PRESSURE ULCER RISK: THE EFFECT OF ANATOMICAL FEATURES ON INTERFACE PRESSURE AND TISSUE DEFORMATION IN PEOPLE WITH SPINAL CORD INJURY

by
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Bachelor of Philosophy in Rehabilitation Science, University of Pittsburgh School of Health and Rehabilitation Sciences, 2016

Submitted to the Graduate Faculty of
University of Pittsburgh School of Health and Rehabilitation Sciences in partial fulfillment
of the requirements for the degree of
Bachelor of Philosophy

University of Pittsburgh
2016

UNIVERSITY OF PITTSBURGH
SCHOOL OF HEALTH AND REHABILITATION SCIENCES

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Pressure ulcers are one of the most common secondary complications for people with spinal cord injury, and add $10 billion annually to healthcare costs in the US. They are the most frequently seen preventable hospital acquired condition. Recent pressure ulcer research has added examination of anatomical risk factors, mainly fat and muscle characteristics, to the many previously identified risk factors. Translation of the new anatomical-based risk assessment theories is contingent on development of clinical techniques for measurement and better understanding of relationships with known factors, which has slowed the integration of this research into clinical settings. This study was designed to help bridge this gap between lab and clinic, by examining how anatomical features affect both tissue deformation and interface pressure.

Six participants – two control and four with spinal cord injury – underwent MRI imaging while seated on a variety of seat cushions and in an unloaded condition, as well as pressure mapping. Three dimensional models of the tissue were created from the images. Significant anatomical differences were observed between the two groups. People with SCI lack muscle under the ischial tuberosity when sitting. The results suggest that tissue thickness was the anatomical feature most indicative of pressure ulcer risk. Greater unloaded thickness was associated with lower interface pressure and less change in tissue volume under seated loads, signifying a decrease in pressure ulcer risk. Higher deformation asymmetry – an imbalance between the change in tissue volume from one side of the buttocks to the other – also suggested increased pressure ulcer risk. Deformation asymmetry is particularly important because it can be partially corrected by adjusting sitting posture. These important characteristics should be used to direct further efforts to implement a more personalized risk model based upon the anatomy of the tissues at risk of breaking down.

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PREFACE

I really appreciate the dedication and hard work that many people have put in to help me along this process. A special thanks to:

- Dr. David Brienza, for serving as a mentor and guide throughout the past two years, and always being available to answer questions no matter what state, country, or continent he was in.
- Dr. Jonathan Akins for teaching me almost everything there is to know about research, and including me in other research pursuits.
- Patricia Karg for spending countless hours talking me through all of the complex problems that arose.
- Dr. J. Peter Rubin for serving on my defense committee.
- Dr. Ellen Cohn for first introducing me to the BPhil program, as well as introducing me to Dr. Brienza.
- Amy Evans for her guidance and helping me balance classes and research.
- The Department of Rehabilitation Science and Technology.
- The Honors College and the Brackenridge Fellowships for allowing me to pursue my research full time in the summer.
- My friends and family for their continued support through this process.

1. INTRODUCTION

Each year in the United States, 2.5 million people develop a pressure ulcer, costing between $9.1 billion and $11.6 billion[1]. A pressure ulcer is an injury to either the skin or deeper tissue due to prolonged pressure. Higher risks for pressure ulcers are associated with higher body mass indexes[2], prolonged immobilization[3], and decreased sensory perception[4], among other factors. These factors all appear in people with spinal cord injury (SCI) who use wheelchairs, putting these people at high risks for developing pressure ulcers. In fact, pressure ulcers are one of the leading causes of unplanned hospitalization for individuals with spinal cord injury[5]. While the exact incidence of pressure ulcers in patients with spinal cord injury is unknown, studies have reported that percentage to be anywhere from 40%[6] to 85%[7].

A deep tissue injury (DTI), is a type of pressure ulcer frequently seen in people who spend a lot of time in wheelchairs. Some pressure ulcers start at the skin and progress deeper, but a DTI progresses from the deepest tissue outwards. DTIs are harder to diagnose than normal pressure ulcers since they do not first present at the skin. Close monitoring of a patient’s skin may not detect a DTI until significant damage has already taken place[8]. Also, individuals with spinal cord injury often have a lack of sensory perception in the buttocks area, so they cannot sense the pain associated with tissue breakdown. The exact pathological cause of a pressure ulcer is not known, however there are four hypothesized causes: cell deformation, capillary occlusion ischemia, reperfusion injury, and impaired lymphatic function [9-13].

1.1. PHYSIOLOGICAL CHANGES FOLLOWING SCI

The spinal cord connects the brain to the rest of the body, and an injury to the spinal cord can disrupt this connection either partially or fully. The spinal cord is clinically divided into levels based off of the spinal vertebrae, and the spinal cord gives off nerve branches at each level. As the level of an injury moves up the spinal cord, the possible affected area increases. The severity of a spinal cord injury is commonly measured by the ASIA impairment scale, which includes five different grades based on muscular and sensory function[14]. The total direct health care cost for spinal cord injury in the United States in 1997 was $7.736 billion dollars[15].

A myriad of changes occur after a spinal cord injury that can affect tissue loading. As described by A. Gefen [16], these changes can be placed into two categories: micro and macro changes. Microchanges refer to the changes in function of an individual with a spinal cord injury, such as sitting posture, prevention behavior, and muscle tone. Sitting has previously been shown to have a considerable effect on tissue deformation under the ischial tuberosities, which is why cushions are designed to provide a balanced sitting surface[17]. The injured individual must also be wary of personal prevention techniques, such as push-up maneuvers and gentle repositioning [18].

Macro changes refer to the changes in the tissues associated with pressure ulcer risk. After a spinal cord injury, a significant weight gain is often observed. In fact, one study showed that two thirds of patients reached over weight obesity levels one year after their injury [19].

This weight could be gained due to decreased activity after an injury. Fat builds up in places that used to be active, adding more fat into the gluteal region. A twin study showed that a twin with a spinal cord injury will have on average 10.5 more pounds of fat than their non-injured twin[20]. Another study showed that people with spinal cord injury had 15.4 more pounds of fat than non-injured people with similar Body Mass Indexes[21]. Fat gain seems to be an inevitable process following a spinal cord injury, and while careful dieting could possibly slow this process, the individual will still face significant decreases in activity.

Another major tissue change that is observed is muscle atrophy. After a complete spinal cord injury muscles are no longer used, which in turn thins the muscle fibers[22]. It has also been shown that gluteal muscle atrophy is greater at the ischial tuberosities, which is the most at risk area of developing a pressure ulcer when sitting. In the first 6 weeks post injury, average muscle cross-sectional area has been suggested to decrease by 45%, decreasing another 24% between week 6 and week 24 [23]. A decrease in muscle and an increase in fat can cause greater tissue deformation in sitting. Muscle has a higher elastic modulus than fat [24], meaning that it is more resistant to being deformed. This can impact pressure ulcer risk, since cellular deformation can cause tissue damage. Functional electrical stimulation was studied as a method to prevent muscle atrophy [25], yet this procedure has not yet been utilized in clinical practice. Studies investigating a relationship between electronic muscle stimulation and pressure ulcer prevention have yet to be carried out.

An increase in fat and decrease in muscle can be generally observed, but there are some other less obvious macrochanges in anatomy that occur after a spinal cord injury. Elder et al. have shown that the amount of intramuscular fat in the thigh can increase up to four times in people with spinal cord injury [26]. It has been shown that in just 3 months following a spinal cord injury, intramuscular fat can increase by 26% [27]. Intramuscular fat can only be observed with diagnostic imaging techniques, which makes it almost impossible to detect with just clinical assessments.

Collagen breakdown has been observed in people with spinal cord injury[28]. Collagen is a key structure protein in connective tissue, most notably skin. This loss of collagen could lead to skin becoming more susceptible to mechanical damage, further increasing the risk of developing a pressure ulcer [29]. People with spinal cord injury also have high levels of plasma glucose, which can contribute to type II diabetes [26]. Diabetes can lead to different types of ulcers caused by lack of blood flow, further damaging the skin [30].

1.2. PRESSURE ULCER RISK ANALYSIS

Inconsistent identification of pressure ulcer risk and lack of a standard risk analysis tool for the SCI population are barriers to providing optimum prevention interventions. The generally accepted standard for pressure ulcer risk assessment, the Braden Scale, has been extensively tested in clinical settings [31], but has shortcomings when applied to the spinal cord injury population. The Braden Scale uses six different categories to measure risk: Sensory Perception, Moisture, Activity, Mobility, Nutrition, and Friction & Shear [4]. Unfortunately, all people with spinal cord injury who use wheelchairs are deficient in sensory perception and activity due to the nature of their injury. Also, they are highly likely to have high amounts of shearing from transferring, as well as limited mobility. For these reasons, the Braden Scale consistently identifies this population as high risk, but with little variation among individuals.

Although research has moved towards identifying anatomical risk factors, risk scales made specifically for the SCI population fail to reflect these advances in research. In a review by Mortenson et al. [41], seven different scales for assessing pressure ulcer risk were examined, some designed specifically for people with spinal cord injury. Out of the seven scales, only one included a variable pertaining to the ischial anatomy (Waterlow Scale), and that variable did not include the muscle, fat, or bone. It was simply "appearance of skin in risk areas", which is not applicable when assessing DTI risk. There needs to be integration of the high risk anatomical features into these risk scales to ensure that scales are as accurate as possible.

In order to increase the accuracy of pressure ulcer risk identification, research has moved toward examining anatomical features. Previously researched risk factors include tissue stiffness [32], Body Mass Index [2, 33], muscle injury [34], intramuscular fat [27], seating asymmetry [35], ischial tuberosity shape [36], sitting posture [17, 37], nutrition [10, 38], scarring, spasticity [34], and gluteus maximus muscle characteristics [39]. It is not clinically feasible to measure every single one of these risk factors for all 270,000 people with spinal cord injury in the USA [40], so a simpler, more efficient model must be created. To do this, the most important risk factors must be identified, as well as any relationships that exist between risk factors.

1.3. ANATOMICAL MODELING

Computer modeling, specifically finite element modeling, has been one of the main tools used in recent pressure ulcer risk research [6, 42-47]. To create these computer models, a participant first undergoes an MRI of the area of interest. Once the image has been collected, radiographers segment the tissue. Segmenting consists of identifying the exact area of each tissue present in the MRI. This is done for each frame in the MRI image, then these areas are combined to form a 3-dimensional object based on the parameters of the image – mainly slice thickness. Finally, these objects are manipulated in specialized programs designed to simulate the properties of human tissue. Using this method, different conditions can be applied and tested, such as muscle loss, fat infiltration, and changing seat cushions properties.

Most pressure ulcer studies have featured the same anatomical model: that directly under the ischial tuberosity is the gluteus maximus muscle, followed by a layer of fat and then skin [6, 37, 42, 43]. This composition tends to be accurate for people who ambulate. Ambulation exercises gluteus maximus muscle, preventing atrophy. Also, people who are ambulatory tend to have full trunk control, giving them the ability to control sitting posture. Recent research by Sonenblum et al. [48] has demonstrated variability in tissue composition under the ischial tuberosity. They showed that only two of their seven participants sat on muscle, challenging the previous assumption. Their study also showed that the tissues in these individuals deform and displace differently, possibly increasing the risk of a pressure ulcers. By examining the anatomy of different participants, Sonenblum et al. have stressed the need to fully understand the differences in anatomy when seated. These differences can be more significant when studying people with spinal cord injury, who are already at a higher risk of developing a pressure ulcer.

1.4. WHEELCHAIR CUSHIONS

The use of a wheelchair cushion is perhaps the most basic yet one of the most important pressure ulcer preventative measures. Cushions are designed to distribute the body weight across the buttocks as evenly as possible. Because people with spinal cord injury are at high risk for pressure ulcers, they are usually prescribed a specialized cushion for their wheelchair. Clinicians face the challenge of selecting the best cushions out of a variety of options. Variables that help these clinicians select a cushion include patient reported comfort, cost, insurance coverage, pressure mapping data, and clinician preferences[49].

There are a myriad of pressure ulcer prevention cushions, with many ways to characterize their performance [50-54]. Despite all previous research, no cushion has shown to be superior in every aspect for every person. That is, different types of cushions work better for different people, with no cushion proven to be better for the majority of people. Cushions are often categorized by the material used, and a few popular materials include foam, water/gel, and air-cell cushions. A possible reason that no cushion has been determined superior is because of the difficulty of performing randomized clinical trials with this purpose[16]. Not only would these trials be extremely costly, but it is virtually impossible to control for all of the 30+ different variables involved in pressure ulcer risk[55]. The only RCT that has been performed that investigated the efficacy of wheelchair cushions noted the difficulty of controlling all of these factors[56]. Also, this study did not test the differences between popular cushions, but rather set out to show that skin protection cushions, regardless of which brand of cushion is selected, perform better than general use foam cushions.

1.5. PURPOSE

Pressure ulcer risk in people with spinal cord injury is a topic that has only been examined with a very fine lens. Past research has shown possible contributors to risk, brought to light changes in anatomy that occur, and postulated about the best clinical measures of risk in all patients, not just those with SCIs. While this research has improved the understanding of some areas of risk, most of these studies cannot be implemented in clinical practice. This study was designed to work towards a better risk assessment tool.

A major gap highlighted by Sonnenblum et al.[48] was the understanding of the ischial anatomy when seated. With the changes in anatomy following a SCI, the tissues do not always follow the conventional skin-muscle-fat model. One aim of this study was to examine the tissue responses to loading in both people who had recently been injured and people who had been injured for a long period of time.

Another gap in the big picture was the relationship between the different aspects of risk that had been identified in previous research, mainly anatomy, loading, and deformation. This study not only aimed to look for relationships between these variables, but to find a variable that was the best predictor of the other aspects of risk. Finding this variable would be an important step in translating the past 15-20 years of pressure ulcer research relating to this population into clinics worldwide.

2. METHODS

2.1. PARTICIPANTS

Six participants were recruited for this study, from three different populations. In this paper, an individual with an SCI was defined as a person who has sustained a spinal cord injury that uses a manual wheelchair full time due to partial or complete loss of lower extremity function associated with their injury. Participants with and without SCI were recruited. The participants included two people without SCI as controls, two people that had been injured less than a year before their testing date, and two people that had been injured more than ten years before their testing date.

2.2. MRI IMAGING

T1 weighted images of the ischial region were taken using a FONAR Upright MRI (FONAR, Melville, NY, USA). Eight imaging series were taken for each participant: one with the buttock tissue unloaded, six in the seated posture on six different wheelchair cushions, and one seated on an air-filled ring. Forty six 3mm thick sagittal slices were taken, centered on the ischial area. The six cushions used were the ROHO Quadtro Select (ROHO, Belleville, IL, USA), Invacare Matrix Flo-Tech (Elyria, OH, USA), Sunrise Jay3 DC (Sunrise, West Midlands, UK), Supracor Stimulite (Supracor, San Jose, CA, USA), Varilite Evolution (Varilite, USA), and Vicair Vector 10 (Vicair, Wormer, NL). Each participant laid supine for the unloaded MRI, with both hips and knees flexed to 90° and supported in this position. All loaded MRIs were taken with the participants sitting in an upright position with both hips and knees flexed to 90°. Examples of both the unloaded and loaded positions are shown in Figure 1. The images were centered on the pelvic region.

Figure 1: Loaded (Left) and Unloaded (Right) Conditions

2.3. INTERFACE PRESSURE MAPPING

Interface pressure mapping was done using an XSensor PX100:36.36.02 mat (XSENSOR, Calgary, CA). The mat, shown in Figure 2, records a 45.7cm by 45.7cm array of interface pressures. Pressure readings were taken for all subjects seated on all six wheelchair cushions used in the MRI images. The pressures on each cushion were measured for 5 minutes while the subject remained as still as possible in a comfortable, self-selected posture, with the average pressure in each cell over this time period used for data analysis. Participants were given a few minutes to settle into the cushion before data collection began.

Figure 2: XSENSOR Interface Pressure Map[57]

2.4. 3D MODELING

Once all of the MRI images had been collected, three-dimensional models were created using Analyze 12.0 (Mayo Clinic, Rochester, MN, USA). The DICOM images were imported into the software, and a combination of semi-automatic and manual segmentation was carried out by one individual to separate the pelvic bone, fat, gluteus maximus, semitendinosus, and semimembranosus. A radiologist was consulted in areas where tissue identifications were difficult to interpret.

The 3D models (Figure 3) were cropped based on the ischial tuberosity (IT) shape so that only the tissue directly under the IT was maintained in the image. This fit was limited in all three anatomical planes. All frames where the IT border was less than 6mm superior to the true IT peak were selected (anterior-posterior). From that range the medial and lateral borders of the IT peaks were selected, and the image was sliced along these borders (medial-lateral). Finally, the most superior ischial peak in this range was identified, and only tissues that were below this peak were measured (rostral-caudal). This cropping was used as the Region of Interest.

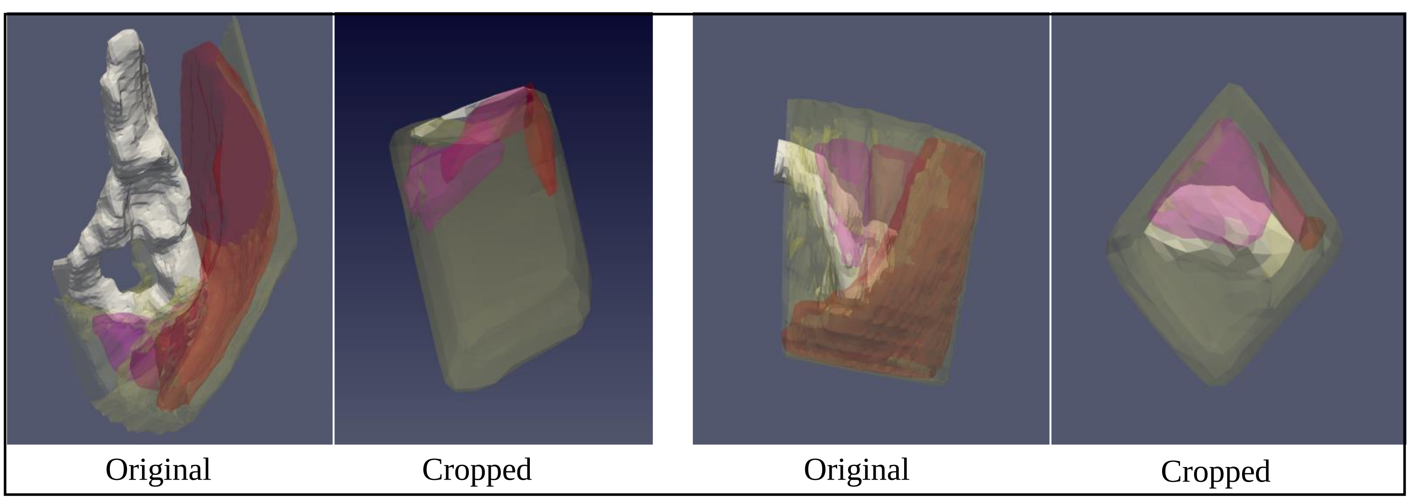

Figure 3: Original and Cropped 3D Renderings

2.5. DATA REDUCTION AND ANALYSIS

The pressure mapping data were exported from the X3 Medical v6.0 (XSENSOR) program into Excel 2013 (Microsoft) to be analyzed. Pressure measures calculated were based on previously used clinical measures [58-60]. To calculate the different measures a combination of manual and automatic calculations were done. The variables calculated for each individual on each cushion were Peak Pressure Index (PPI), Peak (maximum) Pressure, Peak Gradient, Average Top 4 Pressures, Bony Prominence Index, and Average Gradient. Bony Prominence Index was found by making three $9cm^2$ boxes, one around each IT and one around the sacrum. The total pressure in these three boxes was measured, and compared to the total pressure. The Index is displayed as the percentage of total pressure that is contained in the three boxes.

Tissue deformation was found by comparing the total tissue volume in the defined Region of Interest when loaded and unloaded. Volumes were found using the Analyze software to analyze each tissue component separately. This was done for all of the soft tissue in the cropped model as well as each individual tissue type (fat, glut, hamstring) in the region of interest.

Skin curvature for each individual on each cushion was calculated using MATLAB R2014a (The Mathworks Inc. Natick, MA, USA) and Opal Viewer Lite (Viztek Inc. Garner, NC, USA). First, all DICOM images were converted to TIFF files using the export feature in Opal View Lite. Then, a custom MATLAB script was made to calculate radius using user-defined points on the images. Ten points were selected, all of them on the most superficial boundary of skin and under the IT. Frames with the most inferior portion of the ischial tuberosity were used to measure skin curvature. Tissue thicknesses were also measured using MATLAB. User-defined points directly under the peak of the ischial tuberosity were used, with points placed at the borders of the fat and muscle. The skin layers were not included in the tissue thickness measures.

To determine if the able-bodied results were different than the spinal cord injury results, a two-sided t test was done for all measurements with alpha = .05. Pearson correlation coefficients and p values were calculated to test if there was a relationship between any two variables. Any relationship with a p value < 0.05 was determined to be statistically significant. Pearson correlation tests were run on all variables that were in different categories (i.e., pressure, deformation, anatomy). To present the data in an organized fashion in the results, the mean of each value on all six cushions was calculated separately for each subject.

2.6. DEFINITION OF VARIABLES

Minimum Side Total Thickness – The total tissue thickness under the most inferior portion of the ischial tuberosity on the side with the least amount of tissue. This includes both fat and muscle.

Muscle Thickness – The thickness of the muscle directly under the most inferior portion of the ischial tuberosity. This can include the gluteus maximus, semitendinosus, and semimembranosus

Total Thickness - The total tissue thickness under the most inferior portion of the ischial tuberosity. This was the sum of the muscle and fat thicknesses.

Minimum Side Muscle Thickness - The thickness of the muscle under the most inferior portion of the ischial tuberosity on the side with the least amount of tissue.

Average Unloaded Gluteus Maximus Composition – The percentage of tissue volume in the defined ROI that is a part of the gluteus maximus muscle. Only the unloaded condition is included, and the average is taken of both the right and left side.

Average Unloaded Semimembranosus Composition – The percentage of tissue volume in the defined ROI that is a part of the semimembranosus muscle. Only the unloaded condition is included, and the average is taken of both the right and left side.

Average Unloaded Fat Composition – The percentage of tissue volume in the defined ROI that composed of adipose tissue. Only the unloaded condition is included, and the average is taken of both the right and left side.

Average Loaded Fat Composition - The percentage of tissue in the defined ROI that is composed of adipose tissue. This is the average of all six loaded conditions, including both the left and right sides.

Average Loaded Glut Composition - The percentage of tissue in the defined ROI that is part of the gluteus maximus muscle. This is the average of all six loaded conditions, including both the left and right sides.

Average Top 4 Pressures – The average of the four maximum pressures measured on the pressure mat [56].

Bony Prominence Index – The percentage of overall pressure that is contained in the "bony prominence" area. The bony prominence area is three $9cm^2$ boxes representing the left IT, right IT, and sacrum.

Average Gradient – The average of the differences between each cell and the cells surrounding it. For each cell, this was calculated by finding the absolute difference between the cells and each of the eight surrounding cells, then finding the mean of those differences.

Peak Pressure – The single highest pressure reading taken on the mat, regardless of position.

Peak Pressure Index (PPI) – The highest pressure contained in a $9cm^2$ box. First, the peak pressure was found, which was always under a weight bearing surface (IT or sacrum). Then, the average of that cell and the eight cells surrounding it was calculated[61].

Peak Gradient – The highest absolute difference between a cell and the average of the nine adjacent cells.

Fat Deformation – The loaded fat volume in the defined region of interest on the side with the highest amount of deformation divided by the unloaded fat volume in the defined region of interest on that same side. The unloaded volume was compared to the average of all six loaded conditions – one for each cushion, and was expressed as a percentage.

Total Deformation - The total loaded volume in the defined region of interest on the side with the highest amount of deformation divided by the total unloaded volume in the defined region of interest on that same side. The unloaded volume was compared to the average of all six loaded conditions – one for each cushion, and was expressed as a percentage.

Muscle Deformation – The loaded muscle volume in the defined region of interest on the side with the highest amount of deformation divided by the unloaded muscle volume in the defined region of interest on that same side. The unloaded volume was compared to the average of all six loaded conditions – one for each cushion, and was expressed as a percentage. This can include the gluteus maximus, semitendinosus, and semimembranosus.

Deformation Asymmetry – The difference in total deformation in each side. This was calculated using the formula $\frac{L-R}{.5(L+R)} * 100$ where L is the left side total deformation and R is the right side total deformation. The asymmetry is expressed as a percentage.

3. RESULTS

All raw data is presented in Appendix A.1

3.1. PARTICIPANT DEMOGRAPHICS

Table 1 depicts the participant demographics. Two controls, two people with short term SCIs, and two people with long term SCIs participated.

Table 1: Participant Demographic Information

Subject ID	Participant Type	Age (years)	Injury Level	Injury Date	Time since injury (months)	Weight (lbs)
WC01	Control 1	22				162
WC02	Long Term SCI 1	41	T12	4/1/1991	283.6	141
WC03	Control 2	26				110
WC04	Short Term SCI 1	34	T10	7/1/2014	8.2	150
WC05	Short Term SCI 2	31	T3	9/1/2014	6.3	170
WC06	Long Term SCI 2	41	C6	7/1/2001	164.6	190

3.2. INTERFACE PRESSURE DATA

Table 2: Interface Pressure Data (mmHg)

Participant	Peak	Average Top 4	PPI	Peak Gradient	Average Gradient	Bony Prominence
Control 1	71.6	68.7	55.3	28.4	3.5	5.58
Control 2	69.3	60.7	43	36.8	3.2	6.66
Short Term SCI 1	210.3	203	154.5	82.1	4.2	17.15
Short Term SCI 2	120.5	97.7	67.5	58.1	4.6	6.01
Long Term SCI 1	213.3	197.4	146.7	94.9	4.4	12.86
Long Term SCI 2	125.4	117.3	96.8	40.9	4.5	6.50
Control Average	70.45	64.7	49.15	32.60	3.35	6.12
Control S.D.	1.62	5.65	8.69	5.93	0.21	0.76
SCI Average	167.37	153.85	116.37	69	4.42	10.63
SCI S.D.	51.35	54.16	41.41	24.15	0.17	5.35
P value	0.0656	0.0936	0.0981	0.1176	0.0024	0.3254

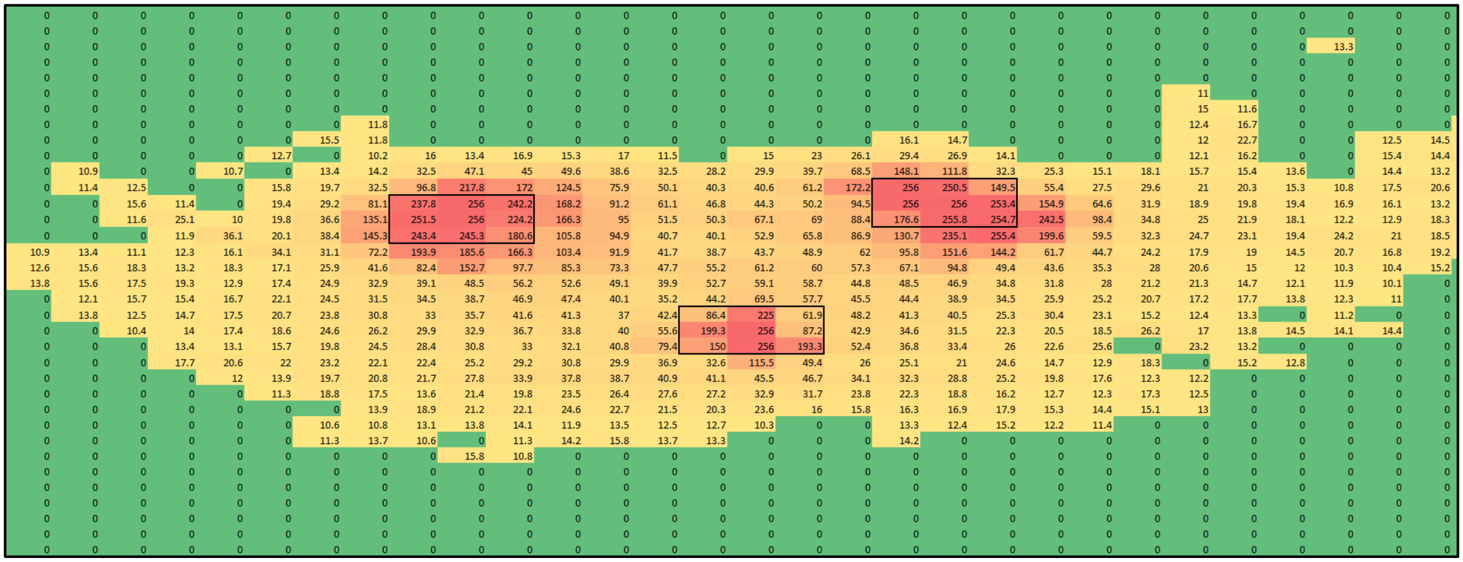

Figure 4: Bony Prominence Index

Most of the loading measurements shown in Table 2 were not significantly different between Control and SCI populations (Table 2). Despite a lack of statistical significance, the pressures were noticeably different between the two groups. Two participants, Short Term SCI 1 and Long Term SCI 1, had notably higher pressures compared to the other participants with spinal cord injury, and their Peak Pressures were tripled compared to the controls. Figure 4 depicts an example pressure map with pressure displayed in mmHg and coded by color of the Bony Prominence areas for a participant with high ischial and sacral pressures. The two top boxes represent the two ITs, and the bottom box is the sacrum.

3.3. ANATOMICAL DATA

All anatomical data was measuring using MRI. Sample images are shown in Figured 5-11.

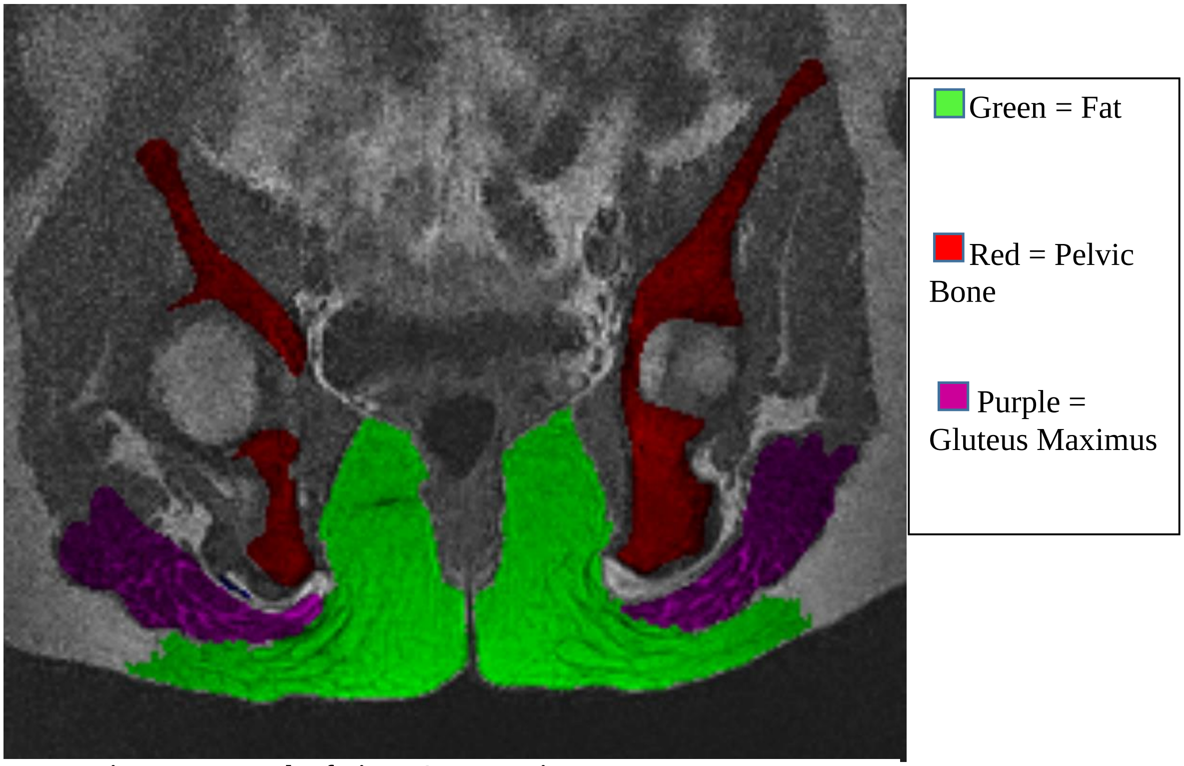

Figure 5: Example of Tissue Segmentation

Figure 6: WC01 MRI – Control 1

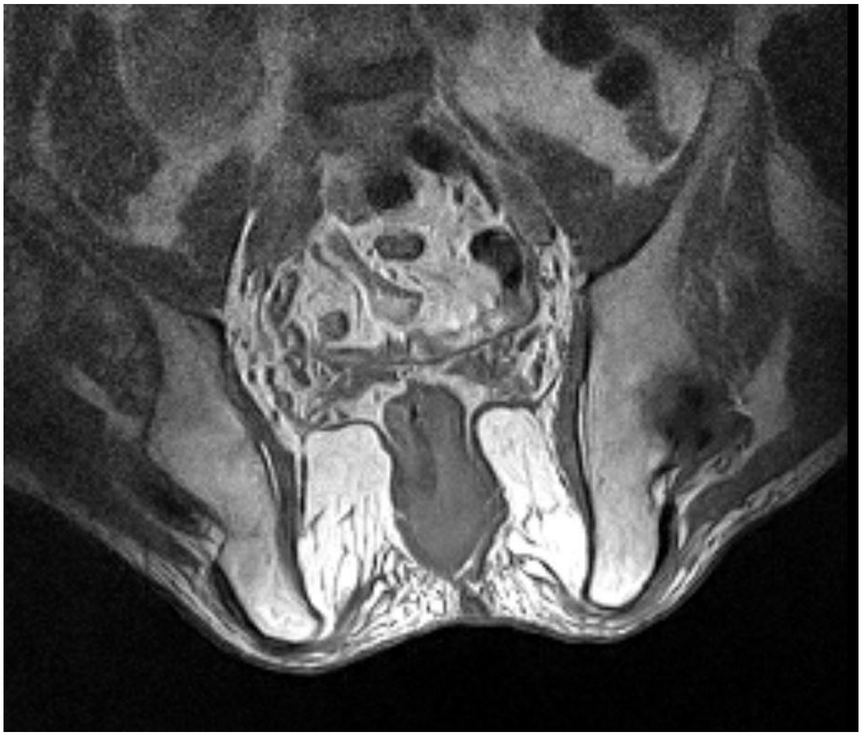

Figure 7: WC02 MRI – Long Term SCI 1

Figure 8: WC03 MRI – Control 2

Figure 9: WC04 MRI – Short Term SCI 1

Figure 10: WC05 MRI – Short Term SCI 2

Figure 11: WC06 MRI – Long Term SCI 2

Notable anatomical differences exist between the non-injured controls and the participants with spinal cord injury. The most obvious difference is the smaller amount of muscle in the people with SCI compared to the controls. Some sitting asymmetry can be seen as well, especially in WC04.

Table 3: Skin Curvature

	Control 1	Control 2	Short Term 1	Short Term 2	Long Term 1	Long Term 2
Average Skin Curvature (cm)	100.528	98.82302	50.20572	94.57168	51.28712	105.1888
Standard Deviation (cm)	11.44799	8.261532	6.924002	16.15951	8.850357	20.59144

Non-Injured Control
Skin Radius = 116.99 cm

Long Term Spinal Cord Injury
Skin Radius = 47.97 cm

Figure 12: MRI Skin Curvature Comparison

Table 4: Loaded Tissue Composition

	Mean Fat % Composition	Mean Semetendinosus % Composition	Mean Semimembranosus % Composition	Mean Glut % Composition
WC01	47.57 ± 16.36	3.39 ± 1.95	5.013 ± 1.93	44.019 ± 17.67
WC02	97.74 ± 2.25	0.15 ± 0.19	0.0011 ± 0.01	2.10 ± 2.12
WC03	79.99 ± 9.29	0.17 ± 0.26	0.13 ± 0.16	16.98 ± 9.97
WC04	98.09 ± 3.38	0.26 ± 0.65	0.23 ± 0.69	1.42 ± 2.47
WC05	96.77 ± 1.50	0.28 ± 0.41	2.60 ± 1.29	0.35 ± 0.55
WC06	98.23 ± 0.57	1.29 ± 0.50	0.49 ± 0.21	0.00 ± 0
Control	63.78% ± 22.9%			
SCI	97.71% ± 0.66%			
p value	0.0269			

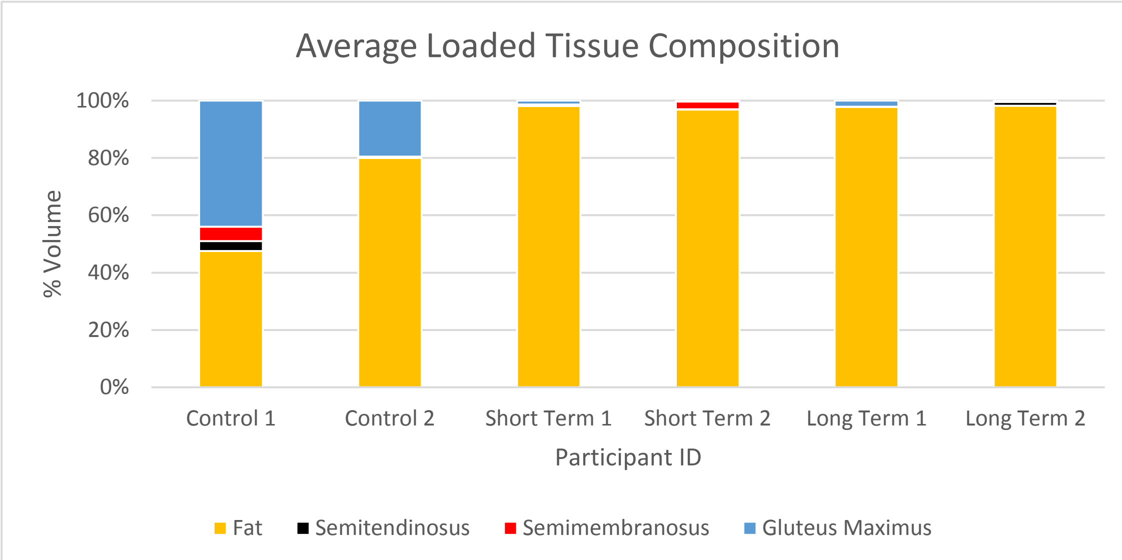

Figure 13: Average Loaded Tissue Composition

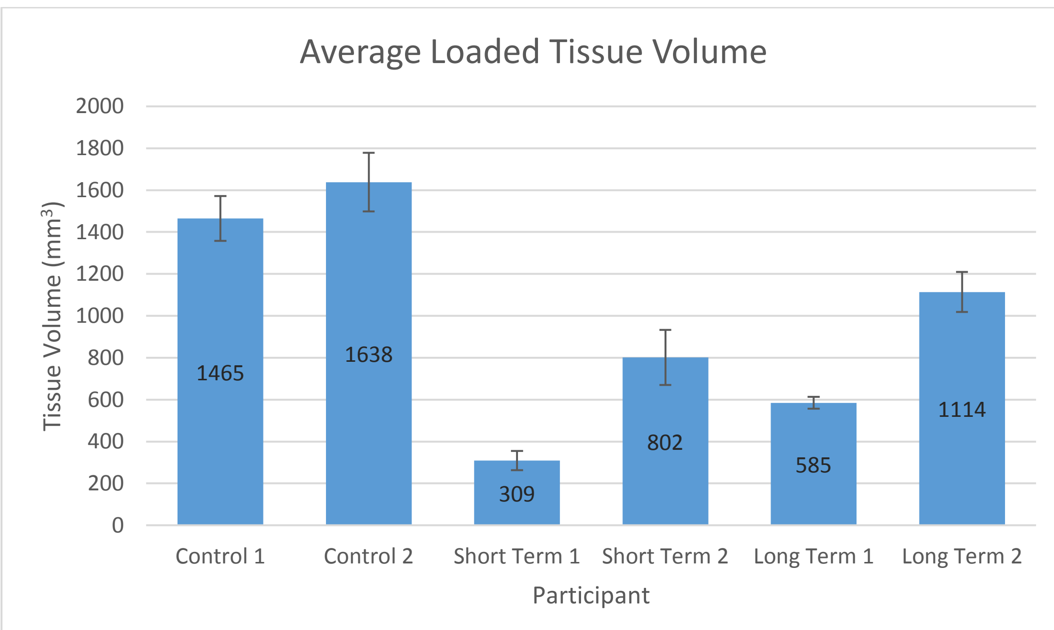

Figure 14: Average Loaded Tissue Volume

Table 5: Average Loaded Tissue Volume

	Mean Tissue Volume (cm^3)
Control	1551.5 ± 122.3
SCI	702.38 ± 340.3
P value	0.0312

Notable anatomical differences exist in the data between the non-injured controls and the participants with spinal cord injury. A major difference is the tissue under the ischial tuberosities under load (Figures 13 and 14). Not only did the participants with spinal cord injury have significantly less tissue under the ITs (Figure 14), but also the composition of the tissue varied significantly (Figure 13). The average skin curvature of Long Term SCI 1 and Short Term SCI 1 was notably smaller than the other participants. Lesser skin curvature means the skin keeps its shape, not enveloping the ischial tuberosity completely. In Figure 14, the average loaded tissue volume is the volume on the most heavily loaded side.

3.4. TISSUE DEFORMATION DATA

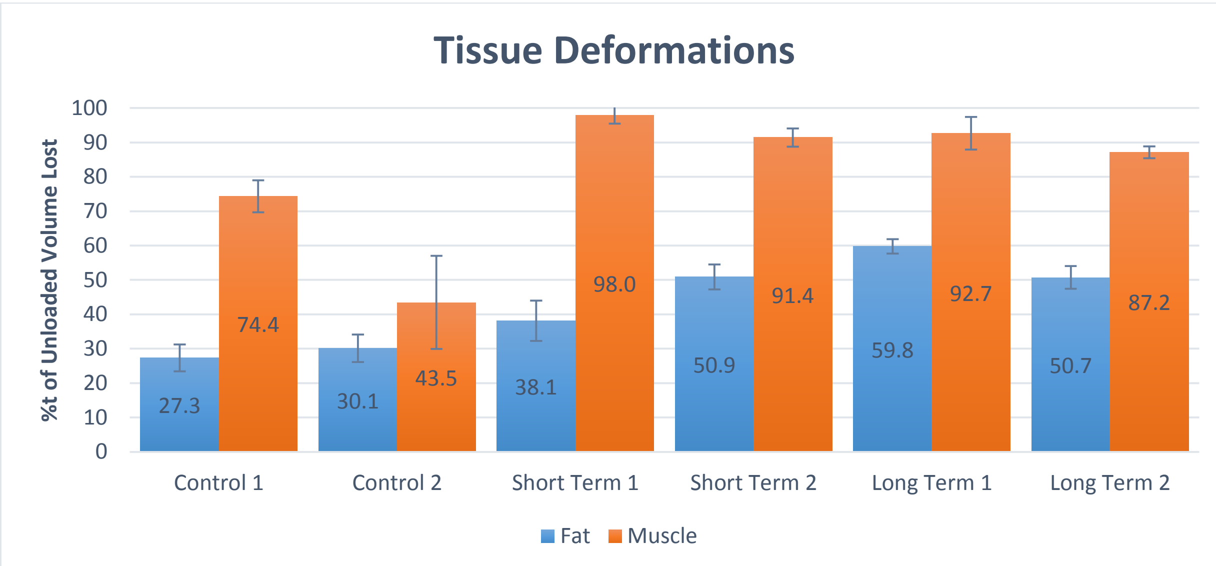

Figure 15: Tissue Deformations

Figure 15 suggests that the tissues of the controls and people with spinal cord injury differ in their response to loading. Deformation in this graph is shown as the % of unloaded tissue volume lost when loading. The muscle in the people with spinal cord injury experiences high amounts of deformation when loaded. The fat follows similar trends, but differs more across individuals.

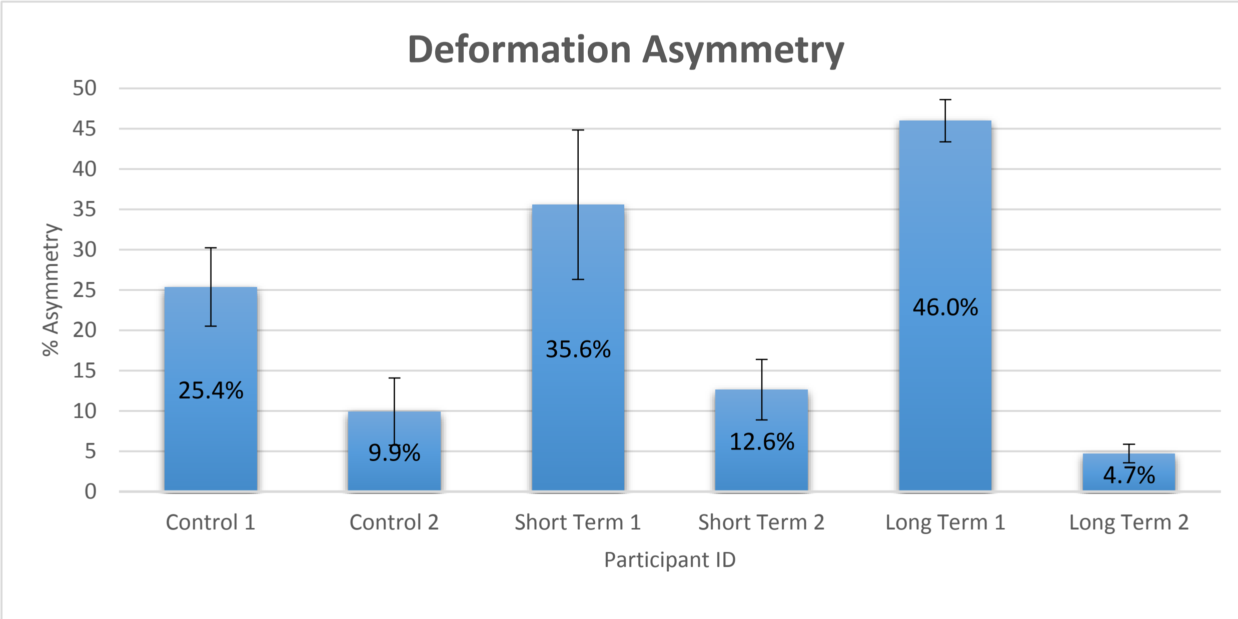

Figure 16: Deformation Asymmetry

Figure 16 depicts the average deformation asymmetry. There was a lot of variability in the different sample subgroups, suggesting that asymmetry is not limited to just controls or just people with SCIs.

Figure 17 depicts the effect of thickness on the relationship between deformation and interface pressure. The two data sets outlined in black, from the highest and lowest thickness measurements, display this relation. The yellow points show the data from the participant with the lowest tissue thickness, while the red points show the data form the participant with the highest tissue thickness. Although they have extremely similar deformations, the PPI of the yellow points is higher on every single cushion, with the highest being five times higher than the highest red PPI.

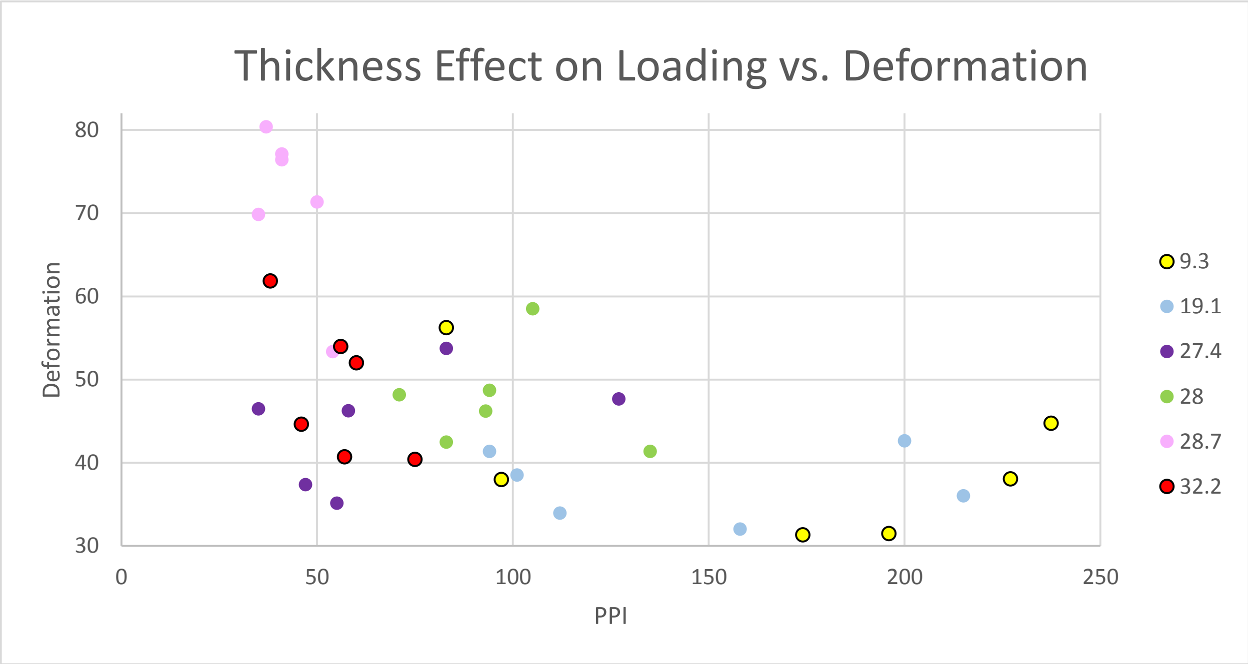

Figure 17: Tissue Thickness, Loading, and Deformation

3.5. RELATIONSHIPS BETWEEN VARIABLES

There was a total of 34 significant relationships between variables in different categories amongst the entire sample. Also, there were a total of 55 significant relationships between variables in different categories amongst only the SCI population. Listed in the tables below are the strongest relationships for each variable. Only relationships with $p < .025$ are listed, a table with all $p < .05$ are listed in the Appendix A.2.

Table 6: Strongest Relationships for Entire Sample

Variable 1	Variable 2	Pearson Correlation Coefficient
Minimum Side Total Thickness	Bony Prominence	-0.9835
Left Total Thickness	Bony Prominence	-0.9804
Minimum Side Total Thickness	Average Top 4	-0.9069
Minimum Side Total Thickness	Peak	-0.8912
Minimum Side Total Thickness	PPI	-0.8902
Right Total Thickness	Bony Prominence	-0.8864
Minimum Side Total Thickness	Average Top 4	-0.8752
Average Gradient	Muscle Deformation	0.8710
Average Gradient	Fat Deformation	0.8688
Left Total Thickness	Peak	-0.8632
Left Loaded Tissue Volume	Total Deformation	-0.8527
Left Total Thickness	PPI	-0.8469
Left Total Thickness	Peak Gradient	-0.8457
Minimum Side Total Thickness	Peak Gradient	-0.8390
Min Loaded Tissue Volume	Total Deformation	-0.8295
Left Muscle Thickness	Peak Gradient	-0.8153
Average Unloaded Glut Comp	Fat Deformation	-0.8134

Table 7: Strongest Relations for Only SCI

Variable 1	Variable 2	Pearson Correlation Coefficient
Fat Deformation	Right Loaded Tissue Volume	0.9975
Deformation Asymmetry	Average Loaded Glut Comp	0.9966
Average Gradient	Min Fat Thickness	0.9962
Fat Deformation	Left Unloaded Tissue Volume	0.9940
Average Gradient	Right Fat Thickness	0.9932
Deformation Asymmetry	Peak Gradient	0.9920
Peak Gradient	Average Loaded Glut Comp	0.9894
Bony Prominence	Minimum Side Total Thickness	-0.9880
Average Gradient	Average Fat Thickness	0.9823
Total Deformation	Left Unloaded Tissue Volume	-0.9791
Bony Prominence	Right Fat Thickness	-0.9772
Bony Prominence	Min Fat Thickness	-0.9759
Fat Deformation	Min Unloaded Tissue Volume	0.9696
Total Deformation	Right Loaded Tissue Volume	-0.9684
Fat Deformation	Right Unloaded Tissue Volume	0.9658
Muscle Deformation	Left Total Thickness	-0.9640
Average Gradient	Minimum Side Total Thickness	0.9631
Total Deformation	Right Muscle Thickness	-0.9619
Deformation Asymmetry	Peak	0.9586
Bony Prominence	Min Fat Thickness	-0.9522
PPI	Average Unloaded Semimembranosus Composition	-0.9497
Fat Deformation	Left Loaded Tissue Volume	0.9479
Average Gradient	Left Fat Thickness	0.9469
Fat Deformation	Min Loaded Tissue Volume	0.9454
Average Gradient	Average Unloaded Semimembranosus Composition	0.9345
Muscle Deformation	Minimum Side Total Thickness	-0.9282
Bony Prominence	Average Fat Thickness	-0.9269
Average Gradient	Right Total Thickness	0.9229
Average Gradient	Left Total Thickness	0.9170
Deformation Asymmetry	Average Top 4	0.9154
Average Gradient	Average Unloaded Gluteus Maximus Composition	-0.9084
Total Deformation	Min Unloaded Tissue Volume	-0.9082
Fat Deformation	Right Muscle Thickness	0.9049
PPI	Average Unloaded Semitendinosus Composition	-0.9047

4. DISCUSSION

4.1. INTERFACE PRESSURE

The data obtained using the pressure map shows a difference between the controls and the participants with a spinal cord injury. Large differences between every single measure are seen, as shown in Table 2. Four out of the five variables had SCI averages that were more than twice as much as the control averages. The cushion selection also had a visible impact on these measures, with major differences observed in the same participant across different cushions. The average PPI among the SCI population in one cushion was 75.75 mmHg, and in another cushion it was 148.50 mmHg. This shows that pressure data is not only dependent on the anatomy of the individual, but also the nature of the cushion.

Bony Prominence Index is a measure that was created based on this data. It has not been clinically tested, but was designed to improve upon the shortcomings of the other pressure measures. It is loosely based on Dispersion Index[61]. This index was created when it was observed that one of the participants with an SCI had three peaks on their seated pressure map, one for each IT as well as one for the sacrum. The sacrum is usually only a high pressure area when lying supine, but this participant sat with a large posterior pelvic tilt that caused high pressures in this region. While this participant had a lower PPI than the others in the same population, they had three risk zones instead of two, which was not represented in the other pressure measures. While most participants did not have extremely high peaks in the sacral area, there were small changes shown which allowed this area to be identified in all of the pressure maps. The measure is not designed to stand alone, but rather to go alongside the other measures to give a more accurate representation of the data. Bony Prominence Index is useful for people without straight sitting posture. Other measures seem to overlook the fact that some people could have high pressures in the sacral area when sitting, creating three high risk areas instead of two. Bony Prominence Index is recommended for people that appear to slouch in their chair.

4.2. ANATOMY

The anatomical data collected by MRI and image segmenting showed differences among the populations that are consistent with the expected changes after an SCI. Some of the anatomical changes expected after a spinal cord injury are muscle atrophy, fat buildup, and fat infiltrating the muscle [16], and all of these can clearly be seen in the examples shown in the Figures 6-11. Each participant with a SCI had a fat composition of at least 96.8%, and this does not even include fat that has partially infiltrated the muscles. This is a major contrast to the control group, where one of the participants had a fat composition of 47.60%. Theoretically increased fat compositions is bad for pressure ulcer risk, since fat deforms more than muscle and can lead to higher internal tissue strains[24].

The results were consistent with Sonenblum et al. [48], showing that everyone does not sit on gluteus maximus, fat, then skin. Control 1, who was an avid weightlifter, sat on not only his gluteus maximus and fat, but also his semitendinosus and semimembranosus. These muscle were enlarged due to his exercise, so they were included in the space under the ITs. It is also worth noting that he sat on these two muscles on every cushion on each side, so it can be assumed that he will always sit on his hamstrings. Long Term SCI 1, Long Term SCI 2, and Short Term SCI 2 also sat on their hamstrings on more than half of the cushions, probably because of their pelvic tilt. This is seen in the WC05 image in Figure 10. This brings into question how the inclusion of hamstrings in the seated anatomy changes pressure ulcer risk. Hamstring composition was not strongly correlated to any of the deformation or loading variables. It could be hypothesized that sitting on the hamstrings would increase tissue thickness, but it is not clear if this comes at the expense of gluteus maximus thickness. Sitting on hamstrings could reduce internal tissue strain since it is the addition of muscle, but the inclusion of two or three distinct muscles could cause more strain because of increased heterogeneity. Hamstring sitting should be studied further so that pelvic tilt adjustments can be made if necessary.

None of the participants with SCI consistently sat on their gluteus maximus. Long Term SCI 2 only had a small amount of glut tissue under his IT while unloaded, with no glut tissue at all when loaded on each cushion. Also, Short Term 2 did not have any gluteus maximus under his IT when unloaded, so the glut under the ITs when loaded was due to tissue displacement. Tissue displacement is a variable that has not been thoroughly investigated, and in people with spinal cord injury it could play a key role in the development of pressure ulcers. If any muscle that is present is displacing away from this critical region, the person would just be sitting on fat, greatly increasing this risk.

The tissue composition of the participants who had suffered a spinal cord injury less than a year before testing suggested that the anatomical changes that take place after a spinal cord injury occur very quickly. There is no significant difference in the anatomical measures between the short term and long term SCI groups. Because of this phenomenon the data analysis was organized into two groups rather than three: Non-Injured Controls and People with Spinal Cord Injury.

Figure 12 and Table 3 show the difference in seated skin curvature while sitting between a control and participant with SCI. The greater skin curvature in the participant with a spinal cord injury means a smaller contact area for the force of the body weight to be distributed through. This can be explained by the lack of muscle around the ischial tuberosity. Muscle is a key factor in skin form[62], so without firm muscle the fat layer simply envelops the IT, creating this curvature. This could explain why people with low BMIs have been shown to develop more pressure ulcers[63]. This could also be due to altered tissue properties associated with malnutrition, but this variable was not explored in this paper.

Figure 17 depicts the effect of thickness on the relationship between deformation and interface pressure. Larger tissue thickness allow for higher deformations without higher Peak Pressure Indices. While it is possible that higher tissue thicknesses can change internal tissue strains, it is shown that they do lower the peak pressure index. The participant with the lowest tissue thickness also has a lot of cushion variability regarding PPI (A.1), stressing the importance of selecting the correct wheel chair cushion in the clinic. This also shows that selecting the correct cushion is more important for people with lower tissue thickness – a fact that can be used to help insurance companies allocate resources accurately.

4.3. DEFORMATION

Deformation data was found by comparing the unloaded condition to the loaded condition. Before discussing the results, the term deformation must be clarified. The classical definition of deformation is the changing of the shape of an object, usually due to compressive forces, but the changes seen in this study are not limited to the classical deformation. This study looks at just a section of the buttocks anatomy, a section that does not include the entirety of any one tissue structure. The changes seen in the loaded and unloaded conditions may also be attributed to displacement: where the tissue not only changes shape, but moves out of the frame of reference. Gluteal displacement was observed by Sonenblum et al.[48], with the gluteus maximus tending to move laterally and posteriorly to the IT when sitting. It is highly likely that the tissue changes in this study are seen are due to both deformation and displacement, so the term deformation in this study refers to the change in volume of a tissue in our region of interest.

A higher overall deformation was seen in the SCI group compared to the controls, which is consistent with the fact that fat deforms more than muscle. More noteworthy is the observation that both the fat and muscle tissue deformed more in the SCI group, as seen in Figure 15. This suggests that infiltrated muscle could have different physical properties compared to healthy muscle. These properties could resemble fat more than muscle, meaning they are more vulnerable to deformation [24]. Fat infiltration was observed in every person with an SCI. Fat infiltration explains why the muscles of people with SCI deformed more than people without SCI.

The difference in fat deformation does not appear to be a difference in the properties of the fat, but rather the composition of the ischial area as a whole. Most of the SCI participants did not have any muscle under their IT, so fat bordered the bone. Without any muscle to distribute some force, more force was concentrated over a small area, causing greater deformation. The anatomical data did show less tissue volume in the SCI participants, which suggests a relationship between an anatomical variable and a deformation variable. This was also shown in Table 6.

4.4. ASYMMETRY

People with spinal cord injury that use wheelchairs tend to sit unevenly when compared to people without SCI [35, 64, 65]. This can cause an uneven distribution of body weight, create areas of high pressure, which in turn leads to a higher risk of pressure ulcer formation on one side. Deformation asymmetry was not highly correlated to other variables when including the non-injured participants (Correlation Coefficient = 0.71-0.77), but in the analysis of only the participants with spinal cord injury it was highly correlated to seven different variables (Correlation Coefficient = 0.82 - 0.997). Increases in Deformation Asymmetry were associated with increased Peak Pressure Index, Peak Pressure, Average Top 4 Pressures, Bony Prominence Index, and Peak Gradient. Deformation Asymmetry was most strongly correlated with Average Loaded Gluteus Maximus Composition (Correlation Coefficient = 0.997), challenging the view that muscle retention in people with spinal cord injury helps decrease the risk of a pressure ulcer. This is important when discussing people with incomplete spinal cord injury who retain small amounts of motor function in only one leg. With this partial motor function they could prevent the degeneration of muscle on one side, leading to more uneven sitting. These results highlight the importance of measuring sitting asymmetry that was described by Gutierrez et al [35]. Another study showed that as lateral tilt increases, compressive deformation of soft tissue also increases[17]. The results in this study partially support this claim, because with increased asymmetry the deformation on one side increased while the deformation on the other side decreased.

Strangely, deformation asymmetry was not significantly correlated with pressure asymmetry (Pearson Correlation Coefficient = 0.182). As shown in A3, pressure asymmetry had high variability, and appears to be representative of the cushion characteristics rather than anatomy. One proposed reason why pressure and deformation asymmetry are not related to each other is because deformation asymmetry could even out the interface pressures. If more pressure is put on the soft tissues by the ITs, those tissues will deform more, and vice versa. With one side of the soft tissues absorbing more pressure, the asymmetry may not be seen at the seating interface. This also can explain why deformation asymmetry was a more accurate of other risk factors, because it is more representative of what is happening in the actual loaded tissues.

As seen in Figure 16, high amounts of asymmetry are observed in some of the participants, with no distinction between groups. The high amount of asymmetry in Control 1 can be explained by the activity level of the participant. As an active weightlifter, it is understandable to develop more muscle on the dominant leg, and this difference was seen in the unloaded muscle thickness. The first Long Term SCI participant had the most deformation asymmetry, while the second Long Term SCI participant had the least deformation asymmetry. It is suspected that Long Term SCI 1 had some functioning muscle left in one of his legs or spasticity on that side, because in all conditions, even unloaded, there was a major difference in both tissue composition and muscle thickness. This imbalance of function appeared to increase asymmetry, which is shown in this paper to increase interface pressure. This points to increased pressure ulcer risk. This risk could be further increased by poor posture, which could cause even more asymmetry.

Among each sub group of participants, the participant with the most gluteus maximus composition when unloaded has the highest asymmetry. The Short Term SCI participants are a great example of this. Short Term SCI 1 has about 40% gluteus maximus in the ROI when unloaded on both sides, while Short Term SCI 2 has no gluteus maximus in the ROI when unloaded. Short Term SCI 1 deviates from the other two individuals with high asymmetry because Short Term SCI 1 had even muscle composition on both sides. Furthermore, this participant seems to have extremely high amounts of displacement, because for most of the loaded conditions they do not sit on any gluteus maximus. With any chance of muscle asymmetry gone when loaded, and no indication of fat asymmetry, it has to be concluded that this participant does not have any ischial anatomical features that would cause sitting asymmetry. The only other explanation for this asymmetry is postural asymmetry. This suggests the dangerous effect that postural asymmetry can have, especially because this subject had the greatest seated interface pressure measurements. With pressure measurements reaching up to four times that of the other Short Term Participant, differences are clearly shown in this two person comparison. First of all, unloaded ROI composition cannot be used to estimate loaded ROI composition. These two participants have similar loaded compositions with completely different unloaded compositions. Concurrent with previous research, these participants show the danger of postural asymmetry. While their loaded anatomies are almost identical, their seated interface pressure measurements are completely different. It could be argued that weight could play a role in the pressure differences, but Short Term SCI 2 is actually 20 pounds heavier than Short Term SCI 1. All of this suggests that postural asymmetry is solely responsible for these pressure differences.

The previously mentioned division can also be seen in Table 2. Amongst the SCI sample, Long Term SCI 1 and Short Term SCI 1 have extremely similar measures. Long Term SCI 2 and Short Term SCI 2 also have similar measures. For example, the Mean Peak for the SCI sample is 167.67 mmHg, with a standard deviation of 51.35 mmHg. For just Long Term SCI 1 and Short Term SCI 1, the mean is 211.8 mmHg with a standard deviation of 2.12 mmHg. For just Long Term SCI 2 and Short Term SCI 2, the mean is 122.95 mmHg with a standard deviation of 3.46 mmHg. The p value for these two populations was 0.0068. In this study causation was not able to be proven, but it is hypothesized that the increased gluteus thickness contributed to the deformation asymmetry, which results in higher interface pressure measures.

4.5. LIMITATIONS

A major limitation to this study is the sample size. Sample size was limited by both cost and ability to recruit participants. Magnetic Resonance Imaging is a costly, time consuming process, and unfortunately it was not plausible to use a larger sample size. Cheaper imaging techniques like ultrasound could be used, but the in depth three dimensional analysis may not be possible with these techniques. Ultrasound has been used in previous volumetric analyses of different anatomical structures [66-68], yet Gebhard et al. [69] point out the lack of extensive research on these methods. Also, recruiting was a challenge in this study, it was difficult to find people who met the specific criteria that could commit the needed time. There were no experimental or analytical limitations, all data needed for the analysis was able to be obtained.

Intramuscular fat was initially intended to be measured by calculating pixel densities, but problems arose in frames where the lighting of the image changed, especially when the subject moved. Methods to quantitatively measure intramuscular fat have been used in live animal models, but no method for doing this with MRI currently exists[70].

One increasingly popular but not clinically proven measure that has been used is internal strain. This requires specialized programs to calculate these strains given the 3D tissue segmentations, and this was not practical for this study. These studies have shown that the actual composition of the tissue plays a role in internal tissue strain, not just overall thickness.

4.6. CONCLUSIONS

The first goal in this study was to simply explore and describe the anatomy of a person with a SCI while seated, comparing it to the seated anatomy of able-bodied people. Despite the tissue composition when unloaded, all of the participants with an SCI had a loaded fat composition of 96.8% or higher. One of them had a relatively low unloaded fat composition of 60.1%, but still had a fat composition of 98.1% when sitting. This suggests that despite unloaded characteristics, the muscles of people with spinal cord injury tend to deform and displace out of this region of interest.

The anatomical feature that was most highly correlated with the most interface pressure measures was unloaded tissue thickness. Tissue thickness was strongly negatively correlated with every interface pressure measure, meaning that as tissue thickness increased, all interface pressure measures decreased. A decrease in all of the interface pressure measures is associated with a decrease in pressure ulcer risk [58]. Tissue thickness was also negatively correlated with deformation, so as the thickness increased there was less of a volume change between the unloaded and loaded conditions. Both the correlations with loading and deformation support the claim that unloaded tissue thickness is the most important anatomical feature when assessing pressure ulcer risk, and as tissue thickness increases, pressure ulcer risk may decrease.

Based on these results, sitting asymmetry appears to be the most clinically important variable to assess pressure ulcer risk in people with spinal cord injury. Asymmetry can be assessed using clinical observation (looking for postural asymmetry), tissue imaging, pressure mapping, and 3D tissue analysis, allowing many options for a clinician. Sitting asymmetry is a unique cross of both a microchange (postural changes) and a macrochange (muscle atrophy). When analyzing the relationship between asymmetry and risk, it is important to remember that each person has two ischial tuberosities, and therefor has two at-risk regions. There is a question of whether each side should be considered independent or dependent of the other side, and this study seems to point to both. They should be considered independent because it only takes one high risk side for a pressure ulcer to occur, regardless of the conditions on the other side. That being said, they should be considered dependent because they are linked by asymmetry. One side could take the majority of the load, lessening the load and therefor risk on the other side. Asymmetry is a great link between anatomy, interface, and deformation because it can be measured in terms to all three variables. Any asymmetry, regardless of which domain it is in, can increase the risk of pressure ulcer development. Since asymmetry can be prevented, clinicians should increase the amount of time spent correcting postural asymmetry, and cushions that prevent asymmetry should be prescribed more often.

High amounts of fat might obscure clinical judgment when using a pressure mapping system to select a proper cushion type [58, 61, 71]. Tissue thickness, regardless of tissue composition, is inversely related with pressure mapping measures. These measures fail to account for internal strain, which arguably is the source for deep tissue injury formation. While pressure mapping measurements may predict pressure ulcer prevalence in some populations[58], the ability to predict pressure ulcers that start within the deep tissues (DTIs) should be challenged.

Overall, there is a lack of cohesion between the most recent pressure ulcer research. It has been estimated that it takes an average of 17 years for medical research to be implemented in clinical settings, but one process that can help speed this timeline up is organization and synthesis of research [72-76]. The Braden Scale is a perfect example of this synthesis: different risk factors were identified and combined to make one, all-inclusive scale representing the most important risks. Scales like the SCIPUS and Waterlow have been designed for the SCI population, but these scales leave out a key risk factor – the anatomy that the person sits on. A new scale should be created that synthesizes past research with this research. Possible risk factors on this new scale could include some items of the existing scales (like nutrition), some anatomical risk factors (like tissue composition or tissue thickness), and some loading risk factors (like PPI or asymmetry). Since deformation characteristics are almost impossible to measure in a clinical setting, anatomical data that have been shown to be highly related to deformation data can be substituted. That being said, efforts must be made to develop clinical tools for measuring anatomy.

Developing a new scale would require extensive research and testing of variables, but this scale would be key tool to reduce the 9-12 billion dollars spent in the US every year on pressure ulcer care. Changes in health care policy have introduced financial penalties for hospital-acquired conditions, with pressure ulcers being included in these conditions[77]. Not only would a new scale for people with spinal cord injury save the hospitals money, but it would also help insurance companies better distribute funding amongst patients. People with higher risks could receive increased funding for higher quality cushions[56] and fitted wheelchairs[78], two variables that are easily modified with increased funding.

4.7. RECOMMENDATIONS

One major question that remains unanswered by this study is if pressure mapping is a viable tool for measuring pressure ulcer risk in the SCI population. Pressure mapping has been studied for another high risk population, people in nursing homes[58], but it is unknown if these results can apply to the SCI population. There is no RCT evaluating the link between interface pressure and pressure ulcer incidence in the SCI population, or even a study linking cushion selection and pressure ulcer incidence for the population. Larger scale studies must be done with this population to help reduce pressure ulcer incidence, not just pressure ulcer risk.

It has been shown that anatomy plays an important role in pressure ulcer risk, and that people with spinal cord injury have unique anatomical features that increase their risk. The anatomical feature that was most correlated to the other measures of pressure ulcer risk was tissue thickness, and this is something that could be assessed in a clinic without the use of expensive technology such as MRI. One simple method to estimate tissue thickness could be clinician palpation of the tissues surrounding the ischial tuberosities. By placing pressure on this area, it would be reasonable for a clinician to estimate the tissue thickness, even if it was something as simple as categorizing the tissue into a couple categories (thin, medium, thick, high fat, high muscle). For a more accurate measure of tissue thickness, a different imaging technique could be used, such as ultrasound. Ultrasound is already a popular clinical tool in imaging the ischial area, used in assessing problems like hamstring injury and bone bursitis [79-81]. Another current clinical use of ultrasound is early detection of DTI [82-85], so if a clinician was trying to assess pressure ulcer risk they could also look for any early signs of ulcer development. Given the current use of ultrasound in the ischial area and the accuracy of measurements [69, 86], ultrasound should be studied as a method to measure ischial anatomy in relation to pressure ulcer risk.

The results of this study highlight the impact that sitting asymmetry on pressure ulcer risk. With greater asymmetry comes higher pressure and more deformation, and asymmetry can be a result of postural or anatomical imbalances. Now that asymmetry has been identified as a variable that links anatomy, interface pressure, and deformation, more research needs to be done to confirm this finding. Furthermore, more prevention techniques should be examined. If clinicians are able to demonstrate ways to maintain proper sitting posture and prescribe cushions that best minimize asymmetry, pressure ulcer risk could be significantly decreased.

Hamstring sitting is a phenomenon that has just recently been observed, and more research needs to go to determine the risks and/or benefits of sitting on hamstrings. Finite element modeling could be a great starting point for this research. Another aspect of this topic that should be analyzed is anterior-posterior pelvic tilt. Posterior pelvic tilt could cause more of the hamstrings to lie under the ITs, affecting risk. If hamstring sitting does play a role in pressure ulcer risk, postural corrections could be made to change anterior-posterior pelvic tilt.

An aspect of pressure ulcer risk that should be further researched is the differences between tissue deformation and tissue displacement, as well how they affect each other. It has been known that tissue deforms when sitting, but the idea of significant tissue displacement has only recently surfaced. Previous finite element modeling studies only look at tissue deformation, but the displacement observed in this study challenges this static assumption. Computational studies should look at the effects of different degrees of displacement, as well as looking into ways to predict displacement. A major question is what levels of displacement are harmful and what levels are beneficial. Once this information has been ascertained, cushions can be designed to not only decrease compression, but also improve on displacement.

Overall, more large-scale research needs to be focused on pressure ulcer prevention for people with spinal cord injury. What is suggested is a collaboration between the three most prevalent research groups focused on this topic – the Brienza group[32, 56, 58, 78, 87-89], the Gefen group[16-18, 34, 37, 42-44, 46, 47, 90, 91], and the Sprigle group[48, 60, 61, 92-94]. In a field where extensive, big picture work is missing, each of these three groups could produce a large keystone study on this topic. With Brienza's prevention RCT experience, Gefen's advanced computer modeling, and Sprigle's critical examination of seated anatomy, the three groups could come together to create the most powerful look into pressure ulcer risk – and prevention – in people with spinal cord injury. If anything, this study has shown that different aspects of risk in this population are related, and need to be examined on a larger scale where the results could change health care practice. Included in this study should be examinations of anatomy, loading, and deformation, as well as added angles such as internal tissue strains and pressure ulcer incidence.

APPENDIX

A.1 RAW DATA

1. WC01 Data

Subject	Side	Cushion	Fat Volume	Semitendinosus Volume	Semimembranosus Volume	Gluteus Volume
WC01	Right	Unloaded	2409	338	413	6080
		ROHO	2908	460	0	2347
		Invacare	2583	183	241	755
		Sunrise	3001	100	259	767
		Supracor	2126	142	175	1293
		Varilite	3148	248	319	1091
		Vicair	2857	172	229	1729
	Left	Unloaded	2538	403	319	5688
		ROHO	1682	98	233	4021
		Invacare	1816	71	291	2947
		Sunrise	2237	110	324	3009
		Supracor	1741	119	207	2737
		Varilite	1816	227	432	3244
		Vicair	1776	100	280	4133

Subject	Side	Cushion	Fat % Composition	Semitendinosus % Composition	Semimembranosus % Composition	Gluteus % Composition
WC01	Right	Unloaded	26.071	3.658	4.470	65.801
		ROHO	50.884	8.049	0.000	41.067
		Invacare	68.660	4.864	6.406	20.069
		Sunrise	72.716	2.423	6.276	18.585
		Supracor	56.906	3.801	4.684	34.609
		Varilite	65.501	5.160	6.638	22.701
		Vicair	57.289	3.449	4.592	34.670
	Left	Unloaded	28.364	4.504	3.565	63.567
		ROHO	27.875	1.624	3.861	66.639
		Invacare	35.434	1.385	5.678	57.502
		Sunrise	39.384	1.937	5.704	52.975
		Supracor	36.241	2.477	4.309	56.973
		Varilite	31.754	3.969	7.554	56.723
		Vicair	28.240	1.590	4.452	65.718

Subject	Side	Cushion	Fat % Deformation	Semitend % Deformation	Semimem % Deformation	Glut % Deformation	Muscle % Deform
WC01	Right	Unloaded	-	-	-	-	-
		ROHO	120.714	136.095	0.000	38.602	0.411
		Invacare	107.223	54.142	58.354	12.418	0.173
		Sunrise	124.575	29.586	62.712	12.615	0.165
		Supracor	88.252	42.012	42.373	21.266	0.236
		Varilite	130.677	73.373	77.240	17.944	0.243
		Vicair	118.597	50.888	55.448	28.438	0.312
	Left	Unloaded	-	-	-	-	-
		ROHO	66.273	24.318	73.041	70.693	0.679
		Invacare	71.552	17.618	91.223	51.811	0.516
		Sunrise	88.140	27.295	101.567	52.901	0.537
		Supracor	68.597	29.529	64.890	48.119	0.478
		Varilite	71.552	56.328	135.423	57.032	0.609
		Vicair	69.976	24.814	87.774	72.662	0.704

Subject	Side	Cushion	Total Volume	Change in Total Volume	Deformation Asymmetry
WC01	Right	Unloaded	9240	-	-
		ROHO	5715	61.851	8.637
		Invacare	3762	40.714	33.802
		Sunrise	4127	44.665	34.794
		Supracor	3736	40.433	28.166
		Varilite	4806	52.013	20.531
		Vicair	4987	53.972	26.256
	Left	Unloaded	8948	-	
		ROHO	6034	67.434	
		Invacare	5125	57.275	
		Sunrise	5680	63.478	
		Supracor	4804	53.688	
		Varilite	5719	63.914	
		Vicair	6289	70.284	

Subject	Cushion	Peak	Average Top 4	PPI	Peak Gradient	Average Gradient	Bony Prominence Index
WC01	ROHO	47.20	46.98	38.00	30.35	5.35	4.84
	Invacare	67.20	65.23	57.00	17.30	3.00	5.71
	Sunrise	53.70	50.15	46.00	24.98	3.03	4.10
	Supracor	82.60	80.68	75.00	17.46	2.57	7.49
	Varilite	65.80	65.15	60.00	16.79	2.67	4.39
	Vicair	112.80	104.30	56.00	63.58	4.19	6.93

2. WC02 Data

Subject	Side	Cushion	Fat Volume	Semitendinosus Volume	Semimembranosus Volume	Gluteus Volume
WC02	Right	Unloaded	11459	291	0	0
		ROHO	7875	6	0	0
		Invacare	7478	8	0	138
		Sunrise	7012	3	0	33
		Supracor	5905	0	0	0
		Varilite	7514	6	0	0
		Vicair	6198	11	0	0
	Left	Unloaded	12778	619	4	922
		ROHO	5713	19	0	196
		Invacare	5716	31	0	360
		Sunrise	5354	0	0	166
		Supracor	4515	0	0	76
		Varilite	4892	27	1	243
		Vicair	4652	0	0	214

Subject	Side	Cushion	Fat % Composition	Semitendinosus % Composition	Semimembranosus % Composition	Gluteus % Composition
WC02	Right	Unloaded	97.523	2.477	0.000	0.000
		ROHO	99.924	0.076	0.000	0.000
		Invacare	98.085	0.105	0.000	1.810
		Sunrise	99.489	0.043	0.000	0.468
		Supracor	100.000	0.000	0.000	0.000
		Varilite	99.920	0.080	0.000	0.000
		Vicair	99.823	0.177	0.000	0.000
	Left	Unloaded	89.213	4.322	0.028	6.437
		ROHO	96.373	0.321	0.000	3.306
		Invacare	93.598	0.508	0.000	5.895
		Sunrise	96.993	0.000	0.000	3.007
		Supracor	98.345	0.000	0.000	1.655
		Varilite	94.751	0.523	0.019	4.707
		Vicair	95.602	0.000	0.000	4.398

Subject	Side	Cushion	Fat % Deformation	Semitend % Deformation	Semimem % Deformation	Glut % Deformation	Muscle % Deform
WC02	Right	Unloaded	-	-	-	-	-
		ROHO	68.723	2.062	0.000	0.000	0.021
		Invacare	65.259	2.749	0.000	0.000	0.502
		Sunrise	61.192	1.031	0.000	0.000	0.124
		Supracor	51.532	0.000	0.000	0.000	0.000
		Varilite	65.573	2.062	0.000	0.000	0.021
		Vicair	54.088	3.780	0.000	0.000	0.038
	Left	Unloaded	-	-	-	-	-
		ROHO	44.710	3.069	0.000	21.258	0.139
		Invacare	44.733	5.008	0.000	39.046	0.253
		Sunrise	41.900	0.000	0.000	18.004	0.107
		Supracor	35.334	0.000	0.000	8.243	0.049
		Varilite	38.285	4.362	25.000	26.356	0.175
		Vicair	36.406	0.000	0.000	23.210	0.139

Subject	Side	Cushion	Total Volume	Change in Total Volume	Deformation Asymmetry
WC02	Right	Unloaded	11750	-	-
		ROHO	7881	67.072	47.3617698
		Invacare	7624	64.885	41.3817093
		Sunrise	7048	59.983	43.5303415
		Supracor	5905	50.255	44.2285864
		Varilite	7520	64.000	55.8799474
		Vicair	6209	52.843	43.4695196
	Left	Unloaded	14323	-	
		ROHO	5928	41.388	
		Invacare	6107	42.638	
		Sunrise	5520	38.539	
		Supracor	4591	32.053	
		Varilite	5163	36.047	
		Vicair	4866	33.973	

Subject	Cushion	Peak	Average Top 4	PPI	Peak Gradient	Average Gradient	Bony Prominence Index
WC02	ROHO	183.20	152.13	94.00	100.61	5.54	9.41
	Invacare	256.00	246.68	200.00	93.28	4.78	16.45
	Sunrise	138.80	126.23	101.00	42.46	4.01	10.56
	Supracor	256.00	255.13	158.00	160.94	4.30	17.81
	Varilite	256.00	253.63	215.00	85.28	4.23	12.91
	Vicair	189.60	150.70	112.00	86.75	3.84	10.00

3. WC03 Data

Subject	Side	Cushion	Fat Volume	Semitendinosus Volume	Semimembranosus Volume	Gluteus Volume
WC03	Right	Unloaded	6932	6	60	1334
		ROHO	5484	0	8	431
		Invacare	5843	0	0	854
		Sunrise	4964	0	0	1461
		Supracor	4188	23	23	213
		Varilite	5532	0	12	824
		Vicair	4718	30	13	1184
	Left	Unloaded	5835	13	85	1812
		ROHO	3879	0	0	1531
		Invacare	5125	0	14	1807
		Sunrise	6070	0	0	1546
		Supracor	3854	13	11	712
		Varilite	3998	0	5	1990
		Vicair	4097	42	31	1993

Subject	Side	Cushion	Fat % Composition	Semitendinosus % Composition	Semimembranosus % Composition	Gluteus % Composition
WC03	Right	Unloaded	83.197	0.072	0.000	0.000
		ROHO	92.588	0.000	0.135	7.277
		Invacare	87.248	0.000	0.000	12.752
		Sunrise	77.261	0.000	0.000	22.739
		Supracor	94.176	0.517	0.517	4.790
		Varilite	86.872	0.000	0.188	12.940
		Vicair	79.361	0.505	0.219	19.916
	Left	Unloaded	75.339	0.168	1.097	23.396
		ROHO	71.701	0.000	0.000	28.299
		Invacare	73.783	0.000	0.202	26.015
		Sunrise	79.701	0.000	0.000	20.299
		Supracor	83.965	0.283	0.240	15.512
		Varilite	66.711	0.000	0.083	33.205
		Vicair	66.477	0.681	0.000	0.000

Subject	Side	Cushion	Fat % Deformation	Semitend % Deformation	Semimem % Deformation	Glut % Deformation	Muscle % Deform
WC03	Right	Unloaded	-	-	-	-	-
		ROHO	79.111	0.000	13.333	32.309	0.314
		Invacare	84.290	0.000	0.000	64.018	0.610
		Sunrise	71.610	0.000	0.000	109.520	1.044
		Supracor	60.415	383.333	38.333	15.967	0.185
		Varilite	79.804	0.000	20.000	61.769	0.597
		Vicair	68.061	500.000	21.667	88.756	0.876
	Left	Unloaded	-	-	-	-	-
		ROHO	66.478	0.000	0.000	84.492	0.802
		Invacare	87.832	0.000	16.471	99.724	0.953
		Sunrise	104.027	0.000	0.000	85.320	0.809
		Supracor	66.050	100.000	12.941	39.294	0.385
		Varilite	68.518	0.000	5.882	109.823	1.045
		Vicair	70.214	323.077	36.471	109.989	1.082

Subject	Side	Cushion	Total Volume	Change in Total Volume	Deformation Asymmetry
WC03	Right	Unloaded	8332	-	-
		ROHO	5923	71.087	1.75374854
		Invacare	6697	80.377	10.9452872
		Sunrise	6425	77.112	24.1920374
		Supracor	4447	53.373	10.4610805
		Varilite	6368	76.428	1.2362565
		Vicair	5945	71.351	10.8961195
	Left	Unloaded	7745	-	
		ROHO	5410	69.852	
		Invacare	6946	89.684	
		Sunrise	7616	98.334	
		Supracor	4590	59.264	
		Varilite	5993	77.379	
		Vicair	6163	79.574	

Subject	Cushion	Peak	Average Top 4	PPI	Peak Gradient	Average Gradient	Bony Prominence Index
WC03	ROHO	51.90	50.90	35.00	35.68	5.09	5.69
	Invacare	68.40	57.33	37.00	35.29	2.96	6.30
	Sunrise	49.70	48.68	41.00	20.89	3.00	5.57
	Supracor	66.90	65.73	54.00	25.03	2.39	8.79
	Varilite	53.70	48.08	41.00	19.69	2.37	5.87
	Vicair	125.30	93.23	50.00	84.23	3.49	7.63

4. WC04 Data

Subject	Side	Cushion	Fat Volume	Semitendinosus Volume	Semimembranosus Volume	Gluteus Volume
WC04	Right	Unloaded	2111	0	0	1257
		ROHO	1696	39	46	114
		Invacare	1478	0	3	27
		Sunrise	1269	14	0	0
		Supracor	1056	0	0	0
		Varilite	1061	0	0	0
		Vicair	1280	0	0	0
	Left	Unloaded	1923	0	0	1420
		ROHO	2313	0	4	169
		Invacare	1567	0	0	0
		Sunrise	1824	0	0	0
		Supracor	1801	0	0	44
		Varilite	1818	0	0	0
		Vicair	1851	0	0	0

Subject	Side	Cushion	Fat % Composition	Semitendinosus % Composition	Semimembranosus % Composition	Gluteus % Composition
WC04	Right	Unloaded	62.678	0.000	0.000	37.322
		ROHO	89.499	2.058	2.427	6.016
		Invacare	98.011	0.000	0.199	1.790
		Sunrise	98.909	1.091	0.000	0.000
		Supracor	100.000	0.000	0.000	0.000
		Varilite	100.000	0.000	0.000	0.000
		Vicair	100.000	0.000	0.000	0.000
	Left	Unloaded	57.523	0.000	0.000	42.477
		ROHO	93.041	0.000	0.161	6.798
		Invacare	100.000	0.000	0.000	0.000
		Sunrise	100.000	0.000	0.000	0.000
		Supracor	97.615	0.000	0.000	2.385
		Varilite	100.000	0.000	0.000	0.000
		Vicair	100.000	0.000	0.000	0.000

Subject	Side	Cushion	Fat % Deformation	Semitend % Deformation	Semimem % Deformation	Glut % Deformation	Muscle % Deform
WC04	Right	Unloaded	-	-	-	-	-
		ROHO	80.341	##########	##########	9.069	0.158
		Invacare	70.014	0.000	##########	2.148	0.024
		Sunrise	60.114	##########	0.000	0.000	0.011
		Supracor	50.024	0.000	0.000	0.000	0.000
		Varilite	50.261	0.000	0.000	0.000	0.000
		Vicair	60.635	0.000	0.000	0.000	0.000
	Left	Unloaded	-	-	-	-	-
		ROHO	120.281	0.000	##########	11.901	0.122
		Invacare	81.487	0.000	0.000	0.000	0.000
		Sunrise	94.852	0.000	0.000	0.000	0.000
		Supracor	93.656	0.000	0.000	3.099	0.031
		Varilite	94.540	0.000	0.000	0.000	0.000
		Vicair	96.256	0.000	0.000	0.000	0.000

Subject	Side	Cushion	Total Volume	Change in Total Volume	Deformation Asymmetry
WC04	Right	Unloaded	3368	-	-
		ROHO	1895	56.265	27.7112611
		Invacare	1508	44.774	4.58211631
		Sunrise	1283	38.094	35.5465779
		Supracor	1056	31.354	55.0842719
		Varilite	1061	31.502	53.2805609
		Vicair	1280	38.005	37.1937471
	Left	Unloaded	3343	-	
		ROHO	2486	74.364	
		Invacare	1567	46.874	
		Sunrise	1824	54.562	
		Supracor	1845	55.190	
		Varilite	1818	54.382	
		Vicair	1851	55.369	

Subject	Cushion	Peak	Average Top 4	PPI	Peak Gradient	Average Gradient	Bony Prominence Index
WC04	ROHO	127.10	119.53	83.00	49.44	5.56	9.27
	Invacare	256.00	256.00	237.40	120.59	4.77	26.32
	Sunrise	256.00	252.93	227.00	72.13	4.16	17.86
	Supracor	228.30	221.03	174.00	99.78	2.85	20.59
	Varilite	241.60	227.65	196.00	78.54	3.78	17.16
	Vicair	152.90	140.68	97.00	72.15	3.89	11.67

5. WC05 Data

Subject	Side	Cushion	Fat Volume	Semitendinosus Volume	Semimembranosus Volume	Gluteus Volume
WC05	Right	Unloaded	9655	410	70	95
		ROHO	4909	40	22	0
		Invacare	5896	69	22	0
		Sunrise	4570	77	24	0
		Supracor	4265	86	37	0
		Varilite	4903	56	32	0
		Vicair	4905	42	38	0
	Left	Unloaded	9677	431	40	3
		ROHO	4762	113	16	0
		Invacare	6228	78	41	0
		Sunrise	4280	26	6	0
		Supracor	4134	59	9	0
		Varilite	4601	67	25	0
		Vicair	5119	48	23	0

Subject	Side	Cushion	Fat % Composition	Semitendinosus % Composition	Semimembranosus % Composition	Gluteus % Composition
WC05	Right	Unloaded	89.238	9.480	1.282	0.000
		ROHO	94.752	1.443	3.805	0.000
		Invacare	95.419	0.509	2.799	1.272
		Sunrise	97.882	0.455	1.662	0.000
		Supracor	95.394	0.272	4.061	0.272
		Varilite	95.693	0.357	3.903	0.048
		Vicair	95.140	0.116	4.417	0.328
	Left	Unloaded	88.390	9.774	1.835	0.000
		ROHO	98.270	0.000	1.730	0.000
		Invacare	98.447	0.000	1.553	0.000
		Sunrise	97.545	0.000	0.781	1.674
		Supracor	98.122	0.000	1.832	0.046
		Varilite	98.699	0.000	1.094	0.207
		Vicair	95.908	0.165	3.537	0.391

Subject	Side	Cushion	Fat % Deformation	Semitend % Deformation	Semimem % Deformation	Glut % Deformation	Muscle % Deform
WC05	Right	Unloaded	-	-	-	-	-
		ROHO	42.861	6.145	119.835	0.000	0.197
		Invacare	62.303	3.128	127.273	##########	0.248
		Sunrise	51.015	2.235	60.331	0.000	0.092
		Supracor	58.267	1.564	172.727	##########	0.233
		Varilite	47.727	1.676	135.537	##########	0.178
		Vicair	58.552	0.670	189.256	##########	0.248
	Left	Unloaded	-	-	-	-	-
		ROHO	39.092	0.000	33.133	0.000	0.052
		Invacare	51.539	0.000	39.157	0.000	0.062
		Sunrise	54.679	0.000	21.084	##########	0.105
		Supracor	52.940	0.000	47.590	##########	0.077
		Varilite	41.756	0.000	22.289	##########	0.042
		Vicair	58.344	0.905	103.614	##########	0.190

Subject	Side	Cushion	Total Volume	Change in Total Volume	Deformation Asymmetry
WC05	Right	Unloaded	9441	-	-
		ROHO	3811	40.366	13.7831245
		Invacare	5501	58.267	22.9448176
		Sunrise	4391	46.510	6.32285192
		Supracor	5146	54.507	13.3427165
		Varilite	4202	44.508	17.369432
		Vicair	5185	54.920	2.1153169
	Left	Unloaded	9044	-	
		ROHO	3180	35.161	
		Invacare	4185	46.274	
		Sunrise	4481	49.547	
		Supracor	4313	47.689	
		Varilite	3382	37.395	
		Vicair	4863	53.770	

Subject	Cushion	Peak	Average Top 4	PPI	Peak Gradient	Average Gradient	Bony Prominence Index
WC05	ROHO	87.70	79.08	55.00	36.66	6.23	4.83
	Invacare	114.80	82.28	58.00	63.66	3.65	4.94
	Sunrise	69.40	65.20	35.00	25.89	4.05	4.81
	Supracor	221.80	166.83	127.00	106.30	4.60	8.49
	Varilite	85.50	75.75	47.00	43.80	3.49	5.19
	Vicair	143.60	116.95	83.00	72.15	5.83	7.81

6. WC06 Data

Subject	Side	Cushion	Fat Volume	Semitendinosus Volume	Semimembranosus Volume	Gluteus Volume
WC06	Right	Unloaded	9655	410	70	95
		ROHO	4909	40	22	0
		Invacare	5896	69	22	0
		Sunrise	4570	77	24	0
		Supracor	4265	86	37	0
		Varilite	4903	56	32	0
		Vicair	4905	42	38	0
	Left	Unloaded	9677	431	40	3
		ROHO	4762	113	16	0
		Invacare	6228	78	41	0
		Sunrise	4280	26	6	0
		Supracor	4134	59	9	0
		Varilite	4601	67	25	0
		Vicair	5119	48	23	0

Subject	Side	Cushion	Fat % Composition	Semitendinosus % Composition	Semimembranosus % Composition	Gluteus % Composition
WC06	Right	Unloaded	94.379	4.008	0.684	0.929
		ROHO	98.753	0.805	0.443	0.000
		Invacare	98.480	1.152	0.367	0.000
		Sunrise	97.838	1.648	0.514	0.000
		Supracor	97.197	1.960	0.843	0.000
		Varilite	98.237	1.122	0.641	0.000
		Vicair	98.395	0.843	0.762	0.000
	Left	Unloaded	95.331	4.246	0.394	0.030
		ROHO	97.363	2.310	0.327	0.000
		Invacare	98.125	1.229	0.646	0.000
		Sunrise	99.258	0.603	0.139	0.000
		Supracor	98.382	1.404	0.214	0.000
		Varilite	98.040	1.428	0.533	0.000
		Vicair	98.632	0.925	0.443	0.000

Subject	Side	Cushion	Fat % Deformation	Semitend % Deformation	Semimem % Deformation	Glut % Deformation	Muscle % Deform
WC06	Right	Unloaded	-	-	-	-	-
		ROHO	50.844	9.756	31.429	0.000	0.108
		Invacare	61.067	16.829	31.429	0.000	0.158
		Sunrise	47.333	18.780	34.286	0.000	0.176
		Supracor	44.174	20.976	52.857	0.000	0.214
		Varilite	50.782	13.659	45.714	0.000	0.153
		Vicair	50.803	10.244	54.286	0.000	0.139
	Left	Unloaded	-	-	-	-	-
		ROHO	49.209	26.218	40.000	0.000	0.272
		Invacare	64.359	18.097	102.500	0.000	0.251
		Sunrise	44.229	6.032	15.000	0.000	0.068
		Supracor	42.720	13.689	22.500	0.000	0.143
		Varilite	47.546	15.545	62.500	0.000	0.194
		Vicair	52.899	11.137	57.500	0.000	0.150

Subject	Side	Cushion	Total Volume	Change in Total Volume	Deformation Asymmetry
WC06	Right	Unloaded	10230	-	-
		ROHO	4971	48.592	0.84718377
		Invacare	5987	58.524	6.61200607
		Sunrise	4671	45.660	7.21876184
		Supracor	4388	42.893	3.55568359
		Varilite	4991	48.788	5.37989149
		Vicair	4985	48.729	4.80434067
	Left	Unloaded	10151	-	
		ROHO	4891	48.182	
		Invacare	6347	62.526	
		Sunrise	4312	42.479	
		Supracor	4202	41.395	
		Varilite	4693	46.232	
		Vicair	5190	51.128	

Subject	Cushion	Peak	Average Top 4	PPI	Peak Gradient	Average Gradient	Bony Prominence Index
WC06	ROHO	112.70	96.28	71.00	46.54	7.17	5.55
	Invacare	112.50	109.93	105.00	22.64	3.40	6.20
	Sunrise	91.80	89.68	83.00	39.38	4.45	5.24
	Supracor	158.90	148.13	135.00	29.91	3.47	8.53
	Varilite	102.20	99.08	93.00	17.09	2.94	5.45
	Vicair	174.00	160.43	94.00	89.71	5.43	8.05

Note: Values listed as ####### were not able to be calculated because of the lack of tissue while unloaded.

A.2 RELATIONSHIP DATA

1. Entire Population Correlations

Variable 1	Variable 2	Pearson Correlation Coefficient
Minimum Side Total Thickness	Bony Prominence	-0.9835
Left Total Thickness	Bony Prominence	-0.9804
Minimum Side Total Thickness	Average Top 4	-0.9069
Minimum Side Total Thickness	Peak	-0.8912
Minimum Side Total Thickness	PPI	-0.8902
Right Total Thickness	Bony Prominence	-0.8864
Minimum Side Total Thickness	Average Top 4	-0.8752
Average Gradient	Muscle Deformation	0.8710
Average Gradient	Fat Deformation	0.8688
Left Total Thickness	Peak	-0.8632
Left Loaded Tissue Volume	Total Deformation	-0.8527
Left Total Thickness	PPI	-0.8469
Left Total Thickness	Peak Gradient	-0.8457
Minimum Side Total Thickness	Peak Gradient	-0.8390
Min Loaded Tissue Volume	Total Deformation	-0.8295
Left Muscle Thickness	Peak Gradient	-0.8153
Average Unloaded Glut Comp	Fat Deformation	-0.8134
Average Unloaded Fat Comp	Fat Deformation	0.7868
Peak Gradient	Deformation Asymmetry	0.7745
Average Loaded Fat Comp	Fat Deformation	0.7581
Peak	Muscle Deformation	0.7570
Bony Prominence	Deformation Asymmetry	0.7560
Average Top 4	Deformation Asymmetry	0.7502
PPI	Muscle Deformation	0.7450
Average Loaded Fat Comp	Average Gradient	0.7415
Average Top 4	Muscle Deformation	0.7376

Peak	Deformation Asymmetry	0.7332
PPI	Deformation Asymmetry	0.7242
Average Gradient	Total Deformation	0.7095
Left Loaded Tissue Volume	Bony Prominence	-0.7000
Average Unloaded Semimem Comp	Peak	-0.7067
Left Total Thickness	Deformation Asymmetry	-0.7068
Minimum Side Muscle Thickness	Peak	-0.7119
Min Muscle Thickness	Fat Deformation	-0.7623
Right Total Thickness	Peak	-0.7709
Minimum Side Muscle Thickness	Peak Gradient	-0.7739
Right Total Thickness	PPI	-0.7779
Average Loaded Glut Comp	Fat Deformation	-0.7839
Right Total Thickness	Average Top 4	-0.7857
Average Loaded Glut Comp	Average Gradient	-0.7971

2. Entire Population Correlations

Variable 1	Variable 2	Pearson Correlation Coefficient
Fat Deformation	Right Loaded Tissue Volume	0.9975
Deformation Asymmetry	Average Loaded Glut Comp	0.9966
Average Gradient	Min Fat Thickness	0.9962
Fat Deformation	Left Unloaded Tissue Volume	0.9940
Average Gradient	Right Fat Thickness	0.9932
Deformation Asymmetry	Peak Gradient	0.9920
Peak Gradient	Average Loaded Glut Comp	0.9894
Bony Prominence	Minimum Side Total Thickness	-0.9880
Average Gradient	Average Fat Thickness	0.9823
Total Deformation	Left Unloaded Tissue Volume	-0.9791
Bony Prominence	Right Fat Thickness	-0.9772
Bony Prominence	Min Fat Thickness	-0.9759
Fat Deformation	Min Unloaded Tissue Volume	0.9696
Total Deformation	Right Loaded Tissue Volume	-0.9684

Fat Deformation	Right Unloaded Tissue Volume	0.9658
Muscle Deformation	Left Total Thickness	-0.9640
Average Gradient	Minimum Side Total Thickness	0.9631
Total Deformation	Right Muscle Thickness	-0.9619
Deformation Asymmetry	Peak	0.9586
Bony Prominence	Min Fat Thickness	-0.9522
PPI	Average Unloaded Semimembranosus Composition	-0.9497
Fat Deformation	Left Loaded Tissue Volume	0.9479
Average Gradient	Left Fat Thickness	0.9469
Fat Deformation	Min Loaded Tissue Volume	0.9454
Average Gradient	Average Unloaded Semimembranosus Composition	0.9345
Muscle Deformation	Minimum Side Total Thickness	-0.9282
Bony Prominence	Average Fat Thickness	-0.9269
Average Gradient	Right Total Thickness	0.9229
Average Gradient	Left Total Thickness	0.9170
Deformation Asymmetry	Average Top 4	0.9154
Average Gradient	Average Unloaded Gluteus Maximus Composition	-0.9084
Total Deformation	Min Unloaded Tissue Volume	-0.9082
Fat Deformation	Right Muscle Thickness	0.9049
PPI	Average Unloaded Semitendinosus Composition	-0.9047
Total Deformation	Right Unloaded Tissue Volume	-0.8970
Fat Deformation	Average Unloaded Fat Composition	0.8895
Total Deformation	Left Loaded Tissue Volume	-0.8872
Muscle Deformation	Bony Prominence	0.8827
Muscle Deformation	Average Unloaded Fat Composition	-0.8810
Total Deformation	Min Loaded Tissue Volume	-0.8758
Muscle Deformation	Average Unloaded Gluteus Maximus Composition	0.8682
Muscle Deformation	Right Total Thickness	-0.8677
Muscle Deformation	Right Fat Thickness	-0.8643
Deformation Asymmetry	Min Muscle Thickness	-0.8530
Deformation Asymmetry	PPI	0.8516
Fat Deformation	Average Unloaded Gluteus Maximus Composition	-0.8439
Muscle Deformation	Average Fat Thickness	-0.8297

Deformation Asymmetry	Bony Prominence	0.8287
Fat Deformation	Right Total Thickness	0.8276
Muscle Deformation	Min Fat Thickness	-0.8205
Muscle Deformation	Right IT Radius	0.8135
Fat Deformation	Left Fat Thickness	0.8080
Muscle Deformation	Min Loaded Tissue Volume	-0.8064
Deformation Asymmetry	Left Muscle Thickness	-0.8028
Muscle Deformation	Average Gradient	-0.8000

A.3 PRESSURE ASYMMETRY

	WC01	WC02	WC03	WC04	WC05	WC06
ROHO	3.23	31.90	4.26	26.76	12.61	38.77
Invacare	3.95	5.99	6.22	0.00	28.62	14.39
Sunrise	9.97	9.43	3.69	15.31	14.25	2.20
Supracor	12.89	8.21	4.90	8.30	93.87	15.97
Varilite	7.90	49.80	0.43	35.76	12.16	9.53
Vicair	49.92	49.80	47.38	2.18	11.54	6.90
Average	14.64	25.86	11.15	14.72	28.84	14.63
Standard Deviation	17.66	20.78	17.86	14.16	32.51	12.84

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