



Implementing local cooling to increase skin tolerance to ischemia during normal seating in people with spinal cord injury



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ABSTRACT

The purpose of this study was to investigate the effectiveness of local cooling in reducing reactive hyperemia after ischemia at the ischial tuberosities for people with spinal cord injury (SCI) during normal seating. The degree of the reactive hyperemic response is indicative of the extent of cellular stress caused by the ischemia. We hypothesized that reactive hyperemic skin blood flow (SBF) responses will be lower when local cooling is implemented by the wheelchair seat cushion. This study used a repeated measures design, and each subject underwent two conditions: normal seating with temperature control ‘on’ (cooling) and ‘off’ (non-cooling) for 30 min. Twenty-three participants with traumatic SCI were recruited. SBF and skin temperature were collected before, during and after seating. SBF signals were processed with short-time Fourier analyses to examine the underlying vascular control mechanisms, including the following (corresponding frequency bands): metabolic (0.0095–0.02 Hz), neurogenic (0.02–0.05 Hz), and myogenic (0.05–0.15 Hz) spectral densities. Our results showed that with cooling, skin temperature decreased (range $-0.4 \sim -3.1$ °C, $p = 0.002$), and reactive hyperemia parameters (normalized peak SBF and perfusion area) were reduced ($p = 0.02$, $p = 0.033$, respectively). In addition, changes in normalized peak SBF (non-cooling – cooling) was moderately correlated with changes in normalized metabolic and neurogenic spectral densities. Our findings suggested that local cooling has a positive effect on reducing the cellular stress caused by ischemia during normal seating. Metabolic and neurogenic SBF control mechanisms may play a minor role. Further exploration of the effect of temperature control on pressure injury prevention is warranted.

1. Introduction

Pressure injuries are common secondary complications of people with spinal cord injury (SCI). Prevalence estimates range from 11.5 to 21% from 1 to 15 years post injury in the U.S [1]. Prevalence is higher, ranging from 26.7 to 46.2% in developing nations [2]. The cost to treat an individual injury is estimated between \$500–70k [3]. Preventative strategies are warranted, especially in this population.

Support surfaces utilizing microclimate (temperature and humidity) control were not commonly considered as prevention interventions until the past decade. Elevated skin temperature was only confirmed as a contributing factor 20 years ago. Two iconic swine studies provided this direct evidence [4,5]. Kokate et al. showed that with the same amount of interface pressure (100 mmHg), higher skin temperature causes more tissue damage at all tissue layers [4]. Iazzo et al.

demonstrated that with the same amount of interface pressure, the skin and muscle tissue could withstand a longer period of pressure with a lower skin temperature (25 °C) [5]. Two recent rat studies from Jan's group further investigated the potential protective mechanisms of the cooling effect on weight-bearing soft tissues without inducing injuries [6,7]. One study found that with the same magnitude and duration of pressure (700 mmHg), local heating of the skin caused continual skin blood flow (SBF) decrease, whereas local cooling kept SBF stable [6]. In addition, wavelet analysis suggested that this stable SBF caused by local cooling was mediated by both metabolic and myogenic control mechanisms [6]. The other study applied the same pressure for a longer period of time, and showed that local heating of the skin increased the concentration of one pro-inflammatory cytokine (TNF- α), whereas local cooling did not [7].

Human studies supported the findings from the animal studies. Tzen

Abbreviations: AIS, ASIA impairment scale; SCI, spinal cord injury; SBF, skin blood flow; TEC, thermoelectric cooler

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et al. used reactive hyperemic response to quantify the effects of tissue ischemia with 60 mmHg pressure loaded on healthy participants [8]. Normalized peak hyperemic response was lower when local cooling of 25 °C was applied, indicating the protective response to ischemia was reduced with local cooling. Short-time Fourier analyses also showed that metabolic and myogenic responses contributed to this protective effect. A follow up study used the identical method on people with SCI and healthy controls [9]. Reactive hyperemic response was reduced with local cooling in healthy controls, but not in participants with SCI. Another human study demonstrated that local cooling reduced reactive hyperemia in both healthy controls and participants with SCI as compared to heating the skin (20 °C difference in skin temperature) [10]. Wavelet analyses showed that the metabolic and neurogenic SBF control mechanisms contributed to this difference in healthy controls, but only the metabolic mechanism contributed in participants with SCI [10]. This suggested that the ‘deprivation of spinal innervation’ and the ‘diminished function of sensory nerves’ after SCI contributed to the reduced response to temperature changes.

All of the foregoing studies had limited applicability to general practice because pressure with temperature control was applied only to the bony prominence. In these prior experiments, the surrounding area was pressure free and exposed to ambient conditions, which does not fully represent the real-world seating condition where an individual is in an upright posture with the buttocks in full contact with a seat cushion. The purpose of this study was to investigate the local cooling effect on weight-bearing skin covering the ischial tuberosity during normal seating in people with SCI. This study also investigated the mechanism of the cooling effect on tissue ischemia using short-time Fourier transform of the SBF signal.

2. Methods

2.1. Participants

Adults with traumatic SCI for longer than one year were recruited for this study. All participants used a wheelchair for mobility, and did not have a current pressure injury, diabetes mellitus, cardiovascular disease, hypertension, or pulmonary disease. All participants were either non-smokers or smokers able to refrain from smoking 4 h prior to the study. The study was approved by an Institutional Review Board and written consent obtained prior to participation.

2.2. Study design and procedures

We utilized a repeated measures laboratory design. Twenty-three participants underwent two procedures: normal seating for 30 min with temperature control ‘on’ (cooling) and ‘off’ (non-cooling). We used the term “normal seating” to describe the condition where the individual is in a self-selected upright posture in which the buttocks are in full contact with the seat cushion. The order of the procedures was randomized. Twelve participants had temperature control ‘on’ first. To minimize the order effect in participants under different ASIA impairment scale (AIS) categories, the order of the procedures was evenly distributed within each AIS category. Of the 12 participants who had temperature control ‘on’ first, 8 were AIS A, 2 were AIS B and 2 were AIS C. Each participant was seated on a Quantum Q6 Edge power wheelchair (Quantum Rehab, Duryea PA) with a customized temperature control wheelchair seat cushion prototype. The prototype temperature control wheelchair seat cushion was a modified multi-cell air cushion (ROHO single chamber high profile—ROHO Group, Belleville, IL) [11]. Cooling elements were added in eight of the 90 air cells where the load-bearing ischial tuberosities contact the cushion (Fig. 1). Individual cooling elements were inserted through the base of the cushion into the individual air chambers. A gel pad was positioned atop a thermoelectric cooler (TEC, model TE-71-1.0-1.3, TE Technology, Traverse City, MI) and the chamber resealed to maintain the internal

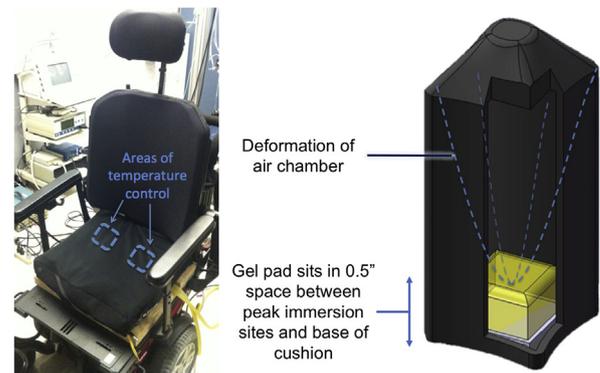


Fig. 1. Prototype temperature control wheelchair seat cushion. (Left) Blue squares indicated areas of temperature control for the left or right ischium. (Right) Cushioning cooling element were added to 4 air cells beneath each ischium location. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

pressure of the cushion [12]. The warm side of the TEC was fixed to a heat sink to draw the generated heat away from the TEC and gel pad. As the air cells deformed, the ischium would come in contact with the gel pad cooled by the TEC. To maximize cooling, the TECs were powered by direct current of 3 amps throughout the 30 min of cooling.

To ensure that pressure was evenly distributed and that at least one of the participant’s ischial tuberosities was center on and immersed to the top of the gel pad, we adjusted the air in the cushion while monitoring pressure using a pressure mapping system (Vista Medical Ltd., Winnipeg, Manitoba, Canada). The pressure map was then removed.

Each procedure included: baseline SBF and temperature measurements while tilted 85° for 5 min, measurements of SBF and temperature during normal seating (0° tilt) for 30 min and measurements of SBF and temperature during post seating while tilted 85° for 15 min (Fig. 2). The only difference between the two procedures was having the temperature control ‘on’ or ‘off’ during the normal seating. A 40-min washout period was provided between the two procedures, where the participant was in the 85° tilt position. The 85° tilt position was selected since it is the maximum tilt angle provided by our powered wheelchair, and it is greater than the minimum 35° tilt (with 100° recline) required to off-load pressure and increase SBF at the ischial tuberosities as suggested in one previous study [13].

All participants wore a thin, 55% cotton-45% polyester blend boxer short for efficient heat transfer. One laser Doppler flowmetry sensor (VP11 low-profile right-angle delivery probe, Moor Instrument, Wilmington DE) and one thermistor were taped to the skin at either the right or left ischial tuberosity to measure the SBF and temperature respectively. Selection of right or left side for measurement depended on which side was positioned better on top of the cells that contained the cooling elements. Fourteen participants had SBF and temperature measurements on the right side. SBF (20 Hz sampling) and temperature (0.0167 Hz sampling) were collected throughout the 50-min procedures.

2.3. Outcome measures

SBF is the primary outcome measure. Although it is affected by the cardiac and respiratory activities of the body, reactive hyperemia reflects the localized ischemia induced response. Other individual differences that may affect overall SBF were minimized by the repeated measures design. The SBF signals were analyzed in the time domain for intensity and duration of the post-loading reactive hyperemic response and in the frequency domain for association with physiological control mechanisms. The time domain parameters include mean baseline SBF, peak SBF, normalized peak SBF [(peak SBF - baseline SBF)/baseline SBF x 100%], and perfusion area (Fig. 3). SBF data was down-sampled to

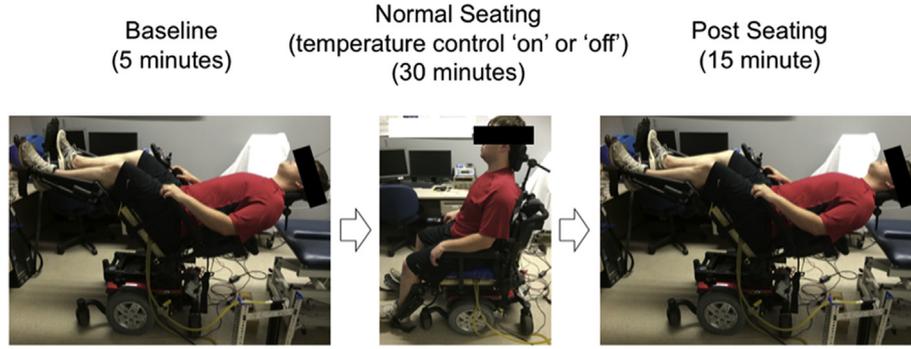


Fig. 2. Test procedure.

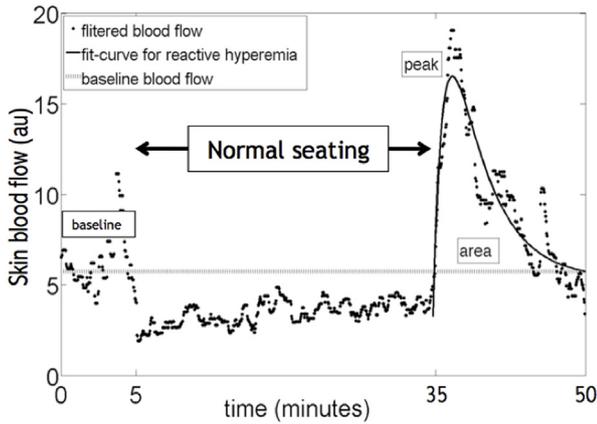


Fig. 3. An example of SBF recording showing baseline, normal seating and post loading periods. Reactive hyperemia occurs during the post loading period and is characterized by peak magnitude of the bi-exponential curve fit above mean baseline.

0.5 Hz and filtered (tenth-ordered Chebyshev I low-pass filter, cut-off frequency 0.15 Hz) to remove the signal components attributable to respiration and cardiac function. The filtered post-loading reactive hyperemia was modeled using a least-squares fit to the bi-exponential function of equation (1) [9]. Peak and area under the curve calculations used the best fit function and mean baseline SBF.

$$y(t) = A_1 e^{-t/\tau_1} + A_2 e^{-t/\tau_2} + B \quad (1)$$

A series of studies suggested that oscillatory pattern of the SBF signal contains information regarding SBF regulation when analyzed in the frequency domain [14–16], and the following frequency intervals were determined to be correlated to certain SBF control mechanisms: metabolic (0.0095–0.02 Hz) [15], neurogenic (0.02–0.05 Hz) [17], and myogenic (0.05–0.15 Hz) [14,15] mechanisms. Spectral densities were calculated in this study using short-time Fourier analysis demonstrated in prior studies [8,9]. To calculate the normalized metabolic, neurogenic and myogenic spectral densities, we first computed the spectrogram ($P_{sp}(t, \omega)$) as, [18]

$$P_{SP}(t, \omega) = |S_t(\omega)|^2 = \left| \frac{1}{\sqrt{2\pi}} \int e^{-i\omega\tau} s(\tau) h(\tau - t) d\tau \right|^2 \quad (2)$$

where $S(\omega)$ is the short-time Fourier transform, $s(t)$ is the SBF signal, $h(t)$ is a 256-sample Hanning window function (512 s) [9]. For the purpose of statistical analyses, integrals of spectral densities within each frequency band during a 120 s window centered around the time of the peak reactive hyperemia were normalized to the corresponding values during the first 120 s of baseline using Equation (3); where T_{peak} is the time when the fitted SBF signal peaked during post-seating, and ω_1 – ω_2 is the frequency range for each vascular control mechanism.

$$NP_{-T\omega} = \left(\int_{\omega=\omega_1}^{\omega_2} \int_{T=T_{peak}-60}^{T_{peak}+60} P_{SP}(T, \omega) dT d\omega \right) / \left(\int_{\omega=\omega_1}^{\omega_2} \int_{T=0}^{120} P_{SP}(T, \omega) dT d\omega \right) \quad (3)$$

This 120-s window for calculating integrals of spectral densities was used to avoid including movement artifacts in the SBF measurement associated with the transition from normal seating to post-seating.

The secondary outcomes of the study included demographic information, medical history, and 7 items from Quebec User Evaluation of Satisfaction with Assistive Technology (QUEST 2.0) [19]. Participants were also asked to select the 3 items most important to them in QUEST as users.

2.4. Data analyses

Wilcoxon signed rank tests were used to compare the differences between cooling and non-cooling procedures for the following outcomes: skin temperature at baseline, normal seating, and post-seating; baseline and normalized peak SBF; perfusion area; and normalized metabolic, neurogenic and myogenic spectral densities during post-seating. To further investigate the relationship between changes in SBF and physiologic responses with cooling, Pearson correlation coefficients were computed for difference in reactive hyperemia and difference in normalized spectral densities. The difference (Δ : non-cooling – cooling) in reactive hyperemia included: Δ normalized peak SBF and Δ perfusion area. The difference in normalized spectral densities included: Δ normalized metabolic, Δ normalized neurogenic, and Δ normalized myogenic spectral densities. Alpha value of 0.05 was used for statistical significance. Since the scores and comments regarding satisfaction with the prototype cushion collected with QUEST 2.0 will only serve as a reference for future cushion/mattress design, no statistical analysis was computed for the scores.

3. Results

Mean age of the 23 adult participants was 38.39 ± 12.92 (range 19–63) years old, and mean BMI of participants was 24.10 ± 5.07 kg/m² (range 16.49–32.98 kg/m²). Table 1 includes the demographic and SCI information of all participants.

Fig. 4 demonstrates representative interface pressure on top of the wheelchair cushion with local cooling on. The mean peak interface pressure for all participants was 167.83 ± 39.67 mmHg. Fig. 5 shows time-series temperature data between cooling and non-cooling procedures. The skin temperature increases slightly during the 30 min seating of the non-cooling procedure, and it decreases gradually during the cooling procedure.

Fig. 6 shows examples of SBF responses collected during both cooling and non-cooling protocols from two subjects. Wilcoxon Signed rank test results are included in Table 2. Skin temperature was significantly lower during normal seating and during post-seating with

Table 1
Demographic and injury information of 23 participants.

Variable		N	%
Gender	Male	19	82.6
	Female	4	17.4
Ethnicity	Caucasian	19	82.6
	African-American	3	13.0
	Hispanic/Latino	1	4.4
Level of injury	C1–C8	7	30.4
	T1–T10	16	69.6
ASIA Impairment Scale	A	15	65.2
	B	4	17.4
	C	4	17.4

cooling activated. The mean within-subject difference in skin temperature between cooling vs. non-cooling during normal seating was $1.25 \pm 0.87 \text{ }^\circ\text{C}$ (range 0.4–3.1 $^\circ\text{C}$), whereas the mean within-subject difference during post-seating was $0.71 \pm 0.61 \text{ }^\circ\text{C}$ (range 0–2 $^\circ\text{C}$). Normalized peak SBF and perfusion area were significantly lower with cooling. There were no significant differences in baseline SBF, skin temperature or spectral densities during reactive hyperemia between cooling and non-cooling.

Pearson correlation coefficient tests showed a positive moderate correlation between Δ normalized peak SBF and Δ normalized metabolic and neurogenic spectral densities, but not with Δ normalized myogenic (Table 3). No correlation between Δ perfusion area and the three Δ normalized spectral densities was found.

Table 4 shows the QUEST 2.0 results for 7 items. The results indicated overall satisfaction of the prototype cushion with local cooling feature, with ‘durability’ considered least satisfied. Comfort, effectiveness and durability were considered as most important.

4. Discussion

This study helped bridge an important gap by assessing the effect of temperature control on pressure injury indicators in a real-world seating condition. The main difference in this study compared to

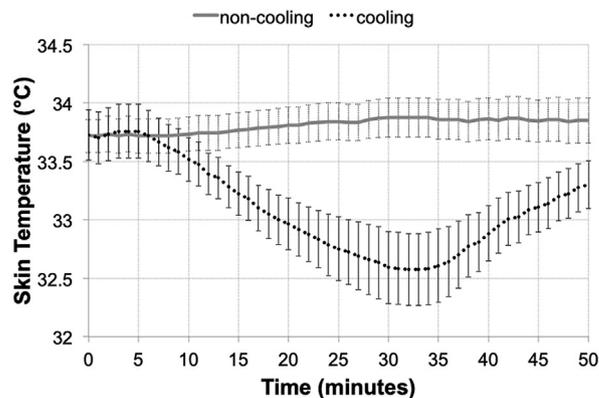


Fig. 5. Mean skin temperature with one standard error at every minute of the 50-min procedure.

previous human studies was how the loading condition was induced. All previous studies used a single-point indenter to apply localized pressure on the sacrum [8–10,20,21]. While single point indentation method is precise in controlling the amount of load on the tissue, it does not represent weight-bearing conditions where the area surrounding the bony prominence is also under load. The procedure in our study simulated seating conditions, where the pressure was the highest over bony prominences (ischial tuberosity in our case) [22], and the surrounding area was exposed to lower interface pressure but not pressure free.

Our results demonstrated the cushion prototype, reduced skin temperature with cooling ‘on’ as compared to ‘off’ for all participants. The skin temperature of participants during cooling ‘off’ was higher in this study than that in previous human studies [9,10]. The decrease in temperature in this study (0.3–4 $^\circ\text{C}$) was smaller than that in previous studies [9,10]. This may be due to the difference in loading methods [9,10]. Close contact of skin with the cushion allows limited heat dissipation, and this leads to increased temperature during sitting [23]. Another potential reason for the smaller decrease in temperature with cooling in our study was we used open-loop and constant current to

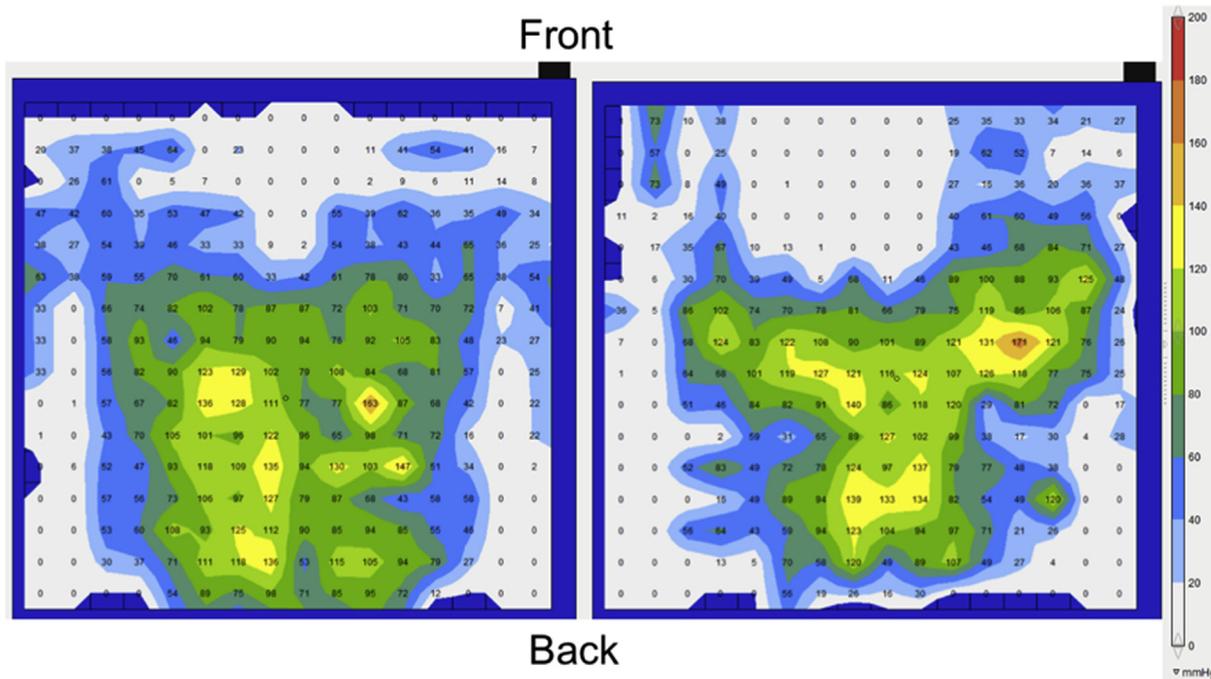


Fig. 4. Representative pressure map images during normal seating. (Left) pressure map for subject SCI_16, SBF and local cooling application took place on the left ischium. (Right) pressure map for subject SCI_11, SBF and cooling application took place on the right ischium.

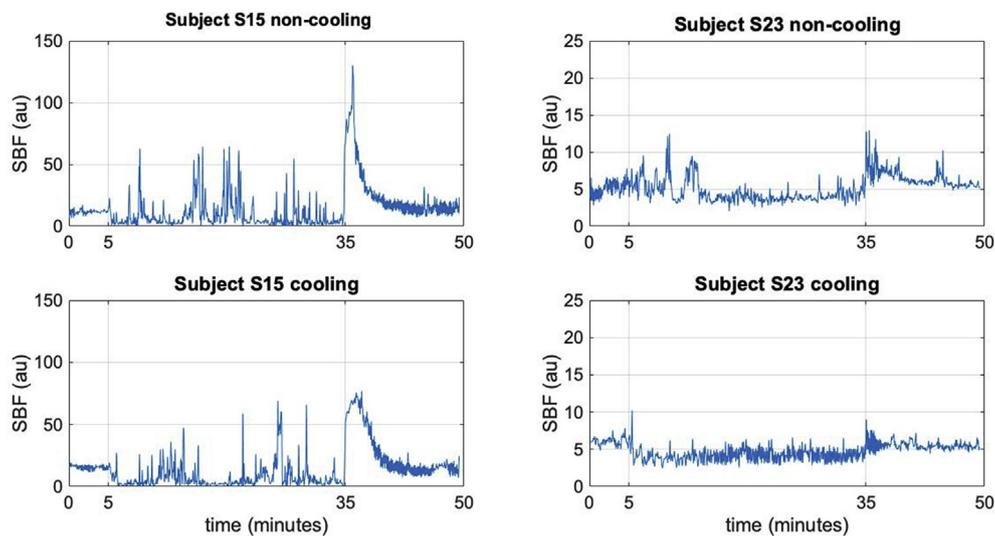


Fig. 6. Filtered SBF from subjects S15 and S23 for non-cooling vs. cooling procedures.

activate the thermoelectric cooling element to simplify the device [8–10,20,21]. We recommend implementing closed-loop temperature control to maintain lower, constant skin temperatures to enhance the protective effect of the temperature regulation.

Our methods also allowed us to quantify reactive hyperemia as an indication of the degree of cellular stress caused by ischemia. Reactive hyperemia was used in previous animal and human studies to investigate the temperature effect on weight-bearing soft tissues [6,8–10]. One difference in our study was that applied pressure was not controlled and depended on each participant's sitting condition. Since our participants were securely positioned with seat and chest belts throughout and did not transfer from the wheelchair during washout, we assume each participant experienced the same amount of pressure with and without cooling for each condition thus allowing us to make a valid comparison and assessment of the cooling effect. The reduction we observed in reactive hyperemia with cooling is consistent with previous human studies on individuals without any neurological deficits [8–10,20,21]. Our findings also complement previous studies on individuals with SCI. The two SCI studies did not demonstrate significant difference when cooling to 25 °C [9] and 10 °C lower than control [10] as compared to non-cooling. The only difference in reactive hyperemia noted in the SCI population was observed when compared between cooling vs. heating (temperature difference of 20 °C) [10]. Both studies suggested that the less profound temperature effect on weight-bearing tissue was caused by changes in microcirculatory function after SCI [9,10]. Another reason that the temperature effect on weight-bearing tissue was observed in our study but not observed in previous studies was that the weight-bearing condition in this study was greater than that used in previous studies [9,10]. Lachenbruch et al. showed that the temperature effect of 4 °C on reactive hyperemia was

Table 2

Mean ± one standard deviation of primary outcome measures with cooling and non-cooling, and the Wilcoxon signed rank test results.

Outcome Measures (unit)		cooling	Non-cooling	p
skin temperature (°C)	Baseline	33.90 ± 0.78	33.82 ± 0.44	0.552
	Normal seating	32.61 ± 1.09	33.86 ± 0.59	0.002 ^a
	Reactive hyperemia	33.41 ± 0.72	34.06 ± 0.61	0.018 ^a
SBF	Baseline (au)	9.99 ± 6.31	11.21 ± 12.11	0.144
	Normalized peak (%)	110.06 ± 169.06	145.28 ± 217.47	0.020 ^a
	Perfusion area (au ² sec)	674.71 ± 1892.15	795.77 ± 1672.64	0.033 ^a
Normalized spectral density (%)	Metabolic	25.87 ± 52.02	42.13 ± 103.66	0.301
	neurogenic	30.82 ± 60.19	67.73 ± 152.77	0.362
	myogenic	16.53 ± 23.73	67.07 ± 204.68	0.831

^a Indication of reaching level of significance 0.05.

Table 3

Pearson correlation coefficient results between Δ normalized peak SBF, Δ perfusion area and the Δ normalized spectral densities.

		Δ normalized peak SBF	Δ perfusion area
Δ normalized spectral densities	metabolic	r = 0.454 p = 0.030 ^a	r = 0.346 p = 0.106
	neurogenic	r = 0.454 p = 0.029 ^a	r = 0.298 p = 0.167
	myogenic	r = 0.280 p = 0.195	r = 0.258 p = 0.236

^a Indication of reaching level of significance 0.05.

Table 4

QUEST results evaluated with a five-point Likert scale, 1-not satisfied at all to 5-very satisfied [19].

QUEST item	Participants' mean rating (out of 5 points)	# users who considered item one of the most important (out of 23 raters)
1. Dimensions	4.48 ± 0.75	2 (8.70%)
2. Ease in adjusting	4.05 ± 0.90	2 (8.70%)
3. Safe and secure	4.41 ± 0.96	6 (26.09%)
4. Durability	3.40 ± 0.84	14 (60.87%)
5. Easy to use	4.52 ± 0.79	3 (13.04%)
6. Comfortable	4.52 ± 0.67	22 (95.65%)
7. Effective (meets needs)	4.33 ± 0.86	17 (73.91%)

more profound at 100 mmHg than at 60 mmHg [20,21], and this suggested that the changes in temperature played a more important role on tissue ischemia when there was more occlusion of SBF. Based on the pressure readings, we suspected that the normal seating condition used in this study caused a greater amount of pressure on a large area of the skin as compared to previous studies, making the weight-bearing condition close to an occlusion. We were therefore able to observe the temperature effect on weight-bearing tissue in this study despite of the small amount of temperature decrease with our cooling feature 'on' and the changes in microcirculatory response after SCI. Based on our results and the findings from Jan et al. [10], we postulate that the temperature effect on weight-bearing tissue may be detectable in the SCI population when the difference in temperature is more than 10 °C or when a large area of blood flow at the weight-bearing tissue is occluded or near occluded.

Our spectral analyses results are consistent with all previous studies that there was no significant differences in normalized spectral densities (metabolic, neurogenic and myogenic) during reactive hyperemia between cooling vs. non-cooling. Only one study from Jan et al. showed significant differences between cooling vs. heating (20 °C difference) in metabolic and neurogenic spectral amplitudes of able-bodied participants, and in metabolic spectral amplitudes of participants with SCI [10]. However, they did not find difference between cooling vs. non-cooling (10 °C difference) in either group. They suspected that the observed difference was a combination of reactive and thermal hyperemia, and the interactions between pressure and thermal stress are yet to be determined. Jan's group also found correlations between hyperemic parameters and spectral densities in able-bodied participants but not participants with SCI. One important contribution from our spectral analyses results was that the changes in normalized metabolic and neurogenic spectral densities with cooling was moderately correlated with the changes in normalized peak SBF with cooling in our participants with SCI. This suggested that the decrease in reactive hyperemia with local cooling may be partially mediated by the local metabolic and neurogenic mechanisms. The lack of difference between normalized spectral densities between cooling vs. non-cooling hinder us from drawing further conclusions regarding the underlying SBF control mechanisms.

A limitation was that the magnitude of local cooling was limited for some participants, for example, one participant only had temperature decrease of 0.3 °C. Further techniques should be explored for implementing cooling in cushion designs.

5. Conclusion

The loading method of this study represented typical wheelchair seating conditions for people with SCI. Our prototype cushion with cooling in the ischial area was capable of lowering skin temperature and reduced physiologic indicators of severity of ischemia in the weight-bearing tissue during prolonged seating in the SCI population. Research on the effect of temperature control on pressure injury is needed, and further exploration of different cooling techniques is warranted.

Declaration of competing interest

None.

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