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Thermal resting pattern and acute skin temperature response to exercise in older adults: Role of cardiorespiratory fitness

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ABSTRACT

Background: Infrared thermography is a growing area of interest in sports science due to the potential of skin temperature (T_{sk}) measurements to provide valuable information from rest to exercise. However, limited research exists on T_{sk} in older adults and the impact of factors such as sex and cardiorespiratory fitness (CRF) on T_{sk}. This study aims to investigate T_{sk} at rest and after acute exercise in older adults and assess whether sex or CRF influences T_{sk}.

Methods: Ninety-two participants (41 women, 68.48 ± 3.01 years) were examined with a thermographic camera in a conditioned room (23.02 ± 3.01 °C) at rest and after a graded protocol. The T_{sk} of 25 regions of interest (ROIs) were extracted and analysed.

Results: Men had higher overall T_{sk} at rest in 76% of ROIs, showing significant differences ($p < 0.010$) in six specific ROIs, independent of CRF. Both sexes had similar T_{sk} responses after graded exercise, with increases in distal parts (1.06 ± 0.50 °C), decreases in proximal parts (−0.62 ± 0.42 °C), and stable central T_{sk} (0.23 ± 0.59 °C). Increases in lower limb T_{sk} were significantly associated with CRF in men and women ($\beta = 0.438$, $p = 0.001$, and $\beta = 0.535$, $p < 0.001$, respectively), explaining 17% and 27% of the variance, respectively.

Conclusions: This study demonstrates a sex-specific effect on resting T_{sk} in older adults, suggesting that sex-specific T_{sk} patterns should be considered when analysing T_{sk} in this population. Additionally, the association between increases in lower limb T_{sk} and CRF suggests that T_{sk} could be a promising predictor of CRF in older adults.

1. Introduction

The human body maintains a nearly constant core temperature of 37 °C through various physiological mechanisms that are crucial for sustaining vital metabolic functions (Fernández-Cuevas et al., 2015). However, unlike core temperature, the temperature of the skin (T_{sk}) can exhibit significant fluctuations influenced by various factors. Ambient conditions, humidity, and solar radiation are examples of external factors that can induce permanent alterations in hot or cold spots on the skin (Fernández-Cuevas et al., 2015). Conversely, certain internal conditions can impact T_{sk} levels as well. Increased levels of body fat, for instance, have been associated with lower T_{sk} (Neves et al., 2017a), while fever or exercise can cause an elevation in T_{sk} levels (Hillen et al., 2020; McBride et al., 2010; McBride et al., 2010; Hillen et al., 2020).

During exercise, the body's core temperature increases, which activates mechanisms to dissipate heat and maintain a balanced core

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temperature (Marins et al., 2014). The hypothalamic system aims to dissipate heat from the core to the skin (Fernandes et al., 2016), causing an increase in blood flow to the skin and an increase in T_{sk} up to 38 °C as a defensive mechanism that favours heat dissipation through sweat evaporation (Tanda, 2018). This process is essential for maintaining physiological processes and exercise intensity until the end of the activity.

Infrared thermography (IRT) is a non-invasive, and mobile technology that allows for real-time quantification and portrayal of changes in body surface radiation, providing an accurate estimation of T_{sk}. The use of IRT in recent years has provided valuable information about alterations such as cancer monitoring (Arora et al., 2008), and obesity and related metabolic disorders (Jimenez-Pavon et al., 2019). However, when using IRT in humans, several factors need to be taken into account, such as internal factors (ethics, age, sex, or fitness level) (Marins et al., 2014; Neves et al., 2017b), or external factors (relative humidity, atmospheric pressure, or ambient temperature, among others) (Fernández-Cuevas et al., 2015), which can influence T_{sk} to a point where specific thermal patterns may be required for appropriate data interpretation.

While there is existing evidence describing the thermal patterns of specific population groups, such as athletes (de Carvalho et al., 2021), individuals with specific medical conditions (Ramirez-GarciaLuna et al., 2020), or young and active individuals (Chudecka and Lubkowska, 2015), there is a notable scarcity of research focusing on the thermal patterns of the older population during rest or post-exercise recovery. Moreover, the available literature primarily centers around male older adults (Best et al., 2014; Coull et al., 2021), further limiting our understanding of thermal responses in diverse populations within the older age group.

In summary, this study aims to fill a gap in the current literature by exploring the use of IRT in the older population, investigating the possible differences between sexes at rest and during exercise and also investigating the acute effects of exercise on skin temperature patterns. This information could provide insight into the thermal response of the skin from rest to exercise and during recovery, as well as the relationship between T_{sk} and cardiorespiratory fitness (CRF) levels in this population.

2. Material and methods

2.1. Study participants

Participants were recruited from 13 Public Health Care Centers of the province of Cádiz. In these Health Care Centers, the medical staff and researchers team members were in charge of recruiting potential candidates to participate in the project. The inclusion criteria for participants in the original project were being between the ages of 65 and 75, possessing adequate language skills, lacking physical injuries that would hinder their ability to engage in exercise, and not engaging in supervised physical activity exceeding 20 min per day. Exclusion criteria encompassed individuals that do not complete all the physical performance tests.

Even though 98 participants were eligible for the study, a total of 92 participants, including 41 women, with an average age of 68.48 ± 3.01 years, performed all the physical tests. Before participation, all participants were provided with an information sheet detailing the study procedures, and potential risks, and provided their informed consent, including consent for the use of their images. This study constitutes a secondary analysis of data derived from another project. The project study protocol received ethical approval from the Human Ethics and Research Committee of research in Cádiz and the Andalusian Coordinating Committee on Biomedical Research Ethics (codes: 0667-M1-17 and 04/2018), and all procedures were conducted in accordance with the principles outlined in the Declaration of Helsinki.

2.2. Measurements

Before the assessments, participants were instructed to refrain from consuming alcohol or caffeine and engaging in vigorous physical activity in the 24 h prior to the measurements. They were also advised to monitor their hydration levels and ensure they were adequately hydrated before the trial, as well as to fast for a minimum of 4 h prior to the assessment and ensure they were well-rested. These measures were taken to ensure the accuracy and validity of the results (Ring, 2014).

2.3. Body composition

Participants' height was measured using a stature-measuring instrument (SECA 225, Hamburg, Germany) while standing with a normal expiration on the Frankfort plane. To assess body composition, a validated multi-frequency bioimpedance (Tanita-MC780MA, Tanita Europe BV, Amsterdam, The Netherlands) was used following the manufacturer's instructions (Kyle et al., 2004; Verney et al., 2015). This included measurements of Body Mass, Body Mass Index (BMI), body fat, and fat-free mass.

2.4. Thermal image procedure and processing

The participants were provided instructions to minimize their clothing attire and undergo a 15-min acclimation period within a controlled environment. The conditions of the room were maintained at an average temperature of 23.02 ± 3.0 °C and a relative humidity of 46.9 ± 5.5%. Throughout this duration, the participants were calmly seated on chairs and solely required to respond to a specific set of questions posed by the researchers. Following acclimation, a first image of an aluminium foil phantom was taken (1.5 m away) to register the reflected temperature. Then, 6 thermal images were recorded for each participant using a FLIR E60 camera (320 × 240 pixels Infrared Camera, thermal sensitivity <0.05 °C at plus 30 °C, accuracy ±2 °C, temperature range from −20 °C to +120 °C, FLIR Systems, Danderyd, Sweden). To enhance the camera's accuracy and mitigate thermal drift, an internal calibration was performed prior to capturing each photo by activating the camera's shutter. The participants were seated on a chair at a distance of 1.5 m for recording thermal images of the head (frontal and lateral) and at a distance of 3.0 m for anterior and posterior views of the body (upper and lower limbs) (Fig. 1).

After completing the graded exercise test and the recovery, which took place at the opposite corner of the same room, the participants proceeded with the thermal imaging protocol. The room's size exceeded 100 m^2, and both the temperature and relative humidity remained stable throughout the procedure, with measurements averaging 23.6 ± 0.8 °C and 46.9 ± 6.5% relative humidity. Prior to capturing the thermal images, all materials that could potentially obstruct the photos, such as the gas analyzer mask, heart-rate band, and electrocardiogram, were removed and participants were asked if they were able to walk on their own. The initial thermal image was taken, on average, 3.0 ± 1.5 min after the conclusion of the recovery period. All participant photos were taken during the morning schedule, between 9:00 a.m. and 12:00 p.m.

Once the thermal images were collected, 25 body regions of interest (ROIs) were established. These included unilateral regions (lateral forehead, eye, and tympanic) and ten bilateral regions. The ROIs were determined by the FLIR ResearchIR software hand-free tool (FLIR Systems, Danderyd, Sweden) using anatomical landmarks (Table 1). The analyses included obtaining the minimum, maximum, and mean temperatures. The skin emissivity value was set at 0.98 (Moreira et al., 2017). The ROIs included the lateral forehead, eye, tympanic, supraclavicular, lumbar, and posterior and anterior views of the arms, forearms, hands, forefingers, little fingers, thighs, legs, and feet.

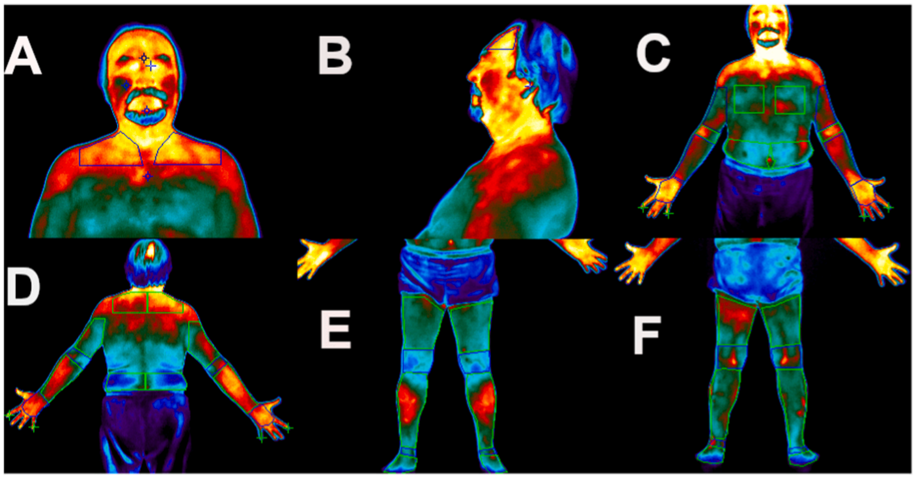

Fig. 1. Thermal images with Infrared Thermography. A: Front Head, B: Lateral Head, C: Anterior Upper Limb, D: Posterior Upper Limb, E: Anterior Lower Limbs, F: Posterior Lower Limbs.

2.5. Graded exercise test

All participants completed a graded exercise test on a Lode Valiant treadmill (Groningen, Netherlands) to measure CRF, identified as the peak of oxygen consumption (VO_{2peak}). The modified Bruce protocol, previously used in a similar sample and designed for a geriatric population, was employed, which consisted of 2-min steps (Burns et al., 2008; Hollenberg et al., 1998). Participants who needed it were familiarized with the treadmill by walking slowly until the initial speed of the protocol was achieved. The protocol started with walking at 2.7 km/h at a 0% inclination grade. During the first three steps, only the inclination was increased, and from that point, both the inclination and speed were increased until voluntary exhaustion. VO_{2peak} was considered the highest observed value of oxygen consumption obtained in the last three intervals of 10 s. Following the graded exercise test, a 5-min active recovery began automatically, with participants walking at 2.7 km/h at 0% inclination grade, followed by a 5-min passive recovery, with participants seated in a chair.

2.6. Statistical analysis

The data are presented as mean ± standard deviation (SD). The normal distribution of the data was verified using the Shapiro-Wilk test, and descriptive statistics were used to analyze the participants' characteristics (Table 2). Supplementary Data (Tables S1, S2, and S3) present preliminary analyses of the minimum, maximum, and mean temperature for the right and left regions, as well as a comparison between regions. The maximum temperature was considered in the statistical analyses because manually selecting ROIs ensures that the temperature is not altered by certain pixels from the background or borders. (Sillero-Quintana et al., 2017). Bilateral regions were calculated as the average maximum temperature value of the right and left ROIs.

To assess the differences between sexes at rest, a paired Student T-Test was performed to determine the significance of these differences. In addition to this, an analysis of covariance (ANCOVA) was performed to evaluate the comparison of group means while controlling for the effects of two covariates, fat mass and relative VO_{2peak} (Neves et al., 2017b). We also calculated the standardized effect sizes using Cohen's d coefficients.

Exercise-induced changes in T_{sk} were calculated as values after recovery minus baseline values for each T_{sk} outcome. Thus, a delta (Δ) to detect differences between men and women was calculated. The Δ in T_{sk} was also classified as No Change (NC) if Δ was less than 0.6 °C, Mild Change (MC) if Δ was between 0.61° and 1.0 °C, both included and Large Change (LC) if Δ were superior to 1.0 °C. Similar to the comparisons at rest, sex differences were evaluated using a paired Student T-Test as well as an ANCOVA controlling for fat mass and relative VO_{2peak} (Neves et al., 2017b).

The acute effect of the graded exercise test was also investigated through several analytical steps. Firstly, a Principal Component Analysis (PCA) was conducted on the absolute differences to identify clusters of variables with similar patterns. This analysis helped to identify groups of variables that exhibited similar changes in response to the exercise test. Next, a Heatmap graph was generated to visualize the temperature patterns of the identified groups. The temperatures of the specific Regions of Interest (ROIs) included in each group were used to calculate the overall temperature for that group. Finally, simple linear regressions were performed to examine the associations between the calculated PCA groups (treated as the dependent variable) and two independent variables: VO_{2peak} and time to exhaustion. This analysis aimed to explore whether there were any significant relationships between the identified groups of variables and the participants' VO_{2peak} levels, and time to exhaustion during the graded exercise test.

All statistical analyses were performed by STATA 13.0 (StataCorp LLC, Texas, United States) and GraphPad Prism 7.0 (GraphPad Software, California, United States). The level of significance was set at $p < 0.05$.

3. Results

Women had significantly higher levels of both relative and absolute fat compared to men ($p \leq 0.020$), while there were no significant differences in BMI levels between the sexes. Furthermore, women demonstrated lower levels of CRF, as shown in Table 2.

3.1. Skin temperature pattern at rest

In Table 3, it can be observed that men had higher T_{sk} in 19 out of 25 anatomical areas compared to women, with 6 of them showing statistical significance ($p < 0.05$). The tympanic area was the hottest area in both sexes, and the little finger had the lowest T_{sk} in men (posterior view) and women (anterior view). The highest differences between sexes were found in the posterior thigh (0.91 °C), followed by the calf (0.90 °C), posterior arm (0.80 °C), and anterior thigh (0.60 °C). These significant differences persisted after adjusting for fat mass and relative VO_{2peak}, except for the differences in the chin T_{sk}, which disappeared.

3.2. Effect of acute exercise on t_{sk} pattern and its relationship with peak oxygen consumption

Both sexes had a similar T_{sk} response after the graded exercise, significant sex-related differences were found in six ROIs, which were the

Table 1
Anatomical landmarks for regions of interest.

Region of interest	Anatomical landmark
Head	
Lateral Forehead	A polygon started at the lateral edge of the supraorbital ridge and extends to the temporal line and fossa reaching the point where the hairline begins.
Eye	A point positioned in the inner canthus. It refers to the inner corner of the eye where the upper and lower eyelids meet. It is the point closest to the nose.
Tympanic	The tympanic region refers to a point-made area around the ear canal.
Chin	A single point is located at the midpoint of the chin region.
Cheekbone	A point located in the zygomatic prominence.
Anterior torso	
Supraclavicular	A polygon that covers the area just above the collarbone, known as the supraclavicular region. The process involves identifying the midpoints of the collarbone, extending the polygon upwards along the natural contour of the supraclavicular area, and connecting the upper edges of the polygons on both sides.
Arm	A polygon that covers the acromion process at the top of the shoulder, the lateral epicondyle on the outer side of the elbow, and the styloid processes of both the ulna and radius at the wrist.
Forearm	A polygon that includes the lateral epicondyle on the outer side of the elbow and the styloid processes of both the ulna and radius at the wrist.
Hand	A polygon that includes the metacarpophalangeal joint, the styloid process of the ulna at the wrist, and the styloid process of the radius at the wrist
Forefinger	A point is located in the last part of the forefinger.
Littlefinger	A point is located in the last part of the little finger.
Abdominal	A polygon that encompasses the abdominal area from the lower rib cage to the upper pelvic region
Posterior torso	
Trapezius	A polygon that covers the trapezius muscle, extending from the base of the skull to the shoulder blades
Arm	A polygon that encompasses the posterior aspect of the arm, extending from the shoulder to the elbow
Forearm	A polygon that encompasses the posterior aspect of the forearm, extending from the elbow to the wrist
Hand	A polygon that includes the metacarpophalangeal joint, the styloid process of the ulna at the wrist, and the styloid process of the radius at the wrist
Forefinger	A point is located in the last part of the forefinger.
Littlefinger	A point is located in the last part of the little finger.
Lumbar	A polygon that includes the superior border of the iliac crest, the midline of the back along the spine, and the lower margin of the rib cage
Anterior Lower Limbs	
Thigh	A polygon that encompasses the front part of the thighs can be defined by including the inguinal crease at the groin, the midline of the thighs, and the lower border of the patella.
Leg	A polygon that encompasses the front surface of the leg, starting from the knee and extending down to the ankle
Foot	A polygon that includes the top surface of the foot from the base of the toes to the ankle
Posterior Lower Limbs	
Thigh	A polygon that encompasses the back part of the thighs can be defined by including the gluteal fold at the buttocks, the midline of the thighs, and the popliteal fossa at the back of the knees.
Leg	A polygon that encompasses the back surface of the leg, starting from the back of the knee and extending down to the ankle
Foot	A polygon surface of the foot from the ankle to the base of the heel.

only ones with a medium to large effect size (Table 4). These significant differences persisted after controlling for relative VO_{2peak}, but only the posterior arm and leg and anterior thigh remained significant after adjusting for fat mass.

The exercise-induced T_{sk} changes revealed 4 clusters of variables in the PCA (Fig. 2A): Upper Distal (UD) including anterior and posterior hands, forefingers, and little fingers; Upper Proximal (UP) including anterior and posterior arms, forearms, trapezius, abdominal, and lumbar; Lower Limbs (L) including anterior and posterior thighs, legs, and feet; and Core (CR) including lateral forehead, eye, tympanic, chin, cheekbone, and supraclavicular. The heat map (Fig. 2B) showed that UD and L increased their temperature after exercise, whereas UP tended to decrease and CR to maintain their temperature.

Table 2
Participant characteristics by sex.

	Total (n = 92)	Men (n = 51)	Women (n = 41)	p	ES
Age (years)	68.5 ± 3.0	68.6 ± 3.0	68.4 ± 3.0	0.715	0.08
Height (cm)	161.1 ± 9.6	166.9 ± 7.4	153.7 ± 6.7	**< 0.001**	1.86
Body Mass (kg)	74.5 ± 13.7	80.4 ± 13.5	67.0 ± 9.9	**< 0.001**	−1.14
BMI (kg/m^2)	28.7 ± 4.5	28.9 ± 4.4	28.5 ± 4.6	0.634	−0.10
Fat-Free Mass (kg)	51.2 ± 10.3	58.9 ± 6.9	41.6 ± 3.4	**< 0.001**	3.07
Fat-Free Mass (%)	69.0 ± 7.9	73.9 ± 5.8	62.7 ± 5.4	**< 0.001**	1.98
Fat Mass (kg)	23.3 ± 7.9	21.5 ± 8.0	25.4 ± 7.3	**0.011**	−0.54
Fat Mass (%)	31.0 ± 7.9	26.1 ± 5.8	37.3 ± 5.4	**< 0.001**	−1.98
VO_2peak (ml/min)	1858.7 ± 481.9	2141.0 ± 403.0	1477.8 ± 272.9	**< 0.001**	1.88
VO_2peak (ml/kg/min)	24.3 ± 5.2	27.1 ± 5.0	22.3 ± 4.3	**< 0.001**	1.03
Time to exhaustion (min)	10.9 ± 3.8	11.8 ± 3.9	9.8 ± 3.5	**0.014**	0.53

Significant differences appear in bold. Values are expressed as mean ± standard deviation, BMI, Body Mass Index; VO_2peak, peak oxygen consumption; ES, Effect Size (Cohen's D).

Simple regression analyses were performed separately per sex (Fig. 3). In men, a positive association was found between VO_{2peak} and L ($\beta = 0.438$, $p = 0.001$, $R2 = 0.17$) and a negative association with UP ($\beta = -0.287$, $p = 0.041$, $R2 = 0.06$). In women, positive associations were found between VO_{2peak} and L ($\beta = 0.535$, $p < 0.001$, $R2 = 0.27$) and UD ($\beta = 0.365$, $p = 0.029$, $R2 = 0.10$), and a negative association was found with CR ($\beta = -0.560$, $p = 0.002$, $R2 = 0.29$). Sensitivity analyses using time to exhaustion instead of VO_{2peak} produced similar results (Fig. 4).

4. Discussion

This study presents novel findings on the distinct resting T_{sk} patterns for older men and women using IRT. Specifically, it reveals that women tend to have lower temperatures in most zones than men. Interestingly, the response of T_{sk} to a graded exercise test was comparable between the sexes with a small size effect in most of the ROIs. The changes in T_{sk} are characterized by an increase in L and UD T_{sk}, a decrease in UP T_{sk}, and a stable CR T_{sk}. In line with these findings, the observed increase in L was associated with higher levels of CRF in both men and women. However, it is important to note that there were some sex-specific differences in the associations between exercise-induced skin temperature changes and CRF. Specifically, in men, a decrease in UP T_{sk} was significantly associated with higher CRF, whereas in women the association was the opposite with an increase of UP being significantly associated with higher CRF. These sex-specific associations highlight the complexity of the relationship between skin temperature changes and CRF, suggesting that physiological responses to exercise may differ between men and women.

4.1. *T_{sk} patterns at rest*

Older men have a higher T_{sk} than older women in around the 75% of the studied regions. Our findings are consistent with previous results of sex temperature differences, showing higher temperatures in young men compared to women (Jimenez-Perez et al., 2020; Marins et al., 2014; Neves et al., 2017b). Regarding specific body regions, it has been displayed higher facial T_{sk} in young (Christensen et al., 2012) and older

Table 3
Thermal body patterns at rest in older adults using Infrared thermography.

	Total (n = 92)	Men (n = 51)	Women (n = 41)	p	ES
Maximum Temperature (°)					
Head					
Lateral Forehead	35.0 ± 0.7	35.1 ± 0.8	34.9 ± 0.6	0.096	0.24
Eye	35.5 ± 0.6	35.6 ± 0.7	35.5 ± 0.5	0.750	0.06
Tympanic	35.7 ± 0.7	35.7 ± 0.7	35.6 ± 0.7	0.710	0.08
Chin	33.6 ± 1.2	33.9 ± 1.2	33.3 ± 1.1	**0.011**	0.47
Cheekbone	33.0 ± 1.7	33.1 ± 1.6	32.8 ± 1.8	0.469	0.19
Anterior Torso					
Supraclavicular	35.1 ± 0.6	35.0 ± 0.6	35.1 ± 0.6	0.875	−0.04
Arm	33.7 ± 0.9	33.6 ± 0.8	33.8 ± 0.9	0.400	−0.18
Forearm	33.2 ± 0.8	33.2 ± 0.7	33.3 ± 0.8	0.285	−0.23
Hand	32.4 ± 1.5	32.3 ± 1.5	32.7 ± 1.4	0.195	−0.27
Forefinger	28.6 ± 3.1	28.8 ± 3.0	28.4 ± 3.3	0.479	0.15
Littlefinger	28.1 ± 3.2	28.4 ± 3.1	27.7 ± 3.2	0.322	0.58
Posterior Torso					
Trapezius	33.4 ± 0.8	33.4 ± 0.8	33.3 ± 0.9	0.322	0.23
Arm	32.3 ± 1.0	32.6 ± 0.9	31.8 ± 1.0	< **0.001**	0.87
Forearm	33.3 ± 0.8	33.5 ± 0.7	33.0 ± 0.8	**0.001**	0.77
Hand	31.8 ± 1.2	31.6 ± 1.2	32.0 ± 1.2	0.100	−0.34
Forefinger	28.7 ± 3.2	28.9 ± 3.1	28.6 ± 3.4	0.700	0.08
Littlefinger	28.1 ± 3.1	28.2 ± 3.1	27.9 ± 3.2	0.570	0.12
Anterior Lower Limbs					
Thigh	32.3 ± 1.1	32.6 ± 0.7	31.9 ± 1.4	**0.008**	0.57
Leg	33.4 ± 0.8	33.5 ± 0.7	33.3 ± 0.9	0.231	0.25
Foot	31.2 ± 1.4	31.2 ± 1.4	31.3 ± 1.5	0.780	−0.06
Posterior Lower Limbs					
Thigh	32.2 ± 1.2	32.6 ± 0.8	31.7 ± 1.4	< **0.001**	0.84
Leg	32.6 ± 1.1	33.0 ± 0.7	32.1 ± 1.1	< **0.001**	1.00
Foot	30.1 ± 1.5	30.3 ± 1.5	29.9 ± 1.5	0.200	0.27

Values are expressed as mean ± standard deviation; ES, Effect Size (Cohen's D).

Table 4
Changes in thermal body patterns after acute exercise (incremental test) in older adults.

	Total (n = 91)	Men (n = 51)	Women (n = 41)	Δ	C	p	ES
Maximum Temperature (°)							
Upper Distal							
Anterior Hand	0.7 ± 1.1	0.9 ± 1.1	0.5 ± 1.0	0.4	NC	0.092	0.36
Anterior Forefinger	1.7 ± 2.3	1.8 ± 2.4	1.6 ± 2.2	0.2	NC	0.461	0.09
Anterior Littlefinger	1.7 ± 2.6	1.8 ± 2.7	1.7 ± 2.5	0.1	NC	0.841	0.04
Posterior Hand	0.3 ± 1.1	0.4 ± 1.1	0.2 ± 1.2	0.2	NC	0.388	0.21
Posterior Forefinger	1.6 ± 2.4	1.8 ± 2.3	1.3 ± 2.5	0.4	NC	0.412	0.18
Posterior Littlefinger	1.6 ± 2.4	1.8 ± 2.4	1.4 ± 2.4	0.4	NC	0.411	0.18
Upper Proximal							
Anterior Arm	−0.9 ± 0.7	−1.0 ± 0.7	−0.7 ± 0.7	0.3	NC	**0.038**	−0.46
Anterior Forearm	−0.3 ± 0.7	−0.4 ± 0.8	−0.1 ± 0.7	0.2	NC	0.285	−0.23
Abdominal	−0.2 ± 0.7	−0.3 ± 0.7	0.3 ± 0.8	0.6	NC	0.126	−0.81
Trapezius	−0.9 ± 0.9	−1.1 ± 1.0	−0.6 ± 0.8	0.5	NC	**0.027**	−0.53
Posterior Arm	0.0 ± 0.7	0.0 ± 0.9	0.1 ± 0.5	0.1	NC	0.754	−0.07
Posterior Forearm	−0.8 ± 0.7	−1.0 ± 0.7	−0.5 ± 0.6	0.5	NC	**0.001**	−0.73
Lumbar	−1.1 ± 1.2	−1.2 ± 1.2	0.0 ± 1.3	1.3	LC	**0.041**	−1.09
Lower							
Anterior Thigh	0.8 ± 0.7	0.7 ± 0.7	1.0 ± 0.6	−0.2	NC	0.098	−0.35
Anterior Leg	0.4 ± 0.7	0.3 ± 0.7	0.4 ± 0.7	0.1	NC	0.372	−0.19
Anterior Foot	1.1 ± 1.3	1.2 ± 1.2	1.0 ± 1.4	0.2	NC	0.354	0.16
Posterior Thigh	0.7 ± 0.6	0.7 ± 0.6	0.7 ± 0.6	0.0	NC	0.778	−0.06
Posterior Leg	0.8 ± 0.6	0.7 ± 0.6	0.9 ± 0.6	0.2	NC	0.256	−0.24
Posterior Foot	1.3 ± 1.2	1.4 ± 1.2	1.2 ± 1.3	0.1	NC	0.590	0.12
Core							
Lateral Forehead	0.0 ± 0.8	−0.1 ± 1.0	0.1 ± 0.6	0.2	NC	0.260	−0.23
Eye	0.3 ± 0.6	0.3 ± 0.6	0.3 ± 0.5	0.0	NC	0.796	0.05
Timpanic	0.5 ± 0.8	0.7 ± 0.8	0.2 ± 0.6	0.4	NC	**0.020**	0.55
Chin	−0.1 ± 0.1	−0.4 ± 1.1	0.3 ± 1.4	0.7	MC	**0.006**	−0.59
Cheekbone	1.2 ± 1.6	1.1 ± 1.6	1.2 ± 1.5	0.1	NC	0.872	−0.09
Supraclavicular	−0.5 ± 0.4	−0.7 ± 1.0	−0.2 ± 0.4	0.5	NC	**0.005**	−0.69

Significant differences appear in bold. Values are expressed as mean ± standard deviation. Abbreviations: Δ, the absolute difference between sex; C, Change in the absolute difference between sex, No Change (NC) if $\Delta \leq 0.6$, Mild Change (MC) if $1.0 \leq \Delta > 0.6$, Large Change (LC) if $\Delta \geq 1.0$; ES, Effect Size (Cohen's D).

(Haddad et al., 2016) men which partially concurs with our results, since men had non-significant higher facial T_{sk}. In the case of the upper limb, sex differences in both posterior arm and forearms were detected in line with previous studies in adults (Marins et al., 2014; Neves et al., 2017b), with no differences in hand temperature T_{sk} (Chudecka and Lubkowska, 2015; Marins et al., 2014). Finally, young men showed higher lower

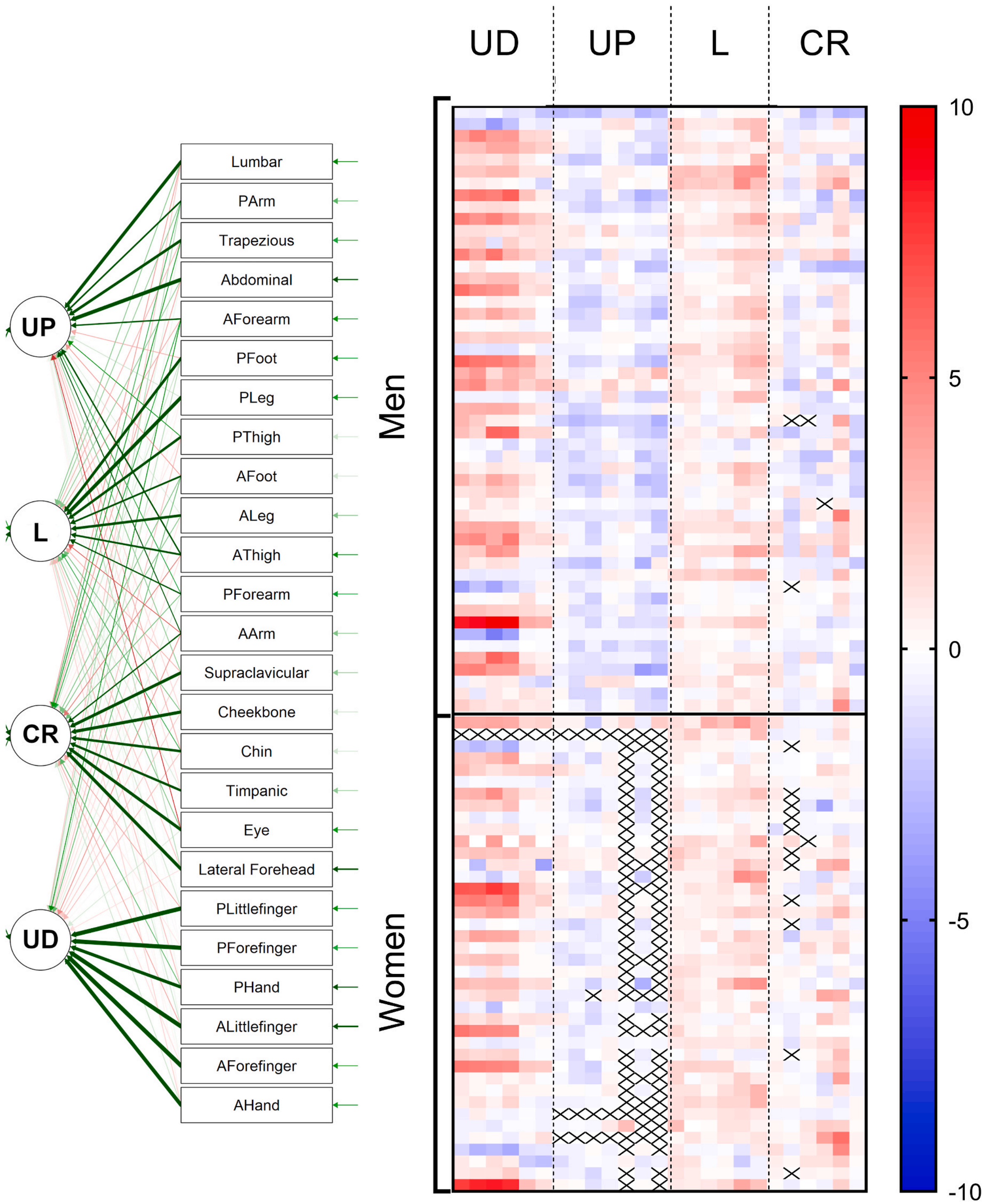

Fig. 2. Exercise-induced changes in thermal body patterns. A: Principal Component Analysis Aggrupation. B: Heatmap of the Spearman's correlation coefficients between temperature changes caused by acute exercise. The red and blue bar indicates increased and decreased temperature after exercise, respectively. A and P before the variables mean Anterior and Posterior, respectively. UD, UP, L, and CR mean Upper Distal, Upper Proximal, Lower and Core respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

limb temperature than women, with the thigh and the calf being the most different (Marins et al., 2014), similar to our older population.

The differences in the resting thermal patterns between sex could be explained by the heat management related to regional adiposity as a mediation mechanism (Claessens-van Ooijen et al., 2006). Men tend to accumulate fat in the abdomen (android) while women tend to store more fat in the thighs (gynoid). This fat distribution phenotype could act as a passive thermal insulation layer that prevents heat transfer from the core to the skin (Fournet et al., 2013). However, it also has been argued that fat mass does not appear to be an important factor for thermal regulation, except for the thighs (Fournet et al., 2013), and our data suggest the same trend, as the initial differences remained significant after adjusting for fat mass. Therefore, an alternative mechanism to explain the higher T_{sk} in men could be a greater amount of fat-free mass and a higher level of CRF, which could increase metabolic activity and heat production (Sillero-Quintana et al., 2015).

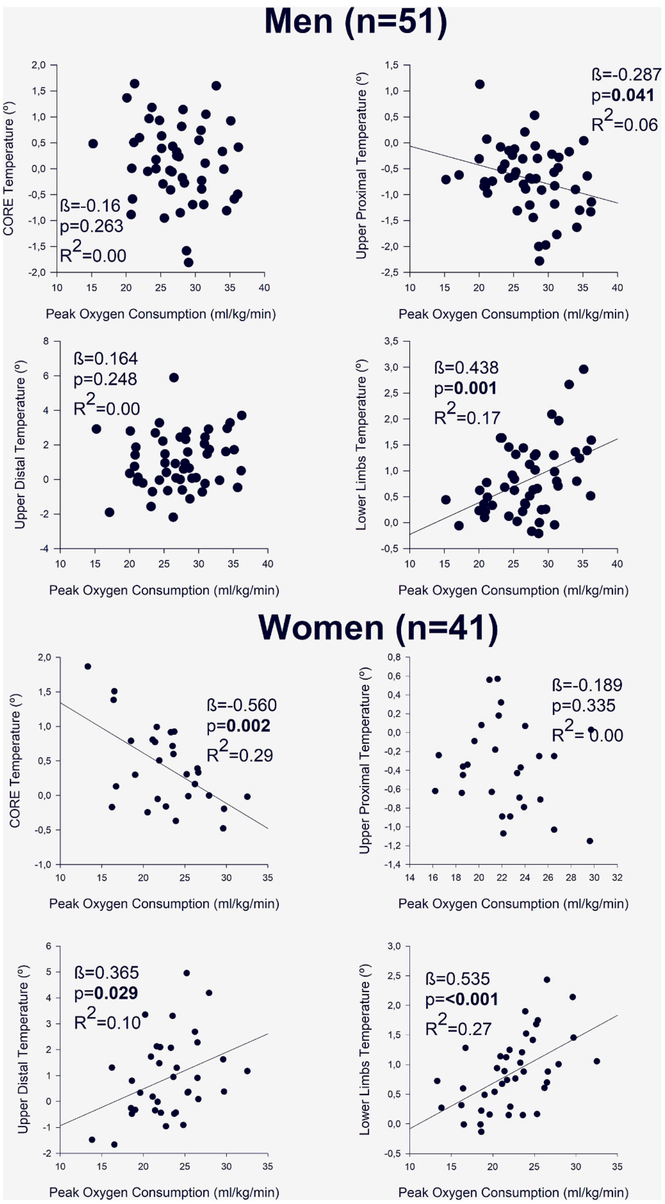

Fig. 3. Associations of Peak Oxygen Consumption with Core, Upper Proximal, Upper Distal, and Lower Limbs exercise-induced changes in temperature using single linear regression analyses. Standardized B coefficient, R2, and P-value are provided for each model.

4.2. *Acute response on the thermoregulation patterns of skin and its relationship with oxygen consumption*

Despite the significant differences observed in T_{sk} at rest between sexes, the acute response of thermoregulation patterns in the skin exhibited similarities between men and women. These findings align with previous data from studies conducted on young adults, which also indicated a diminishing of sex differences in T_{sk} during acute responses (Jimenez-Perez et al., 2020). The similarity in thermoregulation patterns between men and women during acute responses suggests that the physiological mechanisms involved in the regulation of skin temperature may be comparable between the sexes.

Our older participants showed decreases in the UP T_{sk}, increases in L and the UD T_{sk} as well as maintaining stable CR temperature after finishing the graded exercise. These changes could be explained by the active and passive recovery performed after the graded exercise test, which could alter the T_{sk}. It has been found the T_{sk} in lower limbs tends to increase after a few minutes of recovery to resting values (Priego Quesada et al., 2017) or even reaching higher temperatures (Tanda, 2018; Trecroci et al., 2018). Furthermore, increases in T_{sk} in the forearms and hands, the so-called "*hyperthermal spots*", have been reported (Merla et al., 2010) according to what happened in our older participants. Finally, although some parts of the body regained their basal T_{sk} during the recovery process, the temperature of the upper body remained lower during this process in one article (Tanda, 2018), following the same trend we found in our data with UP T_{sk}.

The decline of T_{sk} in some regions after exercise could be a consequence of the activation of the sympathetic noradrenergic nerve and the cutaneous vasoconstriction due to the release of norepinephrine and neuropeptide Y (Hillen et al., 2020). Thus, vasoconstriction redistributes blood from the skin to the brain, the heart, or the active muscles, to fulfil their oxygen requirements (Just et al., 2016). At the same time, active muscles generate and accumulate heat during their contractions. Therefore, to prevent states of hyperthermia the central nervous system triggers cutaneous vasodilatation or sweating to modulate this excess temperature (Mota-Rojas et al., 2021). Finally, after complete acute exercise, the sympathetic tone decreases leading to higher vasodilatation (Hillen et al., 2020) to promote heat dissipation using blood as a vehicle from the core zones to the peripheral parts of the body, especially the hands or the lower limbs (Mota-Rojas et al., 2021), increasing their T_{sk} and maintaining core temperature. Moreover, it could be plausible that the higher L and UD found in our older adults compared to other populations (Hillen et al., 2020) could be partially explained by differences in their population ages due to the slower heat dissipation (Ferreira et al., 2008).

Acute thermoregulation processes are gaining relevance in sports sciences as a potential predictor of human performance (Racinais et al., 2021). A recent case study has suggested that the acute temperature responses to exercise in the lower limbs could predict power losses and fatigue during exercise (Priego-Quesada et al., 2020). In our study, we found significant associations between CRF and T_{sk} in older adults. Higher CRF levels were associated with higher distal T_{sk} and lower proximal T_{sk}, which explained a small percentage of the performance variance in older adults (ranging from 17% to 27% for distal parts and 6%–29% for proximal parts). Specifically, changes in lower limb T_{sk} were related to both CRF and time to exhaustion in both sexes, independent of BMI status. This suggests that higher lower limb T_{sk} following exercise, indicative of improved heat dissipation, may play a modest role in older adults' performance and could be considered a proxy marker of CRF. However, it is important to note that these findings may not be generalizable to other populations (Duc et al., 2015; Priego Quesada et al., 2017), and further studies are required to establish whether changes in lower limb temperature can reliably be a potential marker of CRF, given the relatively low predictive values observed in our study.

4.3. *Strengths and limitations*

The current study has several strengths. One of the methodological aspects to highlight is the way to analyze ROIs using polygons determined by the hand-free allowing us to adapt to the anatomical landmarks of the participants instead of using pre-designed shapes that could not adjust to the different body compositions. Moreover, this study is the first to describe the thermal resting pattern and the acute response of older adults to graded exercise. There are several limitations to consider in this study. Firstly, T_{sk} images were only captured after the completion of the test. Unfortunately, due to the design of the protocol, we were unable to obtain T_{sk} measurements during the test and the recovery phase. This limitation prevented us from acquiring valuable information regarding the temperature dynamics of older adults throughout the entire process. Furthermore, previous studies have demonstrated differences in T_{sk} between during-exercise and post-exercise measurements, with higher T_{sk} levels recorded after completing the exercise (Aylwin et al., 2021, 2023). As a result, it is important to compare the

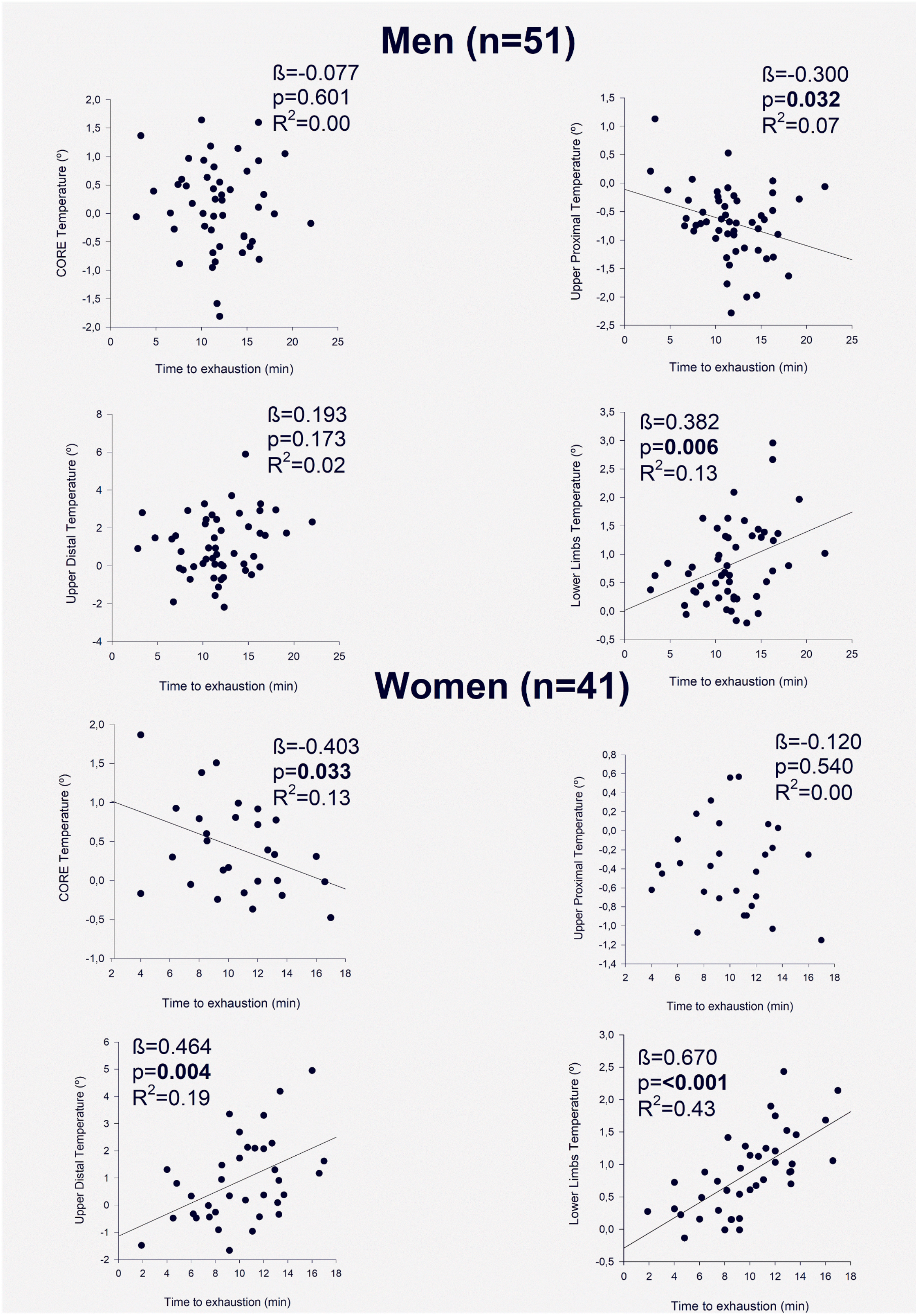

Fig. 4. Associations of time until exhaustion with Core, Upper Proximal, Upper Distal and Lower Limbs exercise-induced changes temperature. Single linear regression analyses were performed to examine these associations. Standardized B coefficient and P-value are provided for each model.

results of this study solely with T_{sk} images obtained after exercise. This is necessary to avoid potential confounding factors, such as the influence of rapid cutaneous vasodilation, which could impact T_{sk} measurements and make it difficult to differentiate the specific effects of exercise on temperature changes.

5. Conclusions

The findings of this study underscore the importance of considering sex-specific thermal patterns when evaluating older adults, as it is crucial for assessing skin temperature in this population given the significant differences observed in T_{sk} across various body regions, regardless of fat mass and CRF.

In addition to this, our results demonstrate that increases in lower limb temperature following submaximal exercise were associated with higher levels of CRF in both men and women older people. The observed association between increased L T_{sk} and CRF suggest a potential role of thermoregulatory responses concerning overall cardiovascular fitness among older adults, highlighting its potential utility as a proxy indicator of cardiovascular fitness in this population.

CRediT author statement

Corral-Pérez, Juan: Writing - Original Draft, Visualization, Investigation, Formal analysis Martinez-Tellez, Borja: Formal analysis, Writing - Review & Editing, Velázquez-Díaz, Daniel: Investigation, Writing - Review & Editing, Ponce-González, Jesús Gustavo: Writing - Review & Editing, Supervision, Carbonell-Baeza, Ana: Conceptualization, Writing - Review & Editing, Supervision, Project administration, Funding acquisition, Jiménez-Pavón, David: Conceptualization, Writing - Review & Editing, Supervision, Project administration, Funding acquisition.

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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

The authors do not have permission to share data.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jtherbio.2023.103678.

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