An Acad Bras Cienc (2022) 94(Suppl.1): e20210593 DOI 10.1590/0001-3765202220210593
Anais da Academia Brasileira de Ciências | *Annals of the Brazilian Academy of Sciences*
Printed ISSN 0001-3765 I Online ISSN 1678-2690
www.scielo.br/aabc | www.fb.com/aabcjournal

HEALTH SCIENCES

A 32-day long fieldwork in Antarctica improves heat tolerance during physical exercise

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Abstract: We evaluated the influence of a 32-day camping in Antarctica on physical performance and exercise-induced thermoregulatory responses. In Brazil, before and after the Antarctic camping, the volunteers performed an incremental exercise at temperate conditions and, two days later, an exercise heat stress protocol (45-min running at 60% of maximum aerobic speed, at 31°C and 60% of relative humidity). In Antarctica, core temperature was assessed on a day of fieldwork, and average values higher than 38.5°C were reported. At pre- and post-Antarctica, physiological (whole-body and local sweat rate, number of active sweat glands, sweat gland output, core and skin temperatures) and perceptual (thermal comfort and sensation) variables were measured. The Antarctic camping improved the participants' performance and induced heat-related adaptations, as evidenced by sweat redistribution (lower in the chest but higher in grouped data from the forehead, forearm, and thigh) and reduced skin temperatures in the forehead and chest during the exercise heat stress protocol. Notwithstanding the acclimatization, the participants did not report differences of the thermal sensation and comfort. In conclusion, staying in an Antarctic camp for 32 days improved physical performance and elicited physiological adaptations to heat due to the physical exertion-induced hyperthermia in the field.

Key words: acclimatization, cold, performance, polar medicine, sweating, temperature.

INTRODUCTION

Moving to or staying in Antarctica under isolation, confinement, and extreme (ICE) conditions challenges the human body (Palinkas & Suedfeld 2008). During Antarctic expeditions, the distress posed by the climatic conditions (i.e., low temperatures, strong winds, and snowstorms) is enhanced by the difficulties of long walks on rugged and snow-covered terrain. Among the Antarctic ICE conditions, the cold thermal sensation seems to be the most prominent. In extreme cold weather with no or insufficient insulative clothes, the maintenance of core body temperature (T_{CORE}) is achieved by the association of physiological (i.e., vasoconstriction and shivering) and behavioral mechanisms (Romanovsky 2018).

The ICE conditions of Antarctica are faced by researchers who participate in field activities. According to previous data from our group, throughout a fieldwork day, displacement activities in rugged terrain generate physical efforts classified as moderate- to high-intensity levels and represents an effective training load for the researchers, thereby increasing aerobic capacity and reducing cardiac strain, after 24-days in the field (Moraes et al. 2018).

In camps and during fieldwork, the individuals use insulative clothes comprised of three layers to increase heat conservation and reduce its dissipation. Despite the low ambient temperatures and strong winds, a balance between metabolic heat production and heat dissipation barriers, dependent on insulative clothes, produces a warm skin microclimate. In this way, the individuals may experience repeated increases in the core temperature in their daily displacements (Moraes et al. 2018).

It is well documented that repeated and frequent physical exercise bouts associated with environmental heat stress elicit heat adaptation (Périard 2015), resulting in a lower physiological strain. The physiological adaptations observed during exercise-heat stress include the higher evaporative heat loss (due to increased local and whole-body sweat rates, more active glands, and sweat redistribution), reduced skin temperature, attenuated rise in core temperature and heart rate (HR), and improved subjective thermal sensation and comfort (Périard et al. 2015, Magalhães et al. 2010, Machado-Moreira et al. 2005).

Evidence indicates that, even in the absence of environmental thermal stress, the hyperthermia induced by repeated bouts of aerobic exercise leads to heat adaptation (Ravanelli et al. 2018, Roberts et al. 1977, Allan 1965). Also, heat adaptations occur within 4 to 14 days of exposure to heat and/or physical training (Gibson et al. 2020, Tyler et al. 2016, Taylor 2014). Moreover, aerobic training, which increases aerobic fitness and mitigates heat-related impairments, is a strategy to reduce thermal stress (Alhadad et al. 2019, Ravanelli et al. 2021), contributing to greater evaporative heat loss and better core temperature regulation under high rates of metabolic heat production. Altogether, these adaptations help improving exercise performance in the heat (Racinais et al. 2015).

Therefore, it was hypothesized that team-workers would exhibit aerobic and heat-related adaptations because they stay in Antarctic camps for more than two weeks and usually perform long displacements using insulative clothes. More specifically, we postulated that these thermoregulatory adaptations would be characterized by improved sweat function (i.e., more active glands, greater sweat production, and sweat redistribution), and reduced body (i.e., core and skin) temperatures, modifying thermal perception during submaximal exercise under heat stress.

MATERIALS AND METHODS

Ethics

This experimental study followed the regulations established by the Brazilian National Health Council (Resolution 466/2012) and was approved by the Research Ethics Committee of the Universidade Federal de Minas Gerais (protocol number 21898619.6.0000.5149). The volunteers were informed about the objectives and all experimental procedures before giving their written informed consent for participation in this study.

Subjects and experimental approach to the problem

Seven Brazilians, non-military individuals (two men and five women; age: 30.8 ± 3.9 years old; height: 171.7 ± 6.8 cm) were recruited to participate in this study. Data acquisition was performed in Brazil (pre-Antarctica trial) (Belo Horizonte, Minas Gerais, Brazil, latitude 19° 52’ 38” S, longitude 43° 58’ 23” W), followed by a period of fieldwork in Antarctica. After regressing from the expedition, another laboratory data acquisition was carried out in Brazil (post-Antarctica trial).

The displacements (from Brazil to Antarctica and from Antarctica to Brazil) were made by plane and ship.

The first data collection occurred 28 days before the participants had traveled to Antarctica. The participants stayed for 6 days on board the Brazilian Navy polar ship "Ary Rongel" (number of tack H-44) and for 32 days in an Antarctic camp settled in the Livingston Island, located in the South Shetland Islands (62° 36'.55" S, 61° 04'35" W). The post-Antarctica data collection occurred 18 days after the camp has ended. Our experiment was conducted between January and February of 2019, during the Antarctic summer season.

Characterization of the 32-day camp in Antarctica

A typical day in the Antarctic camp

During camp, all participants had similar routines and activities. The participants woke up around 7:00 a.m. (Chile hours), had breakfast, and prepared the working materials. The fieldwork usually started between 9:30 and 10:30 am and lasted about 7 hours per day (on some days, this period was shorter due to adverse climatic conditions). About 1:00 pm, there was a pause of approximately 30 min for a snack. The dinner was the main meal and occurred between 7:00 and 8:30 pm. The volunteers went to sleep between 9:00 and 10:00 pm. The participants performed fieldwork routes on 56% of days during the camp (i.e., 17 days), dressed in the appropriate garments weighing about 8 kg, and carrying foods and equipment. During the camping period, the temperature and relative humidity (RH) ranged from -3 to 6°C and from 48% to 100% RH, respectively, and wind speed reached values up to 59 km/h (Time and Date 2021).

Characterization of core body temperature during a fieldwork day in Antarctica

T_{CORE} was measured using an ingestible telemetric sensor (CorTemp HQ Inc., Palmetto, Florida, USA). This data collection was carried out with only one volunteer per day (from the 7^{th} day to the 19^{th} day of camping) to mitigate disruptions in fieldwork. On the same day of data collection, the participants ingested the sensor at 6 am (3 hours before fieldwork) (Domitrovich et al. 2010). The T_{CORE} was measured at seven different time points: *basal*: at the camping, at the beginning of a workday; in *initial uphill walk*: walking to move away from the camp; in three different time points in *fieldwork site:* during the researchers' specific activities (i.e., excavations and handling artifacts); in the *final uphill walk:* moving away from the fieldwork site; and in *arrival at camp*: at the camping, at the end of a workday.

Data collection in Brazil

In the pre-and post-Antarctica trials, the same experimental procedures, divided into two days of data collection and with a 48-h interval, were performed: (i) preliminary procedures for the assessment of anthropometric characteristics and maximum aerobic speed; (ii) exercise heat stress (EHS) protocol for the assessment of thermoregulatory responses during a submaximal exercise in a hot environment. Before all exercise trials, the volunteers received the following recommendations: to sleep at least 8 h on the night before testing, to maintain eating habits, and to abstain from alcohol, caffeine, and strenuous physical exercise 24 h before the visits. The subjects also drank at least 500 mL of water 2 h before the exercises (Convertino et al. 1996) and were considered euhydrated (urine specific gravity (USG) < 1.030; Armstrong 2000) in all trials. USG was measured using a portable refractometer (model JSCP-Uridens, São Paulo, SP, Brazil) previously calibrated with distilled water. The volunteers always wore top (only women), shorts, socks, and regular tennis shoes.

Preliminary procedures

Anthropometric characteristics assessment

Body mass (BM) (Filizola® MF-100 scale, precision of 0.02 kg, São Paulo, SP, Brazil) was measured with volunteers behind a changing screen wearing shorts (men) or shorts and top (women). Skinfold thickness was measured at seven different sites: triceps, subscapular, pectoral, mid-axillary, mid-abdominal, supra-iliac, and mid-thigh. Skinfolds were measured to the nearest millimeter in triplicate using a skinfold caliper (Lange, MI, USA). Body fat (BF) was calculated according to the protocol proposed by Jackson & Pollock (1978). Body surface area (A_D) was calculated according to the equation proposed by Dubois & Dubois (1916).

Aerobic capacity assessment

The participants performed an incremental exercise test in a temperate environment (23 ± 1°C and 50% RH) controlled by an environmental chamber (Russels Technical Products, WMD 1150-5, Holland, MI, USA). The incremental exercise test on the treadmill was adapted from the protocol proposed by Dittrich (2011). Fatigue was determined when subjects could no longer maintain the predetermined speed, voluntarily stopped exercising, or rated 20 on Borg's subjective rate of perceived exertion (RPE) (Borg 1982). The maximum aerobic speed achieved in this test represented the physical performance. The intensity corresponding to 60% of the maximum speed achieved in the incremental test ($S_{60\%}$) was used to determine the running speed of the EHS protocol. Based on previous data from our group, we were aware of a possible training effect by staying in an Antarctic camp (Moraes et al. 2018). Therefore, we adopted a protocol in which exercise intensity was prescribed relative to the maximum aerobic speed attained before and after the expedition. Furthermore, there is robust evidence that the body core temperature, skin temperature, and heart rate responses in humans during treadmill running are related to the relative exercise intensity (Saltin & Hermansen 1966, Gant et al. 2004, Sawka et al. 2011). Also, the present protocol avoids the influences of nonthermal factors associated with an absolute intensity (Shibasaki & Crandall 2010). Thus, a protocol using normalized intensities allows assessing improved ability to work in the heat, an indication of acclimatization (Bass & Henschel 1956).

Experimental design and procedures

Exercise heat stress (EHS) protocol

One day before the EHS protocol, the volunteers received an ingestible telemetric sensor for T_{CORE} measurement, which was ingested 12 h before arriving at the laboratory. The participants reported to the laboratory 1 h before the EHS and, after preparatory procedures, they entered the environmental chamber for 5 min rest sitting in a chair for baseline recordings. The EHS protocol consisted of 45 min running at $S_{60\%}$ on a treadmill with 1% inclination, at 31°C and 60% RH controlled by the environmental chamber. *Ad libitum* water intake was registered, and a wind speed of approximately 2 m/s was provided by an electric fan positioned in front of the participants (~1m). During a continuous moderate-intensity exertion, steady-state sweating is established around 20 to 30 minutes after the exercise initiation, and this time is required to guarantee the validity of gravimetric methods (techniques that include the collection of sweat directly from the skin surface) to measure local sweat rate (Taylor & Machado-Moreira 2013). Therefore, the duration of the EHS was selected to ensure valid local sweat measurements but also to allow the volunteers (untrained individuals) to comply with the exercise requirements without experiencing excessive fatigue, as shown by the submaximal RPE when the exercise was finished. The ambient temperature of 31°C was used because this is a value close to the microclimate created by the clothing (between the first and the last layer of clothing) during displacements in Antarctica, as recorded in previous data from our group (29.9 ± 2.8°C, measured in nine volunteers by telemetry; Coretemp®, unpublished data).

The local sweat production was determined using an absorbent filter paper (4 cm^2) (J Prolab, S.J. dos Pinhais, PR, Brazil) (Vimieiro-Gomes et al. 2005) positioned in the forehead (middle of the forehead), chest (right side, between the nipple line and the armpit), arm (upper right arm), forearm (the proximal third of the anterior right forearm) and thigh (right mid-thigh). The absorbent filter papers were covered with plastic fixed to the skin with impermeable adhesive tape, to prevent sweat evaporation and weighed before and after sweat collection (Shimadzu ® BL320H precision 0.001 g, Kyoto, Japan). At the end of the EHS, the filter papers were removed, an iodine-impregnated paper was immediately pressed against the skin (Sato & Dobson 1970, Bar-Or et al. 1968), and the number of active sweat glands (ASG) was subsequently determined by manual count always by the same experienced investigator. Briefly, the absorbent patch technique consists of hermetically covering the skin and using absorbent filter papers to collect and measure local sweating. Since the early 20th century studies on thermoregulatory sweating, this technique has been used as reported by Kuno (1938) and reviewed by Taylor & Machado-Moreira (2013). During exercise, the gravimetric methods, which consist of collecting sweat directly from the skin surface (for example, using filter papers), are suitable to conditions when steady-state sweating has been established (e.g., 20 to 30 minutes after the exercise has begun) (Taylor & Machado-Moreira 2013), as is the case of the present study. Furthermore, absorbent filter papers have been used in different exercise conditions to measure sweating (Vimieiro-Gomes et al. 2005, Saat et al. 2005, Magalhães et al. 2010); this technique is sensitive to detect increased local sweating caused by a pharmacological stimulus, acute physical exercise (Vimieiro-Gomes et al. 2005), and heat acclimation (Saat et al. 2005, Magalhães et al. 2010).

The skin temperatures (T_{SK}) of the forehead, arm, chest, and thigh were evaluated on adjacent skin regions to local sweat measurements, using an infrared thermometer (Fluke 566, Fluke Corporation, Everett, Washington, USA). $T_{FOREHEAD}$, T_{ARM}, T_{CHEST}, T_{THIGH}, T_{CORE}, thermal sensation (ranging from " "1-cold", "4 neutral" and "7-hot"), thermal comfort (ranging from "1-comfortable" to "4-very uncomfortable") (Gagge et al. 1967), and RPE were measured at each 5 min. Heart rate (HR) was continuously measured (Polar® H10 chest strap and Polar® V800 watch, Polar Electro Oy, P Kempele, Finland). At the pre-exercise (minute 0) and 45th minute, a drop of blood was collected for measuring lactate concentration, a marker of exercise intensity (Accutrend Plus, Roche Diagnostic Systems, Basel, Switzerland). Body mass and USG were measured pre-and post- EHS. All EHS trials were performed between 09:00 am and 01:00 pm, and the EHS time for each participant was similar between pre-and post-Antarctica trials.

Calculations

Whole-body sweat rate (WBSR), local sweat rate (LSR), sweat gland output (SGO), mean T_{SK}, mean body temperature (T_{BODY}), and external work (W), during the EHS protocol were determined using the following equations:

$$WBSR = [(BM\ post\text{-}EHS - BM\ pre\text{-}EHS) \times A_D^{-1}) \times t^{-1}] - water\ ingested \quad (1)$$

where *BM* is the participant's body mass (in kg), A_D^{-1} is the body surface area, and *t* is the total exercise time (in min) (Magalhães et al. 2010).

$$LSR = [(absorbent\ paper\ filter\ weight\ after - before\ sweat\ collection) \times area\ of\ the\ absorbent\ filter\ paper^{-1}] \cdot t^{-1} \quad (2)$$

$$SGO = LSR \times ASG^{-1} \quad (3)$$ (Peter & Wyndham 1966)

$$T_{SK} = (0.43 \times T_{CHEST}) + (0.25 \times T_{ARM}) + (0.32 \times T_{THIGH}) \quad (4)$$ (Roberts et al. 1977)

$$T_{BODY} = (0.8 \times T_{CORE}) + (0.2 \times T_{SK}) \quad (5)$$ (Marino et al. 2004)

$W = BM \times g \times s \times \sin\theta \times t$, where *g* is the acceleration of gravity (9.8 mxs^{-2}), *s* is the treadmill speed ($m \times min^{-1}$), *θ* is the angle of treadmill inclination (0.53°, 1% of inclination) (Teixeira-Coelho et al. 2017). The W was converted from J to kJ. (6)

Statistical analyses

The Shapiro-Wilk test revealed that most of the parameters evaluated presented a normal distribution. The equal variance was tested and confirmed using the Levene Median test.

The non-normally distributed data were submitted to a Log10 transformation and analyzed as normally distributed data (i.e., USG, WBSR, and SGO and for the forehead and arm). LSR for the forehead did not present a normal distribution even after transformation and was analyzed by Wilcoxon signed-rank test.

For the parametric variables evaluated in two different time points (pre- *vs*. post-Antarctica), comparisons were performed using Paired Student's t-tests (i.e., sweating responses, physical characteristics of the volunteers, mechanical variables, intensity markers, and hydration status). The perceptual, non-parametric variables (i.e., RPE, thermal sensation, and thermal comfort) evaluated in these two-time points were assessed using Wilcoxon signed-rank tests.

For body temperatures compared across time points during a fieldwork day (i.e., *basal*, *initial uphill walk*, moments in the *fieldwork site*, *final uphill walk,* and *arrival at camp*), one-way repeated measures analysis of variance (ANOVA RM) was applied. When a significant *F* value was found, we performed Student–Newman–Keuls tests as *post hoc* analyses.

For body and skin temperatures compared across submaximal exercise time points (every 5 min) and between the trials (pre- *vs*. post-Antarctica), two-way ANOVA RM was applied. When a significant *F* value was found, we performed Tukey tests as *post hoc* analyses. The *α* level was set at 0.05. Data are shown as mean ± *SD*. All the analyses described above were performed using the SigmaPlot 11.0 software (*Systat Software Inc., San Jose, CA, USA).*

Because the number of subjects participating in the study was limited (n = 7), Cohen's *d* magnitude effect size (*ES*) was calculated as a supplementary analysis to aid in the understanding of our findings. The *ES* allowed the assessment of the magnitude of the differences between the collected data points and was calculated by the following equation: $d = PreA - PostA / \sigma$, where PreA and PostA indicate the mean values of pre- and post-Antarctica trials, and σ represents the grouped standard deviation.

The *ES* considered in ANOVAs was eta-squared (η^2), calculated by the following equation: η^2 = *SS* effect / *SQ* total, where *SQ* = sum of squares. The values of η^2 were calculated as proposed by Cohen (1988). The *ES* values were classified as trivial (*ES* < 0.2), small (*ES* = 0.2–0.6), moderate (*ES* = 0.6–1.2) or large (*ES* ≥1.2).

RESULTS

T_{CORE} during a fieldwork day in Antarctica

The displacement in the Antarctic field caused a large increase in the T_{CORE} (*P* = 0.001, *ES* = 3.0) as observed in the *initial uphill walk*, *time point 1* of the *fieldwork site*, *final uphill walk*, and *arrival at camp* when compared to the *basal,* and *time points 2* and *3* of the *fieldwork site* (Figure 1). The average values exceed 38.0°C at different times of the day but never oscillated below 37°C.

Anthropometric data, physical performance, cardiovascular, and thermoregulatory responses during EHS in the pre-and post-Antarctica trials

The long-term fieldwork in Antarctica did not modify the BM, fat-free mass (FFM), BF, and A_D of the volunteers (Table I). Moreover, the lactate concentration was moderately higher at the beginning but not at the end of the exercise in the post-Antarctica trial. There were no intertrial differences during EHS in the final HR, RPE, USG (i.e., at pre-and post-exercise), thermal sensation and thermal comfort, although the participants exhibited a moderate increase in water intake in the post-Antarctica trial (Table II).

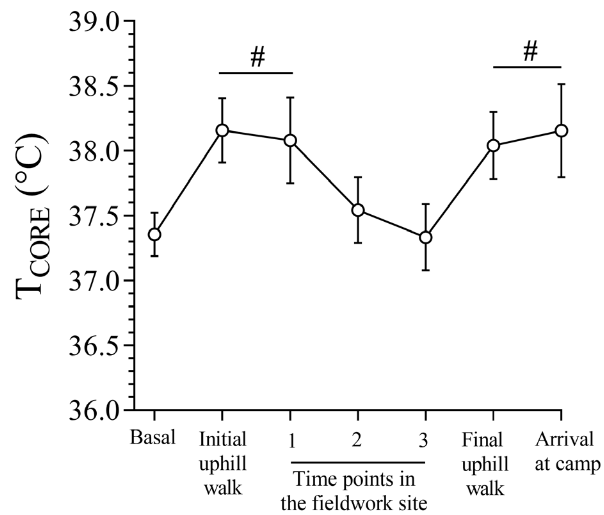

Figure 1. Core body (gastrointestinal) temperature measured throughout a typical day of work in the camp (n = 7). *Basal*: at the camping, at the beginning of a workday. *Initial uphill walk*: after about 22 min of walking up a sloping hill, which was required to move away from the camp. *Time points in the fieldwork site:* these measurements were carried out during the researchers' specific activities (i.e., excavations and handling artifacts); in particular, the *Time point in the fieldwork site* measurements were performed*:* *1*) when arriving at the main point of archaeological excavation after about a 50-min walking; *2*) One hour after the last data collection; *3*) at the end of work on the excavation site. *Final uphill walk:* after about 40 min of walking up a sloping hill, which was required to move away from the fieldwork site, in the exact same location of the *Initial uphill walk*. *Arrival at camp*: at the camping, at the end of a workday. #Significantly different (P < 0.05) from the basal and *time points* 2 and 3 in the fieldwork site. The data are expressed as means ± SD.

Body temperatures

As expected, there were large increases in T_{CORE} (*P* = 0.001; *ES* = 1.4) and in T_{BODY} (*P* = 0.001; *ES* = 1.3), and a moderate increase in T_{SK} (*P* = 0.001; *ES* = 0.6) only over time during the EHS protocol (Figures 2 a-c). Different from our expectations, there were no differences between trials (post- *vs* pre-Antarctica) for all comparisons made (T_{CORE}: P = 0.12; ES = 0.1; T_{BODY}: *P* = 0.78; *ES* = 0.9; Tsk- mean: *P* = 0.15; *ES* = 0.4). Besides, there was no interaction between the factors (trial *vs* time) in the T_{CORE} (*P* = 0.87; *ES* = 0.1), T_{BODY} (*P* = 0.89; *ES* = 0.2) and T_{SK} (*P* = 0.11; *ES* = 0.01) responses.

To better understand the thermoregulatory changes, we calculated the T_{CORE}-to-distance ratio (using the change in T_{CORE} and the distance traveled during EHS), which is inversely correlated with thermoregulatory efficiency (Bittencourt et al. 2020). There was a reduction in the T_{CORE}-to-distance ratio in post- compared to pre-Antarctica (0.25 ± 0.12°C/km vs. 0.27 ± 0.09 °C/km; *P* = 0.05; *ES* = 0.19, n=6).

Skin temperatures

T_{ARM} and T_{THIGH} presented, respectively, a moderate and a large increase during EHS protocol (T_{ARM}: *P* = 0.001; *ES* = 0.9; T_{THIGH}: *P* = 0.001; *ES* = 1.4), with no differences between the pre- and post-Antarctica trials (T_{ARM}: *P* = 0.13; *ES* = 0.1; T_{THIGH}: *P* = 0.66; *ES* = 0.3). There was no interaction between the main factors (trial *vs* time) for T_{ARM} (*P* = 0.49; ES = 0.3) or T_{THIGH} (*P* = 0.28; ES = 0.2) (Figures 3a and b).

Concerning the T_{CHEST}, we observed a significant trial *vs* time interaction between factors (*P* = 0.013; *ES* = 0.1), as evidenced by a T_{CHEST} reduction throughout exercise only in the pre-Antarctica trial (*P* = 0.001), and lower values at the min 0 and 5 in the post-Antarctica compared to the pre-Antarctica trial (*P* = 0.001 and *P* = 0.008, respectively; Figure 3c).

A significant interaction (trial *vs*. time) was observed for $T_{FOREHEAD}$ (*P* = 0.001; *ES* = 0.7), with a moderate reduction during the EHS protocol in the pre-Antarctica trial (*P* = 0.001; *ES* = 0.8) but with no changes over time in post-expedition. Also, $T_{FOREHEAD}$ was lower in the post-Antarctica compared to the pre-Antarctica trial over the initial 25 min of exercise (*P* ≤ 0.05) (Figure 3d).

Sweat production, ASG, and thermodynamics responses

The permanence in the Antarctica continent produced site-specific alterations in LSR, ASG, and SGO (Table III). We observed large and moderate LSR increases in the forehead and forearm regions, respectively, and a moderate reduction in the chest region during the post-Antarctica trial. The ASG in the forehead, forearm, and arm presented large and moderate increases in the post-Antarctica trial; in contrast to these regions, we observed a large reduction in the chest and moderate reduction in the thigh. Concerning SGO, there was a moderate reduction in the forehead, forearm, and arm, despite a large increase in the chest and thigh.

The 32-day Antarctic camp also influenced the percentual contribution of the different skin areas for WBSR. There was a 5.8% increase in the relative contribution to sweating by the forehead, thigh, and forearm (P = 0.03; ES = 0.29), alongside a 5.0% reduction in the contribution of the chest (P = 0.05; ES = 1.08), without concomitant changes for the contribution of the arm (P = 0.81; ES = 0.20) (Figure 4).

Table I. Physical characteristics of the volunteers in the pre-Antarctica and post-Antarctica trials.

Measures	Pre-Antarctica	Post-Antarctica	*P*-value	Cohen's *d* ES
BM (kg)	66.5 ± 15.2	67.8 ± 12.9	0.44	0.03
FFM (kg)	49.8 ± 11.2	50.4 ± 10.1	0.50	0.06
BF (%)	23.8 ± 5.2	25.7 ± 4.2	0.51	0.41
A_D (m^2)	1.74 ± 0.20	1.75 ± 0.18	0.35	0.05

Body mass (BM). Fat-free body mass (FFM). Body fat (BF). Body surface area (A_D). n=7, for all measures. Cohen's *d* effect sizes (ES) were calculated to assess the magnitude of the difference between experimental time points. The data are expressed as means ± SD. *P* < 0.05.

Table II. Mechanical variables, markers of exercise intensity and perceived exertion during the exercise heat stress protocol and hydration status assessed before and after the protocol in the pre-Antarctica and post-Antarctica trials.

Measures	Pre-Antarctica	Post-Antarctica	*P*-value	Cohen's *d* ES
Mechanical variables				
$S_{60\%}$ (km/h)	5.64 ± 0.83	6.21 ± 0.83 *	0.03	0.69^{M}
W (kJ)	1468.40 ± 414.3	1649.6 ± 395.5 *	0.001	0.45
Lactate (mmol/L)				
0 min	2.7 ± 1.1	2.0 ± 0.8	0.09	0.73^{M}
45 min	6.4 ± 2.1	6.5 ± 3.9	0.57	0.03
HR (bpm)				
0 min	81 ± 19	93 ± 17	0.29	0.66^{M}
45 min	160 ± 13	161 ± 16	0.90	0.07
Perceptual variables				
RPE	11.1 ± 3.3	11.1 ± 3.0	0.93	0.003
Thermal sensation	5.5 ± 0.6	5.9 ± 1.1	0.21	0.48
Thermal comfort	2.0 ± 0.8	2.3 ± 0.9	0.62	0.36
Hydration status				
Water intake (mL)	40.0 ± 52.0	107.1 ± 140.1	0.35	0.63^{M}
USG (AU) Pre-exercise	1.018 ± 0.002	1.016 ± 0.006	0.76	0.46
USG (AU) Post-exercise	1.012 ± 0.009	1.017 ± 0.009	0.46	0.55

Speed during exercise, at 60% of the maximum speed ($S_{60\%}$). External work during exercise (W). Blood lactate concentration (Lactate), presented as 0 min, measured before of the exercise, 45 min, measured immediately at the end of the exercise. Heart rate (HR) presented as 0 min, measured at the before of the exercise, and as 45 min, the final measurement obtained during the exercise. n=7, for all measures. Perceptual variables: subjective perception of effort (RPE), thermal sensation and thermal comfort, presented as mean of the values obtained at each 5 min during exercise (from 5 to 45 minutes). Total water intake (ml) during the exercise (0 to 45 minutes). Urine specific gravity (USG), assessed immediately before and after exercise. AU: arbitrary unit. Cohen's *d* effect sizes (ES) were calculated to assess the magnitude of the difference between experimental time points ^{M}Moderate effect size. *Significantly different ($P < 0.05$) from the pre-Antarctica trials. The data are expressed as means ± SD.

DISCUSSION

The core temperature elevation observed during the Antarctic field displacements, associated with the insulative clothes, was a thermal stimulus sufficiently strong to induce heat adaptations. These adaptations included the redistribution of LSR (i.e., greater contribution of forehead, forearm, and thigh). In the forehead, forearm, and arm regions, there was also an increase of moderate-to-large effect sizes in ASG. In contrast, although the chest region also showed a large effect size for an augmented SGO, there were moderate and large effect sizes for reductions in the LSR and ASG. Also, a moderate effect size for the increase in the WBSR was observed after the expedition. Consequently, $T_{FOREHAD}$ and T_{CHEST} were lower in the post-Antarctica condition, most likely due to the greater local sweating rate and the resulting greater evaporative heat exchange. Despite the higher sweat production and lower T_{SK}, the volunteers did not report differences in thermal sensation and comfort during the EHS protocol after the 32-day long fieldwork. Aside from these thermoregulatory adaptations,

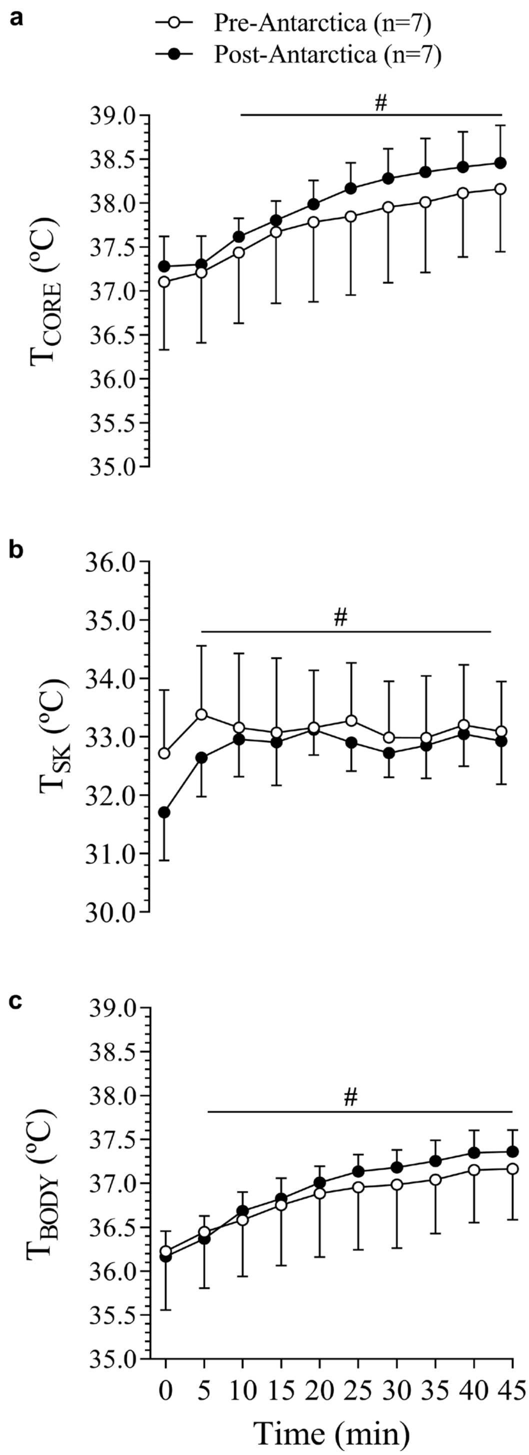

Figure 2. Body temperatures during the exercise heat stress performed before and after the Antarctic expedition (n = 7). The following variables were measured: a) core body temperature (T_{CORE}); b) mean body temperature (T_{BODY}); c) mean skin temperature (T_{SK}). #Significantly different (P < 0.05) from 0 min. The data are expressed as means ± SD.

the physical effort in the field represented an effective training load that improved the physical performance of the participants, as observed by the faster speeds obtained in the incremental test after the expedition to Antarctica (reflected in $S_{60\%}$ results).

As expected, the association between metabolic heat production generated by physical exertion and the microclimate created by the insulated clothes elevated T_{CORE} during fieldwork displacements. These results corroborate our previous findings showing a 1.6°C elevation in one individual's T_{CORE} during a displacement in Antarctica (Moraes et al. 2018). In the present study, we observed an average T_{CORE} rise of 0.9°C (ranging from 0.6°C to 1.5°C) during a typical day of fieldwork, which occurred in 18 of the 32 camping days. Therefore, this thermal challenge resulted in apparent adaptations during the exercise under environmental heat stress performed in a laboratory setting. It is worth mentioning that previous studies showed that 1 or 2 hours of physical exercise causing hyperthermia across 4 to 14 days are sufficient to induce heat adaptations (Gibson et al. 2020, Tyler et al. 2016, Taylor 2014, Magalhães et al. 2010). We should point out that heat adaptations were observed even 18 days after withdrawal of relevant thermal stimuli, suggesting that our findings were obtained when adaptations were decaying (Daanen et al. 2018). Hence, it is tempting to suggest that if the data on thermoregulatory parameters have been acquired immediately after the camp, broader and more intensive heat adaptations would have been observed.

Despite the average values of the core temperature during the fieldwork exceeding 38.0°C, these did not exceed 39.0°C, disregarding a risk for hyperthermia. As the participants felt uncomfortable in the heat, they removed or opened the windbreaker; thus, a combination of thermoregulatory behavior with the skin wet

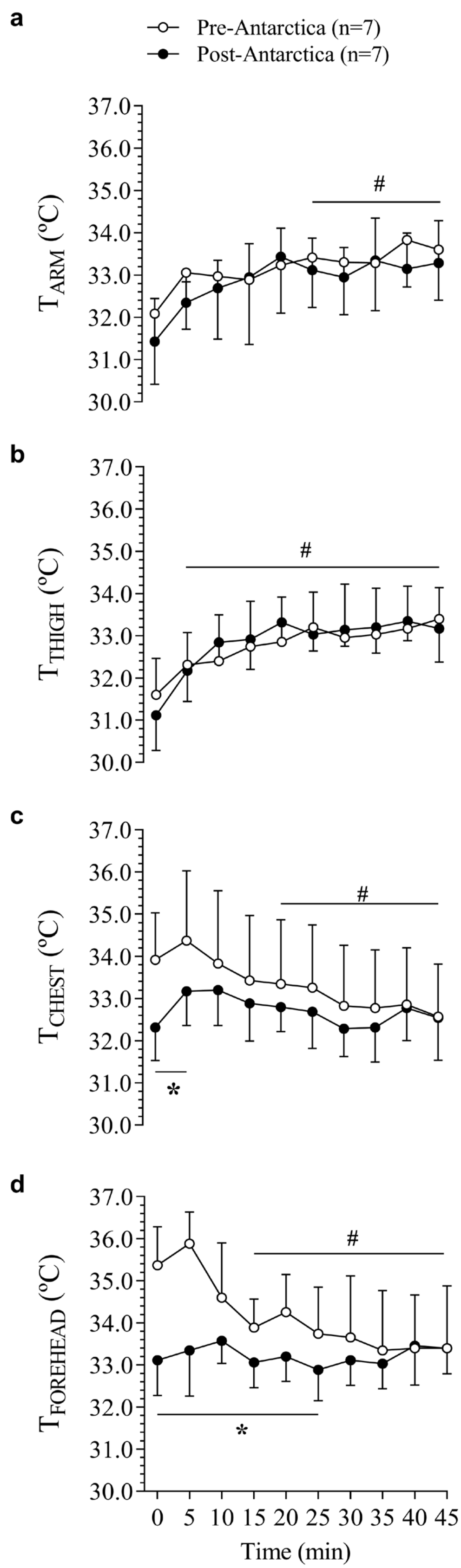

Figure 3. **Skin temperatures (T_{SK}) during the exercise heat stress protocol performed before and after the Antarctic expedition (n = 7). The following variables were measured: a) arm (T_{ARM}); b) thigh (T_{THIGH}), c) chest (T_{CHEST}), and d) forehead ($T_{FOREHEAD}$). *Significantly different ($P < 0.05$) from the pre-Antarctica trial. #Significantly different ($P < 0.001$) between time points; for T_{ARM} and T_{THIGH}, different from 0 min; for T_{CHEST} at pre-Antarctica, 30th to 45th min different from 0 to 10th min, and 20th to 25th min different from 5th min; for $T_{FOREHEAD}$ at pre-Antarctica, 15th to 45th min were lower than 0 and 10th min. The data are expressed as means ± SD.**

by non-evaporated sweat and the cold climate prevented the achievement of critical T_{CORE} values.

According to previous studies from our group (Moraes et al. 2018) and others (Shephard 1991, Brotherhood et al. 1986), improved physical performance was observed after Antarctic expeditions (i.e., time to fatigue and maximum aerobic speed recorded during an incremental test under temperate conditions). These findings indicate that the physical effort required to displace in Antarctica, wearing heavy clothing and carrying heavy backpacks (reaching up to 40% of body mass), represented an effective training load for the subjects in this study.

It is important to point out that EHS resulted in a continuous rise in core temperature and the thermal steady state was not achieved (the regression analyzes of the curves concerning core temperature x exercise time points are shown in Figure S1 - Supplementary Material; the R-value corresponded to 0.97 for both the pre- and post-Antarctica situations); thus, the combination of 31°C and 60% RH with $S_{60\%}$ resulted in an uncompensable heat stress (Kraning & Gonzalez 1991, Ravanelli et al. 2019), the most appropriate environment to identify thermoregulatory adaptations (Ravanelli et al. 2019).

The physiological responses observed in the present study (i.e., increased LSR, more

Table III. Thermoregulatory variables during the exercise heat stress protocol in the pre-Antarctica and post-Antarctica trials.

Measures	Pre-Antarctica	Post-Antarctica	*P*-value	Cohen's *d* ES
WBSR ($g.cm^{-2}.min^{-1}$)	6.52 ± 3.88	8.70 ± 3.20	0.33	0.61^{M}
LSR ($mg.cm^{-2}.min^{-1}$)				
Forehead	1.13 ± 0.23	1.35 ± 0.12*	0.03	1.20^{L}
Arm	1.04 ± 0.23	1.02 ± 0.41	0.63	0.06
Forearm	1.04 ± 0.22	1.20 ± 0.07	0.09	0.98^{M}
Chest	1.25 ± 0.06	1.15 ± 0.20	0.17	0.68^{M}
Thigh	0.61 ± 0.54	0.76 ± 0.41	0.14	0.31
ASG ($glands.cm^{2}$)				
Forehead	61 ± 23	136 ± 59*	0.01	1.67^{L}
Arm	38 ± 22	74 ± 40	0.17	1.11^{M}
Forearm	36 ± 27	93 ± 41	0.08	1.64^{L}
Chest	33 ± 16	12 ± 7	0.14	1.70^{L}
Thigh	69 ± 30	47 ± 14	0.32	0.89^{M}
SGO ($mg.min^{-1}.ASG^{-1}$)				
Forehead	0.023 ± 0.015	0.011 ± 0.004	0.06	1.09^{M}
Arm	0.040 ± 0.030	0.023 ± 0.024	0.09	0.63^{M}
Forearm	0.056 ± 0.061	0.016 ± 0.007	0.29	0.92^{M}
Chest	0.050 ± 0.030	0.156 ± 0.114	0.21	1.28^{L}
Thigh	0.007 ± 0.005	0.017 ± 0.007	0.07	1.64^{L}

Whole-body sweat rate (WBSR). Local sweat rate (LSR), number of active sweat glands (ASG) and sweat gland output (SGO) measured in the forehead, arm, forearm, chest, and thigh. For WBSR and LSR, n=7, except for LSR in the thigh, n=6. For ASG and SGO, n=7 for forehead, for the other sites, n=4. For Cohen's *d* effect sizes (ES) were calculated to assess the magnitude of the difference between experimental time points. ^{M}Moderate effect size. ^{L}Large effect size. *Significantly different (P < 0.05) from the pre-Antarctica trial. The data are expressed as means ± SD.

ASG, higher SGO, and sweating redistribution) are classical adaptations observed in protocols designed to induce heat acclimation (Périard et al. 2015, Magalhães et al. 2010, Machado-Moreira et al. 2005, Peter & Wyndham 1966). It is noteworthy that ASG did not increase in all measured sites (e.g., the chest and thigh responded in the opposite direction), which suggests a site-dependent adaptation caused by acclimatization. Also, Cramer et al. (2012) showed that 'aerobic fitness alters local sweating on the forehead, but not the forearm, independently of evaporative requirements for heat balance'; in contrast, forearm SGO and ASG tended, with respectively large and moderate effect sizes, to increase post-Antarctica in our volunteers, therefore, evidencing some heat acclimatization. The recruitment of thermoeffectors could prevent an enhanced core temperature increase despite a higher work rate, evidencing an augmented work capacity in the hot environment (i.e., acclimatization).

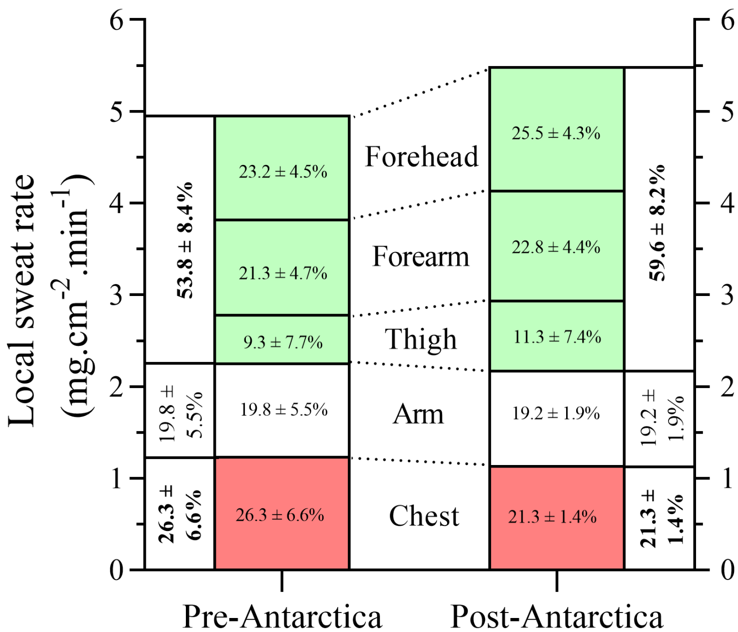

Figure 4. **Changes in local sweat rate and in percentage contribution of the different surface areas during the exercise heat stress protocol performed before and after the Antarctic expedition (n = 7). The measurement sites were grouped according to the contribution of local sweating to whole-body sweat rate: increase (forehead, forearm and thigh), maintenance (arm), and reduction (chest) of the contribution. The data are expressed as means ± SD.**

Regarding sweating responses, there is plenty of evidence showing that, for a given individual, the higher is the exercise intensity, the higher is the sweating rate (Saltin & Hermansen 1966, Kondo et al. 1998). Most likely, under the present conditions, the greater sweating rate favors an augmented evaporative heat loss, which may compensate for the greater metabolic heat production caused by faster treadmill speed during the post-Antarctica exercise. Therefore, augmented heat loss and production coincide, thus allowing core temperature to be regulated at the same level, despite the faster running speed after the expedition. Thus, in this scenario, both the enhanced sweating rates (which contribute to reducing forehead and chest skin temperatures) and the similar core temperature at post- compared to pre-Antarctica suggest thermoregulatory adaptations. These responses indicate the occurrence of acclimatization, defined by Bass & Henschel (1956) as 'the dramatic improvement in the ability to *work* in the heat which occurs within 4 to 7 days of first exposure'. These adaptive responses likely ensured the maintenance of similar T_{CORE} and T_{SK} values, despite the higher absolute exercise intensity in the post-Antarctica situation. Thus, increased LSR (i.e., in the forehead and forearm) may favor a better evaporative heat loss.

In the present study, heat adaptation was evidenced by increased LSR and more ASG in the forehead, thus inducing a local cooling effect, via sweat evaporation, during the initial minutes (from 0 to 25 min) of the EHS protocol in the post-Antarctica condition. The forehead is the body site with the highest density of sweat glands, presenting more significant sweat production than other skin regions (Machado-Moreira et al. 2008, Hertzman et al. 1952). Although Patterson et al. (2004) observed an augmented sudomotor sensitivity in the forehead and Magalhães et al. (2010) noticed a sweat redistribution in the direction of higher output in the members, they did not report changes in forehead sweat production, and their findings contrast with our data. Methodological differences from the present and the other two studies may explain the divergent results. The first evident difference between the studies is the duration of exposure to extreme environmental conditions. While our participants remained 32 days in Antarctica, Magalhães et al. (2010) subjected their volunteers to treadmill exercise for 11 days, and Patterson et al. (2004) used a 16-day cycle exercise protocol, both under environmental heat stress. Another important difference between studies was the clothes worn by the individuals. During the heat adaptation protocols proposed by Magalhães et al. (2010) and Patterson et al. (2004), the participants wore only shorts while exercising, allowing heat exchange between almost all body surfaces and the surroundings. In contrast, our participants exercised during fieldwork with almost the entire body covered by insulative clothes, with only the face and, less frequently, the hands being exposed; of note, the face and hands were the sites that allowed heat dissipation. Thus, the increase in the forehead sweating rate may be a situation-specific adaptation due to the difficulties in dissipating heat through the other body surface sites during Antarctic fieldwork.

For the forehead, forearm, and arm, the increase in ASG was greater than the increase in the LSR, thus leading to a reduction in SGO, which not necessarily indicates reduced thermoregulatory capacity. For the thigh and chest, despite the reduced number of ASG, the SGO increased after the Antarctic fieldwork, which allowed the maintenance of thigh LSR. This finding can be explained either by a possible expansion in the glands' size (i.e., hypertrophy) or higher sweat glands' sensitivity to thermal and hormonal stimuli (Périard et al. 2015, Sato & Sato 1983).

Heat adaptations induced by the Antarctic fieldwork also included sweat redistribution. Our data indicated that, when analyzed together, the relative contribution of the most exposed and/or limb regions - forehead, thigh, and forearm - to WBSR was increased, whereas the chest contribution was decreased. Sweat redistribution may represent a relevant physiological adaptation, as indicated by earlier evidence showing heat acclimation can change the local sweat rate pattern among body regions (i.e., acclimation causes sweat redistribution), favoring sweat evaporation and thermal homeostasis during exercise (Magalhães et al. 2010, Shvartz et al. 1977, Höfler 1968). Magalhães et al. (2010) reported an increase in the limb compared to the trunk sweat output after an 11-day protocol consisting of treadmill exercise. However, Patterson et al. (2004) observed an opposite pattern, with a relative increase in the chest contribution after a protocol in which exercise was performed on a cycle ergometer. As the body's convection area differs during a cycle exercise compared to a treadmill running, the body position during physical exertion may have influenced thermoregulatory adaptations in Patterson et al. (2004). Another possible explanation for our findings is the adaptive resistance of chest sweat glands (Taylor 2014), compared to other regions (e.g., forearm, thigh, and forehead) that are highly responsive to repeated thermal challenges (Patterson et al. 2004). The improved sweating pattern in the limbs has physiological significance because the limbs represent an increased body surface for sweat evaporation, favoring heat exchange between the body and the environment.

Our volunteers reported unchanged thermal sensation and thermal comfort in the post-Antarctica trial. Thermal sensation and comfort are influenced by both the absolute T_{SK} values (Flouris & Schlader 2015, Mower 1976) and the alterations in T_{CORE} (Flouris & Schlader 2015, Gagge et al. 1967). Therefore, the participants' thermal perceptions seem to reflect-the absence of differences in average core temperature in the present study. However, given the lower $T_{FOREHEAD}$ and T_{CHEST} at the beginning of the exercise after returning from Antarctica, we could have expected thermal perception improvements. Even though displacements in the Antarctic field have augmented core temperature, the individuals were constantly subjected to cold climate. These conditions resulted in a parallel exposure to cold (external source affecting exposed body surfaces) and heat stress (internal source affecting the body core), similarly to the observations made by Glaser & Shephard (1963) and Park et al. (2019). Because parallel exposure may have favored developing a psychological trait for cold tolerance, as shown in Park et al. (2019), the absence of an improved thermal sensation during the EHS in the present study may reflect a perceptual adaptation to the cold Antarctic environment.-

It is worth noting that RPE did not differ between pre- and post-Antarctica trials. Since RPE reflects “the conscious sensation of how hard, heavy, and strenuous a physical task is” (Marcora & Staiano 2010), and results from the integration between all physiological and perceptual responses (Noakes et al. 2004), the maintenance of a similar RPE also reinforces that relative exercise intensity was the same in both conditions.

It is important to highlight that our findings are limited to Antarctic expeditions, in which the researchers stay at a camp, make considerable displacements, and perform fieldwork in outdoor conditions. Also, the lack of measurements concerning the metabolic heat production and mechanical efficiency before and after the 32-day Antarctic expedition is a limitation of the present study. However, the present experimental design possibly mitigated this limitation, as the exercise intensity was relativized to maximum aerobic capacity. Therefore, a possible increase in mechanical efficiency would also contribute to the ability in maintaining physical effort at higher absolute exercise intensities. In the present study, the use of relative exercise intensity revealed an improved ability to work in the heat, as evidenced by the capacity to perform more work with similar thermal stress (i.e., hyperthemia). However, as increasing aerobic fitness allows sustaining a greater absolute exercise intensity that generates more metabolic heat, further *research* is needed to investigate if the present responses will also be observed when exercising at the same heat production (Jay 2014), before and after staying in Antarctica. Notably, the heterogeneous sample characteristics and the time elapsed between the end of the field and post-Antarctica measurements may have prevented us from observing other or even more apparent thermoregulatory adaptations. However, because of the logistics, we consider that evaluating a group composed of seven individuals before and after an Antarctic expedition, under controlled conditions in an environmental chamber, is a unique opportunity to understand, with great ecological validity, the thermoregulatory adaptations induced by exposure to extreme cold environments while using insulative clothes.

Lastly, it is relevant to state that despite the existing limitations, evident and classic physiological patterns of adaptation to the hot environment have emerged; quite exciting and novel, the changes revealed in this study can be considered long-lasting adaptations. In this sense, our results contribute to advancing knowledge about the acclimatization effects induced by alternating and parallel exposure to heat and cold environments (Glaser & Shephard 1963, Tipton et al. 2008, Park et al. 2019). As highlighted by Park et al. (2019), studies involving parallel adaptations to heat and cold are scarce but necessary, considering crew-members from different nationalities that displace to icy environments (Bishop 2004, Sandal et al. 2006, Pattyn et al. 2018), people that are exposed to heat regularly due to their jobs or daily habits during the cold winter (Park et al. 2019), and militaries that have to switch between environments quickly (Jones et al. 2017). The present study can also contribute to developing specific garments to facilitate heat exchange in the sites with high sweating rates, favoring people who need to protect themselves from extreme cold and perform physical activities that induce marked metabolic heat production. Furthermore, Antarctica is an isolated, confined, and extreme environment (ICE), often used as an open-air laboratory to understand the possible changes individuals may experience on space missions (Sandal et al. 2006, Pattyn et al. 2018). Thus, it is relevant to investigate the factors underlying adaptive physiological responses in Antarctica to advance our knowledge of how the human body copes with extreme conditions (Choukér & Stahn 2020).

In conclusion, in Antarctica, the physical effort caused by long displacements associated with the microclimate created by insulative clothes resulted in a thermal stimulus strong enough to provoke thermoregulatory adaptations, as evidenced by similar core temperatures despite the faster running speed after the expedition. Interestingly, the physiological adaptations occurred in the direction of a reduced strain induced by an EHS protocol, whereas heat perception adaptations did not occurred in the same direction.

Acknowledgments

The authors thank the military personnel involved in the Brazilian Antarctic Operation (OPERANTAR) for logistical support and the volunteers who participated in this study. We also thank Professor Andres Zarankin for granting permission to evaluate his work team volunteers in the field. This study was supported by Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) / Ministério da Ciência, Tecnologia e Inovações (MCTI) / Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) / Fundo Nacional de Desenvolvimento Científico e Tecnológico (FNDCT) / Programa Antártico Brasileiro (PROANTAR) [grant 442645/2018-0]; Fundação de Amparo à Pesquisa do Estado de Minas Gerais (FAPEMIG) [grants AEC-00017-18; CDS- PPM 000304/16; CBB- APQ-01419-14] and Pró-Reitoria de Pesquisa da Universidade Federal de Minas Gerais (PRPq UFMG). RMEA received research fellowship from Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) [grant 305952/2017-0]. This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brazil (CAPES) - Finance Code 001; MMM was the recipient of a post-doctoral fellowship CAPES/BRAZIL [88887.321687/2019-00] and YATM was the recipient of a master's fellowship.

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SUPPLEMENTARY MATERIAL

Figure S1. Regression line of the curves concerning core temperature x exercise time points during the heat protocol, in the pre-Antarctic and post-Antarctic situations. The conditions of uncompensable heat stress were confirmed by calculating the Pearson's correlation coefficient and plotting the regression line of the curves concerning core temperature x exercise time points; the R-value corresponded to 0.97 for both the pre- and post-Antarctica situations (n = 7).

How to cite
MARTINS YAT ET AL. 2022. A 32-day long fieldwork in Antarctica improves heat tolerance during physical exercise. An Acad Bras Cienc 94: e20210593. DOI 10.1590/0001-3765202220210593.

Manuscript received on April 17, 2021;
accepted for publication on August 20, 2021

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Each author contributed individually and significantly to the development of this study and approved the final version submitted for publication. YATM, RLFP, SPW, MMM, RMEA and DDS: designed research; YATM, RLFP and ALM: performed data collection; YATM, CNE, MMM and DDS: analyzed data; YATM, MMM and DDS: wrote the paper; YATM, RLFP, ALM, DAPG, TTM, CNE, LOCR, SPW, MMM, RMEA and DDS: edited the paper and approved the submitted version.