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Effect of spinal cord injury on the skin temperature of different regions of interest during a graded exercise test in a moderate temperature environment

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ABSTRACT

The gradient between core and skin temperature is a relevant factor in heat exchange between the human body and the environment, but people with spinal cord injury (SCI), due to their autonomic dysfunction, have impaired mechanisms that condition skin temperature response. This study aimed to determine how SCI affects skin temperature response in different ROIs during a graded exercise test in a moderate temperature environment. 32 participants were included in the study [SCI (N = 16); Non-SCI (N = 16)]. A graded exercise test was conducted on an arm crank ergometer, with a staged duration of 3 min separated by 1 min of rest. Skin temperature was measured using infrared thermography at rest, after each interval and during recovery. Individuals with SCI exhibited lower skin temperature in the anterior leg during exercise than Non-SCI ($p < 0.001$). During recovery, SCI athletes experienced a lower skin temperature restoration in the anterior arm, posterior arm and anterior leg ($p < 0.05$). The anterior leg is an interesting region to measure during exercise in people with SCI for assessing the physiological effect of the injury, probably for the autonomic dysfunction in skin temperature regulation, but the effect observed during recovery in the arms suggests the presence of different mechanisms involved in skin temperature regulation.

1. Introduction

Individuals with spinal cord injury (SCI) suffer an alteration in the autonomic nervous system which involves the loss of vasomotor control and the sweating capacity below the level of the injury (Henke et al., 2022; Price and Trbovich, 2018). Therefore, as both capacities are relevant in heat exchange between the individual and the environment, thermoregulation in individuals with SCI may be affected (Cruz and Blauwet, 2018; Price and Campbell, 2003; Walter and Krassioukov, 2018). Although core temperature is usually considered the gold standard for the assessment of heat stress, its methods of measurement (e.g., rectal thermometer or ingestible pills) can be uncomfortable, invasive or financially costly (Richmond et al., 2015). Raised skin temperatures (Tsk) are also associated with a higher risk of heat stroke due to the lower thermal gradient with the core (Racinais et al., 2022). For this reason, interest in measuring Tsk has been increasing over recent years, also for those suffering from SCI (Sanchez-Jimenez et al., 2022).

Tsk during exercise in SCI has been assessed previously using different tools (e.g., thermocouple or wireless sensors), under different environmental conditions and employing different exercise protocols (Sanchez-Jimenez et al., 2022). Price and Campbell (2003) carried out a continuous test in warm conditions and observed that participants with tetraplegia (TP) experienced a greater increase in arm Tsk than those with paraplegia (PP). Similar results were observed in the study of Griggs et al. (2017) during a rugby wheelchair match, observing that people with TP had a greater increase in Tsk than participants without SCI.

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Infrared thermography is a non-contact and non-invasive imaging technique used for measuring Tsk (Priego-Quesada et al., 2017). Due to its non-contact nature, the results are not influenced by attachment type, sensor applied pressure, or environmental conditions, as may be the case with thermal contact sensors (MacRae et al., 2018). In the field of sports, infrared thermography is primarily employed for injury detection and thermoregulation assessment (Crenna and Tanda, 2021; De Andrade et al., 2014; Gómez-Carmona et al., 2020; Sillero et al., 2017). However, in the SCI population, this tool has not been widely employed during exercise (Sanchez-Jimenez et al., 2022). Rossignoli et al. (2016) analysed the trapezius, shoulder and arm area during a 30-s maximum test in wheelchair athletes, but they did not detail the number of participants with SCI and their characteristics. Shida et al. (2018) undertook tests during wheelchair rugby and basketball matches on the forehead and upper arm area in wheelchair athletes with paraplegia and tetraplegia. However, these previous studies did not assess how SCI can affect the different regions of interest (ROIs) measured which could be essential to understanding in which ROIs focus the analysis depending on the objective of the study. Additionally, identifying the ROIs that can differentiate between Non-SCI and SCI athletes can enhance the understanding of how SCI impacts Tsk regulation.

The aim of this study was to determine how SCI affects Tsk response in different ROIs during a graded exercise test in a moderate temperature environment. Moreover, we aimed to analyse whether some ROIs are more susceptible to differ between SCI and Non-SCI population. Due to the location of the injury, we hypothesized that the variation of Tsk in ROIs of the lower limbs during exercise would differ between people with SCI and those without and would also differ from the ROIs of the upper limb and head.

2. Methods

2.1. Participants

32 volunteers (16 with SCI and 16 without SCI referred to as Non-SCI) participated in the study (Table 1). The participants were recruited from local associations and the National Paraplegics Hospital of Toledo. The characteristics of the individuals with SCI are presented in Table 2. The etiology of all the SCI was a traumatic injury, produced (mean ± SD) 13 ± 13 years before the study. Individual information about the injury characteristics was included as supplementary material. Inclusion criteria for all the participants included: (1) age between 20 and 65 years; (2) having not suffered any injury in the last three months; (3) not being pregnant; (4) being physically active, undertaking sports activities (e.g., endurance exercise, resistance exercise or team sports) at least twice per week and to (5) having the injury for at least one year. The participants with SCI employed daily treatments with the following objectives: spasticity (N = 6), neuropathic pain (N = 5), laxative (N = 8) and bladder management (N = 13). All individuals with SCI followed at least one treatment. The exclusion criteria established were suffering cardiovascular or metabolic disease. All participants signed the written informed consent before starting their participation in the study. The study was performed in agreement with the Declaration of Helsinki, and it was approved by the ethics committee of the University of Valencia (register number 1994739).

All the participants were instructed to avoid drinking alcohol or caffeine, cosmetics, smoking, large meals, ointments, sunbathing during the 6 h before the test, physiotherapy treatment during the 24 h before the test, physical activity the day of the test, and high-physical activity at the day before the test to reduce the variability of Tsk (Priego-Quesada et al., 2017).

Table 1
Sociodemographic characteristics of the sample.

Characteristics	SCI (N = 16)	Non-SCI (N = 16)	*P* Value
Sex	13 (M); 3 (F)	13 (M); 3 (F)	1.000
Age (years)	39 ± 8	34 ± 10	0.102
Body mass (kg)	74.1 ± 11.8	73.7 ± 12.5	0.712
Height (cm)	176.2 ± 7.6	175.9 ± 7.4	0.907

M = Male; F = Female. The analysis of core temperature was conducted with a reduced sample [SCI (N = 10); Non-SCI (N = 10)], but no statistical differences were obtained between groups in any of the characteristics ($p < 0.05$). Data is presented as mean ± standard deviation (SD).

Table 2
Characteristics of the individuals with SCI.

Level	Extension	
	Complete	Incomplete
Cervical Injury	N = 3	N = 0
High Thoracic Injury > T6	N = 3	N = 3
Low Thoracic Injury < T6	N = 6	N = 1

2.2. Protocol

The participants visited the laboratory once to perform a graded exercise test in an arm crank ergometer (SciFit Pro1 Arm Ergometer; SCIFIT Systems Inc, Tulsa, Oklahoma, USA) (Fig. 1). First, the participants remained for 10 min sitting in the ergometer saddle (Non-SCI), or in their wheelchair (SCI) in a resting state for thermal room adaptation (Marins et al., 2014). After that, they conducted a warm-up of 5 min at an intensity of 10W. The duration of each interval was set at 3 min (Burns et al., 2012; Lewis et al., 2007) followed by a rest period of 1 min (Goosey et al., 2010; Lovell et al., 2012). The start resistance for participants with TP was set at 15W and 30W for PP and Non-SCI. The definition of start resistance was diverse in the previous publications (Al-Rahamneh and Eston, 2011; Hooker and Wells, 1992; Pelletier et al., 2013), and for this reason, we decided the start resistance to have durations of the protocol between 12 and 20 min considering the maximum power observed in previous studies with similar sample characteristics (Al-Rahamneh and Eston, 2011; Hjeltnes and Wallberg-Henriksson, 1998; Pelletier et al., 2013). Moreover, the resistance increased after each interval by 5W for TP and 10W for high PP (>T6) (Hol et al., 2007; Pelletier et al., 2013). Low-level PP (<T6) and Non-SCI increased the resistance by 15W (Theisen et al., 2001). The cadence was self-selected by the participants in the first stage, and they were supervised to maintain that cadence throughout the test, with instructions given to decrease or increase cadence when necessary. According to the number of stages, the SCI group completed 5.3 ± 0.8 stages (maximum power output of 76 ± 29 W) and Non-SCI 5.6 ± 0.9 stages (92 ± 18 W). The individuals with TP included in the study had injuries at the C6-C7 segments. Consequently, they retained the use of the flexor muscles of the arms but lacked function in posterior muscles such as the triceps brachii. Additionally, forearm muscles were also affected by the SCI, necessitating that their hands be attached to the handle of the ergometer.

2.3. Data collection

2.3.1. Skin temperature

Tsk was measured using an infrared camera (Flir E60, FLIR Systems Inc., Wilsonville, U.S.A.) with a sensor array size of 320 × 240 pixels, with noise equivalent temperature difference (NETD) < 0.05 °C and measurement uncertainty of ±2 °C or 2%. The calibration of the camera was checked before starting the experiments using a blackbody (BX-500 IR Infrared Calibrator, CEM, Shenzen, China) with a target emissivity of 0.95 and resolution of 0.1 °C. Infrared images were taken at rest, after each interval and during recovery (one, five and 10 min after the exercise ended).

The camera was situated perpendicularly to the ROIs assessed during measuring, and it was always located at the same distance (1 m)

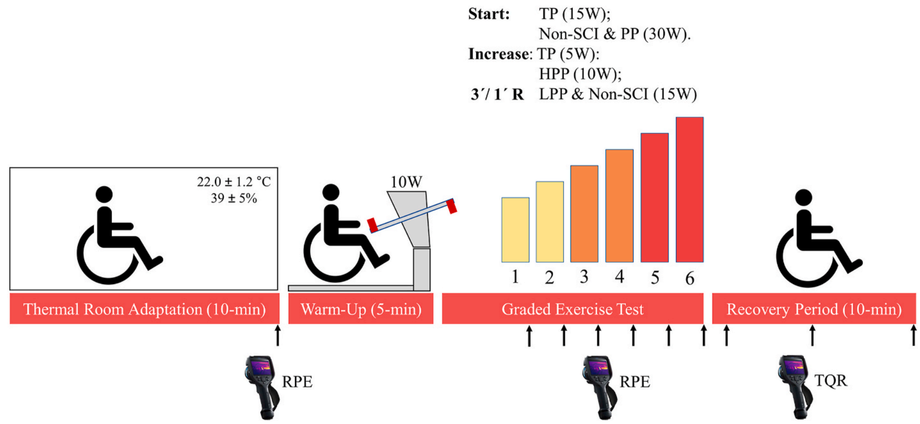

Fig. 1. Graphical representation of the design of the study. TP = tetraplegia; PP = Paraplegia; HPP = high paraplegia; LPP = low paraplegia; Non-SCI = participants without spinal cord injury; RPE = rate of perceived exertion. TQR: Total quality recovery scale.

(Moreira et al., 2017). The infrared camera was turned on 10 min before the measurement for electronic stabilization (Moreira et al., 2017). Room temperature and relative humidity were monitored using a digital thermo-hygrometer (TFA Dostmann, Wertheim-Reicholzheim, Germany), obtaining the following environmental temperature and relative humidity considered as moderate environmental conditions (Cheung and Robinson, 2004): 22.0 ± 1.2 °C; 39 ± 5%. No differences in environmental conditions were observed between groups ($p > 0.05$). The reflected temperature was measured (22.9 ± 1.0 °C) according to the standard method ISO 18434-1, 2008 and introduced in the camera setup.

Four ROIs were determined in the study, the anatomical points being shown in Fig. 2: (1) anterior arm, (2) posterior arm, (3) forehead and (4) anterior leg. All the images were taken on the dominant side of the participants. Mean Tsk was obtained for each ROI using thermographic software (ThermaCam Researcher Pro 2.10, FLIR Systems, Wilsonville, Oregon, EEUU). The same researcher carried out the entire thermographic analysis to ensure consistency. Images were processed using a skin emissivity factor of 0.98 (Moreira et al., 2017).

2.3.2. *Core temperature*

Core temperature analysis included 20 participants (SCI N = 10; Non-SCI N = 10). Core temperature was measured with ingestible pills (e-Celsius, BodyCap, Caen, France), and the data was recorded every 15s. The ingestible pills were distributed to the participants the day before the graded exercise test together with the instructions to consume the pill 4–6 h before the test. Core temperature values were obtained during the minute of recovery after each stage.

2.3.3. *Perceived variables*

The rate of perceived exertion (RPE) was measured using the 6–20 points Borg's scale (Borg, 1982). The scale ranges from 6 to 20, with 6 being considered "very, very light" and 20 "very, very hard" (Borg, 1982). The scale was shown to the participants at rest and after each interval.

The individual perception of recovery was assessed using the total quality recovery scale (TQR). The scale ranges from 6 to 20, with 6 being considered "very, very poor recovery" and 20 "very, very good recovery" (Kenttä and Hassmén, 1998). The scale was shown to the participants one, five and 10 min after the test ended.

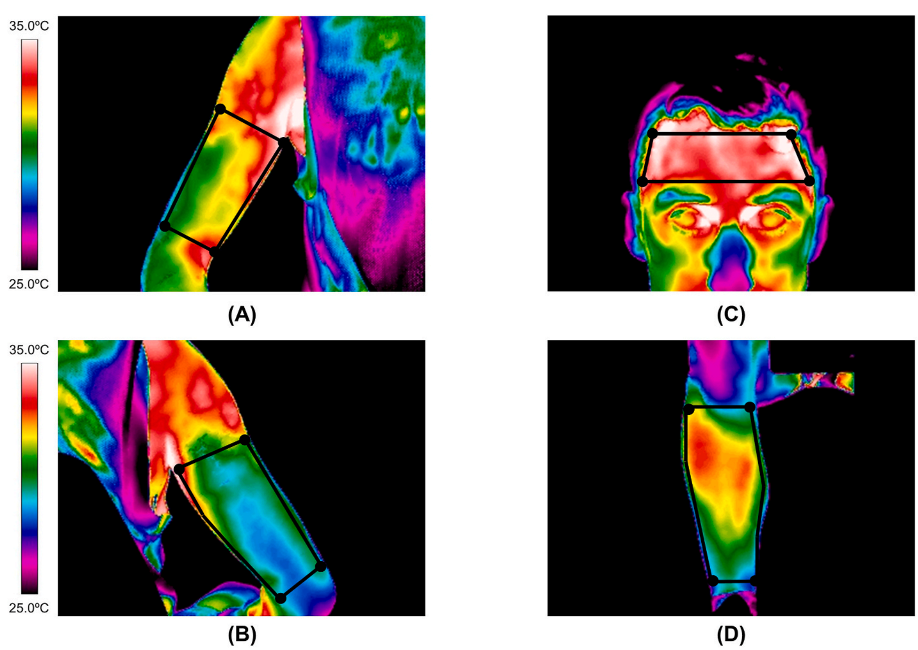

Fig. 2. The delimited Regions of Interest of the study: (A) anterior arm; (B) posterior arm; (C) forehead; (D) anterior leg.

Table 3
Results of mixed regression models for skin temperature during exercise and recovery.

	ROI	Predictors	Estimates	95%CI	*P* Value
Exercise	**Anterior Arm**	*Intercept*	32.23	31.60, 32.86	**<0.001**
		Group [SCI]	0.11	−0.82, 1.03	0.817
		Percentage of test [%]	−0.01	−0.01, −0.00	**0.001**
		Group [SCI] x Percentage of test [%]	0.00	−0.00, 0.01	0.621
		R^2 Marginal/Conditional R^2		0.020/0.833	
	Posterior Arm	*Intercept*	30.22	29.59, 30.86	**<0.001**
		Group [SCI]	0.55	−0.38, 1.48	0.234
		Percentage of test [%]	0.00	−0.00, 0.00	0.687
		Group [SCI] x Percentage of test [%]	−0.00	−0.01, 0.00	0.129
		R^2 Marginal/Conditional R^2		0.020/0.847	
	Forehead	*Intercept*	34.42	33.90, 34.93	**<0.001**
		Group [SCI]	−0.58	−1.34, 0.17	0.124
		Percentage of test [%]	−0.01	−0.02, −0.01	**<0.001**
		Group [SCI] x Percentage of test [%]	0.00	−0.00, 0.01	0.474
		R^2 Marginal/Conditional R^2		0.168/0.712	
	Anterior Leg	*Intercept*	30.56	29.81, 31.31	**<0.001**
		Group [SCI]	−2.50	−3.60, −1.41	**<0.001**
		Percentage of test [%]	−0.03	−0.03, −0.03	**<0.001**
		Group [SCI] x Percentage of test [%]	0.02	0.02, 0.02	**<0.001**
		R^2 Marginal/Conditional R^2		0.857/0.999	
Recovery	**Anterior Arm**	*Intercept*	31.64	31.02, 32.25	**<0.001**
		Group [SCI]	0.49	−0.42, 1.40	0.277
		Moment	0.13	0.10, 0.16	**<0.001**
		Group [SCI] x Moment	−0.04	−0.08, −0.00	**0.043**
		R^2 Marginal/Conditional R^2		0.117/0.888	
	Posterior Arm	*Intercept*	30.32	29.62, 31.01	**<0.001**
		Group [SCI]	0.62	−0.41, 1.65	0.226
		Moment	0.13	0.11, 0.16	**<0.001**
		Group [SCI] x Moment	−0.04	−0.08, −0.01	**0.014**
		R^2 Marginal/Conditional R^2		0.112/0.933	
	Forehead	*Intercept*	32.83	32.15, 33.51	**<0.001**
		Group [SCI]	−0.03	−1.03, 0.98	0.959
		Moment	0.00	−0.04, 0.04	0.984
		Group [SCI] x Moment	0.02	−0.04, 0.08	0.476
		R^2 Marginal/Conditional R^2		0.002/0.813	
	Anterior Leg	*Intercept*	27.62	26.85, 28.39	**<0.001**
		Group [SCI]	−0.26	−1.41, 0.88	0.640
		Moment	0.06	0.05, 0.08	**<0.001**
		Group [SCI] x Moment	−0.06	−0.08, −0.03	**<0.001**
		R^2 Marginal/Conditional R^2		0.576/0.999	

The thermal sensation was measured using the Gagge et al. (1967) scale, modified by Toner et al. (1986). The scale ranges from 0 to 8, with 0 being considered “unbearably cold” and 8 “unbearably hot” (Toner et al., 1986). The scale was shown to the participants after each interval and one, five and 10 min after the test ended.

2.4. Statistical analysis

Statistical analysis was performed using RStudio (version 2022.02.03). A multivariate mixed regression model (package nlme, version 3.1–161) was used for each ROI, for exercise moments and for recovery moments, in order to characterize mean Tsk responses for each ROI, using the participant as a randomized factor adjusted for the intercept and analyzing the main effect of the group, and percentage of the test. The interaction between the group and the percentage of the test were considered during exercise, and during the recovery the interaction between the group and the moment (minutes recovery). The same analysis was used to characterize core temperature, RPE, thermal sensation and TQR responses using the participant as a randomized factor adjusted for the intercept and analyzing the main effect of the group, the percentage of test and the interaction between the group and the percentage of the test. During the recovery, the interaction considered was established between the group and the moment. The assumption of normality for the residuals to the fitted values and convergence were confirmed for each mixed model. The models were provided with the marginal R^2 of the fixed effects (without random effects), and the conditional R^2 that includes the fixed and random effects. The relationship of skin temperature with core temperature, RPE and thermal sensation was determined using Pearson correlation coefficient (package corrr). Significant correlations were classified as ($0.2 < |r| < 0.5$), moderate ($0.5 < |r| < 0.8$), or strong ($|r| \geq 0.8$). Significance was established at $p < 0.05$.

3. Results

3.1. Skin temperature during exercise and recovery

Table 3 shows the results of the mixed regression model for Tsk during exercise and recovery. The marginal R^2 values ranged from 0.002 to 0.86, and the conditional R^2 values from 0.71 to 0.99. Regarding the Tsk during exercise (Fig. 3), the anterior leg was the only ROI which presented a main effect between groups, lower Tsk being found in SCI than in the Non-SCI. The percentage of the test presented a main effect in three ROIs (anterior arm, forehead and anterior leg), showing a reduction in Tsk of the ROI whenever the power output increases in both groups. The interaction between the group and the percentage of the test presented a main effect only with the Tsk of the anterior leg, and the results show that as intensity increases, Non-SCI experience a greater reduction in their Tsk than SCI.

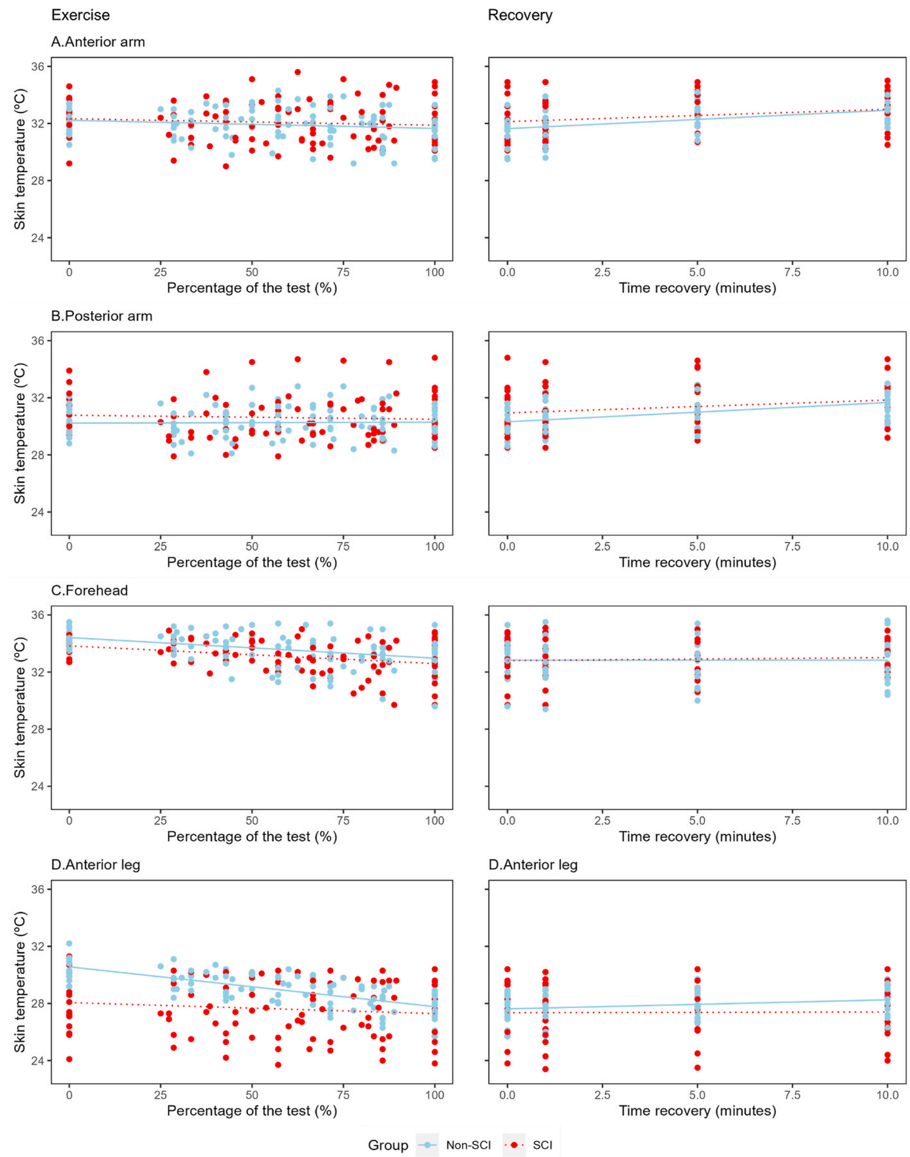

Fig. 3. Graphical representation of mixed regression models (lines are the mean prediction of the models) for skin temperature during exercise and recovery in the four regions of interest measured.

With regard to Tsk during recovery, the group did not produce a main effect in the Tsk of any of the ROIs assessed ($p > 0.05$). The moment factor presented a main effect in three ROIs (anterior arm, posterior arm, and anterior leg), resulting in an increase in Tsk during the recovery period. The interaction between group and moment presented a main effect in three ROIs (anterior arm, posterior arm, and anterior leg), and the results show that the Tsk of SCI during recovery increases slower than the Non-SCI.

3.2. Core temperature during exercise and recovery

The marginal R^2 of mixed regression models explaining core temperature is 0.14 for exercise and 0.18 for recovery, and the conditional R^2 is 0.90 for exercise and 0.94 for recovery. The mixed regression model revealed a main effect in core temperature of the percentage of the test, with an increase in core temperature as the intensity of the test increases ($p < 0.001$) (Fig. 4; Table 4). During the recovery period, the moment presented a main effect on core temperature, showing an increase in core temperature during the recovery period ($p < 0.001$). Moreover, the interaction between group and moment revealed that SCI experienced a lesser increase than the Non-SCI in core temperature when the exercise ended ($p = 0.02$).

3.3. Perceived variables during exercise and recovery

Table 4 shows the results of the mixed regression model on RPE and thermal sensation during exercise and recovery and the marginal R^2 values ranged from 0.02 to 0.83, and the conditional R^2 from 0.18 to 0.94. Regarding perceived variables during exercise, the group did not produce a main effect on RPE and thermal sensation ($p > 0.05$). However, the percentage of the test produced a main effect on RPE and thermal sensation, both values increasing together when the intensity of the test increased ($p < 0.001$). The interaction between group and percentage of the test resulted in a main effect in RPE, SCI experiencing a lower increase than the Non-SCI in RPE as the intensity of the test increased ($p < 0.01$).

In relation to the perceived variables during the recovery period, the group and the interaction between group and moment did not show a main effect in TQR and thermal sensation. However, the moment showed a main effect in thermal sensation during recovery, and the

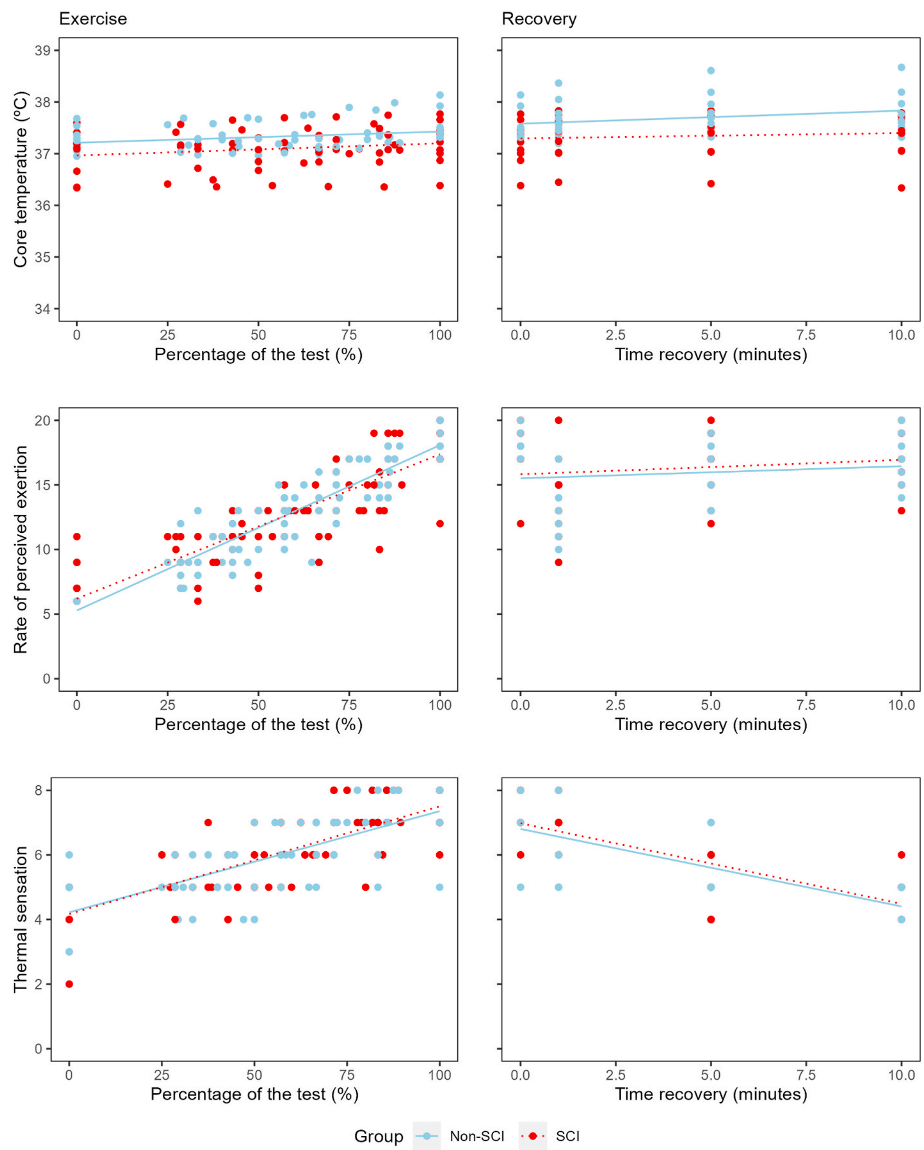

Fig. 4. Graphical representation of mixed regression models for core temperature, rate of perceived exertion and thermal sensation during exercise and recovery.

results showed a reduction in thermal sensation during the recovery period ($p < 0.001$).

3.4. *Correlation between skin temperature, core temperature rate of perceived exertion and thermal sensation*

The correlation analysis between Tsk in each ROI with core temperature, RPE and thermal sensation in each group is shown in Table 5. A moderate correlation was observed between the Tsk of the posterior arm and core temperature in the Non-SCI group ($r = 0.52$; $p < 0.001$). In the SCI group, the Tsk of the anterior arm, posterior arm, and forehead showed a weak correlation ($r = 0.39$ to 0.46). Similarly, in the Non-SCI group, the Tsk of the anterior arm and anterior leg exhibited a weak correlation ($r = -0.28$ to 0.48). When considering all participants, the Tsk of the anterior arm, posterior arm, and forehead demonstrated a weak correlation ($r = 0.25$ to 0.46). Regarding the correlation between Tsk and RPE, the SCI group showed a weak correlation in the Tsk of the posterior arm ($r = 0.27$; $p = 0.01$). In contrast, the Non-SCI group exhibited a moderate correlation in the Tsk of the anterior leg ($r = -0.61$; $p < 0.001$), while the Tsk of the forehead had a weak correlation ($r = -0.49$; $p < 0.001$). When all participants were considered, a weak correlation was observed in the Tsk of the posterior arm, forehead, and anterior leg ($r = 0.19$ to -0.31; $p \leq 0.02$). No significant correlations between skin temperature (Tsk) and thermal sensation were observed in the SCI group ($p > 0.05$). In the Non-SCI group, weak correlations were found with the Tsk of the forehead and anterior leg ($r = -0.33$ and -0.46; $p < 0.001$). When considering all participants, weak correlations were reported for the Tsk of the anterior arm, forehead, and anterior leg ($r = -0.16$ to -0.22; $p \leq 0.03$).

4. Discussion

The aim of this study was to determine how SCI affects Tsk response in different ROIs during a graded exercise test in a moderate temperature environment. The main result of our study was that the anterior leg is the only ROI which presented differences between the groups during the exercise, with lower values of Tsk in SCI. Moreover, SCI presented a lower Tsk recovery after exercise in three of the ROIs in comparison to the Non-SCI.

4.1. *SCI effect on skin temperature*

One of the aims of this work was to assess whether the Tsk of a specific ROI was more susceptible to being different due to the presence

Table 4
Results of mixed regression models in core temperature, rate of perceived exertion and thermal sensation during exercise and recovery.

		Predictors	Estimates	95%CI	*P* Value
Exercise	**Core Temperature**	*Intercept*	37.21	37.00, 37.42	**<0.001**
		Group [SCI]	−0.25	−0.56, 0.07	0.116
		Percentage of test [%]	0.002	0.00, 0.00	**<0.001**
		Group [SCI] x Percentage of test [%]	0.00	−0.00, 0.00	0.756
		R^2 Marginal/Conditional R^2		0.142/0.899	
	RPE	*Intercept*	5.28	4.50, 6.06	**<0.001**
		Group [SCI]	0.91	−0.24, 2.07	0.116
		Percentage of test [%]	0.13	0.12, 0.14	**<0.001**
		Group [SCI] x Percentage of test [%]	−0.02	−0.03, −0.00	**0.005**
		R^2 Marginal/Conditional R^2		0.827/0.904	
	Thermal Sensation	*Intercept*	4.22	3.88, 4.57	**<0.001**
		Group [SCI]	−0.05	−0.56, 0.45	0.836
		Percentage of test [%]	0.03	0.03, 0.03	**<0.001**
		Group [SCI] x Percentage of test [%]	0.00	−0.00, 0.01	0.409
		R^2 Marginal/Conditional R^2		0.647/0.819	
Recovery	**Core Temperature**	*Intercept*	37.58	37.33, 37.83	**<0.001**
		Group [SCI]	−0.29	−0.66, 0.09	0.124
		Moment	0.03	0.02, 0.03	**<0.001**
		Group [SCI] x Moment	−0.01	−0.03, −0.00	**0.018**
		R^2 Marginal/Conditional R^2		0.181/0.943	
	TQR	*Intercept*	15.51	14.36, 16.66	**<0.001**
		Group [SCI]	0.31	−1.37, 1.99	0.708
		Moment	0.09	−0.08, 0.27	0.292
		Group [SCI] x Moment	0.02	−0.23, 0.27	0.884
		R^2 Marginal/Conditional R^2		0.023/0.176	
	Thermal Sensation	*Intercept*	6.80	6.49, 7.12	**<0.001**
		Group [SCI]	0.18	−0.29, 0.65	0.447
		Moment	−0.24	−0.29, −0.19	**<0.001**
		Group [SCI] x Moment	−0.01	−0.08, 0.06	0.788
		R^2 Marginal/Conditional R^2		0.571/0.635	

of SCI. This is important in studies monitoring SCI as it could indicate that the measurement should focus on only one ROI during exercise. Here, our results showed that individuals with SCI presented a lower Tsk in anterior leg during exercise than the Non-SCI group, but no statistical differences were observed between groups for the anterior arm, posterior arm and forehead. Also observed was an interaction between the group and the percentage of the test, showing that SCI in comparison with the Non-SCI group experienced a lower reduction in the Tsk of the anterior leg as the intensity increased. In this sense, these findings are also supported by the weak correlation observed in SCI ($r = 0.01$) and moderate in Non-SCI ($r = -0.61$) between Tsk of the anterior leg and RPE. The loss of sympathetic signaling below the level of the injury and the consequent disruption to skin vascular responses (Buckwalter and Clifford, 2001; Horiuchi and Fukuoka, 2019; Thijssen et al., 2009) may be the reason why SCI presented a lower Tsk than the Non-SCI in the anterior leg, and also lower Tsk responses during exercise due to their difficulties of moving the blood to the upper limbs. A previous study supports this idea observing higher reductions of calf volume (measured by plethysmography) during exercise in Non-SCI compared to participants with SCI (Hopman et al., 1993). Previous studies observed an increase in the Tsk of the calf in PP and a reduction in Non-SCI during exercise (Price and Campbell, 1997, 1999, 2002). Moreover, Forsyth et al. (2019) observed that the Tsk of the calf during the exercise increased in PP and TP whereas in the Non-SCI group it remained stable. Horiuchi and Fukuoka (2019) conducted a continuous test in which the Tsk of the thigh increased in PP and Non-SCI group, but with a greater increase in PP. However, Veltmeijer et al. (2014) during a wheelchair tennis match did not observe different responses in Tsk of the lower region between SCI and Non-SCI. Here, the authors argued that the lack of differences in Tsk between groups could be related to the design of the study due to a limited heat load and exercise duration (Veltmeijer et al., 2014). Therefore, the differences between groups in the ROI located at the lower leg (e.g., calf or anterior leg) may allow us to differentiate between SCI and Non-SCI athletes under moderate conditions. In our study the assessment of the ROIs located at the upper arm and the forehead did not allow us to make a distinction between SCI and

Table 5
Correlation of skin temperature in each region of interest (ROI) with core temperature, rate of perceived exertion (RPE) and thermal sensation.

ROI		SCI		Non-SCI		All	
		r	P Value	r	P Value	r	P Value
Anterior Arm	Core Temperature	0.46	**<0.001**	0.48	**<0.001**	0.46	**<0.001**
Posterior Arm		0.39	**<0.001**	0.52	**<0.001**	0.38	**<0.001**
Forehead		0.40	**<0.001**	−0.01	0.89	0.25	**<0.001**
Anterior Leg		−0.06	0.54	−0.28	**0.01**	0.02	0.77
Anterior Arm	Rate of Perceived Exertion	0.15	0.15	−0.08	0.43	0.04	0.61
Posterior Arm		0.27	**0.01**	0.09	0.38	0.19	**0.01**
Forehead		−0.16	0.16	−0.49	**<0.001**	−0.31	**<0.001**
Anterior Leg		0.01	0.89	−0.61	**<0.001**	−0.17	**0.02**
Anterior Arm	Thermal Sensation	−0.06	0.59	−0.25	0.013	−0.16	**0.03**
Posterior Arm		−0.04	0.69	−0.16	0.12	−0.09	0.23
Forehead		−0.11	0.30	−0.33	**<0.001**	−0.22	**<0.01**
Anterior Leg		−0.06	0.54	−0.46	**<0.001**	−0.21	**<0.01**

Non-SCI as there were no differences between groups. Regarding the correlations analysed in these ROIs, only the posterior arm of Non-SCI presented a moderate relation ($r = 0.52$) with core temperature, while the remaining ROI's in both groups obtained a weak relation ($r = -0.01$ to 0.48). Griggs et al. (2017) observed that changes in forearm, upper arm, chest, back, thigh and calf Tsk during a rugby wheelchair match presented similar values in both the SCI and Non-SCI groups, showing an increase for the forearm, upper arm and back during the match in both groups. Similar results were obtained by Horiuchi and Fukuoka (2019), who found an increase in the Tsk of the arm during the exercise but with no differences between SCI and Non-SCI. However, Price and Campbell (1999) observed similar Tsk responses for the forehead and upper arm in PP and Non-SCI during exercise. The Tsk, however, of the forearm was higher in PP than in Non-SCI during the exercise (Price and Campbell, 1999). Therefore, it seems that the upper arm and forehead did not differ between SCI and Non-SCI, but the forearm would be an interesting ROI to consider in further research.

In our study, during the recovery time after exercise, more ROIs were different between groups, a different pattern of Tsk recovery being observed for the anterior arm, the posterior arm and the anterior leg. In these ROIs, individuals with SCI had a lesser increase in Tsk than the Non-SCI. In contrast to the exercise period, the ROIs measured in the arm presented changes in Tsk whereas during exercise they remained with similar values, so suggesting the presence of different factors involved in Tsk recovery. Only the muscles of the posterior arm in three of the participants (cervical injuries) may be affected due to the level of the injury and their innervation (C6-C8). Moreover, the pattern of Tsk recovery in the anterior arm, posterior arm and anterior leg was similar (SCI had a lower increase than Non-SCI). As the ROIs located on the arm in our study sample are not affected by SCI, the expected recovery to baseline values should be similar to Non-SCI. Therefore, there may exist a possible difference in the vasomotor control between groups, even if the ROI is not affected by the SCI. One possible explanation may be that SCI could have peripheral adaptations in the arms produced by the daily use of the wheelchair and the practice of sport activities which mainly involve the arms (Martín-Manjarrés et al., 2021). Despite core temperature increases, ~0.3 °C during the recovery period, this may not be enough to affect the Tsk response of the ROIs assessed. Regarding the anterior leg, as we commented in the previous paragraph, the differences observed between groups during the recovery may be due to the loss of vasomotor control of people with SCI (Buckwalter and Clifford, 2001; Horiuchi and Fukuoka, 2019; Thijssen et al., 2009).

It is important to note that our study was performed under moderate environmental conditions, and it seems that the thermoregulatory system was able to dissipate the amount of heat produced by an increase in metabolic activity. Moreover, the SCI sample was mainly composed of individuals with thoracic injuries which compromise to some extent the thermoregulatory response. This is supported by our values of core temperature and thermal sensation that did not differ between groups, and the slight increases in core temperature observed during exercise (~0.2 °C). Previous studies with higher core temperature associated its increase to the higher environmental temperature and level of injury (Forsyth et al., 2019; Griggs et al., 2015; Price and Campbell, 2003). Hence, SCI above T6 presented higher core temperatures than Non-SCI (Forsyth et al., 2019). Therefore, although our study is interesting for providing a reference in a moderate environment, further studies should replicate our study in a hot environment when differences between ROIs could be higher. Moreover, the choice of exercise testing is a critical factor when comparing two populations with distinct characteristics. The fact that the group was not a significant main factor in the mixed model for explaining RPE supports the idea that groups were correctly matched and the characteristics of the protocol (workload increases of each step) were correctly adapted to each group. However, the regression model revealed that SCI participants experienced a lower increase in RPE as the intensity (percentage of the test) increased compared to Non-SCI participants. This could be due to the adaptation of SCI athletes to upper limb exercise, which may result in a lower RPE. In contrast, Non-SCI individuals are not used to this type of physical activity and it might be limited by peripheral mechanisms, leading to a higher RPE. Finally, the lower marginal R^2 and higher conditional R^2 values presented by the mixed models suggest that although having a SCI injury is important, individual variability has a great influence.

4.2. Exercise effect on skin temperature

Future studies could consider replicating the exercise protocol used and comparing their results with those of the present study. For this reason, it is interesting to discuss the general responses to the exercise performed irrespective of the group (SCI or Non-SCI). In this sense, the increase in exercise intensity resulted in a reduction of Tsk of the anterior arm, forehead and anterior leg, but the posterior arm did not alter Tsk. However, the correlation analysis between Tsk and RPE, which is related to the exercise intensity, revealed a weak relation between both variables in all the ROIs ($r = -0.31$ to 0.19). This Tsk reduction may be due to the onset of sweating (Priego-Quesada et al., 2020) or the presence of peripheral vasoconstriction during intense physical exercise (Jastrzębska et al., 2022). Moreover, the reduction in Tsk of the anterior leg may also be affected by the blood redistribution from lower limbs to working muscles (e.g., upper limbs) (Buckwalter and Clifford, 2001; Hopman et al., 1993; Thijssen et al., 2009). However, the absence of differences in the Tsk of the posterior arm may be due to a balance in that ROI between the skin blood flow and sweat evaporation.

Concerning Tsk responses during recovery from exercise, this increased in the anterior arm, the posterior arm and the anterior leg, but the forehead did not change its Tsk. The increase observed in Tsk may be mediated by skin vasodilation to restore rest values after exercise, as during incremental exercise peripheral vasoconstriction, which decreases Tsk, is common (Jastrzębska et al., 2022). However, the Tsk of the forehead did not change during recovery. The previous studies which assessed the forehead during recovery from exercise present discrepancies in their results, Hillen et al. (2023) observed a reduction in Tsk and Jastrzębska et al. (2022) obtained an increase in Tsk in the temporal ROI. Hillen et al. (2023) suggest that the differences in the results could be related to vasculature differences between ROIs.

A considerably increased thermal sensation was observed during the exercise protocol (most of the reported values at the end were between "Warm" and "Unbearibly Hot"). The negative correlation observed between Tsk and thermal sensation supports these results, but despite being weak in all cases, the Non-SCI group obtained slightly higher values than the SCI group (SCI $r = -0.11$ to -0.04; Non-SCI $r = -0.16$ to -0.46). Kroesen et al. (2022) observed that the thermal sensation increased with the intensity of the test during an incremental exercise test. So, the continuous increase in external load affects metabolic heat production and therefore, the thermal sensation. In the same way, during recovery, a reduction in thermal sensation was observed. When exercise finishes heat production diminishes and this may be the reason why the thermal sensation decreases when the exercise ends.

4.3. Practical application

Understanding the response of different ROIs during physical exercise is of practical interest when monitoring Tsk of people with SCI. The wheelchair and the position of the athlete makes monitoring the entire body complicated and, therefore, more research could focus on a particular ROI, which will possibly depend on the objectives of the study. In our study, the anterior leg is the ROI that differs between SCI and Non-SCI athletes, and it is located below the injury. This ROI could be interesting if the aim of the study is to evaluate the physiological effect of the injury. However, another different application is to identify a ROI that is more susceptible to experiencing changes in Tsk during exercise as a consequence of SCI in the prevention of heat-related illness.

Tsk of the anterior leg probably cannot reflect the effect of warm environments and heat stress situations, as this increase during exercise is lower. So, the ROIs with no differences with the Non-SCI (ROIs of the upper limbs) may be more appropriate for assessing whether high Tsk are reached during exercise in hot conditions. However, this idea is mere speculation as our results were in a moderate environment, and therefore, future studies should consider the effect of SCI on different ROIs in warm environments.

4.4. Limitations

The main limitation of this study was that all the injuries were not complete, and the heterogeneity that occurs between incomplete injuries may affect the results measured. Moreover, the sample was primarily made up of individuals with PP, who suffer lower impairment in the thermoregulatory system than TP. Assessing other physiological outcomes (e.g., nervous innervation of each participant) also would help to explore the mechanism that explains our results. Finally, the lower number of women assessed in our sample did not allow us to also assess the sex interaction in our models.

5. Conclusion

The anterior leg is an interesting region to measure during exercise in individuals with SCI in moderate temperature conditions for assessing the physiological effect of the injury, probably for the autonomic dysfunction in Tsk regulation. Moreover, the recovery pattern to baseline values of Tsk in the anterior arm and posterior arm differs between groups during the recovery period despite these regions not being affected by the injury, something that suggests the presence of peripheral adaptations.

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Data accesibility statement

The dataset generated and analysed during the current study is available in the Mendeley repository (DOI:10.17632/2z2d5wvy43.1; https://data.mendeley.com/datasets/2z2d5wvy43/1).

CRediT authorship contribution statement

Jose Luis Sanchez-Jimenez: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Rosa M. Cibrian-Ortiz de Anda:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Maria Vazquez-Fariñas:** Writing – review & editing, Resources, Conceptualization. **Soraya Martin-Manjarres:** Writing – review & editing, Resources, Conceptualization. **Jose Ignacio Priego-Quesada:** Writing – review & editing, Supervision, Software, Resources, Methodology, Formal analysis, Conceptualization. **Inmaculada Aparicio-Aparicio:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jtherbio.2024.103969.

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