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Relationship between shoulder pain and skin temperature measured by infrared thermography in a wheelchair propulsion test

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HIGHLIGHTS

- T_{sk} response of wheelchair athletes before and after a propulsion test is presented.
- The relation between SP and T_{sk} before and after the propulsion test is obtained.
- Subjects showed lower resting T_{sk} and slower heat dissipation than able-bodied.
- There were significant negative correlations between the T_{sk} and SP.
- There were no correlations between the kinematic variables and the shoulder pain.

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ABSTRACT

Introduction: Wheelchair Users (WCUs) depend on their upper extremities for their daily living. Therefore, it is not unusual to find that shoulder pain (SP) is a problem for WCUs and reduces their participation in sport and leisure activities.
Objectives: The aims of this study were 1 – to analyse skin temperature measured by infrared thermography (IRT) before (pre-test), one minute after (post-test) and 10 min after (post-10) the kinematic wheelchair propulsion test (T-CIDIF) of athletic wheelchair users; 2 – to evaluate the relationship between shoulder pain (SP) and Skin Temperature Asymmetry (ΔT_{sk}) before and after (pre-test, post-test, post-10) the T-CIDIF, and to relate the SP with the kinematic variables of the T-CIDIF.
Participants & interventions/procedure: A volunteer sample of 12 wheelchair athletes completed an exercise test (T-CIDIF) in their own wheelchair. It consisted in a 30-s maximum test performed on two rollers. Two linear transducers connected to the rollers registered the number of propulsions, maximum and mean velocity and power of each arm. SP was assessed with the Wheelchair Users Shoulder Pain Index (WUSPI). Skin temperature (T_{sk}) of the anterior and posterior upper body was measured before and after the T-CIDIF by using an infrared camera. A total of 26 ROIs were evaluated with respect to the opposite side of the body to identify significant (ΔT_{sk}).
Results/main outcome measure(s): Significant differences were observed between the T_{sk} of the post-10 and pre-test in 12 ROIs, and between the post-10 and the post-test in most of the ROIs. These differences are attenuated when the ΔT_{sk} is compared before and after exercise. T_{sk} tends to initially decrease immediately after the test and then significantly increase after 10 min of completing the T-CIDIF. The ΔT_{sk} vs SP analysis yielded significant inverse relationships (from $r = -0.58$ to $r = -0.71$, $p < 0.05$) in 5 of the 26 ROI. No significant correlations between propulsion variables and SP questionnaire were found. All T-CIDIF variables were significantly correlated with the temperature asymmetries in multiple ROIs (from $r = -0.86$ to $r = -0.58$, from $p < 0.05$ to $p < 0.001$).
Conclusions: These results present indications that high performance wheelchair athletes exhibit similar capacity of heat production than able-bodied. The thermographic data inversely correlates with the SP and the kinematic variables, but the last is not related to SP. This work contributes to improve the

Abbreviations: BMI, Body Max Index; SCI, Spinal Cord Injury; WUSPI, Wheelchair Users Shoulder Pain Index; WCUs, Wheelchair Users; T-CIDIF, *Test del Centro de Investigación en Discapacidad Física* (Kinematic Wheelchair Propulsion Test); T_{sk}, Skin Temperature; ROI, Region of Interest; SP, Shoulder Pain; PC-WUSPI, Performed-Corrected Wheelchair Users Shoulder Pain Index; IRT, Infrared Thermography.

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understanding about temperature changes in wheelchair athletes during exercise, and could be used to assess the efficacy of various sports and rehabilitation programs.

1. Introduction

WCUs depend on their upper extremities for ambulation and several activities of daily living, such as transfers. Therefore, it is not unusual to find that shoulder pain (SP) is a problem in up to 73% of WCUs [1], and reduces their participation in sport and leisure activities for 84% of WCUs suffering from shoulder pain [2,3], as well as other daily activities, especially weight-bearing tasks such as transfers and weight relief lifts [4,5].

Thermal asymmetry between contralateral sides is an indicator of underlying pathologies or physical dysfunctions [6]. For example, Uematsu et al. indicated that calculation of skin temperature asymmetry (ΔT_{sk}) is especially effective in evaluating reported pain [6]. Furthermore, Sherman et al. [7] determined difference of temperatures in degrees Celsius between the area with normal sensations and the one with no or abnormal sensations in subjects with complete and incomplete SCI, (1.50 ± 0.62 °C and 0.58 ± 0.29 °C respectively [7]). Thermography measures the emission of infrared radiation and monitors the temperature distribution of human skin. There is a direct relationship between the increased temperature of an overloaded body region and risk of injury [8–10]. Thermography can measure this change of T_{sk} by comparing contralateral sides, and it has been consolidated as a valuable tool to clinically assess progress and treatment of sport injuries and musculoskeletal disorders [8,11–13], in particular shoulder injuries [14]. The application and usefulness of this tool in WCUs has been demonstrated at restcondition [15,16], as well as its relation with SP in this population [15]. However, thermographic studies during exercise have been carried out only with able-bodied at present [17–24]. To the best of our knowledge, there are two pilot studies from the same research team that have studied the T_{sk} of wheelchair users in response to exercise using infrared thermography [25,26], unfortunately they do not provide demographic or IRT data. Understanding the thermographic response to wheelchair exercise in relation to SP may offer an insight into the development of SP, which is necessary for an appropriate intervention. The current study is an extension of an earlier cross-sectional study that addressed the relationship between SP and IRT in nonathletic and athletic WCUs [15]. The objectives of the current study are (a) to study the thermographic response to exercise in athletic wheelchair users (pre-test, post-test, post-10); (b) to investigate the relationship between SP and skin temperature (T_{sk}) (pre-test, post-test, post-10) after the T-CIDIF, and to relate the SP with the kinematic variables of the T-CIDIF.

2. Material and methods

2.1. Participants

Twelve male wheelchair athletes (age: 32.58 ± 6.16 years; height: 173.58 ± 8.34 cm; body mass: 74.24 ± 12.73 kg; body mass index: 24.61 ± 3.66 kg/m^2) recruited from one elite and one recreational wheelchair basketball teams, volunteered to participate in this study. They were considered athletes if they trained at least 3 h wk^{-1}, and were involved in at least three competitions per year. The athletes involved in the study trained 6 h a week and competed almost every weekend; they won the Spanish league of wheelchair basketball. All subjects signed an informed consent in agreement with the Declaration of Helsinki and the Ethical Committee of the Technical University of Madrid.

2.2. Procedures

This cross-sectional study of wheelchair athletes investigated variables associated with SP and T_{sk}. Data collection took place at the Rehabilitation Center of ASPAYM Castilla y León during the month of November, in the beginning of the season. Subjects attended one session at a laboratory, in which T_{sk} data was collected, one maximal wheelchair propulsion test was completed, and a shoulder pain questionnaire was passed. Experiments were performed on their own daily wheelchair because its width is compatible to the T-CIDIF.

2.2.1. Thermal imaging protocol

2.2.1.1. Thermal imaging collection test. Three sets of 4 thermographs for each subject in anatomical position were shot and analyzed by the same previously trained observer. Subjects were instructed to remove clothes and jewelry from their upper body and remain 10 min at rest in a conditioned room (23 °C ± 1.9 °C). After the acclimatization period and before the wheelchair propulsion test, four thermograms were recorded including two images each (trunk/upper limbs) of the anterior and posterior sides of the body (pre-test); right after performing the T-CIDIF, the subject placed his wheelchair in the same location of the previous IRT analysis and another four thermograms were recorded (post-test); 10 min after the post-test two new thermograms were taken (post-10).

The camera was placed perpendicular to the ground, at 2–3 m away from the subject's skin to match the center of the image with the geometric center of the area to be evaluated. A transparent template was affixed to the camera screen to ensure the correct placement of the camera during the session. The wall behind body figures was covered with a white background to avoid any kind of reflection emitted by other objects. A 'step' was placed for slightly raising the subject from the floor surface.

Before the assessment, subjects were instructed to avoid consuming alcohol or caffeine, using any type of cream or perfume, smoking, sunbathing, showering, receiving treatment, therapy, massage or performing vigorous exercise in the 24 h preceding the measurements.

2.2.1.2. Thermal imaging analysis and devices. The infrared images were recorded using a FLIR T335 infrared camera (FLIR Systems, Danderyd, Sweden) with a measurement range of −20 to +120 °C, an accuracy of ±2 °C or 2% of the measurement, a sensitivity of 50 mK, a length spectrum range of 7.5–13 μm, and an infrared spectral band of 320×240 pixels FPA (Focal Plane Array). Twenty minutes before each trial, an external temperature reference source (thermistor PT-100, Telemeter Electronic, Donauworth, Germany) was used in order to calibrate the IRT camera. A fixed area of the black background was taken as the reference temperature. Images were obtained assuming skin emissivity of 0.98 [27] and analyzed with the software ThermaCAM Reporter 8 (FLIR Systems, Danderyd, Sweden). A portable weather station (BAR-908-HG model, Oregon Scientific, Portland, OR, USA) was utilized to estimate and control the ambient temperature in the testing room.

The T_{sk} of the body ROIs was obtained from thermographic images following the same criteria described by Rossignoli et al. [15]. The T_{sk} analysis included the following ROIs: anterior and posterior Arm, anterior and posterior Shoulder, anterior and posterior Forearm, Pectoral, anterior and posterior Trapezius, Dorsal, Infraspinatus, Supraspinatus and Central Trapezius. The ROI were manually drawn on the basis of previous studies [15,28–30].

2.2.2. Exercise testing and analysis

After the basal thermographic data collection, the subjects performed a maximum wheelchair propulsion test (T-CIDIF) [31]. Each subject placed his wheelchair over two rollers located one meter from a wall, in which there was a fitness pulley (En-TREEPulley, Enraf–Nonius, Rotterdam, Holland) and two linear position transducers (Sportmetrics, Valencia, Spain). Each transducer was attached to the subject's arm through a glove. A cable connected each glove with the correspondent pulley to provide resistance to the movement. The load of the pulley was selected according to the body mass of each subject (Table 1). The subject completed a 10 min warm-up, consisting on 6 min propelling their wheelchair at a high speed, followed by 4 min of progressions of 20 s propelling and 20 s resting. Two minutes after the warm-up period, the subject was asked to propel his wheelchair as fast as possible during 30 s. Kinematic data were collected bilaterally at a registration frequency of 200 Hz. The number of propulsions, mean and maximum peak power, and mean and maximum velocity of each arm were by this means obtained.

2.2.3. Shoulder pain data collection and analysis

The WUSPI is a questionnaire with a maximum total score of 150, which integrates a series of visual analogue scales (consisting of 10-cm lines anchored by 'no pain' and 'worst pain ever experienced') to provide an accumulated index of the intensity of SP suffered during the previous week while performing 15 different daily activities. The Performed-Corrected (PC-WUSPI) score reflects the actual intensity of SP experienced during the activities performed, since not all subjects have equal activity levels [32]. PC-WUSPI was calculated by dividing the total raw score by the number of activities executed and multiplied by 15 [32]. The WUSPI and the PC-WUSPI [33] has been shown to be both reliable and valid for people with SCI [15]. We used the Spanish version of this questionnaire validated by Arroyo-Aljaro and González-Viejo [34].

2.3. Statistical analysis

The interside temperature difference (ΔT_{sk}) was calculated for each ROI by subtracting the temperature of the right side from that of the left side. Contralateral ΔT_{sk} higher than 0.5 °C was considered abnormal [35].

The normality of the thermographic values and the variables obtained in the T-CIDIF were tested with the Kolmogorov–Smirnov and the Shapiro–Wilk tests. If normality was assumed, the repeated measures ANOVA test was used to compare the absolute levels of ΔT_{sk} before (pre), one minute after (post1) and 10 min after (post-10) the T-CIDIF. The post hoc applied was the least significant difference, due to the reduced number of participants. If normality was not assumed, the Friedman's test with the Bonferroni procedure was applied for this comparison.

The relations between the T-CIDIF variables and WUSPI or PC-WUSPI, likewise between thermographic values and WUSPI or PC-WUSPI, were analysed with the Spearman rho, since WUSPI or PC-WUSPI are ordinal variables. The correlation between thermographic values and T-CIDIF variables was analysed with the Spearman rho coefficient, and following this correlations range: low ($r \leqslant 0.3$), moderate ($0.3 < r \leqslant 0.7$) to high ($r > 0.7$).

The statistical analysis was performed using SPSS 19.0 software for Windows (SPSS Inc., Chicago, IL, USA). Alpha rejection region was set at 0.05 in all calculations. The values are presented as mean ± standard deviation (SD).

Table 1
Rolling resistance to overcome depending on the subject's mass, based on Menéndez et al. [31].

Subject mass (kg)	Selected pulley mass (kg)	Real mass transmitted to the forearm anchorage[a] (kg)
<65	6	1.43
66–75	10	2.57
76–85	14	3.63
86–95	18	4.77
>96	22	6.2

[a] Mass calculated trough placing a load cell (KERN HCB 200K100, Kern & Sohn GmbH, Balingen, Germany) in the cable that is connected to the glove. The pulley system gears down the initially selected load.

3. Results

The mean WUSPI and PC-WUSPI scores were 5.49 ± 6.57 (0.0, 16.58) and 5.58 ± 6.59 (0.0, 16.58), respectively. The maximum and average T_{sk} and ΔT_{sk} were compared before (pre-test), one minute after (post-test), and 10 min after (post-10) the T-CIDIF. The thermal results and ROIs with significant differences are showed highlighted in bold in Tables 2 and 3.

An inverse correlation between SP and the ΔT_{sk} of the anterior and posterior Shoulder ROIs prior to T-CIDIF is observed. One minute after the wheelchair propulsion test, a negative relationship between SP and the ΔT_{sk} of the Central Posterior Trapezius is detected. Ten minutes after the test the ΔT_{sk} of the Dorsal ROI correlates negatively with SP, while the ΔT_{sk} of the Central Posterior Trapezius and the Anterior Trapezius correlate positively with SP. These are only a few correlations in comparison with the amount of ROIs measured. Most of them were negative; hence higher WUSPI or PC-WUSPI scores are related with lower ΔT_{sk}.

Significant inverse relationships between changes in ΔT_{sk} in the Shoulder ROI and the results from the SP questionnaire were found before the wheelchair propulsion test; while Posterior Central Trapezius ROI presented significant inverse correlation with the questionnaire in the post-test and post-10. In addition, negative relationships were verified between the Dorsal ROI and both WUSPI and PC-WUSPI, as well as the Anterior Trapezius ROI with the PC-WUSPI. Those inverse correlations imply that the higher the SP the lower the thermal asymmetry and vice versa.

No significant correlations were observed between the kinematic variables and the SP questionnaire.

The following significant differences between the kinematic variables and the thermographic data (ΔT_{sk}) were found. The number of propulsions correlated with the maximum values of the Dorsal ROI ($r = 0.778$, $p = 0.008$) and the anterior Forearm ($r = -0.862$, $p < 0.001$) in the pre-test.

The mean peak torque correlated with the average values of the Pectoral ($r = -0.578$, $p = 0.063$), Infraspinatus ($r = -0.565$, $p = 0.056$) and Central Posterior Trapezius ($r = -0.716$, $p = 0.009$) ROIs, as well as maximum values of the Infraspinatus ($r = -0.637$, $p = 0.026$) in the post-test; and with the average values of the Arm ($r = 0.667$, $p = 0.050$) and Central Posterior Trapezius ($r = -0.730$, $p = 0.007$) ROIs, as well as the maximum values of the anterior Forearm ($r = 0.734$, $p = 0.010$) and Infraspinatus ($r = -0.637$, $p = 0.026$) in the post-10.

Mean power was the variable with higher number of correlated ROI, being for pre-test: anterior Forearm ($r = 0.695$, $p = 0.026$) average values; for post-test: Infraspinatus average ($r = -0.668$,

Table 2
Descriptive values of the skin temperature (°C) of 22 ROIs in wheelchair athletes; ANOVA for repeated measures.

	ROI	Pre-test Mean ± SD	Post-test Mean ± SD	Post-10 Mean ± SD	F	p	η^2
Maximum T_{sk} values	R A Arm	33.51 ± 0.62	33.59 ± 0.92	**34.29 ± 0.75**[a,b]	10.670	0.001	0.886
	L A Arm	33.12 ± 0.78	32.94 ± 1.02	**33.90 ± 0.91**[a,b]	12.185	0.002	0.902
	R A Shoulder	33.91 ± 0.67	33.90 ± 1.44	**34.48 ± 1.27**[#,∞]	2.385	0.143	0.670
	L A Shoulder	33.44 ± 1.06	**33.38 ± 1.36**[a]	34.36 ± 1.25	1.686	0.208	0.381
	R Pectoral	34.06 ± 0.70	34.04 ± 1.04	**34.69 ± 1.16**[b]	3.879	0.036	0.573
	L Pectoral	33.93 ± 0.69	33.84 ± 0.87	**34.58 ± 0.90**[a,b]	5.215	0.014	0.735
	R A Trapezius	33.90 ± 0.41	33.90 ± 1.14	**34.64 ± 1.08**[a,b]	5.415	0.012	0.669
	L A Trapezius	33.96 ± 0.70	33.73 ± 1.29	**34.49 ± 1.03**[∞]	3.221	0.093	0.812
	R P Arm	32.08 ± 0.81	32.23 ± 1.18	**33.15 ± 1.12**[a,b]	8.883	0.001	0.744
	L P Arm	32.12 ± 0.97	32.30 ± 1.18	**33.09 ± 0.72**[a,b]	12.606	0.000	0.760
	R Dorsal	32.76 ± 1.13	32.20 ± 0.91	**32.90 ± 0.99**[∞]	3.179	0.066	0.599
	L Dorsal	32.82 ± 1.17	32.29 ± 0.97	**32.95 ± 0.90**[∞]	2.709	0.094	0.596
	R P Shoulder	32.13 ± 1.39	32.25 ± 1.38	**32.97 ± 1.54**[∞]	3.267	0.090	0.716
	L P Shoulder	32.73 ± 1.11	32.66 ± 1.37	**33.32 ± 1.29**[a,b]	5.284	0.013	0.690
	R P Infraspinatus	32.46 ± 1.20	32.13 ± 1.13	**32.87 ± 1.48**[a,b]	8.067	0.003	0.677
	L P Infraspinatus	32.92 ± 1.29	32.58 ± 1.51	**33.12 ± 1.51**[∞]	2.833	0.083	0.616
	R P Supraspinatus	32.63 ± 1.03	32.31 ± 1.34	**32.99 ± 1.44**[b]	3.824	0.038	0.598
	L P Supraspinatus	32.88 ± 1.19	32.80 ± 1.50	**33.37 ± 1.49**[∞]	2.949	0.073	0.601
	R P Central Trapezius	33.52 ± 0.94	33.13 ± 1.49	**33.74 ± 1.24**[∞]	2.503	0.127	0.507
	L P Central Trapezius	33.39 ± 0.90	32.87 ± 1.45	**33.57 ± 1.28**[b]	3.272	0.057	0.554
	R P Trapezius	33.26 ± 0.84	32.98 ± 1.28	**33.63 ± 1.28**[b]	3.903	0.035	0.607
	L P Trapezius	33.26 ± 0.82	32.96 ± 1.27	**33.58 ± 1.28**[b]	3.756	0.040	0.583
Average T_{sk} values	R A Arm	31.54 ± 1.32	31.78 ± 1.03	**32.82 ± 1.18**[a,b]	5.606	0.031	0.808
	L A Arm	31.76 ± 0.75	31.42 ± 1.13	**32.29 ± 1.23**[#,b]	5.380	0.016	0.775
	R A Shoulder	32.93 ± 0.73	32.55 ± 1.43	**33.37 ± 1.47**[b]	4.808	0.034	0.708
	L A Shoulder	32.66 ± 0.99	32.35 ± 1.34	**33.39 ± 1.38**[a,b]	5.792	0.011	0.762
	R Pectoral	31.24 ± 2.44	30.99 ± 2.34	**31.66 ± 2.37**[∞]	2.443	0.141	0.687
	L Pectoral	31.68 ± 1.57	31.55 ± 1.61	**32.43 ± 1.47**[#,b]	4.219	0.046	0.644
	R A Trapezius	33.11 ± 0.45	32.96 ± 1.27	**33.78 ± 1.17**[∞]	2.648	0.130	0.766
	L A Trapezius	33.21 ± 0.69	32.88 ± 1.39	**33.59 ± 1.31**[∞]	2.545	0.106	0.698
	R P Arm	30.23 ± 1.05	30.50 ± 1.12	**31.46 ± 1.23**[a,b]	11.850	0.000	0.779
	L P Arm	30.10 ± 0.74	30.40 ± 1.19	**31.26 ± 1.12**[a,b]	10.155	0.005	0.810
	R Dorsal	31.33 ± 1.26	30.90 ± 1.18	**31.48 ± 1.34**[∞]	2.472	0.116	0.588
	L Dorsal	31.08 ± 1.60	31.18 ± 1.21	31.52 ± 1.24	0.524	0.601	0.466
	R P Shoulder	31.45 ± 1.26	31.18 ± 1.44	**31.87 ± 1.61**[b]	5.505	0.012	0.704
	L P Shoulder	31.65 ± 1.27	31.44 ± 1.46	**32.10 ± 1.54**[#,b]	4.819	0.018	0.593
	R P Infraspinatus	31.36 ± 1.42	31.08 ± 1.40	31.59 ± 1.64	1.369	0.276	0.143
	L P Infraspinatus	32.09 ± 1.41	31.57 ± 1.66	**32.23 ± 1.62**[b]	3.671	0.044	0.643
	R P Supraspinatus	32.03 ± 1.07	31.65 ± 1.31	**32.38 ± 1.50**[b]	4.591	0.022	0.644
	L P Supraspinatus	31.73 ± 1.74	30.69 ± 2.61	**31.63 ± 2.09**[∞]	1.841	0.201	0.504
	R P Central Trapezius	31.33 ± 1.41	30.63 ± 1.71	**31.23 ± 1.70**[∞]	1.026	0.338	0.597
	L P Central Trapezius	32.33 ± 0.82	3**1.14 ± 1.80**[a]	**31.91 ± 1.71**[b]	5.391	0.013	0.570
	R P Trapezius	32.66 ± 0.93	**32.18 ± 1.26**[#]	**32.78 ± 1.35**[b]	4.632	0.021	0.641
	L P Trapezius	32.64 ± 0.93	**31.88 ± 1.40**[#]	**32.78 ± 1.56**[b]	6.630	0.007	0.651
	Total maximum T_{sk}	33.13 ± 0.93	32.95 ± 1.23	33.67 ± 1.18			
	Total average T_{sk}	31.57 ± 1.21	31.17 ± 1.48	31.87 ± 1.52			

Note: ROI, region of interest; T_{sk}, skin temperature; η^2, effect size; A, anterior; P, posterior; R, right; L, left.
[a] Significantly different with respect to pre-test at $p < 0.05$.
[b] Significantly different with respect to post-test at $p < 0.05$.
[#] Tendency to significance with respect to pre-test $p < 0.1$.
[∞] Tendency to significance with respect to post-test $p < 0.1$.

$p = 0.018$) and maximum values, and average values of Central Posterior Trapezius ($r = -0.688$, $p = 0.013$) and posterior Trapezius ($r = -0.737$, $p = 0.015$); for post-10: average values of anterior Trapezius ($r = -0.820$, $p = 0.004$), posterior Shoulder ($r = -0.660$, $p = 0.020$), and Central Posterior Trapezius ($r = -0.575$, $p = 0.050$), and maximum values of Infraspinatus ($r = -0.688$, $p = 0.013$) and Central Posterior Trapezius ($r = -0.596$, $p = 0.041$).

The maximum velocity correlated with average values of posterior Arm ($r = 0.718$, $p = 0.013$) in pre-test; maximum values of Infraspinatus ($r = -0.633$, $p = 0.027$) in post-test and anterior Forearm ($r = 0.706$, $p = 0.0153$) in post-10.

Average maximum velocity present correlations with posterior Arm ($r = 0.662$, $p = 0.026$) and Infraspinatus ($r = -0.667$, $p = 0.025$) average values in pre-test; posterior Forearm ($r = -0.5633$, $p = 0.056$) and Infraspinatus ($r = -0.601$, $p = 0.039$) maximum values, and pectoral ($r = -0.799$, $p = 0.003$) average values in post-test; and maximum values of anterior Forearm ($r = 0.678$, $p = 0.022$) in post-10.

Finally, total work showed correlations in pre-test with the ROIs: average values of anterior Forearm ($r = 0.800$, $p = 0.005$), and maximum values of anterior Trapezius ($r = 0.593$, $p = 0.042$) and Dorsal ($r = -0.673$, $p = 0.033$); in post-test with the ROIs: maximum values of Infraspinatus ($r = -0.615$, $p = 0.033$), and average values of Infraspinatus ($r = -0.547$, $p = 0.065$), Central Posterior Trapezius ($r = -0.663$, $p = 0.019$) and posterior Trapezius ($r = -0.712$, $p = 0.021$); in post-10 with the ROIs: average values of anterior Trapezius ($r = 0.712$, $p = 0.021$), posterior Shoulder ($r = -0.695$, $p = 0.012$), and maximum values of Infraspinatus ($r = -0.713$, $p = 0.009$) and Central Posterior Trapezius ($r = -0.635$, $p = 0.027$).

Table 3
Descriptive values of the side-to side differences (°C) of the 26 measured ROIs in wheelchair athletes; ANOVA for repeated measures.

	ROI	Pre-test Mean ± SD	Post-test Mean ± SD	Post-10 Mean ± SD	*F*	*p*	η^2
Maximum ΔT_{sk} values	A Arm	0.47 ± 0.25	0.62 ± 0.38[#]	0.37 ± 0.29	1.988	0.161	0.336
	A Shoulder	0.40 ± 0.35	0.43 ± 0.25	0.33 ± 0.24	0.621	0.547	0.186
	A Forearm	0.37 ± 0.53	0.27 ± 0.23	0.30 ± 0.19	0.257	0.668	0.030
	Pectoral	0.27 ± 0.28	0.22 ± 0.08	0.12 ± 0.15	0.004	0.996	0.001
	A Trapezius	0.20 ± 0.14	0.30 ± 0.36	0.13 ± 0.12	0.241	0.788	0.040
	P Arm	0.25 ± 0.23	0.48 ± 0.40	0.37 ± 0.23	0.038	0.963	0.015
	Dorsal	0.32 ± 0.20	0.10 ± 0.06	0.13 ± 0.08	0.260	0.774	0.131
	P Shoulder	0.40 ± 0.22	0.53 ± 0.25	0.37 ± 0.45	0.750	0.428	0.229
	P Forearm	0.61 ± 0.56	0.49 ± 0.55	**0.28 ± 0.29**[a,∞]	5.126	0.015	0.428
	P Infraspinatus	0.35 ± 0.33	**0.80 ± 0.50**[a]	**0.62 ± 0.44**[b]	3.582	0.047	0.568
	P Supraspinatus	0.13 ± 0.20	**0.55 ± 0.49**[a]	0.65 ± 0.37	2.466	0.108	0.426
	P Central Trapezius	0.10 ± 0.11	0.17 ± 0.14	0.22 ± 0.20	1.193	0.322	0.214
	P Trapezius	0.22 ± 0.17	0.12 ± 0.13	0.17 ± 0.23	0.815	0.413	0.91
Average ΔT_{sk} values	A Arm	0.35 ± 0.21	**0.13 ± 0.10**[a]	**0.35 ± 0.30**[b]	4.142	0.036	0.736
	A Shoulder	0.33 ± 0.23	0.27 ± 0.18	0.38 ± 0.34	0.235	0.793	0.058
	A Forearm	0.28 ± 0.18	0.25 ± 0.19	0.46 ± 0.56	1.498	0.250	0.217
	Pectoral	0.63 ± 0.93	0.20 ± 0.15	0.23 ± 0.19	0.290	0.645	0.129
	A Trapezius	0.15 ± 0.10	**0.22 ± 0.16**[#]	0.15 ± 0.14	1.617	0.226	0.315
	P Arm	0.23 ± 0.19	0.22 ± 0.18	0.27 ± 0.15	1.048	0.371	0.153
	Dorsal	0.23 ± 0.24	0.25 ± 0.25	0.27 ± 0.31	0.018	0.983	0.004
	P Shoulder	0.33 ± 0.26	0.32 ± 0.23	0.48 ± 0.48	0.119	0.888	0.038
	P Forearm	0.31 ± 0.21	0.37 ± 0.15	0.28 ± 0.23	1.181	0.328	0.342
	P Infraspinatus	0.48 ± 0.54	0.47 ± 0.36	0.58 ± 0.36	0.288	0.631	0.038
	P Supraspinatus	0.18 ± 0.18	**0.45 ± 0.29**[a]	0.45 ± 0.39	3.470	0.087	0.470
	P Central Trapezius	0.10 ± 0.11	1.02 ± 1.24	**1.02 ± 1.20**[#]	0.158	0.707	0.200
	P Trapezius	0.22 ± 0.17	**0.43 ± 0.37**[#]	0.30 ± 0.17	2.416	0.118	0.320
	Total average ΔT_{sk} values	0.29 ± 0.27	0.35 ± 0.30	0.40 ± 0.37			

Note: ROI, region of interest; ΔT_{sk}, difference between right and left skin temperature; η^2, effect size A, anterior; P, posterior.
[a] Significantly different with respect to pre-test at $p < 0.05$.
[b] Significantly different with respect to post-test at $p < 0.05$.
[#] Tendency to significance with respect to pre-test $p < 0.1$.
[∞] Tendency to significance with respect to post-test $p < 0.1$.

4. Discussion

Our study focuses on the response of the T_{sk} to a maximal wheelchair propulsion test and its relation (pre-test, post-test, post-10) with SP in WCUs. Most the studies in which the subjects were exposed to constant and prolonged exercise resulted in an increased T_{sk} [17,36–46]. In contrast, graded, intermittent or maximal exercises normally performed for brief period, resulted in decreased T_{sk} [18,47–55]. Based on this trend our short test should produce a reduction of the T_{sk} once it finalized. Our T_{sk} values in Table 2 clearly show a tendency to initially decrease immediately after the test (in 81.81% of the ROIs, average values) and then a significant increase after 10 min of completing the T-CIDIF (in 86.36% of the ROIs, average values). These results are more common of prolonged exercises.

In WCUs, it seems primordial to transfer the metabolic heat from the core to the skin as it is reflected by the prompt increase of T_{sk}. Another possible explanation could be the SCI condition presented by most of our sample, this population may present cardiovascular limitations, and patients with compromised cardiac function are characterized by a higher extent of vasoconstriction in comparison with healthy [45], which could explain the initial reduction of the T_{sk}. Another characteristic of paraplegic athletes is to have a larger heat storage in the lower body that ends in a diminished ability to reduce their core temperature during the recovery phase [56], that may explain the rise of T_{sk} in the reduced body surface area for active thermoregulation even in brief exercises. Price et al. [56,57] found that lower body T_{sk} increased during prolonged upper body exercise due to the increased heat storage in that region. Gass et al. [58] also found an initial decrease of the T_{sk} (measured with thermistors) followed by an increase in the Arm ROI during a prolonged wheelchair exercise with trained paraplegic men. Normell [59] indicates that there is a large individual variation of the cutaneous thermoregulatory vasomotor response, specially at the lower spinal lesion levels, highlighting differences in the somatosensory and sympathetic pathways, in the sympathetic outflow response, and in the type and degree of reinnervation [59]. The extent of vasodilation and sweating depend on the lowermost intact portion of the sympathetic chain, level and completeness of SCI [58], in other words, fluid losses during exercise and heat retention during passive recovery from exercise are related to lesion level [56]. Probably the findings would be different with a higher number of subjects having the same level of injury. For example, five of our subjects have a lesion level above T_{10}, which implies a lack of sympathetic innervation to the splanchnic area and therefore may not have the ability to redirect blood flow from an inactive area to the active areas. In subjects with extended skin regions denervated, the loss of sympathetic vasomotor afferent fibers results in microcirculation changes that are reflected in locally increase of the blood flow and T_{sk}.

Because of each subject performed the T-CIDIF in their own daily wheelchair, the differences in the wheelchair design and seating position could have influenced the venous return dynamics, and thus impact the blood distribution.

The lack of significant differences between the pre-test and post-test T_{sk} in contrast with the important differences with respect to post-10 could be due to the short duration of the T-CIDIF; 30 s normally is not enough time to activate the thermoregulation system, as the hypothalamus starts to respond after 6–7 min of the exercise's onset [56]. Most of the IRT studies chose longer exercise protocols with the exception of Adamczyk et al. [60], who found similar results to those of our study: a decrease of the lower limbs *Tsk* (1.44 °C) right after finishing the exercise and a posterior rise during the recovery period. However, we have chosen the T-CIDIF for being a validated test for WCUs [31] and because of its characteristics allow trained as well as untrained participants to perform it.

The thermal pattern can also be influenced by the fitness level; trained subjects present better cooling capacity during exercise and faster recovery [51] thanks to an improved thermoregulation system and greater vascularization of the musculature compared with non-trained [24,46,61]. The muscles of our highly skilled sample may present earlier and more responsive skin blood flow responses, consequently the onset of vasodilation would occur at lower internal temperatures [62] and the T_{sk} would start growing sooner than in a less fit sample. This finding is in agreement with previous thermal study of a martial art comparing skilled and novice physically active females, where the skilled group presented higher post-exercise T_{sk} values than the novice group [42]. The opposite will happen with a sample with greater fat percentage, as adipose tissue has lower thermal conductivity preventing the transfer of the heat from the muscles to the skin [63]. Future studies could compare the thermoregulation response at exercise of athletes vs. nonathletes wheelchair users, in order to know whether the athletes' rise of T_{sk} is not only happening earlier (more responsive) than in nonathletes but also during a shorter period (faster recovery), as it happens in able-bodied population [19,24,53].

A previous research of T_{sk} measurement during wheelchair exercise [26] found that the ROIs with higher T_{sk} under exercise (Shoulder, upper Pectoral major, anterior and posterior Forearm, Palm, anterior and posterior Trapezius) showed marked increase in T_{sk} during the first 15 min recovery phase, and coincided with the areas of raised activity in EMG under wheelchair driving. Interestingly, the ROI with lower EMG was the upper arm. Shin-ichi et al. [26] concluded that the surface temperature could be an index of muscle activity during exercise. They also found a great body surface temperature difference depending on the body fat percentage of the subject, with higher drop of the T_{sk} during the test and larger T_{sk} variations between the pre-test, during wheelchair driving and recovery in the fat subject.

According to Table 3, the ΔT_{sk} is statistically modified by exercise increasing in post-test respect to pre-test in 5 ROIs (anterior Arm, Infraspinatus, Supraspinatus, anterior and posterior Trapezius); rising in anterior Arm ROI and decreasing in two ROIs (posterior forearm and Infraspinatus) in post-10 respect to post-test; growing in one ROI (posterior Central Trapezius) and diminishing in another ROI (posterior forearm) in post-10 respect to pre-test.

There is not a consistent tendency of the growth or decrement of the ΔT_{sk} after the T-CIDIF, although both average (0.29 ± 0.27 vs 0.35 ± 0.30) and maximum (0.31 ± 0.27 vs. 0.39 ± 0.29) total ΔT_{sk} values increased in post-test respect to pre-test. The clear trend in T_{sk} vs. the no-tendency in ΔT_{sk} makes suspect a different influence of exercise in each ROIs, and/or different implication of each muscle in the wheelchair propulsion test. On one side, there is a different percentage of involvement of the several muscles used during the wheelchair propulsion task, and different wheelchair propulsion techniques applied (e.g. depending on their impairment type and the size of the wheelchair). Any of the SCI participants have tetraplegia, hence their upper extremities are fully innervated, and also, all of them trained the same number of hours per week and same load of training, so they have similar upper body work capabilities. On the other side, the initial cutaneous vasoconstriction response needs dynamic activity from a significant musculature, not being effective for smaller muscle groups [64]. It is also known that dominant side has a higher capacity to loss temperature and better thermoregulation [65], getting cold in response to the onset of the activity because of the vasoconstriction effect. This is not reflected in our results and it can be due to the bilateral propulsion of the wheelchair that may compensate this asymmetry in WCUs [66]. Finally, Shin-ichi et al. [26] found a non-uniform distribution of the temperature in the bust rising heterogeneously during both wheelchair exercise and recovery, which is consistent with our lack of pattern in ΔT_{sk} after exercise. Although the thermographic results are not conclusive enough to make definitive assumptions, they provide an insight in the thermal pattern of WCUs at exercise.

Previous studies of the author found several negative relationships between the SP test and the T_{sk} of 6 ROIs, but only one correlation with the contralateral differences [15]. These findings could be explained because of the low SP experienced by our sample, our WUSPI and PC-WUSPI scores were no higher than 6 in comparison with the range of the scale from 0 to 150.

Our study has not found any correlation between SP and the kinematic variables of the T-CIDIF. These results are contrary to previous findings that reported significant inverse relationships between the kinematic variables of the T-CIDIF and the PC-WUSPI test [31]. One explanation could also be the low SP score of our subjects. Moreover, they were very disposed to give their best during the test due to their athletic and competitive attitude, thereby they may have propelled at their maximum in spite of their SP.

The findings show multiple correlations (mostly negative) between all the kinematic variables of the T-CIDIF and the ΔT_{sk} of many ROIs. Although it was not part of our aims, we provide information of the relation between the exercise and the thermographic variables. Menéndez et al. [31] discovered high positive correlations between the variables of the T-CIDIF and the peak torque, total work, mean power, and mean of the peak torques of the internal and external shoulder rotators obtained in a maximum isokinetic strength test. Based on this outcome, they affirmed that T-CIDIF could be used as an alternative to the isokinetic strength test. Consequently, the inverse correlations found between the kinematic variables and the thermal data in our study could be translated to the isokinetic dynamometer, such as, higher torque and power may also correlate with lower ΔT_{sk}. This is a good reason to promote the strengthening of the shoulder joint for WCUs. Additionally, the isokinetic strength test performed by them did not correlate with the SP questionnaire, implying that the pain is limited to functional gestures more than maximum strength.

5. Limitations and practical considerations

For future studies, we recommend to check the IRT response 30 min after finalization of the T-CIDIF, since one minute and 10 min may not be enough time to test the T_{sk} recuperation.

We have chosen WUSPI test due to its specificity for WCUs population. However, it has a great limitation since it does not differentiate between shoulders and it only focuses on this ROI. We have analyzed more ROIs, apart of Shoulder, because we wanted to study the rest of the muscles involved in the wheelchair propulsion task. For future researches not exclusively centred on SP (studying the full upper body T_{sk} response), we recommend to use the Borg CR-10 scale, which points out the pain in the ROIs analyzed and at the time of the test. Otherwise, a suggestion would be to analyse as well the current SP, as WUSPI only refers to the previous week of being evaluated.

This is an initial exploratory study; future larger studies with larger sample or broader populations, will allow establishing more causal relationships and a more precise diagnostic.

6. Conclusions

The results show that the thermal pattern of the wheelchair athletes observed after the T-CIDIF was more typical of prolonged exercises (reduction followed by an increase of the T_{sk}). The reduced amount of skin surface innervated of subjects with SCI limits the capacity to perspire, so even after brief exercises their T_{sk} rapidly increases to dissipate the core heat and to keep the thermal homeostasis. The shorter period of T_{sk} reduction in comparison with able-bodied may correspond to the briefer phase of blood redistribution from the inactive areas to the active muscles, and the lesser sweat evaporation performed by the innervated skin.

There are significant inverse relationships between the SP and the ΔT_{sk} of some ROIs before and after exercise, as well as multiple significant correlations (mostly negative) between all the kinematic variables of the T-CIDIF and the ΔT_{sk} of many ROIs. No correlation was found between SP and the kinematic variables of the T-CIDIF.

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