were assessed (de Korte et al., 2021). The results were a decrease in time to exhaustion and peak power (endurance 27.9% and 17%; power 25.7% and 16%; and skill 23% and 14%; respectively) as the ambient temperature increased from 15.9°C (RH 55%) to 31.6°C (RH 74%) (de Korte et al., 2021). In addition, in the performance to exhaustion test (increasing every 3 min by 5% of the workload corresponding to 70% of the HR_{MAX}), an increase in gastrointestinal and skin temperature (T_s) was observed (endurance 0.6% and 1.1%; power 0.3% and 1.2%; and 0.2% and 1.8%; respectively) (de Korte et al., 2021).

Recent studies have shown that infrared thermography is a valid tool for the measurement and quantification of the metabolic response of the muscular system, including in sports (Fernandes Ade et al., 2014; Hillen et al., 2020). In particular, infrared thermography is a reliable, non-invasive, low-cost diagnostic tool that measures the intensity of infrared radiation emitted by body surfaces, converting it into a temperature pattern. Studies have observed that thermographic body asymmetries or sudden changes in skin infrared wave emissions coincide with metabolic responses of living tissues (Cabizosu et al., 2018; Law et al., 2018; Ring and Ammer, 2012).

Although numerous studies have shown the importance of hydration and control of fluid loss which are influenced by thermoregulation, especially in endurance exercise, for optimizing performance in both team and individual athletes (Baker, 2017; Maughan and Shirreffs, 2010; Nuccio et al., 2017; Von Duvillard et al., 2004), currently no study has established the infrared thermographic pattern in international race walkers. Although there are previous studies where the thermographic pattern has been analyzed in cycling (Priego Quesada et al., 2015), swimming (Novotny et al., 2015), running (moderate intensity) (Fernandes Ade et al., 2016) and cross-country skiing (Binek et al., 2022), the biomechanics of race walking is very different to aforementioned sports. Therefore, the results found in these studies cannot be extrapolated to race walkers, which makes it necessary to investigate this question. The findings of this study can provide the basis of knowledge so that any sports science can use this methodology to assess thermoregulation.

Therefore, the main objective of this study was to evaluate the thermographic pattern of different areas of the body before, during and after exercise (rectangular test) under normothermic (17.5°C) and mid (28.2°C) conditions in international race walkers.

2. Methodology

2.1. Study design

A randomized, crossover experimental design was performed. Randomization was performed using software (Randomizer) to assign codes to the groups generated in this study (Urbaniak and Plous, 2013). Participants were international race walkers who performed a rectangular test under normal ($17.5 \pm 1.3^\circ\text{C}$; $28 \pm 10.8\%$ relative humidity) and mid ($28.2 \pm 1.2^\circ\text{C}$; $31 \pm 7.3\%$ relative humidity) temperatures 3 weeks prior to the World Cup in Muscat (Oman) in teams. The anterior and posterior thermographic pattern of the body was measured basal

(TO), after the 5th (5s), 10th (10s) and 15th (15s) set in of the rectangular test (Fig. 1). All race walkers had similar training both the week before and during the study. In addition, they followed a standardized diet, accounting for body weight (b.w.), the day before and the day of (i. e., breakfast before the tests) by a sports nutritionist (FJMN). Each participant performed the rectangular tests at the same time in the morning (between 9am and 2pm) in order to minimize the effect of the circadian rhythm. The rectangular test visits were separated by five days.

2.2. Participants

Three international race walkers from the Spanish National Race-Walking Team participated and completed this study. It is important to note that these elite athletes won the team gold medal in the 35 km race walking World Cup in Muscat (Oman 2022), and individually finished 2nd, 3rd and 20th place in the general classification. The athletes' characteristics are presented in Table 1, and the final time in the Spanish Championship 35 km race-walking was ~ 2 h 30 min. The inclusion criteria were to have: 1) had a minimum time (2 h 37 min) in the Spanish Championship 35 km race-walking, 2) qualified for the World Cup (Oman), 3) at least 3 years of experience in international competitions, and 3) to have at least ten years of race-walking experience. Participants were excluded from the study if they: suffered a muscular injury at least 3 months before the study, had any pathological or metabolic disease and were taking any supplement or medication that would affect thermoregulation or performance. All participants were informed about the study procedures and signed informed consent. The study was conducted in accordance to the Helsinki Declaration for Human Research (Mundial, 2019) and was approved by the Ethics Committee of the Catholic University of Murcia (CE102102). This study was registered in ClinicalTrials.gov with ID: NCT05295836.

2.3. Procedures

Participants visited the laboratory on four different occasions. Visit 1 consisted of a medical exam, blood extraction to determine health status and a familiarization of the rectangular test. On visit 2, athletes performed an incremental test to establish the exercise zones for the rectangular test. At visits 3 and 4, a rectangular test was performed in room temperature set at either 17.5°C or 28.2°C . The day before visit 3 and 4, athletes consumed a standardized diet, composed of 9.0 g/b.w. carbohydrate, 1.5 g/b.w. protein and 0.9 g/b.w. fat. Additionally, participants were instructed to consume a standardized breakfast 2 h before the rectangular test, which consisted of 1.3 g/b.w. carbohydrate, 0.43 g/b.w. protein and 0.57 g/b.w. fat.

2.4. Test

2.4.1. Medical exam

The medical exam included a medical history, resting electrocardiogram and medical examination (auscultation, blood pressure, etc.) to confirm that the participants were healthy before they were enrolled in the study.

2.4.2. Blood samples

Venous blood was collected into one 3.0 mL ethylenediaminetetraacetic acid (EDTA) tube for hemogram and another 3.5 mL polyethylene terephthalate (PET) tube for overall health analysis. Red blood cell count was carried out in an automated Cell-Dyn 3700 analyzer (Abbott Diagnostics, Chicago, IL, USA) using internal (Cell-Dyn 22) and external (Program of Excellence for Medical Laboratories-PEML) controls. Estimated values of erythrocytes, hemoglobin, hematocrit and hematimetric indexes were obtained. The blood extraction was performed by a registered nurse, the results are shown in Table 1.

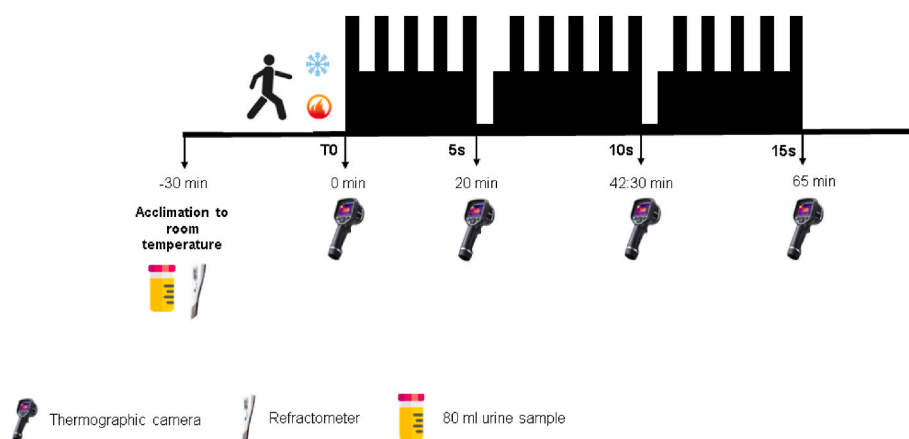


Fig. 1. Protocol for visits 3 and 4, which include a rectangular test at normal (17.5 °C) and high (28.2 °C) temperatures.

Table 1

General baseline characteristics of the race walkers.

Characteristics	
Age (years)	29.0 (4.58)
Body mass (kg)	68.6 (3.67)
Height (cm)	182.0 (3.06)
BMI (kg·m ⁻²)	23.1 (1.53)
BF (%)	6.80 (0.79)
MM (kg)	34.8 (1.82)
VO _{2MAX} (mL·kg ⁻¹ ·min ⁻¹)	55.0 (6.24)
Hct (%)	43.1 (1.68)
Ert (10 ⁶ μL ⁻¹)	4.83 (0.45)
Hb (g·dL ⁻¹)	14.9 (0.50)
MCV (fl)	90.0 (6.16)
MCH (pg)	31.3 (2.50)
MCHC (g·dL ⁻¹)	34.5 (0.92)
GOT (U/L)	29.4 (7.86)
GPT (U/L)	27.1 (9.56)
GAMMA GT (U/L)	19.1 (0.80)

Values are expressed as mean (standard deviation (SD)). BMI = body mass index; BF = body fat (Yuhasz formula); Ert = erythrocytes; Hb = hemoglobin; Hct = hematocrit; GAMMA GT = gamma-glutamyl transferase; GOT = aspartate aminotransferase; GPT = alanine aminotransferase; MCH = mean corpuscular hemoglobin; MCHC = mean corpuscular hemoglobin concentration; MCV = mean corpuscular volume; MM = muscle mass; VO_{2max} = maximum oxygen volume.

2.4.3. Incremental test

An incremental maximal test was performed on a treadmill (Technogym Run Excite Med., Cesena, Italy) using a metabolic cart (Metyzer 3B, Leipzig, Germany) (1029mBar) to determine VO_{2PEAK} in race walking. The test started with a 5 min of warm up at 5.0 km/h, following by 2 min steps since 9 km/h with 1 km/h of increments until technical or physiological exhaustion. The data from this test were used to establish the working zones for the rectangular test.

2.4.4. Rectangular test

Before testing, urine specific gravity (USG) was analyzed using a digital Atago PEN-Urine S.G. refractometer (Atago Co., LTD Tokyo, Japan) to check for hydration status. If athletes were not in the normal USG range (1.002–1.028), they were hydrated to this level. The rectangular test was performed on a treadmill (Technogym Run Excite Med., Cesena, Italy) (1029 mBar) where the race walkers performed 15 sets of 2 min at high intensity (14.5 km/h = 90–95% of VO_{2PEAK}) and 2.5 min at moderate intensity (11.5 km/h = 70–75% VO_{2PEAK}) of recovery between sets. After the 5s and 10s sets the race walkers did 1 min of rest followed by 1.5 min at 11.5 km/h and continuing with the 2 min at 14.5 km/h series (Fig. 1). Blocks of 5 series were performed, where after each block

they got off the treadmill quickly to take the temperature with the thermographic camera (Fig. 1).

2.4.5. Anthropometry

A certified ISAK Level-1 researcher performed the anthropometric measurements (FJMN). Height and body weight were measured using a digital scale with a stadiometer for clinical use (SECA 780; Vogel & Halke GmbH & Co. Hamburg, Germany). Skinfold thickness was measured using Holtain Skinfold Calipers (Holtain, Ltd Crymych Pembrokehire, UK), in accordance with the International Society for the Advancement of Kinanthropometry guidelines (Stewart et al., 2011). Percentage of body fat was determined using the Faulkner equation (Faulkner, 1966), while percentage of muscle mass was calculated using the modified Matiegka equation (Norton et al., 2000). The sum of the eight skinfolds (triceps, subscapular, bicep, iliac crest, supraspinal, abdominal, thigh and calf) was also calculated.

2.4.6. Thermography protocol

Before the thermographic measurements, all participants were acclimatized to the lab environment (60 m²) for a period of 15–20 min at the assigned norm temperature (16.9–18.1 °C; mean 17.5 °C) or mid (27.8–28.5 °C; mean 28.2 °C). The humidity of the room was never higher than 40 ± 0.8%, and the atmospheric pressure was always equal to 1ATM, which agrees with previous studies (Bruning et al., 2013; Ganio et al., 2009; Moreira et al., 2017). No electronic devices were present near the measurement point, and light and heat sources were kept away from the measurement site to avoid thermographic acquisition interference. During this acclimatization period, as suggested by other authors, patients underwent a body temperature check (with a digital thermometer; Berrcom, JXB-178) to rule out changes in basal temperature, and weight, height and BMI was determined to comply with the TISEM protocol (Cabizosu et al., 2019, 2020; Moreira et al., 2017).

The thermograph used was the Flir E75 model (FLIR Systems, Inc., Madrid, Spain), infrared resolution: 320 × 240 pixels, thermal sensitivity <0.04 °C and with fixed thermal recordings from 20 °C to 120 °C. The emissivity was 0.98, as suggested by the manufacturer, and this amount was corroborated in other studies (Bernard et al., 2013; Steketee, 1973; Tomkinson and Olds, 2007). To ensure the machine's correct configuration to the room, it was switched on 1 h before the first recording and placed on a tripod at an inclination of 10–15° and 1 m away from the patient's measurement site.

The race walkers wore sneakers, shorts but no shirt and were positioned a 1 cm artificial turf pad. For all measurements, the regions of interest (ROIs) in the body were defined using conventional anatomical and scientific bibliography (Bouzas Marins et al., 2014; Elsharkawy et al., 2019; Hellinger et al., 2016; Moore and Dalley, 1999) (Fig. 2). A

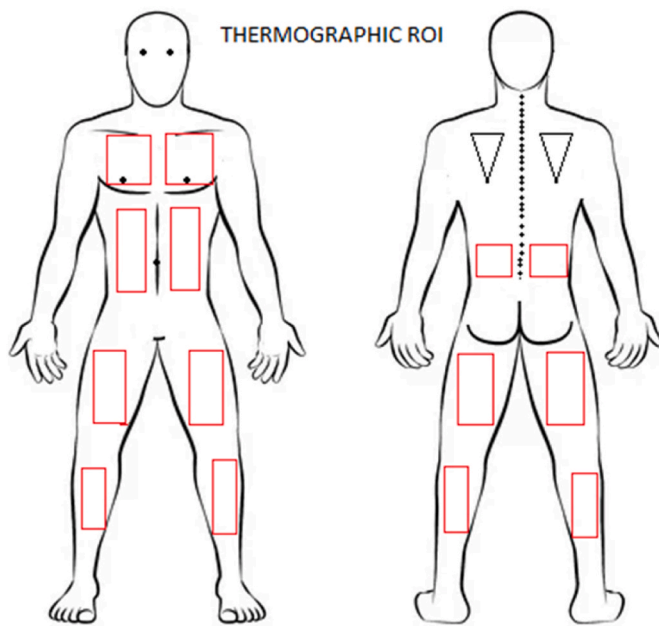


Fig. 2. Representation of anatomical ROI self-made image.

total of 14 regions, 7 in each hemibody were thermographically measured and analyzed. To guarantee a depth analysis of images, the ROIs were marked on the digitized photo and the thermographic image was subsequently selected. Anteriorly, the pectoral and abdominal ROIs were selected. The pectoral region was segmented in rectangular from the lateral border of the sternum to the lateral border of the chest. Superiorly and inferiorly, from the lower border of the clavicle to the distal limit of the chest. The abdominal region was defined from the lateral border of the alba line to the anterior superior iliac spine with a rectangular ROI, setting the upper limit at the xiphoid appendix. For the anterior thigh, the proximal ROI began 15 cm below the anterior superior iliac spine and extended to 2 cm above the upper border of the patella (quadriceps region). For the anterior leg, the ROIs started 2 cm below the inferior border of the patella up to 2 cm above the tibial malleolus (tibia region). Posteriorly, the trunk was segmented using a rectangular ROI from the sides of the transverse lines from T12/L1 to S1, marking the lateral at the iliac crest. The posterior thigh began immediately below the gluteal fold and extended to the upper edge of the Popliteal fossa (hamstring region). In the anterior view of the leg the ROIs starts 2 cm below the inferior border of the patella up to 2 cm higher than the tibialis malleolus (tibialis region), while in the posterior leg was identified from the inferior border of the Popliteal fossa up to 8 cm above the inferior border of the calcaneus (gastrocnemius region).

Two researchers with more than five years of experience in thermography recorded and analyzed images of the whole body in a blinded manner to ensure for reliability. Image processing was carried out using the Flir IR research programme.

2.5. Statistical analysis

IBM Social Sciences software (SPSS, v.21.0, Chicago, IL, USA) was used for statistical analysis. Data are presented as mean $\pm$ SD. Homogeneity and normality of the data were checked with the Levene and Shapiro–Wilk tests, respectively. For each ROI variables, a two-way repeated-measures ANOVA with time factor (T0 vs. 5s vs. 10s vs. 15s) and group factor (17 vs. 28 °C) was performed. For VO_2 variables, repeated-measures two-way ANOVA with time factor (1s vs. 5s vs. 10s vs. 15s) and group factor (17 vs. 28 °C) was applied. Tukey's post hoc analysis was carried out if significance was found in the ANOVA models. Partial eta squared (η^2) was also calculated as effect size for time, group

and time $\times$ group interaction of all variables in the ANOVA analysis. Partial eta square thresholds were used as follow: <0.01 , irrelevant; ≥ 0.01 , small; ≥ 0.059 , moderate; ≥ 0.138 , large (Cohen, 2013). Cohen's d effect sizes (ES) (95% confidence interval) were calculated for comparisons between groups for VO_2 . Threshold values for ES statistics were as follows: >0.2 small, >0.5 moderate, >0.8 large (Cohen, 2013). Significance level was set at $p \leq 0.05$.

3. Results

Table 2 and Fig. 3 show the changes in body temperature measured by thermography in the chest, abdomen and back, anatomically segmented into left and right of the international race walkers. During the rectangular test, the temperature of the right and left chest area was higher at 28.2 °C compared to 17.5 °C (T0: 6.1% and 6.8%; 5s: 6.2% and 5.9%; 10s: 7.5% and 6.2%; 15s: 8.9% and 8.8%; $p \leq 0.05$, respectively). However, we observed reverse trends after the tenth set (10s) in the left chest area, where the temperature increased with 28.2 °C and decreased with the 17.5 °C condition. On the other hand, the right pectoral muscle temperature was stable with 28.2 °C, whereas at 17.5 °C there was a decrease from T0 to 15s during the rectangular test. In addition, a group $\times$ time interaction from the ANOVA analysis was detected on both sides of the chest.

At the abdominal level, the dynamics of the thermographic profile were similar but there was an increase of the temperature (T0: 5.5%; 5s: 8.3%; 10s: 12.5% and 15s: 13.2%; $p \leq 0.05$; respectively) in the left abdominal area with 28.2 °C compared to 17.5 °C in throughout the rectangular test. However, the right abdomen had a temperature increase from 5s to 15s (8.8%, 12.2%, 12.5%; $p \leq 0.05$, respectively) when comparing the different temperature conditions during the rectangular test (Table 2 and Fig. 3). It was also observed a descending dynamic in temperature on both sides of the abdomen, but stabilizing the temperature earlier in the intervention at 28.2 °C than at 17.5 °C. In addition, an ANOVA analysis of group $\times$ time interaction was detected on both sides of the abdomen (right, $p = 0.010$ and left, $p = 0.011$).

On the posterior side, the temperature evolution during the rectangular test was similar in both conditions, but with significant differences between interventions in 10s and 15s (10.8%; 11.1%, all $p \leq 0.05$; respectively) on the right side, with an upward trend in 15s (11.1%, $p = 0.056$) on the left side with 28.2 °C compared to 17.5 °C in race walkers during the rectangular test (Table 2 and Fig. 3). In addition, a group $\times$ time interaction was detected by ANOVA only on the left side of the back.

In the quadriceps area, a downward dynamic was observed on both sides and between conditions, but there were only significant differences between groups at 10s (right: 10.7% and left: 11.1%; $p < 0.05$, respectively) (Table 2 and Fig. 4).

On the other hand, the temperature of the right and left hamstrings area was higher at 28.2 °C compared to 17.5 °C (T0: 5.7% and 7.5%; 5s: 7.3% and 5.9%; 10s: 9.4% and 9.7%; 15s: 12.0% and 12.0%; all $p < 0.05$, respectively) during the rectangular test with similar development of the temperature during rectangular test in international race walkers (Table 2 and Fig. 4). However, the analysis of group $\times$ time interaction by ANOVA showed a trend ($p = 0.053$) in the right hamstring area.

At the tibial level, the temperature remained stable throughout the rectangular test at 28.2 °C, however, at 17.5 °C, there was a decrease in temperature from T0 to 10s and maintained at 15s. When comparing the two temperature conditions, significant differences were found at 5s, 10s and 15s on both sides (right: 8.6%, 10.4%, 10.4% and left: 8.3%, 9.8%; 9.3%, respectively), and at T0 only in the right-side (6.5%), during the rectangular test (Table 2 and Fig. 5).

In the left calf, an inverse evolution in temperature was found during the rectangular test with no significant changes when comparing the conditions group. Alternatively, we found significant differences throughout the rectangular test on both sides (right: 6.1%, 7.2%, 8.9%,

Table 2

Differences in the thermoregulation pattern measured by thermographic camera between 17.5 °C and 28.2 °C during a rectangular test in international race walkers. Values are mean (SD).

		Baseline	5s	10s	15s	Time p-value	Group p-value	Interaction time x group p-value
RC	17.5 °C	32.7 (0.70)	32.1 (0.50)	32.1 (0.47)	31.6 (0.67)	0.503	0.007	0.047
	28.2 °C	34.7 (0.35)	34.1 (0.72)	34.5 (0.67)	34.4 (0.90)			
	p-value	0.007	0.007	0.003	0.002			
	η^2					0.305	0.986	0.710
LC	17.5 °C	32.2 (0.17)	32.4 (0.06)	32.4 (0.29)	32.0 (0.75)	0.973	0.005	0.006
	28.2 °C	34.4 (0.36)	34.3 (0.21)	34.4 (0.70)	34.8 (0.85)			
	p-value	0.003	0.006	0.005	0.001			
	η^2					0.035	0.990	0.860
RA	17.5 °C	32.7 (0.95)	29.8 (0.68)	28.7 (1.62)	28.9 (1.62)	0.009	0.014	0.010
	28.2 °C	34.4 (0.06)	32.2 (0.61)	32.2 (1.23)	32.5 (1.56)			
	p-value	0.094	0.030	0.007	0.006			
	η^2					0.835	0.972	0.830
LA	17.5 °C	32.6 (0.92)	30.0 (0.83)	28.8 (1.61)	28.8 (1.44)	0.014	0.008	0.011
	28.2 °C	34.3 (0.17)	32.5 (0.64)	32.4 (1.21)	32.6 (1.55)			
	p-value	0.040	0.005	< 0.001	< 0.001			
	η^2					0.807	0.985	0.827
RB	17.5 °C	31.6 (0.46)	30.1 (1.69)	30.6 (0.86)	30.6 (0.21)	0.356	0.025	0.069
	28.2 °C	33.9 (0.35)	33.0 (1.25)	33.9 (0.64)	34.0 (1.06)			
	p-value	0.135	0.072	0.049	0.047			
	η^2					0.395	0.951	0.669
LB	17.5 °C	31.5 (0.64)	30.4 (1.69)	30.8 (0.50)	30.5 (0.12)	0.566	0.027	0.044
	28.2 °C	33.8 (0.36)	33.0 (1.25)	33.8 (0.72)	33.9 (1.04)			
	p-value	0.136	0.106	0.072	0.053			
	η^2					0.270	0.947	0.717
RQ	17.5 °C	31.3 (0.76)	30.1 (1.95)	29.1 (2.95)	29.2 (3.45)	0.175	0.031	0.719
	28.2 °C	33.5 (0.90)	32.7 (1.00)	32.2 (2.26)	31.5 (2.18)			
	p-value	0.163	0.079	0.035	0.130			
	η^2					0.537	0.940	0.188
LQ	17.5 °C	31.4 (0.91)	30.1 (2.49)	28.7 (2.90)	28.6 (3.40)	0.073	0.030	0.673
	28.2 °C	33.3 (1.06)	32.6 (1.21)	31.9 (2.19)	31.3 (2.20)			
	p-value	0.292	0.118	0.040	0.090			
	η^2					0.661	0.941	0.212
RH	17.5 °C	31.2 (0.12)	30.3 (0.70)	29.9 (1.03)	29.2 (1.80)	0.216	0.002	0.053
	28.2 °C	33.0 (0.80)	32.5 (0.46)	32.7 (1.56)	32.7 (1.40)			
	p-value	0.013	0.004	< 0.001	< 0.001			
	η^2					0.500	0.995	0.699
LH	17.5 °C	30.8 (0.38)	30.5 (1.10)	29.8 (1.04)	29.1 (1.51)	0.317	0.002	0.084
	28.2 °C	33.1 (0.40)	32.3 (0.57)	32.7 (1.74)	32.6 (1.35)			
	p-value	0.005	0.017	< 0.001	< 0.001			
	η^2					0.422	0.995	0.645
RT	17.5 °C	30.9 (0.81)	30.2 (0.70)	29.7 (1.06)	29.8 (1.25)	0.620	0.006	0.282
	28.2 °C	32.9 (0.60)	32.8 (0.46)	32.8 (1.00)	32.9 (1.22)			
	p-value	0.027	0.005	0.001	0.001			
	η^2					0.240	0.989	0.447
LT	17.5 °C	30.9 (0.92)	30.3 (0.76)	29.6 (0.85)	30.1 (1.15)	0.442	0.010	0.348
	28.2 °C	32.7 (0.75)	32.8 (0.40)	32.5 (0.89)	32.9 (1.31)			
	p-value	0.071	0.010	0.004	0.005			
	η^2					0.341	0.979	0.400
RCa	17.5 °C	31.0 (0.25)	30.4 (0.70)	30.3 (1.37)	29.9 (1.40)	0.815	0.005	0.043
	28.2 °C	32.9 (0.67)	32.6 (0.87)	33.0 (1.40)	33.3 (1.27)			
	p-value	0.003	0.002	< 0.001	< 0.001			
	η^2					0.136	0.991	0.719
LCa	17.5 °C	30.5 (0.81)	30.7 (1.00)	30.3 (1.51)	30.1 (1.44)	0.989	0.004	0.101
	28.2 °C	33.0 (0.27)	32.4 (0.91)	32.8 (1.47)	33.2 (1.35)			
	p-value	< 0.001	0.010	< 0.001	< 0.001			
	η^2					0.019	0.991	0.620

In bold are p-values = ≤ 0.05 and trends between 0.05 and 0.07. LC = left chest; RP = right chest; RA = right abdomen; LA = left abdomen; RB = right back; LB = left back; RQ = right quadriceps; LQ = left quadriceps; RH = right hamstring; LH = left hamstring; RT = right tibial; LT = left tibial; RCa = right calf; LCa = left calf.

11.3% and left: 8.2%, 5.5%; 8.3%, 10.3%, respectively) at 28.2 °C when compared to 17.5 °C in international race walkers (Table 2 and Fig. 5). ANOVA only detected a group $\times$ time interaction in the right calf area.

During the rectangular test, although the ANOVA analysis showed no significant differences in the group $\times$ time interaction, there were significant differences in the between-group comparison. In addition,

Cohen's effect size was calculated for these variables, which showed a large effect size after 10s and 15s (Table 3 Fig. 6A). Fig. 6B shows how oxygen consumption remained stable from 5s onwards and the evolution of the skin temperature of the analyzed areas on the lower limbs decreased until the end of the test. Fig. 6C demonstrates that the temperature was also stable from 5s, but the skin temperature of the

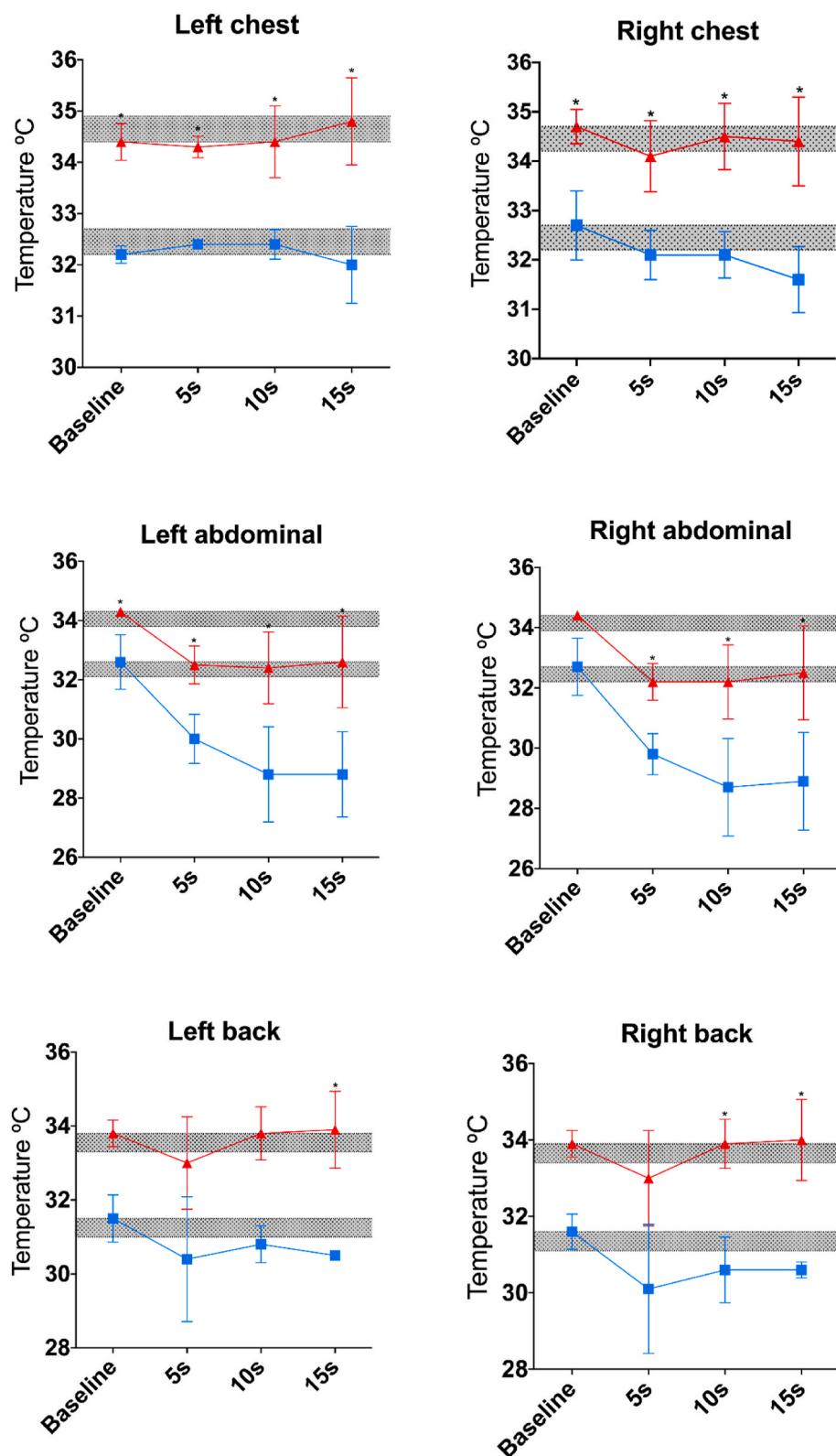


Fig. 3. Changes in skin temperature on the chest, abdomen and back measured by thermographic camera during the rectangular test at 17.5 and 28.2 °C. The blue square refers to the 17.5 °C intervention and the red triangles to the 28.2 °C intervention. The dark colour band shows a 0.5 °C change in temperature from baseline values. * = ≤ 0.05 significant difference between groups. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

muscular area of the lower limbs decreased from T0 to 5s. However, the evolution of the temperature was different in the quadriceps than in the hamstrings and calf muscles until the end of the test.

4. Discussion

The main purpose of this study was to determine the thermoregulatory profile of different anatomical areas (anterior-posterior and right-left) using infrared thermography, which is a novel technology in sport practice, in international race walkers. The main findings from this

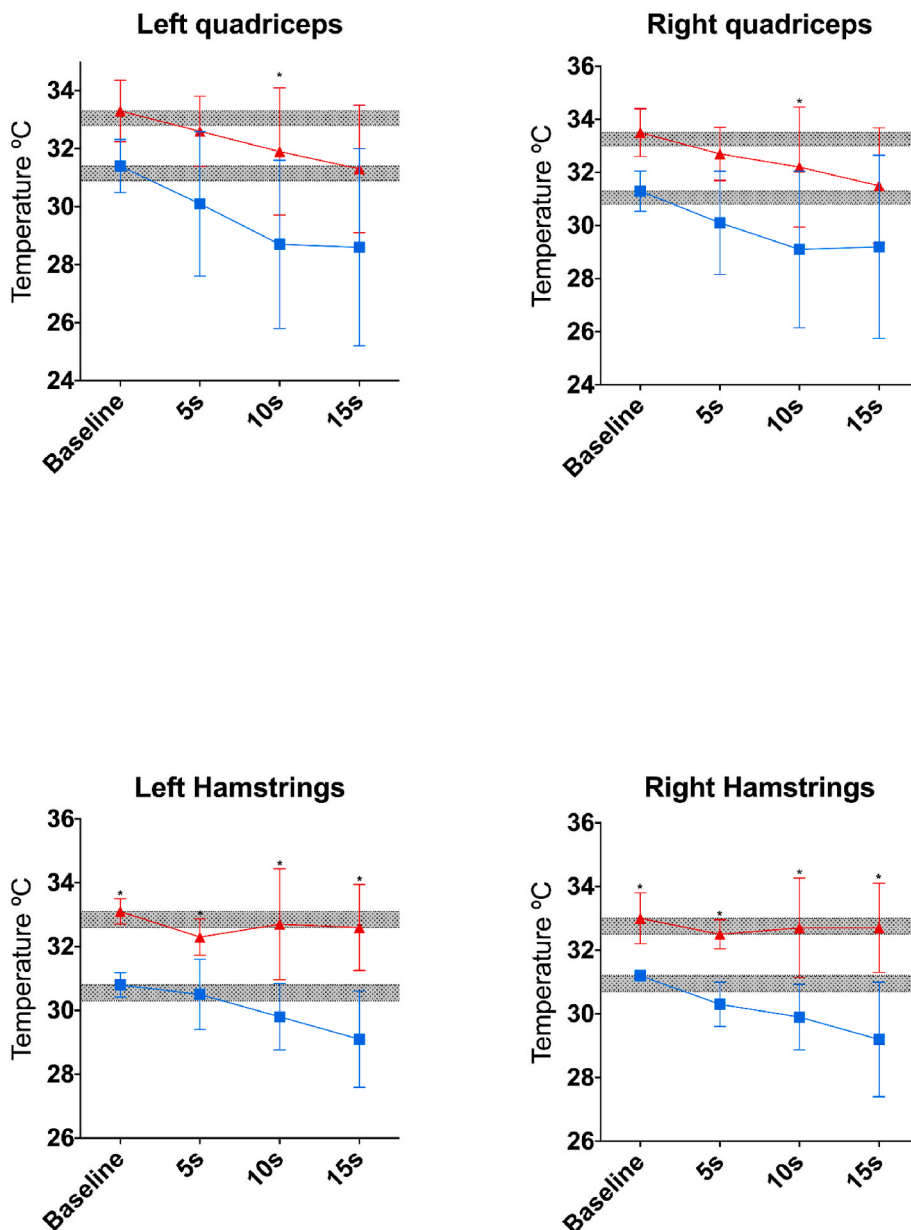


Fig. 4. Changes in skin temperature in the quadriceps and hamstrings measured by thermographic camera during the rectangular test at 17.5 and 28.2 °C. The blue square refers to the 17.5 °C intervention and the red triangles to the 28.2 °C intervention. The dark colour band shows a 0.5 °C change in temperature from baseline values. * = ≤ 0.05 significant difference between groups. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

study were that, at mid temperature (28.2 °C), there was a temperature increase on both sides of the chest, hamstring and calf compared to 17.5 °C throughout the rectangular test. At the abdominal level, differences were found on the left side throughout the rectangular test, however on the right side of the abdomen no significant differences were found at T0 between the two temperature conditions. On the other hand, in the tibial area, an increase was found on the right side throughout the rectangular test, however on the left side of the tibia, no significant differences were observed at T0 when comparing between 28.2 °C and 17.5 °C in international race walkers.

The organism that establishes the temperature ranges in which heat stress occurs is the World Meteorological Organization in cooperation with other institutions, and they generate the Universal Thermal Climate Index (UTCI) where they classify the different temperature ranges according to thermal heat stress: “No thermal stress” (+9/+26), “Moderate heat stress” (+26/+32), “Strong heat stress” (+32/+38), “Very strong heat stress” (+38/+46) and “Extreme heat stress” (>+46) (Blażejczyk et al., 2010). Based on the UTCI, we can say that the temperature increases from 17.5 °C (no thermal stress) to 28.2 °C (moderate heat

stress) in international walkers during a rectangular test produces an increase in temperature both at T0 and during the rectangular test on the skin surface of the body, but not in a similar way for all anatomical areas. De Korte et al. (de Korte et al., 2021) evaluated Ts in “no thermal stress” (15.9 ± 1.2 °C, relative humidity (RH) $55 \pm 6\%$) and moderate heat stress (31.6 ± 1.0 °C, RH $74 \pm 5\%$) environmental conditions during a rectangular test in elite athletes preparing for the Tokyo 2021 Olympic Games. This author found that an increase of 15.7 °C and 19% RH produced an increase in Ts of 3.2 °C on mean (neck, left hand, right shoulder, right shin) at rest in endurance, mixed, power and skill athletes. After exercise (incremental until exhaustion on the cycloergometer) an increase of the Ts of 1.3 °C on mean was also observed in the different disciplines evaluated (de Korte et al., 2021). Furthermore, the changes in body temperature were coupled with an increase in gastrointestinal T° after exercise of 1 °C on average (+1.4 °C in endurance athletes), a decrease in time to exhaustion of 26% (–27% in endurance athletes) and in power output of 38 W (–49 W in endurance athletes) in the incremental test when comparing the different environmental conditions. It should be mentioned that the Ts were measured

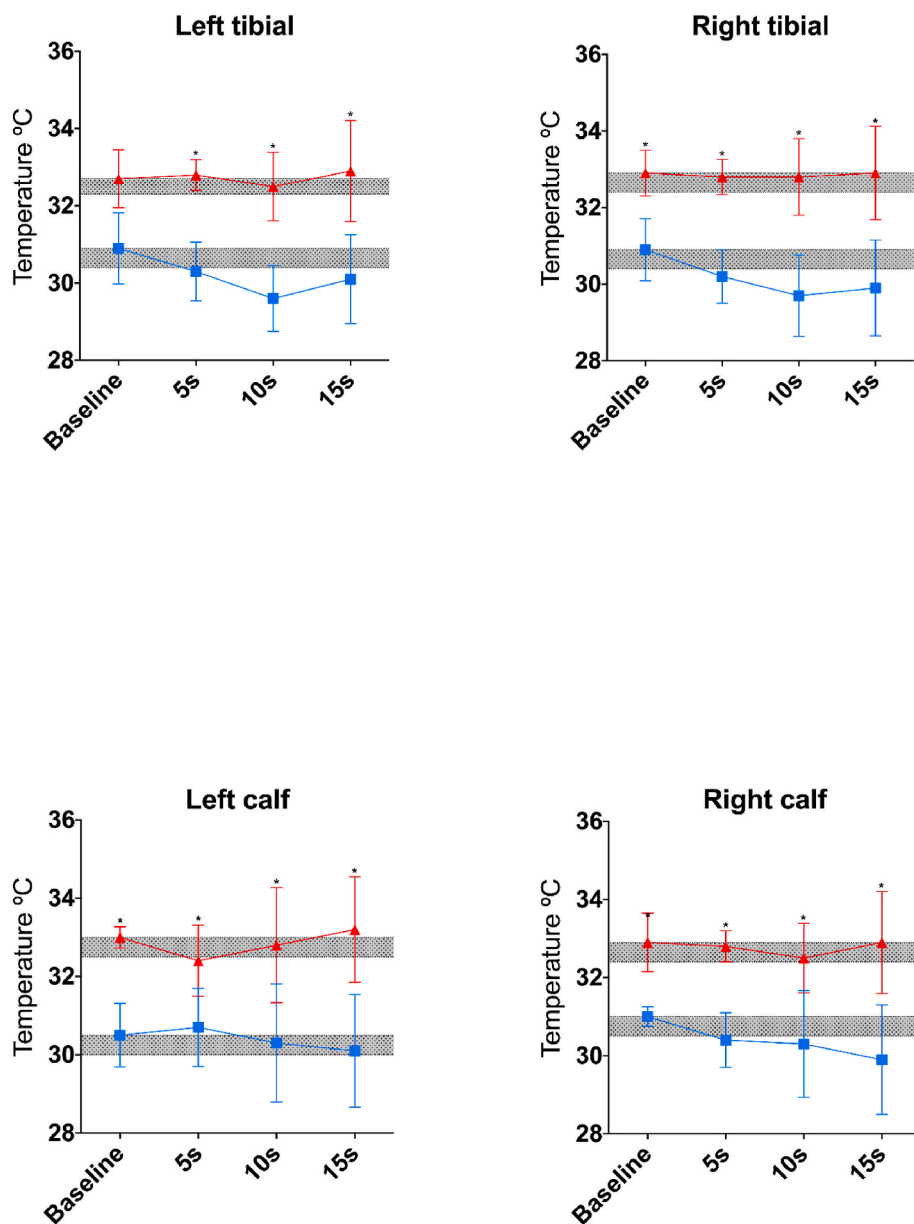


Fig. 5. Changes in skin temperature at the tibial and calf muscles measured by thermographic camera during the rectangular test at 17.5 and 28.2 °C. The blue square refers to the 17.5 °C intervention and the red triangles to the 28.2 °C intervention. The dark colour band shows a 0.5 °C change in temperature from baseline values. * = ≤ 0.05 significant difference between groups. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 3

Differences in oxygen consumption measured by indirect calorimetry between 17 °C and 28 °C during a rectangular test in international race walkers. Values are mean (SD).

		1s	5s	10s	15s	Time p-value	Group p-value	Interaction time x group p-value
VO ₂	17.5 °C	3.76 (0.30)	3.93 (0.23)	3.92 (0.28)	3.93 (0.33)	0.169	0.022	0.853
	28.2 °C	3.65 (0.31)	3.81 (0.39)	3.72 (0.23)	3.79 (0.31)			
	p-value	0.819	0.756	0.264	0.621			
	ES	0.61	0.72	2.18	3.28			
					η^2	0.543	0.956	0.115

In bold are p-values = ≤ 0.05 and trends between 0.05 and 0.07. VO₂ = oxygen uptake.

by a sensor installed on the skin's surface (iButton DS1922L, Dallas Semiconductor Corp, USA) (de Korte et al., 2021).

On the other hand, Racinais et al. (2021) evaluated changes in Ts (thermography) and core temperature (Tc) in international 20 and 50 km race walkers at the Doha 2019 IAAF World Athletics Championships. The environmental conditions in which this test was performed in 20 (women: 31.6 °C and 77% RH; men: 32.7 °C and 81% RH) and 50 km (women: 31.1 °C and 76% RH; men: 31.1 °C and 76% RH) (Racinais

et al., 2021), were under moderate thermal stress according to the UTCI. The mean Ts (head, neck, trunk, shoulder, upper and lower arm, upper and lower leg) pre-competition was 32.7 °C (regardless of the event), which is below our values (33.6 °C, mean of the evaluated ROIs) observed pre rectangular test at an environmental condition of 28.2 °C. But we have to keep in mind that our study was conducted in a laboratory and the other one in an outdoor environment.

A very interesting finding by Racinais et al. (2021) is that the

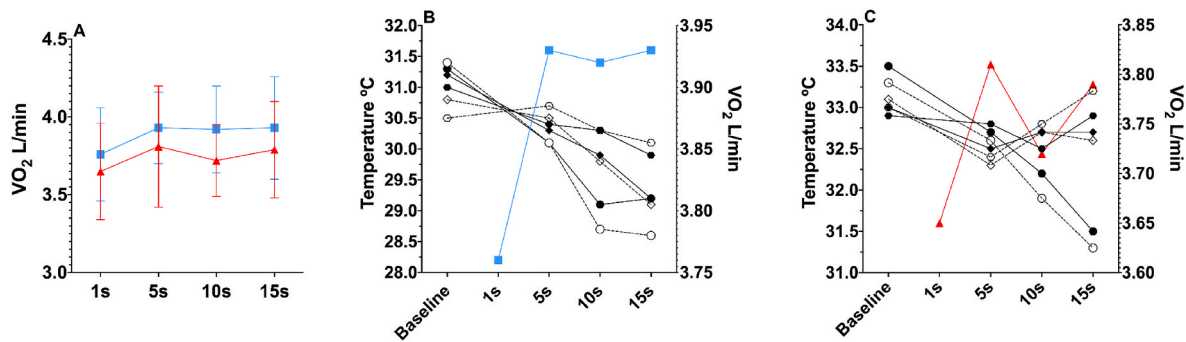


Fig. 6. A) Changes in oxygen consumption during the rectangular test at 17.5 °C and 28.2 °C. B) Changes in oxygen consumption at 17.5 °C and temperature evolution in the selected area of the quadriceps, hamstrings and calf on both sides, during the rectangular test. C) Changes in oxygen consumption at 28.2 °C and temperature evolution in the selected area of the quadriceps, hamstrings and calves on both sides, during the rectangular test. Description of the figures: dark circle (right quadriceps), dark rhombus (right hamstring), dark pentagon (right calf), transparent circle (left quadriceps), transparent rhombus (left hamstring) and transparent pentagon (left calf).

pre-race skin Ts of the disqualified athletes was higher than that of the finishers (33.8° versus 32.6 °C, $p = 0.014$). In addition, pre-competition Ts correlated (albeit with a small/moderate association) with faster running ($r = 0.32$, $p = 0.046$). However, pre-race Tc was not statistically related to performance or did not finish. Therefore, training and competing under conditions of moderate heat stress is sufficient to produce an increase in Ts (rest and after exercise to exhaustion), Tc and decreased performance. This justifies that sports nutritionists should consider nutritional and supplementation strategies pre, during and post-competition aimed at decreasing the effects of moderate heat stress. This situation shows the importance of knowing the Ts in different situations, especially as it is a non-invasive and quick technique to perform.

The problems of thermal stress are due to temperature increases under hot conditions, mainly caused by convective heat transfer (mass flow) from the dynamically contracting muscles of the limbs to the core of the body and to the surrounding subcutaneous tissues of the limbs (according to Fick's principle) (González-Alonso et al., 2000b). This depends on the blood flow in the tissues and the temperature difference of the arteriovenous blood (González-Alonso et al., 2000b). In addition, it is known that prolonged whole-body exercise in hot conditions is associated with increased heart rate, cutaneous and central hyperthermia. (González-Alonso et al., 2000a; Montain and Coyle, 1992).

However, recent studies indicate that cutaneous hyperthermia, secondary to resistance exercises, is involuntarily, counteracted by the central nervous system. Through the mechanism of sweating and heat release, within the imbalance and rebalancing of the sympathetic nervous system in relation to the parasympathetic (Sillero-Quintana et al., 2022). Thus, environmental conditions and the type and intensity of exercise determine the thermal and metabolic demands on systemic and local blood flow, while the duration of exercise defines the regulatory alterations and limitations of cardiovascular function over time (González-Alonso et al., 2008; Mortensen et al., 2008). Disruption of these mechanisms would lead to excessive heat accumulation, compromising the physiological function of cellular and organ systems, which can lead to a decrease in athletic performance (González-Alonso et al., 2008).

At the chest level, there was a 0.4 °C increase in left chest temperature from 10s to 15s, whereas the right chest did not undergo temperature changes at 28 °C. Also, there were differences in both temperature conditions by to -2.8 °C on both sides of the chest during rectangular test. At 28.2 °C, the increase in temperature at the end of the rectangular test may be due to augmented heat production in the exercising muscles, which is not locally dissipated and returns to the core via blood flow (González-Alonso et al., 2008).

At the abdominal level, the thermoregulatory pattern was distinctive in relation to other anatomical areas. On both sides, there was a decrease

in temperature from T0 to 5s, which then remained constant until the end of the test at 28.2 °C. However, at 17 °C, the temperature decrease was longer from T0 to 10s, from which did not change until the end of the rectangular test. There were significant differences between both conditions and sides, however less at T0 in the left abdomen. In line with our results, Priego et al. (Quesada et al., 2016) also observed a decrease in abdominal temperature in cyclists after a constant load test (temperature: 21.8 ± 0.7 °C and relative humidity $39.4 \pm 4.5\%$) at 35 and 50% of maximum power. This may be due a reduction in splanchnic blood flow of 39% and liver blood flow of 14% during peak exercise (Froelich et al., 1988) with the corresponding drop in temperature. Reduced splanchnic blood flow is due to the release of norepinephrine near sympathetic nervous system adrenoreceptors that induces splanchnic vasoconstriction, thereby increasing total splanchnic vascular resistance (Gil et al., 1998; Mensink et al., 2011; Wright et al., 2011). In addition, blood is rapidly redistributed from the splanchnic area to be used for perfusion of tissues with increased activity during exercise, such as the heart, lungs, active muscle and skin (van Wijck et al., 2012). Therefore, future studies could examine whether thermography is a valid method to assess the modulation of blood flow at the intestinal level, which is important in endurance athletes.

In the quadriceps area, at 28.2 °C, there was a continuous decrease in temperature on both sides from T0 to the end of the rectangular test. However, at 17.5 °C, there was also a continuous decrease in temperature from T0 to 10s, from which remained unchanged until the end of the rectangular test. One should bear in mind that there is lower muscle activation in the quadriceps compared to the hamstrings (0% slope) at 9 km h⁻¹ in race walkers (Padulo et al., 2013). Also, exercise and temperature increases induces the production of nitric oxide, which in turn vasodilates blood vessels (Schmidt et al., 2020). Thus, together, these physiological phenomena (low heat production and high blood flow from the quadriceps to the body core) are likely responsible for the decrease in temperature in both conditions in the quadriceps.

Interestingly, the temperature remained constant on both sides of the hamstring area during the rectangular test at 28.2 °C, but the temperature continued to decrease on both sides from T0 to the end of the test at 17.5 °C. Contrary to the quadriceps, race walkers have greater hamstring muscle activation (Padulo et al., 2013), which would entail a greater production of energy and heat, as well as higher blood flow (Schmidt et al., 2020). It appears that at 28.2 °C, there may have been a balance between heat production and heat output from the muscle and blood supply from the central zone (González-Alonso, 2012), which may explain the lack of temperature changes. However, the pronounced decrease from T0 to 15s to 17.5 °C on both sides of the hamstrings may be due to a combination of increased blood flow and an increased temperature gradient between the hamstring skin and the environment that enhances heat dissipation in this muscle area.

In the tibial area, the thermoregulatory dynamics were similar on both sides and in different conditions compared to the hamstring area. At 28.2 °C, we found no temperature changes on both sides of the tibial area, whereas, at 17.5 °C, we observed a decrease in temperature from T0 to 10s with no additional temperature change until the end of the rectangular test on both sides of the tibial area. Quesada et al. (2016) also found a decrease in the anterior tibial area when cyclists were tested during a constant load (at 35% and 50% of maximum power) posttest, coupled with a negative correlation with core temperature. This is due mainly to the substantial increase in core temperature that results in an increased sweating rate (Fujii et al., 2014) and, therefore, a more pronounced reduction in skin temperature can be observed if sweat evaporation is not affected. In addition, this mechanism helps to enhance the dissipation of core body heat from the body by increasing the body's heat gradient (Cuddy et al., 2014).

In the left calf there was a decrease of 0.6 °C from T0 to 5s and then an increase of 0.8 °C until the end of the rectangular test at 28.2 °C. However, in the right calf there was no change in temperature during the rectangular test. This temperature changes in the left calf could be explained by leg dominance, where there may have been less involvement of the left calf in the biomechanics of the race walkers at the start of the test with a greater involvement at the end of the test. This indicates an improvement in thermoregulation of the right calf at 28.2 °C. However, at 17 °C, the left calf showed a decrease of 0.6 °C from 5s to 15s, while the right calf showed a decrease of 1.1 °C from T0 to 15s, suggesting greater cooling and less temperature accumulation in the distal anatomical area.

During the rectangular test, VO_2 was slightly lower at the different time points (1s: 2.93%, 5s: 3.05%, 10s: 5.10% and 15s: 3.56%) at 28.2 °C than at 17 °C. Prior to our study, a strong correlation between a decrease in $\text{VO}_{2\text{MAX}}$ and an increase in skin and core temperature was established in triathletes and runners using an incremental test with exposure to high temperature (Arngrímsson et al., 2004). In this regard, Nybo et al. (2001) observed a 16% decrease in $\text{VO}_{2\text{MAX}}$ after warm-up, when the esophageal temperature was 39 °C and skin temperature was 37 °C, coupled with a halving of performance time during the constant load test. The mechanisms through which $\text{VO}_{2\text{MAX}}$ might be reduced in the heat is not yet known. But there is evidence that a lower arteriovenous oxygen difference and a reduction in systolic volume and oxygen pulse may be responsible for a reduction in $\text{VO}_{2\text{MAX}}$ at high temperatures (Arngrímsson et al., 2004).

The reduction of systolic volume in the heat could be caused by cutaneous vasodilatation, which produces an increase in venous volume and a decrease in central blood volume, ventricular filling pressure and end-diastolic volume (Rowell et al., 1966). In addition, the presence of dehydration would reduce blood volume and contribute to decreased ventricular filling pressure and end-diastolic volume (González-Alonso et al., 1995). On the other hand, higher sympathetic nervous system activity would increase systemic vascular resistance and heart rate (Kim et al., 1979). The lower maximal cardiac output would be associated with lower blood flow and oxygen delivery to active muscles, thereby limiting $\text{VO}_{2\text{MAX}}$.

According to these results, the mid temperature challenge and thermography, together, could be a useful tool to determine the level of activation, metabolic and functional response of the muscle system in professional race walkers. However, the small sample in this study is a limiting factor. Future studies of activation of the nervous, cardiovascular and musculoskeletal systems are needed, as it could influence the response to resistance exercise, which in turn can affect the optimization of workloads. This would help to understand how the different levels of functional activation in athletes could lead to different temperature responses of the skin surface, and could provide insight on discovering a better motor response. Recording the level of metabolic activation before, during and after exercise could be interesting to predict the athlete's response to resistance training. It would be interesting to associate these thermographic results with physiological effects of

workload performed, such as lactate levels, in a larger sample of specific athletes.

One of the main limitations of this study is the low sample size, as it is difficult to recruit international race walkers in the same geographical area. In addition, a small sample size may have reduced the statistical power, but we believe that the results obtained in the study may help to develop future research. It is important to note that there are few athletes who are at the World Champions level.

5. Conclusions

Our results confirmed that exposure to moderate heat stress can significant change in temperature patterns in professional race walkers at different times of physical exertion. In addition, we can observe that metabolic activation to exercise affects the response of skin surface temperature.

Future directions

Based on the results found in our study, future research could evaluate how higher temperatures than those used in this study affect the pattern of thermoregulation at the skin level. Also, it would be interesting to investigate how the use of ergogenic aids can modulate the thermoregulatory profile, in search of improved performance in hot conditions in race walkers or other endurance athletes, in which thermoregulatory mechanisms are key to the success of these athletes.

Authors' contributions

Conceptualization, F.J.M.N., C.M.-P. and P.E.A.; methodology, F.J.M.N., C.M.P. and P.E.A.; formal analysis, F.J.M.N., C.M.P. and A.C.; investigation, F.J.M.N., C.M.P. and A.C.; resources, F.J.M.N. and C.M.P.; data curation, F.J.M.N., C.M.P. and A.C.; writing—original draft preparation, F.J.M.N.; writing—review and editing, F.J.M.N., A.C. and C.M.P.; visualization, C.M.P.; supervision, C.M.P. and P.E.A.; project administration, C.M.P. and P.E.A.; funding acquisition, P.E.A. All authors read and approved the final manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

- Arngrímsson, S.A., Pettitt, D.S., Borrani, F., Skinner, K.A., Cureton, K.J., 2004. Hyperthermia and maximal oxygen uptake in men and women. *Eur. J. Appl. Physiol.* 92, 524–532.
- Baker, L.B., 2017. Sweating rate and sweat sodium concentration in athletes: a review of methodology and intra/interindividual variability. *Sports Med.* 47, 111–128.
- Bernard, V., Staffa, E., Mornstein, V., Bourek, A., 2013. Infrared camera assessment of skin surface temperature—effect of emissivity. *Phys. Med.* 29, 583–591.
- Binek, M., Drzazga, Z., Socha, T., Pokora, I., 2022. Do exist gender differences in skin temperature of lower limbs following exercise test in male and female cross-country skiers? *J. Therm. Anal. Calorim.* 147, 7373–7383.
- Błażejczyk, K., Bróde, P., Fiala, D., Havenith, G., Holmer, I., Jendritzky, G., Kampmann, B., 2010. UTCI—new index for assessment of heat stress in man. *Przegląd Geogr.* 82, 49.

- Bouzas Marins, J.C., de Andrade Fernandes, A., Gomes Moreira, D., Souza Silva, F., Magno A. Costa, C., Pimenta, E.M., Sillero-Quintana, M., 2014. Thermographic profile of soccer players' lower limbs. *Rev. Andal. Med. Deporte* 7, 1–6.
- Bruning, R.S., Dahmus, J.D., Kenney, W.L., Alexander, L.M., 2013. Aspirin and clopidogrel alter core temperature and skin blood flow during heat stress. *Med. Sci. Sports Exerc.* 45, 674–682.
- Cabizosu, A., Carboni, N., Martínez-Almagro Andreo, A., Vegara-Meseguer, J.M., Marziliano, N., Gea Carrasco, G., Casu, G., 2018. Theoretical basis for a new approach of studying Emery-Dreifuss muscular dystrophy by means of thermography. *Med. Hypotheses* 118, 103–106.
- Cabizosu, A., Carboni, N., Figus, A., Vegara-Meseguer, J.M., Casu, G., Hernández Jiménez, P., Martínez-Almagro Andreo, A., 2019. Is infrared thermography (IRT) a possible tool for the evaluation and follow up of Emery-Dreifuss muscular dystrophy? A preliminary study. *Med. Hypotheses* 127, 91–96.
- Cabizosu, A., Carboni, N., Martínez-Almagro Andreo, A., Casu, G., Ramón Sánchez, C., Vegara-Meseguer, J.M., 2020. Relationship between infrared skin radiation and muscular strength tests in patients affected by Emery-Dreifuss muscular dystrophy. *Med. Hypotheses* 138, 109592.
- Cohen, J., 2013. *Statistical Power Analysis for the Behavioral Sciences*. Routledge.
- Cuddy, J.S., Hailles, W.S., Ruby, B.C., 2014. A reduced core to skin temperature gradient, not a critical core temperature, affects aerobic capacity in the heat. *J. Therm. Biol.* 43, 7–12.
- de Korte, J.Q., Bongers, C., Hopman, M.T.E., Eijssvogels, T.M.H., 2021. Exercise performance and thermoregulatory responses of elite athletes exercising in the heat: outcomes of the thermo Tokyo study. *Sports Med.* 51, 2423–2436.
- Elsharkawy, H., El-Boghdady, K., Barrington, M., 2019. Quadratus lumborum block: anatomical concepts, mechanisms, and techniques. *Anesthesiology* 130, 322–335.
- Faulkner, J.A., 1966. Physiology of swimming. *Res Q* 37, 41–54.
- Fernandes Ade, A., Amorim, P.R., Brito, C.J., de Moura, A.G., Moreira, D.G., Costa, C.M., Sillero-Quintana, M., Marins, J.C., 2014. Measuring skin temperature before, during and after exercise: a comparison of thermocouples and infrared thermography. *Physiol. Meas.* 35, 189–203.
- Fernandes Ade, A., Amorim, P.R., Brito, C.J., Sillero-Quintana, M., Bouzas Marins, J.C., 2016. Regional skin temperature response to moderate aerobic exercise measured by infrared thermography. *Asian J. Sports Med.* 7, e29243.
- FLIR Systems | Sistemas de termografía, visión nocturna y cámaras infrarrojas [Internet], [cited 2017 May 22]. <http://www.flir.es/home/>.
- Froelich, J.W., Strauss, H.W., Moore, R.H., McKusick, K.A., 1988. Redistribution of visceral blood volume in upright exercise in healthy volunteers. *J. Nucl. Med.* 29, 1714–1718.
- Fujii, N., Honda, Y., Komura, K., Tsuji, B., Sugihara, A., Watanabe, K., Kondo, N., Nishiyasu, T., 2014. Effect of voluntary hypocapnic hyperventilation on the relationship between core temperature and heat loss responses in exercising humans. *J. Appl. Physiol.* 117, 1317–1324, 1985.
- Galloway, S.D.R., Maughan, R.J., 1997. Effects of ambient temperature on the capacity to perform prolonged cycle exercise in man. *Med. Sci. Sports Exerc.* 29.
- Ganio, M.S., Brown, C.M., Casa, D.J., Becker, S.M., Yeargin, S.W., McDermott, B.P., Boots, L.M., Boyd, P.W., Armstrong, L.E., Mares, C.M., 2009. Validity and reliability of devices that assess body temperature during indoor exercise in the heat. *J. Athl. Train.* 44, 124–135.
- Gerrett, N., Griggs, K., Redortier, B., Voelcker, T., Kondo, N., Havenith, G., 2018. Sweat from gland to skin surface: production, transport, and skin absorption. *J. Appl. Physiol.* 125, 459–469, 1985.
- Gil, S.M., Yazaki, E., Evans, D.F., 1998. Aetiology of running-related gastrointestinal dysfunction. How far is the finishing line? *Sports Med.* 26, 365–378.
- González-Alonso, J., 2012. Human thermoregulation and the cardiovascular system. *Exp. Physiol.* 97, 340–346.
- González-Alonso, J., Mora-Rodríguez, R., Below, P.R., Coyle, E.F., 1995. Dehydration reduces cardiac output and increases systemic and cutaneous vascular resistance during exercise. *J. Appl. Physiol.* 79, 1487–1496, 1985.
- González-Alonso, J., Mora-Rodríguez, R., Coyle, E.F., 2000a. Stroke volume during exercise: interaction of environment and hydration. *Am. J. Physiol. Heart Circ. Physiol.* 278, H321–H330.
- González-Alonso, J., Quistorff, B., Krstrup, P., Bangsbo, J., Saltin, B., 2000b. Heat production in human skeletal muscle at the onset of intense dynamic exercise. *J. Physiol.* 524 Pt 2, 603–615.
- González-Alonso, J., Crandall, C.G., Johnson, J.M., 2008. The cardiovascular challenge of exercising in the heat. *J. Physiol.* 586, 45–53.
- Hellinger, A., Roth, I., Biber, F.C., Frenken, M., Witzleb, S., Lammers, B.J., 2016. [Surgical anatomy of the abdominal wall]. *Chirurg* 87, 724–730.
- Hillen, B., Pfirrmann, D., Nägele, M., Simon, P., 2020. Infrared thermography in exercise physiology: the dawn of exercise radiomics. *Sports Med.* 50, 263–282.
- Kim, Y.D., Lake, C.R., Lees, D.E., Schuette, W.H., Bull, J.M., Weise, V., Kopin, I.J., 1979. Hemodynamic and plasma catecholamine responses to hyperthermic cancer therapy in humans. *Am. J. Physiol.* 237, H570–H574.
- Law, J., Chalmers, J., Morris, D.E., Robinson, L., Budge, H., Symonds, M.E., 2018. The use of infrared thermography in the measurement and characterization of brown adipose tissue activation. *Temperature (Austin)* 5, 147–161.
- Maughan, R.J., Shirreffs, S.M., 2010. Dehydration and rehydration in competitive sport. *Scand. J. Med. Sci. Sports* 20 (Suppl. 3), 40–47.
- Mensink, P.B., Moons, L.M., Kuipers, E.J., 2011. Chronic gastrointestinal ischaemia: shifting paradigms. *Gut* 60, 722–737.
- Montain, S.J., Coyle, E.F., 1992. Influence of graded dehydration on hyperthermia and cardiovascular drift during exercise. *J. Appl. Physiol.* 73, 1340–1350, 1985.
- Moore, K., Dalley, A., 1999. *Clinically Oriented Anatomy*. Lippincott Williams & Wilkins, Philadelphia. PJ Kelly, pp. 550–575.
- Moreira, D.G., Costello, J.T., Brito, C.J., Adamczyk, J.G., Ammer, K., Bach, A.J.E., Costa, C.M.A., Eglin, C., Fernandes, A.A., Fernández-Cuevas, L., Ferreira, J.J.A., Formenti, D., Fournet, D., Havenith, G., Howell, K., Jung, A., Kenny, G.P., Kolosovas-Machuca, E.S., Maley, M.J., Merla, A., Pascoe, D.D., Priego Quesada, J.I., Schwartz, R.G., Seixas, A.R.D., Selfe, J., Vainer, B.G., Sillero-Quintana, M., 2017. Thermographic imaging in sports and exercise medicine: a Delphi study and consensus statement on the measurement of human skin temperature. *J. Therm. Biol.* 69, 155–162.
- Mortensen, S.P., Damsgaard, R., Dawson, E.A., Secher, N.H., González-Alonso, J., 2008. Restrictions in systemic and locomotor skeletal muscle perfusion, oxygen supply and VO2 during high-intensity whole-body exercise in humans. *J. Physiol.* 586, 2621–2635.
- Mundial, A.M., 2019. Declaración de Helsinki de la AMM-Principios éticos para las investigaciones médicas en seres humanos.
- Norton, K., Whittingham, N., Carter, L., Kerr, D., Gore, C., Marfell-Jones, M., 2000. *Técnicas de medición en antropometría*. Antropométrica, pp. 23–60.
- Novotny, J., Rybarova, S., Zacha, D., Bernackikova, M., Ramadan, W.A., 2015. The influence of breaststroke swimming on the muscle activity of young men in thermographic imaging. *Acta Bioeng. Biomech.* 17, 121–129.
- Nuccio, R.P., Barnes, K.A., Carter, J.M., Baker, L.B., 2017. Fluid balance in team sport athletes and the effect of hypohydration on cognitive, technical, and physical performance. *Sports Med.* 47, 1951–1982.
- Nybo, L., Jensen, T., Nielsen, B., González-Alonso, J., 2001. Effects of marked hyperthermia with and without dehydration on VO(2) kinetics during intense exercise. *J. Appl. Physiol.* 90, 1057–1064, 1985.
- Padulo, J., Annino, G., Tihanyi, J., Calcagno, G., Vando, S., Smith, L., Vernillo, G., La Torre, A., D'ottavio, S., 2013. Uphill racewalking at iso-efficiency speed. *J. Strength Cond. Res.* 27, 1964–1973.
- Périard, J.D., Racinais, S., Sawka, M.N., 2015. Adaptations and mechanisms of human heat acclimation: applications for competitive athletes and sports. *Scand. J. Med. Sci. Sports* 25 (Suppl. 1), 20–38.
- Périard, J.D., Travers, G.J.S., Racinais, S., Sawka, M.N., 2016. Cardiovascular adaptations supporting human exercise-heat acclimation. *Auton. Neurosci.* 196, 52–62.
- Périard, J.D., Eijssvogels, T.M.H., Daanen, H.A.M., 2021. Exercise under heat stress: thermoregulation, hydration, performance implications, and mitigation strategies. *Physiol. Rev.* 101, 1873–1979.
- Priego Quesada, J.I., Carpes, F.P., Bini, R.R., Salvador Palmer, R., Pérez-Soriano, P., Cibrián Ortiz de Anda, R.M., 2015. Relationship between skin temperature and muscle activation during incremental cycle exercise. *J. Therm. Biol.* 48, 28–35.
- Quesada, J.I.P., Martínez, N., Palmer, R.S., Psikuta, A., Annaheim, S., Rossi, R.M., Corberán, J.M., de Anda, R.M.C.O., Pérez-Soriano, P., 2016. Effects of the cycling workload on core and local skin temperatures. *Exp. Therm. Fluid Sci.* 77, 91–99.
- Racinais, S., Ihsan, M., Taylor, L., Cardinale, M., Adami, P.E., Alonso, J.M., Bouscaren, N., Buirago, S., Esh, C.J., Gomez-Ezeiza, J., Garrandes, F., Havenith, G., Labidi, M., Lange, G., Lloyd, A., Moussay, S., Mtibaa, K., Townsend, N., Wilson, M. G., Bermon, S., 2021. Hydration and cooling in elite athletes: relationship with performance, body mass loss and body temperatures during the Doha 2019 IAAF World Athletics Championships. *Br. J. Sports Med.* 55, 1335.
- Ring, E.F., Ammer, K., 2012. Infrared thermal imaging in medicine. *Physiol. Meas.* 33, R33–R46.
- Rojas-Valverde, D., Martínez-Guardado, I., Sánchez-Ureña, B., Timón, R., Scheer, V., Pino-Ortega, J., Olcina, G., 2021. Outpatient assessment of mechanical load, heat strain and dehydration as causes of transitional acute kidney injury in endurance trail runners. *Int. J. Environ. Res. Publ. Health* 18.
- Rowell, L.B., Marx, H.J., Bruce, R.A., Conn, R.D., Kusumi, F., 1966. Reductions in cardiac output, central blood volume, and stroke volume with thermal stress in normal men during exercise. *J. Clin. Invest.* 45, 1801–1816.
- Schmidt, M.D., McGarr, G.W., Muia, C.M., Fujii, N., Amano, T., Kenny, G.P., 2020. Regional influence of nitric oxide on cutaneous vasodilation and sweating during exercise-heat stress in young men. *Exp. Physiol.* 105, 773–782.
- Shiohara, T., Sato, Y., Komatsu, Y., Ushigome, Y., Mizukawa, Y., 2016. Sweat as an efficient natural moisturizer. *Curr. Probl. Dermatol.* 51, 30–41.
- Sillero-Quintana, M., Jones-Rando, J., Refoyo, I., Marins, J.C.B., Seixas, A., 2022. Effects of resistance training on skin temperature and its relationship with central nervous system (CNS) activation. *Healthcare (Basel)* 10.
- Stekette, J., 1973. Spectral emissivity of skin and pericardium. *Phys. Med. Biol.* 18, 686–694.
- Stewart, A., Marfell-Jones, M., Olds, T., De Ridder, H., 2011. International society for the advancement of kinanthropometry: international standards for anthropometric assessment. *Int. Soc. Adv. Kinanthropometry* 115.
- Tomkinson, G.R., Olds, T.S., 2007. Secular changes in pediatric aerobic fitness test performance: the global picture. *Med. Sport Sci.* 50, 46–66.
- Urbanik, G., Plous, S., 2013. *Research Randomizer (Version 4.0)*[computer Software].
- van Wijck, K., Lenaerts, K., Grootjans, J., Wijnands, K.A., Poeze, M., van Loon, L.J., Dejong, C.H., Buurman, W.A., 2012. Physiology and pathophysiology of splanchnic hypoperfusion and intestinal injury during exercise: strategies for evaluation and prevention. *Am. J. Physiol. Gastrointest. Liver Physiol.* 303, G155–G168.
- Von Duvillard, S.P., Braun, W.A., Markofski, M., Beneke, R., Leithäuser, R., 2004. Fluids and hydration in prolonged endurance performance. *Nutrition* 20, 651–656.
- Wright, H., Collins, M., Villiers, R.D., Schwellnus, M.P., 2011. Are splanchnic hemodynamics related to the development of gastrointestinal symptoms in Ironman triathletes? A prospective cohort study. *Clin. J. Sport Med.* 21, 337–343.