Research Article

The relationship between pressure offloading and ischial tissue health in individuals with spinal cord injury: An exploratory study

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Objectives: To compare thickness and texture measures of tissue overlying the ischial region in able-bodied (AB) individuals vs. individuals with spinal cord injury (SCI) and to determine if there is a relationship between pressure offloading of the ischial tuberosities (IT) and tissue health in individuals with SCI.
Design: Exploratory cross-sectional study.
Setting: University setting and rehabilitation hospital.
Outcome Measures: Thickness and texture measurements from ultrasound images of tissues overlying the IT were obtained from AB individuals ($n = 10$) and individuals with complete or incomplete traumatic and non-traumatic SCI American Spinal Injury Association Impairment Scale (AIS) classification A–D ($n = 15$). Pressure offloading was measured in individuals with SCI and correlated with tissue health measurements.
Results: The area overlying the IT occupied by the muscle was significantly greater in the SCI when compared with AB cohort. The area occupied by the muscle in individuals with SCI appeared to lose the striated appearance and was more echogenic than nearby skin and subcutaneous tissue (ST). There was no correlation between offloading times and thickness, echogenicity and contrast measurements of skin, ST and muscle in individuals with SCI.
Conclusion: Changes in soft tissues overlying the ischial tuberosity occur following SCI corresponding to the loss of striated appearance of muscle and increased thickness of the area occupied by the muscle. Further studies using a larger sample size are recommended to establish if thickness and tissue texture differ between individuals with SCI who sustain pressure injuries vs. those who do not.

Keywords: Pressure injuries, Pressure offloading, Spinal cord injuries, Ischial tuberosity, Sitting, Wheelchair users

Introduction

A pressure injury (PI) is a localized area of injury to skin and/or underlying tissue over a bony prominence, due to pressure, or pressure in combination with shear.[1] Some suggest that external pressure is the primary reason why PIs develop[2] which can occur within two hours of immobility.[3] Deep tissue injury (DTI) occurring under intact skin in the deeper muscle and subcutaneous tissue (ST) has been recognized as a form of PI.[1,4] In DTI, edema accumulates in the deep tissue which migrates up to the skin surface[5] potentially resulting in an open wound.

Approximately 1.3–3 million individuals in the United States have a PI.[6] Annual health care costs for hospital acquired PI are \$2.2–\$3.6 billion.[7] PIs are a highly prevalent and costly medical complication in

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DOI 10.1080/10790268.2019.1645404

individuals with spinal cord injury (SCI). Prevalence rates of PI following SCI vary, with one study reporting 39%.[8] The average monthly cost for the management of a PI in an individual living with an SCI in the community is $4,745[9] with profound adverse impact on vocation and quality of life.[10]

The ischial tuberosity (IT) is the major weight bearing bone during sitting and is a common site for PI development since it bears the mechanical stresses during sitting.[11] Frequent offloading of weight bearing tissues is recommended for PI prevention.[12] To prevent PIs, Lyder and Ayello[13] recommend maintaining the external pressure over tissue below the average capillary pressure of 32 mmHg. However, tissues overlying the IT (i.e. gluteus maximus, ST and skin) present with varying degrees of stiffness and viscoelasticity and potentially different tolerances to applied loads. Adipose tissue is comparable to incompressible fluid, in contrast to viscoelastic muscle,[14] suggesting that muscle tissue may be more sensitive to applied loads compared with adipose tissue. When compared with adipose and muscle, skin is able to withstand greater compressive forces without injury.[14,15]

Individuals with SCI should engage in weight shifting for approximately 2 min every 15-min while sitting to mitigate seated acquired PIs.[12,16,17] Difficulty unloading soft tissues over the IT due to immobility secondary to SCI, can result in prolonged soft tissue deformation,[11] damage of epidermal and dermal layers[18] and increased risk of PI secondary to ischemia and reperfusion damage.[19] Structural changes in skin, ST and muscles following SCI further increase the risk of seated acquired PIs.[20]

Post SCI, skin undergoes an adaptive process, known as disuse adaptation.[21] Individuals with SCI have up to 25% less thickness of skin over the ischium and sacrum[22,23] compared with able-bodied (AB) individuals. Additionally, malnutrition, dehydration,[24–26] reduced fibroblastic activity and microvascular changes in skin[21] can result in reduced collagen formation.[23] Due to the protective nature of skin[27] and its relatively minimal response to strain[28] reduced collagen content and skin thickness may predispose individuals with SCI to PIs during prolonged loading.

Within four weeks following SCI, muscles below the level of injury undergo atrophy,[29] fat infiltration,[30] reduced number of slow oxidative fibres[31] and a greater proportion of low-density muscle.[32] In addition, micro and macrovascular changes[21] secondary to reduced sympathetic nervous system activity impair the protective vasodilatatory response of muscle to prolonged pressure.[33] The resultant reduction in oxidative capacity and diminished ability of the muscle to remove accumulated metabolites[34,35] compromises tissue health especially when exacerbated by applied loads. The severity of changes in muscle post SCI are dependent on injury level and time since injury.[29]

Changes in the physical properties of tissues associated with PIs can be captured using ultrasound imaging.[36] Ultrasound imaging is portable, minimally invasive, inexpensive and provides real-time bedside information.[37] High frequency ultrasound has been used to detect dermal and subdermal edema in individuals at high risk of PIs.[5,37] Ultrasound imaging has also been used to document tissue healing through the changes in tissue homogeneity and regularity,[38] the presence of ill-defined layered structures and hypoechoic areas[23] reflecting edema. While these methods have employed subjective interpretation of ultrasound images, more detailed quantification of changes in tissue texture overlying the IT obtained from gray scale measures such as pixel intensity (i.e. echogenicity) and homogeneity (i.e. contrast) can be captured in individuals with SCI to document changes in tissue integrity.

Measures obtained in regions of interest (ROI) from ultrasound images such as echogenicity and contrast may help quantify tissue texture[39–41] and collagen content.[42] The proportion of low echogenic pixels of an ultrasound image can provide additional insight compared with subjective visual image inspection of tissue texture in response to applied loads.[43]

Intrinsic factors including altered neurogenic control of circulation, poor oxygen, nutrient availability and vasoactive medication,[44] moisture, loss of consciousness, impaired sensation, medication, and smoking increases PI risk.[20] That said, the relationships between pressure loading/offloading and identifiable changes in tissue properties using ultrasound imaging have not been explored. The objectives of this study were to: (1) explore relative tissue thickness of tissues overlying the IT in individuals with SCI in comparison with an AB cohort using high frequency ultrasound, (2) characterize the texture of tissues overlying the IT in individuals with SCI and, (3) determine if pressure offloading is related to thickness, echogenicity and contrast measures of skin, ST and muscle in individuals with SCI. These objectives could collectively inform rehabilitation strategies to mitigate the development of seated acquired PIs following SCI over the life course.

Materials and methods

Study design

This cross-sectional study used a single-visit, single-evaluator, observational design.

Data were collected from AB individuals at the Department of Physical Therapy at the University of Toronto. Data from individuals with SCI were collected at the SCI Mobility Lab, Lyndhurst Centre, Toronto Rehabilitation Institute – University Health Network, a tertiary rehabilitation hospital serving individuals with traumatic and non-traumatic SCI. The study was approved by the institutional review boards of both settings. Informed consent was obtained from each participant prior to study participation.

Study population

AB individuals

Ten healthy men ($n = 4$) and women ($n = 6$) ages 18–70 participated in the study. Exclusion criteria included history of hip, knee, ankle, shoulder or elbow injury or surgery, history of muscle disease (e.g. muscular dystrophy, polymyositis) or skin conditions (e.g. dermatitis, psoriasis).

Individuals with SCI

Fifteen inpatient men ($n = 12$) and women ($n = 3$) with SCI participated in the study. To be included, participants were ≥ 18 years old with complete or incomplete (AIS A–D), traumatic or non-traumatic SCI. Participants had to be medically stable, engaged in inpatient rehabilitation and use their wheelchair as the primary means of mobility for at least 2 h per day. Individuals with significant musculoskeletal conditions, impaired neurological status affecting sitting balance other than those due to their injury, an existing PI or a documented brain injury were excluded.

Pressure offloading

Pressure offloading of the IT was captured as described previously.[45] A customized 0.95 cm thick pressure mat "SensiMAT" (SENSIMAT Systems Inc., Canada) with 6 square force sensitive resistors, each measuring 43.7 mm in diameter, with an actuation force of 0.1 N and force sensitivity of $0.1–10.0^2$ N was placed under the wheelchair cushion. Data from each force sensor was sampled at 1 Hz and transferred to an iPhone using Bluetooth technology and uploaded to a secure server through Wi-Fi. Analog signals from each sensor were processed using MATLAB (Mathworks, USA) to capture offloading times (in seconds). Offloading was defined as a period of time during which the two rear pressure sensors registered a force equivalent in value to that when no pressure was applied for a minimum of 2 s.

Each IT was examined separately. Individuals who engaged in offloading of the IT less than 1% of the time were categorized as "Loaders", whereas those who engaged in offloading of the IT more than 1% of the time were characterized as "Offloaders". The 1% cut off corresponds to 36 s in a one-hour period.

Data were collected for a minimum of 2-h while each individual used their own wheelchair and wheelchair cushion and engaged in their activities of daily living including rehabilitation. Given that sitting duration varied for each participant (1.1–5.3 h) as some individuals exited their wheelchair prior to completion of data collection, offloading times were expressed as a percentage of total wheelchair time.

Ultrasound imaging

For the AB cohort, a Linear Array B-Mode 8 – 13 MHz Ultrasound Transducer (GE LOGIQ-E Ultrasound system, GE Healthcare, USA) was used to scan the tissue overlying the IT of preferred kicking (dominant) leg. For the individuals with SCI, a linear array B-Mode 6–18 MHz Ultrasound Transducer (Siemens Acuson S2000 Ultrasound System, Siemens Healthcare, Germany) was used to scan the tissues overlying each IT.

Three transverse ultrasound images overlying the IT of individuals with SCI and the AB cohort were collected in side lying (right IT while left side lying and vice versa) with the participants' hips and knees placed in 90 degrees of flexion and hip in the neutral abduction/adduction and internal/external rotation positions using a pillow between the knees. The distance between the greater trochanter and the coccyx was recorded and a perpendicular distance from this line to the IT was used for consistent probe placement during image acquisition.

For each participant, the frequency, gain and focus were adjusted to obtain optimal image quality. Images were exported into a customized program using the Imaging Processing Toolbox of MATLAB (Mathworks, Natick, MA, USA) described in Gabison *et al.*[46] One individual (SG) acquired the images and outlined the ROIs corresponding to skin, ST and muscle. ROIs were confirmed by one of the senior investigators (SM). Mean thickness for each ROI was calculated and adjusted as a percentage of total tissue thickness. Echogenicity and contrast were computed for each ROI.

Statistical analysis

SPSS Statistics (SPSS Statistics 23, IBM, USA) was used for analysis. The Shapiro Wilk Test was used to assess normality of the demographic, pressure offloading and ultrasound data. An Analysis of Variance (ANOVA) was used to determine if demographic variables were significantly different between AB and SCI cohorts. Medians and interquartile ranges for thickness, echogenicity and contrast were calculated for each ROI for the right IT in AB individuals and for both ITs in individuals with SCI. Due to different ultrasound image capture for both cohorts, only thickness measures were used for statistical analysis using the Mann Whitney U test for between group differences of the right (dominant) IT. Spearman's rank order correlations were used to determine the relationship between percent of offloading time and ultrasound measures for the individuals with SCI. Correlation coefficients were interpreted according to Altman;[47] $r = 0.21–0.40$ representing poor correlation, $r = 0.41–0.60$ representing moderate correlation, and $r = 0.61–0.80$ representing good correlation, and $r > 0.81$ representing very good correlation.

Results

Demographics of the AB and SCI groups are reported in Table 1. Characteristics of individuals with SCI are reported in Table 2. ANOVA revealed no significant differences in demographic variables between AB and SCI groups.

Ultrasound images: AB vs. SCI individuals

Figure 1(A,B) represents a typical image obtained from the tissue overlying the IT in an AB individual and the outlined ROI corresponding to skin (S), ST and muscle (M). Fascial planes are clearly identified separating the skin from the ST and muscle. Clear striated patterns are observed in the region corresponding to the gluteus maximus muscle. Figure 2(A,B) depict a typical image obtained from the tissue overlying the IT in an individual with SCI and the corresponding outlined ROI. Fascial planes in the muscle are not clearly identified and the gluteus maximus muscle lacks the typical striated pattern. More uniform gray scale intensity throughout the gluteal muscle region is noted corresponding to reduced contrast. The echogenicity in the AB group was highest in the skin (median 92.02), followed by ST (median 74.87) and muscle (median 72.99). The echogenicity in the SCI group was similar in the skin and ST (median 59.31 and 59.93, respectively) and lower in the muscle (median 54.64). In both AB and SCI groups, the lowest contrast was seen in the muscle (median: 9.81 and 6.32 respectively) (Table 3).

Table 1 Demographics of AB individuals and individuals with SCI.

	AB individuals (n = 10) Count/ Mean ± 1 SD	Individuals with SCI (n = 15) Count/ Mean ± 1 SD
Males/Females	4/6	12/3
Age (years)	42.8 ± 16.3	42.7 ± 17.2
Height (cm)	173.4 ± 6.0	172.9 ± 6.2
Weight (kg)	71.3 ± 12.5	73.1 ± 12.0

Tissue thickness: AB compared with individuals with SCI

Mean thickness of skin, ST and muscle were not normally distributed for both groups ($P < 0.05$). The thickest layer overlying the IT in AB and SCI groups was the area occupied by muscle (38.06–74.89%), followed by the ST (17.33–51.38%) and skin (4.53–16.63%) (Table 3). Skin thickness in individuals with SCI (median = 2.19 mm, range: 2.03–2.52 mm) did not differ significantly when compared with the AB individuals (median = 2.32 mm, range: 1.69–3.00 mm), ($U = 68.0$, $z = -0.388$, $P = 0.723$). ST thickness in individuals with SCI (median = 8.15 mm) did not differ significantly from AB individuals (median = 8.31 mm), ($U = 67.0$, $z = -0.555$, $P = 0.683$). The thickness of the region corresponding to muscle in individuals with SCI (median = 18.62 mm) differed significantly from AB individuals (median = 12.93 mm), ($U = 30.5$, $z = -2.469$, $P = 0.012$) (Fig. 3).

Individuals with SCI: offloading patterns

Figure 4 illustrates the loading and offloading patterns of individuals with SCI. Offloading of only the right IT was not performed by any participants. Participants who offloaded the right IT also offloaded the left IT.

Tissue health measure: loaders vs. offloaders in individuals with SCI

Tissue health measures of the Loaders and Offloaders are presented in Table 4. Mean thickness of the skin, ST and muscle overlying the left IT was greater in the Loaders when compared with Offloaders. Thickness of the skin and muscle over the right IT was greater in the Loaders compared with Offloaders. Less contrast was seen in the Loaders compared with the Offloaders for both the left and right ITs. Echogenicity was greater in the Loaders compared with the Offloaders in the skin, ST and muscle over the left IT, whereas greater echogenicity was observed over the right IT only in the muscle. There were no significant correlations between pressure offloading and thickness of skin, ST and muscle (r: $-0.023–0.445$, P: 0.096–0.934) (Table 5).

Table 2 Demographic and clinical characteristics of individuals with SCI.

	Demographics						Injury characteristics			
ID	Sex (M/F)	Age (years)	Height (cm)	Body Mass (kg)	BMI* (kg/m^2)	Days post injury / Surgery	Injury Level	T/NT	AIS*** (A/B/C/D)	C/I****
4	M	53	172	68.2	23.1	442	C4	T	A	C
12	M	35	170	68.2	23.6	79	T3	T	A	C
8	M	25	176	54.5	17.6	46	T4	T	A	C
1	M	36	175	74.0	24.2	55	T4	T	A	C
5	M	25	173	70.0	23.4	60	T9	T	A	C
10	M	32	180	98.2	30.3	27	T10	T	A	C
2	F	48	172	77.0	26.0	36	T11	T	A	C
3	M	52	174	74.0	24.4	38	L3	NT	A	C
7	M	44	173	80.0	26.7	166	C4	T	B	I
11	M	50	170	77.3	26.7	97	C4	T	B	I
15	M	53	180	82.0	25.3	29	T10	T	B	I
6	M	21	182	72.7	21.9	61	T10	T	B	C
9	F	16	165	47.6	17.5	35	T12	T	B	I
14	M	65	175	84.5	27.6	97	C5	NT	D	I
16	F	78	157	68.0	27.6	27	C6	NT	D	I
Mean ± SD/Count	12/3	42.7 ± 17.2	172.9 ± 6.2	73.1 ± 12.0	24.4 ± 3.5	126.2 ± 99.7	C4–T12	12/3	8/5/0/2	9/5

*BMI = Body Mass Index.
**T = Traumatic Spinal Cord Injury, NT = Non-Traumatic.
*** AIS = American Spinal Injury Association Impairment Scale.
**** C = Complete, I = Incomplete.

Discussion

Although thickness of skin and ST were not significantly different between AB and individuals with SCI, the area occupied by muscle was significantly greater in individuals with SCI compared with the AB cohort. Clearly defined striations were not visible in the region occupied by muscle in individuals with SCI and this region appeared more homogenous. Additionally, it was challenging to identify clearly defined borders separating ST from muscle in SCI. These findings are not surprising given that Wu *et al.*[32] found fat infiltration of gluteus muscle post SCI. Although the cohorts were similar with respect to height and weight, it is possible that participants with SCI had extensive fat infiltration of

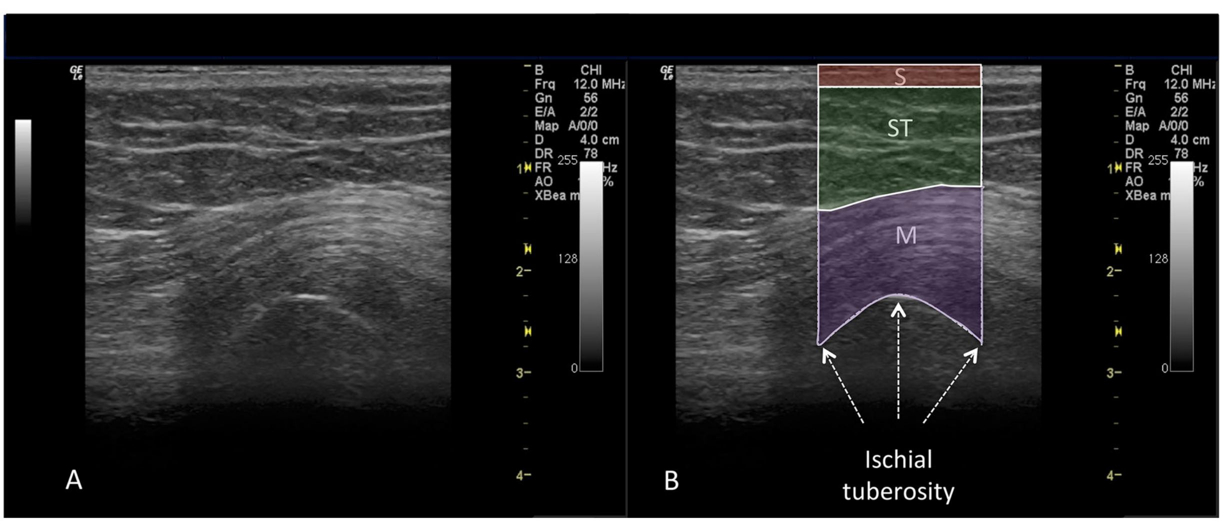

Figure 1 (A,B) Ultrasound images of tissues overlying the ischial tuberosity (IT) obtained from AB individual. The unprocessed image (A) is visualized on the left. The image on the right (B) depicts the selected ROI analyzed. S = skin, ST = subcutaneous tissue, M = muscle. Frequency, gain and depth were adjusted for each participant to optimize image quality. The skin is depicted as an area with hyperechoic lines, parallel to the skin surface, with a clear delineated border separating the ST. The ST is identified as a low echoic intensity area with echogenic regions corresponding to the connective tissue. The lower boundary of the ST is separated by a clearly identified reflective fascial layer overlying the muscle. The region of muscle corresponds to the area where fascicular architecture is visible. The depth of the IT is measured at approximately 2.75 cm.

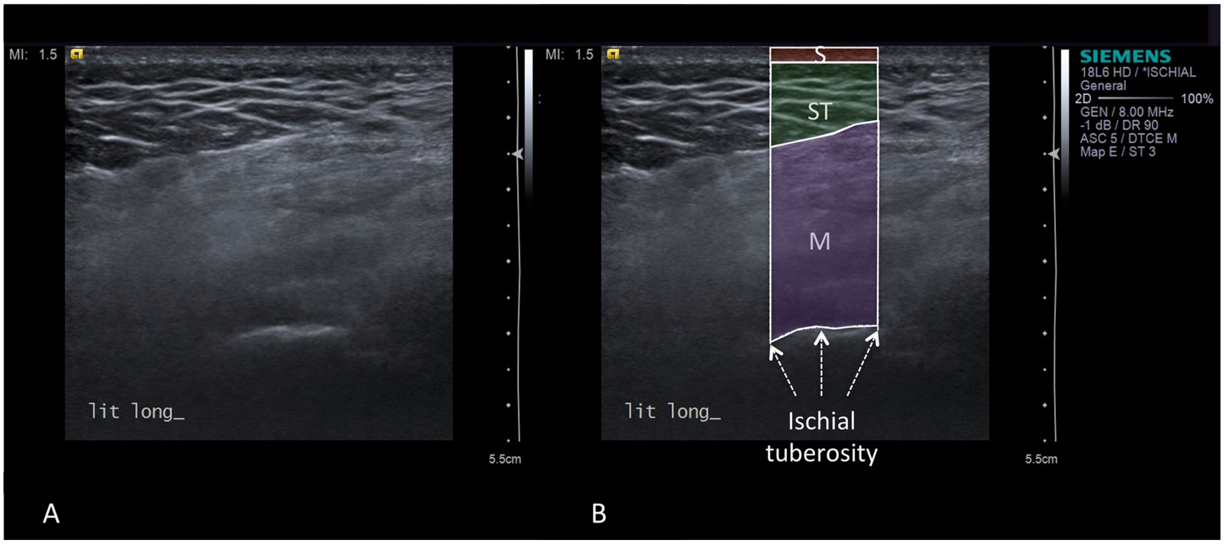

Figure 2 (A,B) Unprocessed ultrasound images over the left ischial tuberosity in one individual with SCI (A) with ROI outlined in processed image (B). Frequency, gain and depth were adjusted for each participant to optimize image acquisition. The image reveals a homogenous pattern of ultrasound reflection in the skin and muscle region. The region of ST is illustrated through regions of hypoechoic tissue separated by hyperechoic bands. The ischial tuberosity is identified by the presence of a hyperechoic area. The depth of the IT is measured at approximately 4.0 cm.

gluteus maximus giving the appearance of a homogeneous hyperechoic pattern with a larger area designated as muscle. It has also been reported that in an AB individual, while sitting, the gluteus maximus muscle moves laterally from under the IT.[48] It is possible that the gluteus maximus moved out of the ROI during image acquisition in the AB cohort, potentially underestimating the true thickness measure. Fat infiltration in SCI along with the gluteus maximus moving out of the ROI in the AB cohort may have led to the differences in thickness measures of muscle observed between groups.

Our findings of subcutaneous thickness measures are in contrast to Sonenblum *et al.*[49] who examined the soft tissues over the IT in AB individuals and individuals with SCI. Sonenblum *et al.*[49] found that thickness measures of unloaded ST varied between 8–59 mm in AB individuals and 6–30 mm in individuals with SCI. Our study found that ST in AB individuals and individuals with SCI to be much smaller than reported by Sonenblum *et al.*,[49] measuring 4.21–15.0 mm in the AB cohort and 4.0–13.0 mm in the SCI cohort. In contrast, thickness of the muscle was found to be greater in

Table 3 Ultrasound measurements over the right ischial tuberosity of AB individuals and individuals with SCI.

	AB individuals				Individuals with SCI			
	Median	IQR	Min	Max	Median	IQR	Min	Max
Mean thickness (mm)								
Skin	2.32	2.04–2.70	1.69	3.00	2.19	2.03–2.51	2.03	2.51
ST	8.30	5.89–10.18	4.21	15.00	8.15	7.08–10.94	4.01	12.96
Muscle†	12.93	9.33–15.84	6.92	31.93	18.62	15.32–21.43	9.74	30.95
Percentage thickness								
Skin	10.15	8.00–11.52	6.56	12.77	7.68	6.50–8.68	4.53	16.63
ST	35.34	21.48–29.39	17.33	51.38	27.76	25.15–33.22	18.96	44.77
Muscle	54.13	42.61–66.33	38.06	76.11	63.83	58.21–67.71	46.56	74.89
Contrast								
Skin	18.73	11.60–19.99	9.01	23.94	12.88	7.88–15.86	5.23	20.05
ST	17.14	11.98–22.95	10.48	40.08	25.28	20.15–35.08	5.09	57.20
Muscle	9.81	6.45–13.08	5.30	19.94	6.32	4.59–10.65	1.31	16.08
Echogenicity								
Skin	92.02	86.01–95.66	82.79	100.37	59.31	45.95–71.94	28.66	80.42
ST	74.87	66.44–83.65	55.70	99.07	59.93	48.77–71.30	31.51	81.01
Muscle	72.99	61.42–85.14	5.30	19.94	54.64	44.42–71.60	37.59	77.20

†Denotes significance at $P < 0.05$.

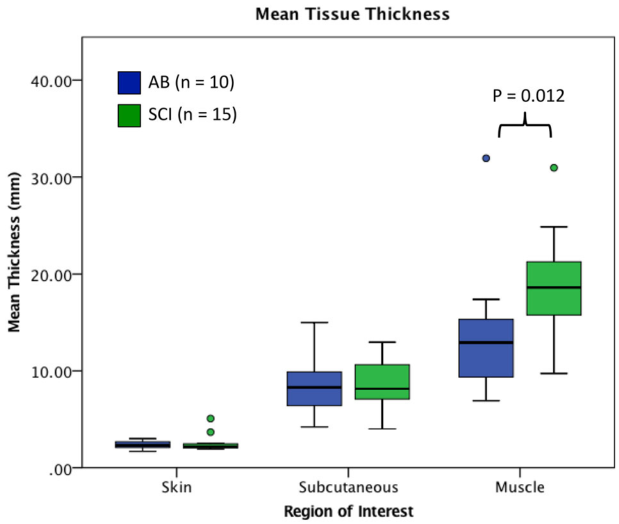

Figure 3 Thickness measures of each region of interest of the right IT in AB and individuals with SCI. The thickest region corresponded to the area occupied by muscle, followed by the ST and skin. Muscle thickness was significantly greater in SCI when compared with AB (P = 0.012).

both our AB and SCI cohorts compared to Sonenblum *et al*.[49] These differences may not be surprising given that Sonenblum *et al*.'s[49] experimental paradigm of an unloaded condition comprised individuals sitting on a customized cushion in which an opening in the cushion over the IT was created as participants sat in an MRI. Furthermore, muscle and subcutaneous deformation occurs over the IT during loaded conditions in healthy individuals and individuals with SCI.[11,50,51] Al-Dirini *et al.*[51] found that during a loaded condition, greater deformation of the muscle overlying the IT occurred when compared with ST in healthy individuals and it is uncertain as to what deformation of the tissue, if any, occurred in Sonenblum's study.[49] Participants in our study assumed a side lying position while ultrasound measurements were obtained, minimizing any potential compression or distortion of tissue. Since muscle is more compressible than fat, it is possible that the pressure redistribution during Sonenblum's[49] unloaded paradigm, in which participants lay on a cushion with an opening over the IT may have resulted in changes in 3D anatomy, and discrepancies recorded thickness compared to our study.

Given that muscle is more compressible than fat and is more sensitive to tissue deformation with prolonged loading,[14] it is not surprising that the region corresponding to muscle appeared to be more homogeneous. It would be interesting to investigate if following SCI, fat infiltration of muscle provides a protective mechanism by providing the cushioning needed for the overlying tissue or if fat infiltration may be a risk factor for PI development. In a study conducted by Lemmer *et al.*,[52] individuals with greater than 15% of intramuscular fat in the gluteus maximus muscle were at higher risk to have a PI. Longitudinal evaluation of a cohort of individuals with SCI would explore the nature of changes in echogenicity, atrophy and fat infiltration and their respective relationships to total tissue volume and development of PIs.

Previous investigators have used texture analysis to characterize tissue composition, however it has not been used to characterize tissue over the IT in SCI populations. Studies have investigated the presence of hypoechoic lesions under the skin in individuals at risk of developing PIs using subjective observation.[5,53] This study was the first of its kind to quantify texture in the tissues overlying the ITs using echogenicity and contrast measures in individuals post SCI and relate them to pressure offloading durations. These measures could potentially be captured longitudinally and in conjunction with histological evaluation in individuals at risk

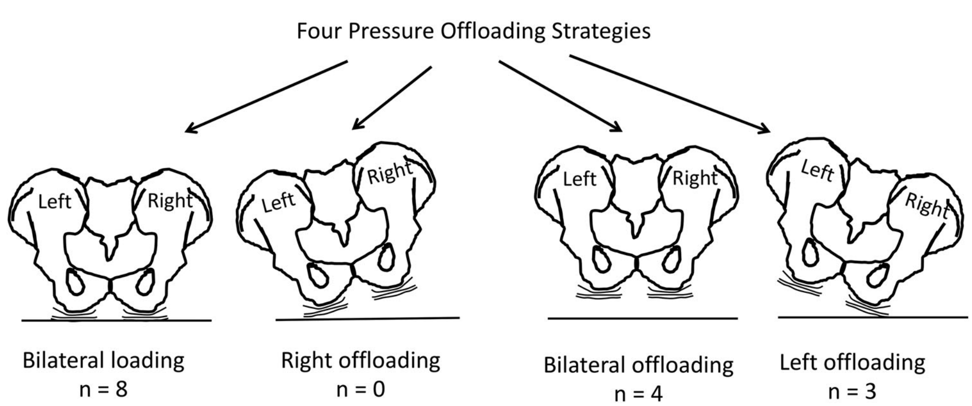

Figure 4 Offloading patterns of the left and right IT in individuals with SCI. No individual only offloaded their right IT. 4 participants engaged in bilateral offloading. Three participants engaged in only left offloading. Over half of the participants did not offload at all (*n* = 8).

Table 4 Ultrasound measures of offloaders and loaders in individuals with SCI for the left and right ischial tuberosities.

	Left ischial tuberosity				Right ischial tuberosity			
	Offloaders (*n* = 7)		Loaders (*n* = 8)		Offloaders (*n* = 4)		Loaders (*n* = 11)	
	Median	IQR	Median	IQR	Median	IQR	Median	IQR
Mean Thickness (mm)								
Skin	2.19	1.89–2.81	2.43	1.88–2.85	2.15	1.97–4.37	2.19	1.96–2.52
ST	9.15	7.55-14.65	9.60	8.53–15.74	10.25	7.85–10.80	8.70	7.08–12.69
Muscle	16.97	16.14-21.34	17.65	13.44–22.49	17.94	15.81–20.73	19.59	13.48–23.99
Contrast								
Skin	13.35	10.06–17.48	7.87	5.78–12.46	14.35	9.80–18.91	7.88	5.51–12.88
ST	28.67	18.66–34.69	20.39	14.08–25.54	39.25	21.64–46.28	20.17	18.98–25.28
Muscle	5.98	4.81–15.14	4.48	2.39–8.87	6.70	5.70–10.99	5.37	3.71–10.44
Echogenicity								
Skin	56.33	41.79–77.72	64.87	37.52-67.52	64.47	47.24–77.72	58.30	40.66–71.94
ST	50.51	45.37–59.50	51.32	42.19-65.09	59.42	55.27–69.91	50.26	41.07–73.33
Muscle	52.09	48.79–63.57	55.43	37.03-79.12	53.68	49.64–61.65	58.68	42.62–77.09

for the developmental of DTI. For example, Lal *et al.*[54] found texture analysis to correlate with histological evaluation of blood, lipid, fibromuscular and calcium composition in carotid plaques however, to date, no studies have compared histological evaluation of tissues and texture analysis of tissues overlying the IT in humans. Correlating ultrasound gray scale measures with histological evaluation could provide additional insight into the changes in tissue properties that could potentially be detected using ultrasound imaging.

Our study examined tissue health using an ultrasound imaging paradigm and its relationship to pressure offloading behavior in individuals with SCI. There were no significant correlations between tissue thickness or texture measures and pressure offloading durations. Additionally, we could not determine if tissue texture measures between Loaders and Offloaders were significant due to our small sample size and customization of ultrasound system settings for each participant. Additionally, we could not compare our texture measures with any other established ischial tissue texture measures, as there are no gold standard measures to date. Using the differences in skin thickness measures between AB individuals and individuals with SCI from Yalcin *et al.*'s study,[23] with a significance level of 0.05, we estimated that we would require 11 participants in each group to obtain a power of 0.80. Further studies using larger sample size, longer offloading times, in conjunction with additional tissue health measures are recommended.

Table 5 Correlation coefficients and corresponding P - values (in brackets) between thickness, echogenicity and contrast and percent of offloading time.

	Offloading left IT (% sitting time) (*n* = 15)	Offloading right IT (% sitting time) (*n* = 15)
Mean thickness		
Skin	−0.093 (0.742)	−0.143 (0.612)
ST	−0.279 (0.524)	−0.036 (0.899)
Muscle	0.445 (0.096)	0.364 (0.182)
Echogenicity		
Skin	0.023 (0.934)	0.157 (0.576)
ST	0.113 (0.689)	0.061 (0.830)
Muscle	−0.259 (0.351)	0.043 (0.879)
Contrast		
Skin	0.388 (0.153)	0.305 (0.271)
ST	0.352 (0.198)	0.339 (0.216)
Muscle	0.468 (0.079)	0.050 (0.860)

Limitations

Subcutaneous adipose tissue thickness is influenced by gender and body mass index.[55] Due to our small sample size, we could not determine if there were any sex differences with respect to tissue measurements over the IT.

Although our experimental paradigm captured offloading behavior for a minimum of two hours, some participants got out of their wheelchair prior to the termination of the data collection period. Given the short duration of sitting evaluated, we could not confirm if the offloading behavior exhibited during our data collection period was representative of the typical offloading behavior of the participant. However, we were able to demonstrate how little time participants were offloading during the data collection period which is consistent with Sonenblum and Sprigle's[56] study which demonstrated that the majority of individuals with SCI do not engage in the recommended weight-shifting schedule. Furthermore, our selected cutoff for offloading was well below the recommended offloading time every 15 min for a period of 2 min.[17] Additionally, all but one participant in this study was less than one year post SCI. Further studies using longer sitting times over multiple days and with individuals with chronic SCI and varying cutoff times for offloading should be undertaken to increase the generalizability of the results and as such inform clinical guidelines. Furthermore, additional at risk areas prone to PI development (e.g. heels, sacrum) during different body positions (e.g. supine, side lying) using different support surfaces (e.g. mattresses) should be explored.

There are several documented methods for evaluation of tissue health in healthy controls including measuring local transcutaneous oxygen levels ($TcPO_2$),[15,34] transcutaneous tissue carbon dioxide ($TcPCO_2$), sweat lactate, urea,[57] erythema,[58–60] skin temperature[19] and hydration[60] while few studies have examined markers of tissue health in individuals with PI or SCI.[15,32,35, 61–63] Assessing these auxiliary variables and their relationship to loading/offloading in individuals with SCI may be highly informative.

Conclusions

This study is the first of its kind to explore differences in tissues overlying the IT while taking into consideration loading/offloading behavior in the natural environment. Additionally, the relationship between offloading duration and tissue thickness, gray scale and texture measures were explored in individuals with SCI. Longitudinal approaches and evaluation of tissue measures via ultrasound imaging while monitoring for the development of PI are recommended to establish potential thresholds for thickness, gray scale and texture measures that could be used to predict PIs among individuals with SCI. Understanding the implications of offloading to tissue properties may enable the development of customized rehabilitation programs for at risk individuals whose changes in tissue properties may be more pronounced.

Disclaimer statements

Contributors None.

Funding was supported through the Health Commercialization Fellowship, Health Innovation Hub, Faculty of Medicine, University of Toronto, the Dalton Whitebread Scholarship and the Ontario Student Opportunity Trust Fund (OSOTF) Toronto Rehabilitation Institute – University of Toronto Scholarship and the Ontario Neurotrauma Foundation-Résau provincial de recherche en adpatiation-réadaptation (ONF-REPAR) Research Grant.

Conflicts of interest The authors report that there are no conflicts of interest.

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