Measuring the Impact of Cushion Design on Buttocks Tissue Deformation: An MRI Approach

Abstract

Aim: To establish a research approach for describing how different wheelchair cushion designs impact buttocks tissue deformation during sitting.

Materials and Methods: The buttocks of 4 individuals with spinal cord injury and significant atrophy were scanned sitting in a FONAR Upright MRI. Scans were collected with the individuals' buttocks fully suspended without pelvic support, and seated on 3 different commercially available wheelchair cushions. Multi-planar scans were analyzed to provide 3D renderings and measurements of tissue thickness and shape.

Results: Bulk tissue thicknesses at the ischium, which rarely included muscle, were reduced by more than 60% on enveloping cushion designs studied (i.e., Roho HP and Matrx Vi), and more variably (23-60%) on an orthotic off-loading design (i.e., Java). Adipose was typically displaced posterior and superior from the unloaded condition, with more lateral displacement on the Roho HP and Matrx Vi and more medial displacement present on the Java. Large changes in angle at the sacro-coccygeal joint indicated significant loading on the region. Deformation at the greater trochanter was more consistent across surfaces. Greater interface pressures tended to be associated with greater deformation, but the relationship varied by individuals and was highly non-linear.

Conclusions: The buttocks in this study all deformed significantly, but at different locations and in different manners across all 3 surfaces. Attention needs to be paid to the regions of greatest

deformation. A future metric of shape compliance should consider cushion performance at all high risk regions, and changes to the amount and shape of tissue in the regions of interest.

Keywords

Pressure Ulcer, Wheelchair cushion, MRI, buttocks, multi-planar, tissue deformation

Background

Individuals who use wheelchairs are at high risk of developing pressure ulcers due to their reduced mobility and sensation. Consequently, pressure ulcers negatively impact health, activities of daily living, employment, and quality of life of wheelchair users (1-4). Individuals with a pressure ulcer are at increased risk for future pressure ulcer development (5) and premature death (2, 5).

Although there are many contributing factors to pressure ulcer development, tissue deformation is implicated in all physiological pathways including direct deformation damage, as well as ischemia secondary to deformation of blood vessels and impaired lymphatic drainage (6-10). Individuals who experience more tissue deformation when seated are considered to have a high Biomechanical Risk for pressure ulcer development. In distinction, deformation resistance is defined as “the intrinsic characteristic of an individual’s soft tissues to withstand extrinsic applied forces.” (11) (12). Pressure ulcer prevention therefore seeks to reduce tissue deformation.

Skin protection wheelchair cushions are frequently prescribed for wheelchair users considered at risk for pressure ulcers (13). Skin protection cushions require that cushions meet a minimum level (40 mm) of immersion using a standardized test (14, 15). That standard is met by a variety of approaches that manage body weight very differently in terms of design, materials and construction. Two common

approaches to managing body weight include envelopment and offloading. With an enveloping design, the buttocks immerse into the wheelchair cushion and the cushion envelops the tissue to increase contact area and minimize pressure gradients. An offloading cushion will redistribute body mass away from particular bony prominences, ideally to tissue better suited to withstand the load (16). One metric of cushion performance that can be used across designs of wheelchair cushions is shape compliance. Shape Compliance describes the ability of a cushion to support the buttocks with minimal buttocks deformation.

Recent studies have moved beyond interface pressure as the primary metric of cushion performance, and have begun to consider internal responses using a compliant buttocks model (16) and human participants (17, 18). The studies of humans have been focused on the amount of tissue present underneath the peak of the ischial tuberosity (17, 18). However, these studies miss two important issues. First, they do not explain how the cushions work, only how much tissue is displaced away from the ischium. Second, they do not consider tissue loading and deformation at the other high risk areas for seated pressure ulcers: the sacrum and greater trochanters.

Therefore, the primary objective of this study was to utilize a case series to establish a research approach for describing how different wheelchair cushion designs impact buttocks tissue deformation during sitting.

Methods

Participants

For this case series, we selectively targeted four participants at high risk for pressure ulcer development. They were full-time wheelchair users with complete spinal cord injuries and significant atrophy who represented some of the more challenging active individuals to safely seat. Participants needed to sit

with a level and neutral pelvic posture, and be able to sit safely on the cushions under investigation for 15 minutes each. Participants were excluded if they had a current pressure ulcer, could not maintain a stable upright posture on the cushions being studied, or had any condition that contraindicated safe participation in MRI scans. Institutional Review Board approval was received from the local institution and informed consent was acquired from the recruited subjects.

MRI Test Environment

Subjects wore loose fitting clothing to the study. Subjects were scanned in an upright unloaded posture, and seated on 3 commercially available wheelchair cushions. These cushions were: an orthotic offloading cushion (Java, Ride Designs), a pressure redistribution cushion made with contoured foam (Matrx Vi, Invacare), and a pressure redistribution cushion that uses air flotation (Roho HP, Permobil). In the unloaded condition, the participants maintained a seated posture, and body weight was supported under the thighs and through a thoracic suspension support, thereby offloading the ischium, greater trochanters, coccyx and lower sacrum.

The scan environment included a flat, rigid seat base including the MRI coil, topped with a petroleum jelly-filled platform surface marker, and the wheelchair cushion or thigh support for the unloaded condition (Figure 1). The seat to back angle was 96^{o} and a Java seat back insert with integrated abdominal support (Ride Designs) was adhered to a rigid seat back to provide trunk suspension in the unloaded condition and improve balance on the three cushion test conditions.

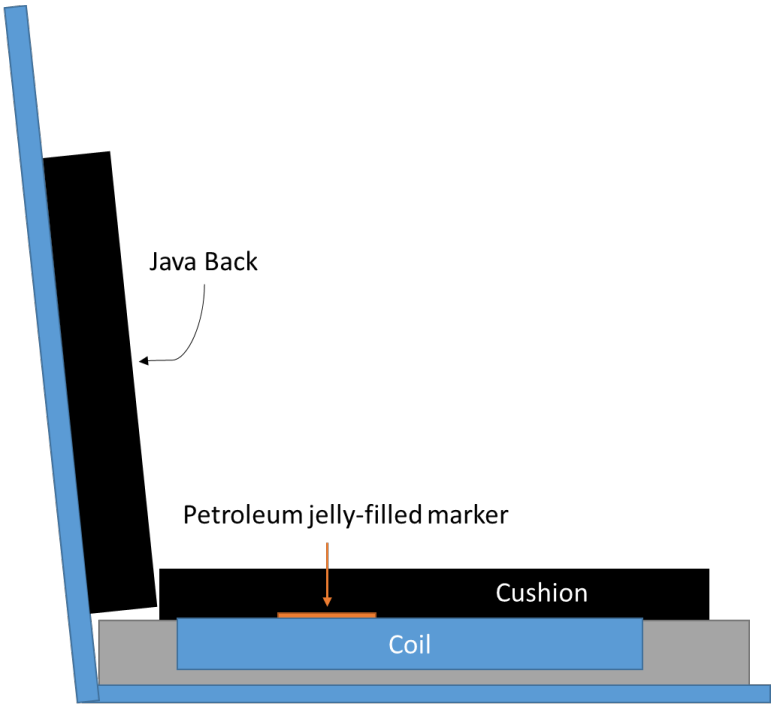


Figure 1. Illustration of test environment

MRI Study Protocol

For loaded cushions, a random order was used and determined prior to the scan session. The cushions were then placed in the scanner on top of the coil and marker (Figure 1). Subjects were seated on the cushion in compliance with each cushion manufacturer's instructions for use. An effort was made to align their pelvis in a neutral posture. The footrest was adjusted to properly load the thighs and to keep the knees and hips close to 90 degrees of flexion and ensure consistent thigh support in each test condition.

Subjects seated on the Roho cushion were palpated to confirm inflation of the cushion in accordance with the manufacturer's recommendations. A range of 0.5-1" of air between the user's bottom and the seating surface was targeted. An MRI scout image containing 5 slices near the ischial tuberosity was collected to permit measurement from the cushion base (identified by the platform surface marker) to the skin below the ischium, and adjustments were made to the cushion inflation as appropriate.

Subjects seated on the Java cushion were palpated to confirm that the ischium were offloaded. The subjects were also palpated to confirm that their greater trochanters rested in relief on the sides of the cushion. Subjects were centered on the Matrx Vi, but no further adjustments were performed. When possible, the tissue was briefly unloaded after palpating via a weight shift.

Imaging Protocol

The scans were collected using a RF-spoiled Gradient Recalled Echo protocol, with 80 contiguous sagittal slices of 3 mm thickness which provided a coverage of 240 mm. The effective slice thickness was 3.8 mm due to under sampling in the slice-encoding direction, which was done to save time. An in-plane resolution of 1.5 mm was acquired in both the frequency- and phase-encoding directions. The total scan time was 8 minutes and 24 seconds.

Data Processing

Raw DICOM scans were imported into AnalyzePro (AnalyzeDirect, Overland Park, KS) for review and segmentation of the pelvis, femur, gluteus maximus, and subcutaneous fat. Segmentation was performed under the supervision of an experienced radiographer (BLINDED FOR REVIEW). Skin was included within the subcutaneous fat segmentation when visible, since the scan resolution did not allow for separate segmentation of the two. Point clouds of the 3D segmented surfaces of the bones, muscle, and fat were exported for further analysis in Matlab R2016 (MathWorks, Natick, MA). The peak of the ischial tuberosity and the most inferior point of the greater trochanter when seated were manually identified by a trained student (BLINDED FOR REVIEW) and a radiographer (BLINDED FOR REVIEW), and consensus was reached with regards to the locations.

Data Analysis

Muscle volume was reported from AnalyzePro based on the manually segmented gluteus maximus and, consistent with previous work, the percent gluteus coverage was defined as the percent of a cylindrical 50 mm region under the peak of the ischial tuberosity covered by more than 2 mm of gluteus maximus (12).

The amount of tissue present inferior to the bony prominences, or the average Bulk Tissue Thickness, was defined to include skin, connective tissue, adipose, and muscle (when present). Bulk Tissue Thickness under the ischium was measured in an oblique plane in a region 50mm long. The oblique plane was defined as the plane running through the ischium in a posterior-lateral orientation, such that the 50mm region of interest included predominantly tissue beneath bone, rather than tissue surrounding the bone (Figure 2). More specifically, an axial slice 15 mm superior to the peak of the ischium was selected. In that plane, a line was drawn connecting the most medial anterior point and the most lateral, posterior point of the ischium. The oblique plane was defined to run through this line and perpendicular to the axial plane. This Bulk Tissue Thickness was highly correlated with the fat and gluteus maximus tissue thicknesses reported on in (12) but was easier to calculate. Tissue deformation was defined as the normalized change in bulk tissue thickness compared with unloaded.

$$Deformation = \frac{Thickness_{Unloaded} - Thickness_{Cushion}}{Thickness_{Unloaded}} * 100$$

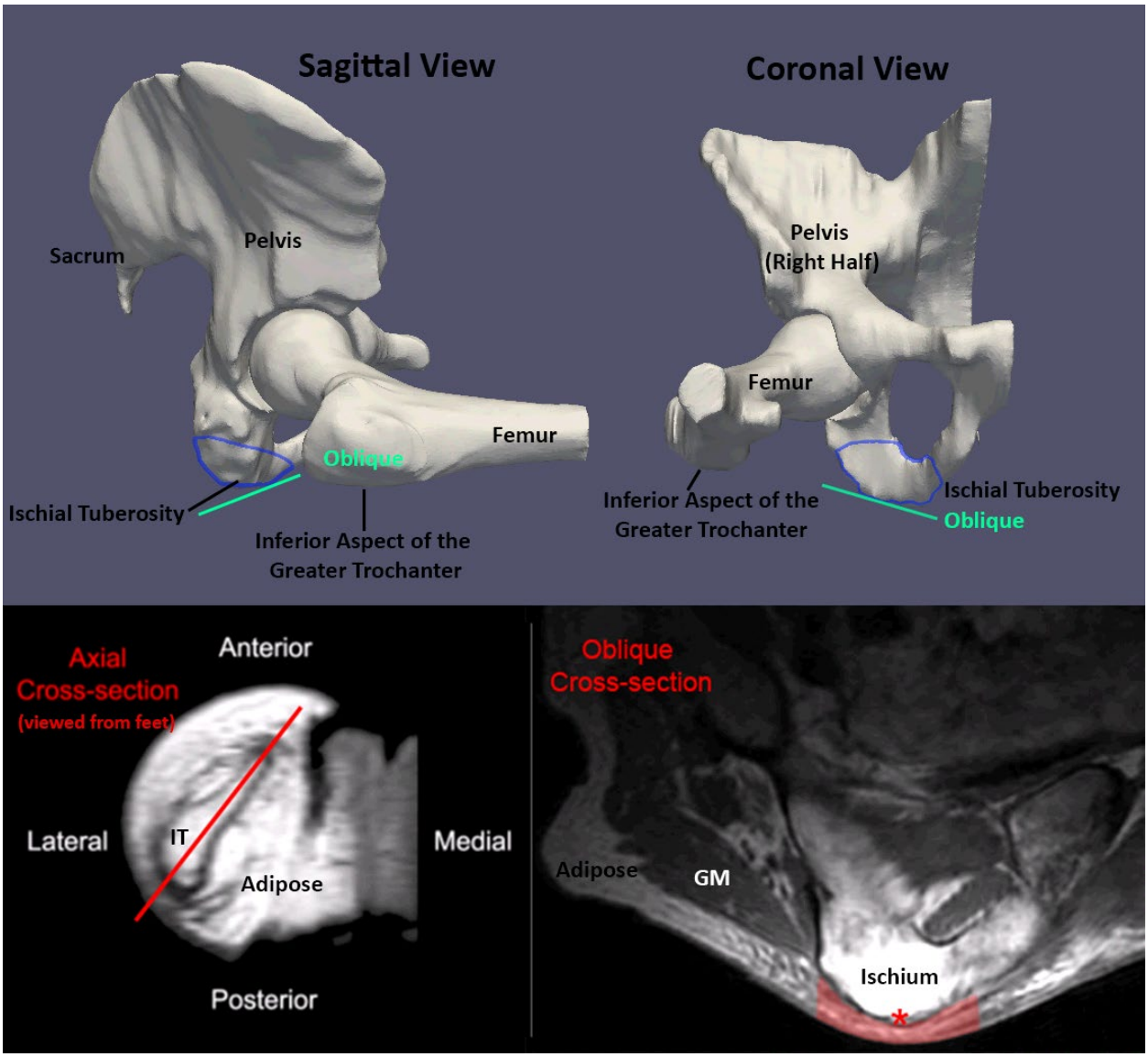
We also calculated the radius of curvature of the superficial skin surface within a cylindrical 50 mm region of interest centered on the ischium in the sagittal and coronal planes (12).

Greater trochanter bulk tissue thickness was calculated in a 50 mm cylindrical region of interest under the most inferior point of the greater trochanter (Figure 2). Similar to measurements calculated at the ischium, this included skin, connective tissue, adipose and muscle.

Finally, changes in the sacro-coccygeal angle were measured, as loads applied at the coccyx will rotate this mobile joint, reducing the sacro-coccygeal angle. The angle was defined as the angle between the line drawn from the midpoint of the upper edge of the S1 vertebra and the midpoint of the upper edge of the coccyx (Cx1) vertebra, and the line drawn from the midpoint of the upper edge of the coccyx (Cx1) vertebra with the distal aspect of the coccyx Cx3 vertebra according to (19) (Figure 3).

Interface Pressure Mapping Protocol

Interface pressure mapping (IPM) was done in the same seated posture, but in a wheelchair with seating configured to match that of the MRI, specifically a complete Java back and a rigid seat pan, with a 96 degree seat to back angle and horizontal seat pan orientation as in the MRI platform. Participants transferred onto the wheelchair cushion (studied in the same order that cushions were scanned in the MRI) with an FSA Boditrak (Vista Medical) mat on top of the cushion. Ischial tuberosities (ITs) were palpated to locate the ITs on the FSA mat and then participants performed a depression lift to relieve pressure on their buttocks. Participants sat for 2 minutes and then data was collected at 0.2 Hz for 30 seconds. Peak pressure index (20) was calculated under both ischium and averaged across all frames.



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158 *Figure 2. Identification of relevant bony anatomy. Sagittal and coronal views of a rendering of the right half of the pelvis and*
159 *proximal femur are shown with the inferior aspect of the greater trochanter marked, as well as the oblique orientation of the*
160 *ischium. The axial cross section of the MRI (bottom left) illustrates the oblique plane that runs through the posterior-lateral*
161 *orientation of the ischial tuberosity (IT). Peak of the ischial tuberosity (*) marked on the oblique cross-section, and bulk tissue*
162 *included in the calculation of average thickness is highlighted in red (bottom right). Adipose and gluteus maximus (GM) are also*
163 *identified in the image.*

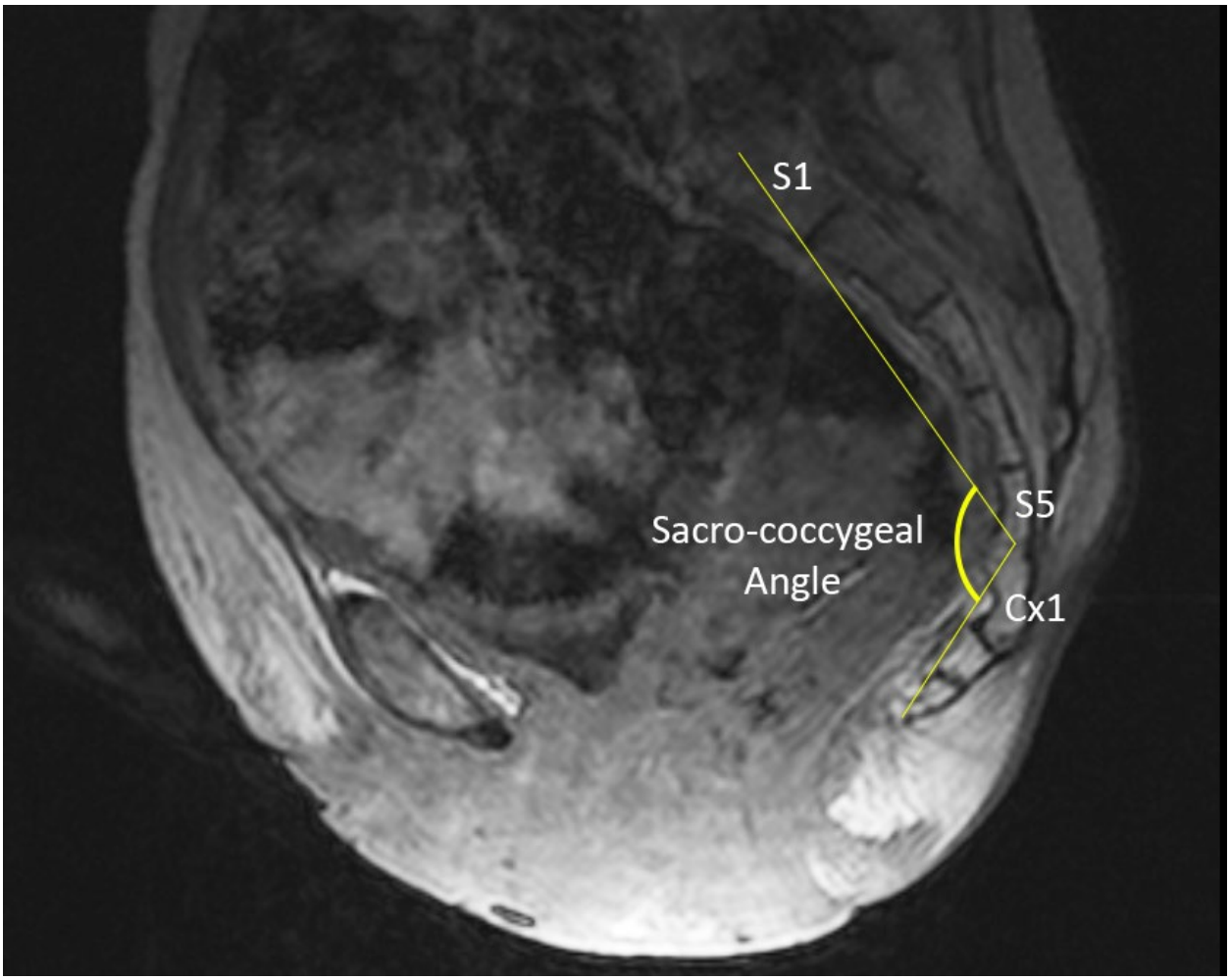


Figure 3. Sacro-coccygeal angle was defined as the angle between the line drawn from the midpoint of the upper edge of the S1 vertebra and the midpoint of the upper edge of the coccyx (Cx1) vertebra, and the line drawn from the midpoint of the upper edge of the coccyx (Cx1) vertebra with the distal aspect of the coccyx Cx3 vertebra.

Results

Study Participants

Four participants with complete spinal cord injuries (Table 1) were included in this study.

Subject ID	Gender	Age	Weight (lbs)	Level of SCI	Years Post Injury	PrI Status
A	F	32	95	T11	5	None
B	M	44	163	T5-6	18	Recurrent (Ipsilateral)
C	F	46	124	T12	24	None
D	F	46	130	T2-4	16	Right after injury

Buttocks Anatomy

The buttocks anatomy was consistent across the four participants in that each presented with significant muscle atrophy (Muscle volume average: 265 cm^3 and range: 171 to 447 cm^3) and limited soft tissue at the ischium (Bulk tissue thickness range: 28-40 mm, Figure 4). In one participant (C), we were unable to assess muscle characteristics because the fatty infiltration was so significant that it was not possible to determine where adipose tissue ended and muscle began.

Previous studies have raised the question of where the gluteus maximus is located during sitting. In this cohort of participants, gluteus maximus wrapped posterior and lateral to the ischium, with < 17% of the ischium covered by gluteus maximus across all unloaded and loaded conditions. This is evident in Figure 5 by noticing the ischium (white) visible below the red gluteus maximus.

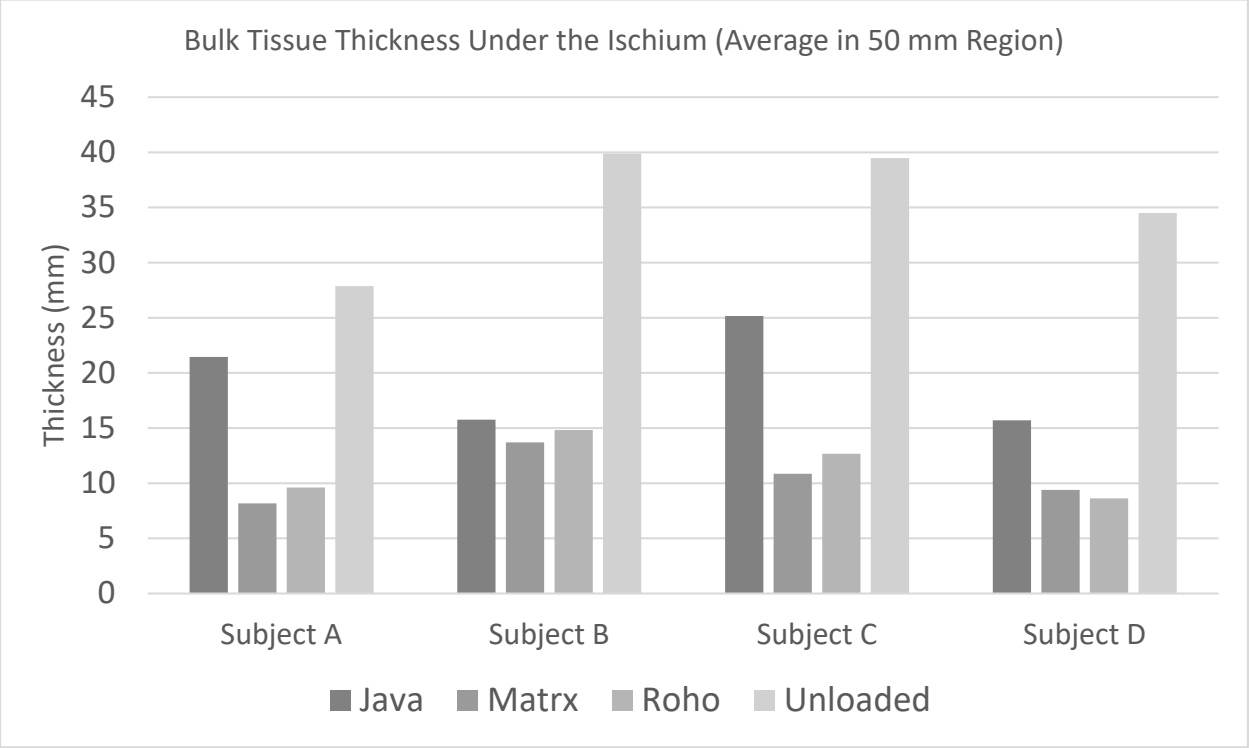


Figure 4. Bulk tissue thickness under the ischium varied across cushions., but were fairly similar across subjects.

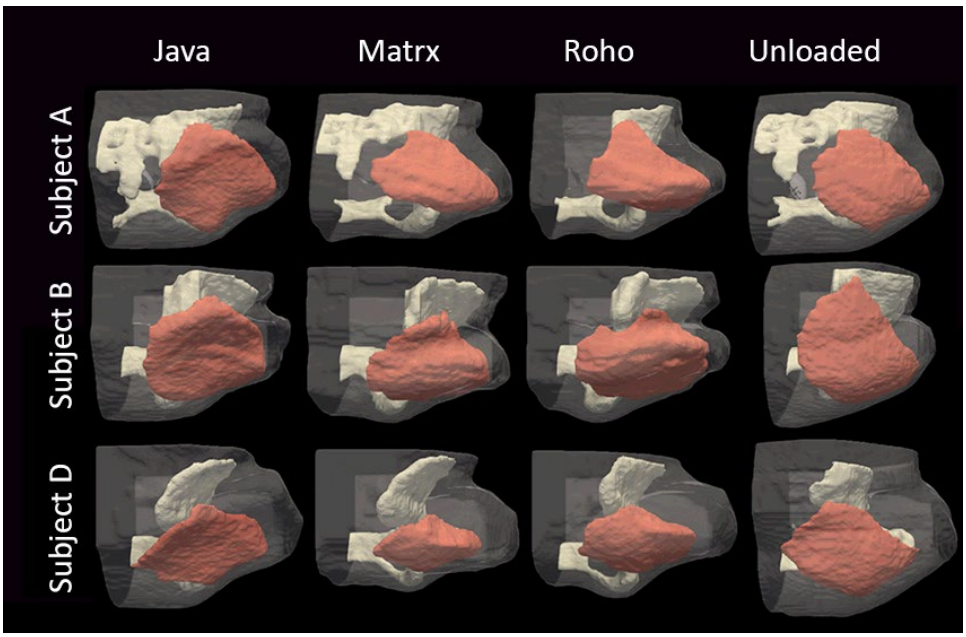


Figure 5. 3D renderings of the right half of the buttocks pictured from the posterior present the skin as semi-transparent so that the pelvis (white) and gluteus maximus (red) are visible. Note that the sacrum is not included or is only partially included in these images

Quantitative description of cushion loading

Bulk Tissue Deformation under the IT

Reduction in bulk tissue thicknesses when seated on the Matrx Vi and Roho HP as compared with unloaded thicknesses was greater than 60% (Figure 4). Bulk tissue thicknesses on these surfaces were fairly similar and small across subjects. More variation in tissue thicknesses and deformation was evident across cushions, with thicknesses on the Java being considerably larger than on the Roho HP and Matrx Vi for 3 of 4 participants. Subject B, however, had a similar bulk tissue thickness and deformation under the ischium on all 3 cushions.

When tissue thickness was reduced under load, it did so via displacement rather than compression. Typically, adipose was displaced posterior and superior from the unloaded condition, although the precise displacement varied by individual and especially by cushion. More lateral displacement was evident on the Roho HP and Matrx Vi, while there was more medial displacement on the Java.

Bulk Tissue Deformation under the Trochanter

Bulk tissue thickness under the greater trochanter was relatively consistent across subjects and cushions (Figure 6). Tissue thickness under the trochanter, which included gluteus maximus as well as adipose, connective tissue, and skin, ranged from 12-27mm in the loaded condition, or deformation from unloaded of 19-61%. Subject B displayed the largest tissue deformations beneath the trochanter relative

to unloaded (61%). Adipose and gluteus maximus present under the trochanter in the unloaded condition displaced laterally under load.

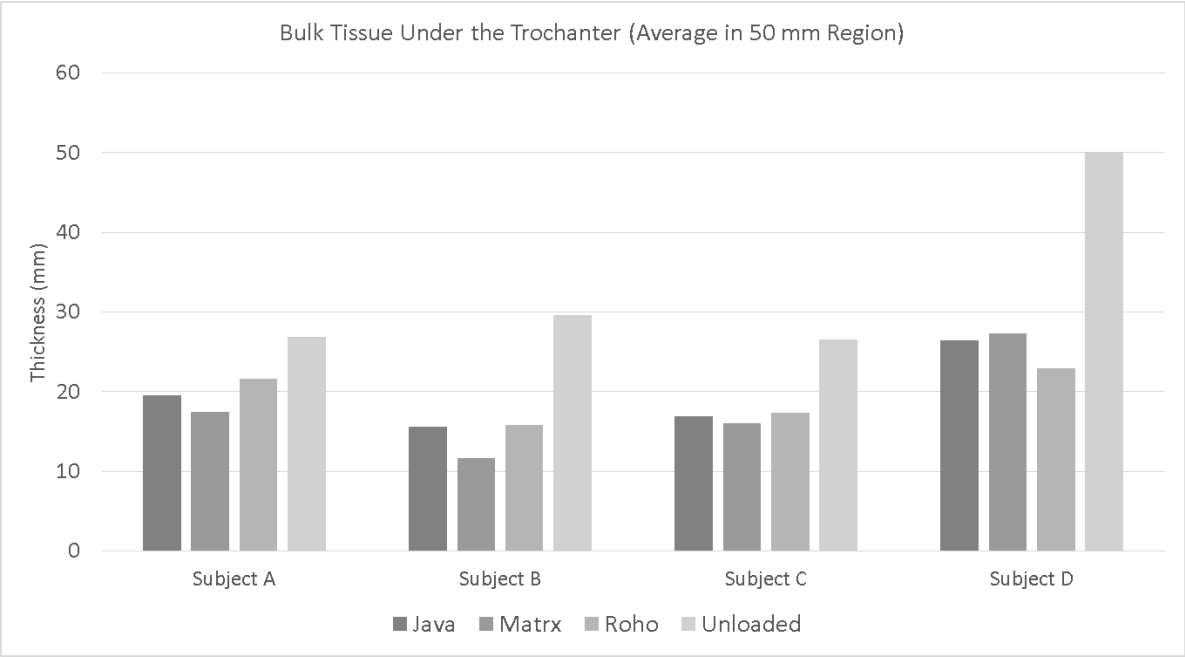
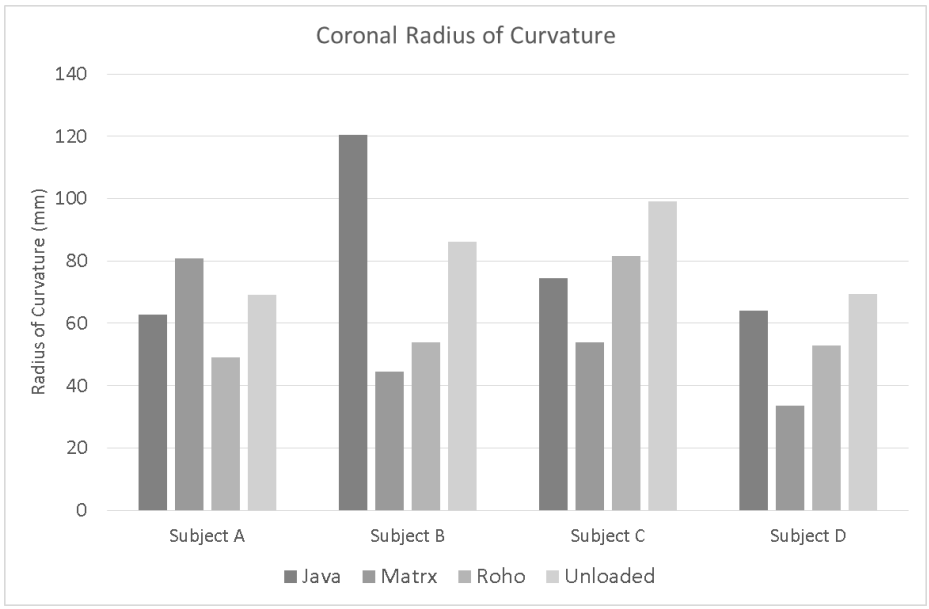


Figure 6. Bulk tissue under the greater trochanter was similar across cushions.

Radius of Curvature of Superficial Tissue under the IT

In most cases, the buttocks experienced the greatest radius of curvature, or flattest surface contour, in the unloaded condition (Figure 7, Figure 8, Figure 9). In the sagittal plane, the tissue with the smallest radius of curvature, or most pointed surface was seen when seated on the Matrx Vi and Roho HP, with similar curvatures across the surfaces. The sagittal curvature was typically greater on the Java than Matrx Vi and Roho HP, but the magnitude of that difference varied across subjects. Curvatures in the coronal plane differed more across cushions. The high radius of curvature on the Java for Subject B is indicative of the skin making contact with the bottom surface of the cushion well, creating an essentially flat shape.



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227 *Figure 7. Radius of curvature of the skin beneath the ischium in the coronal plane.*

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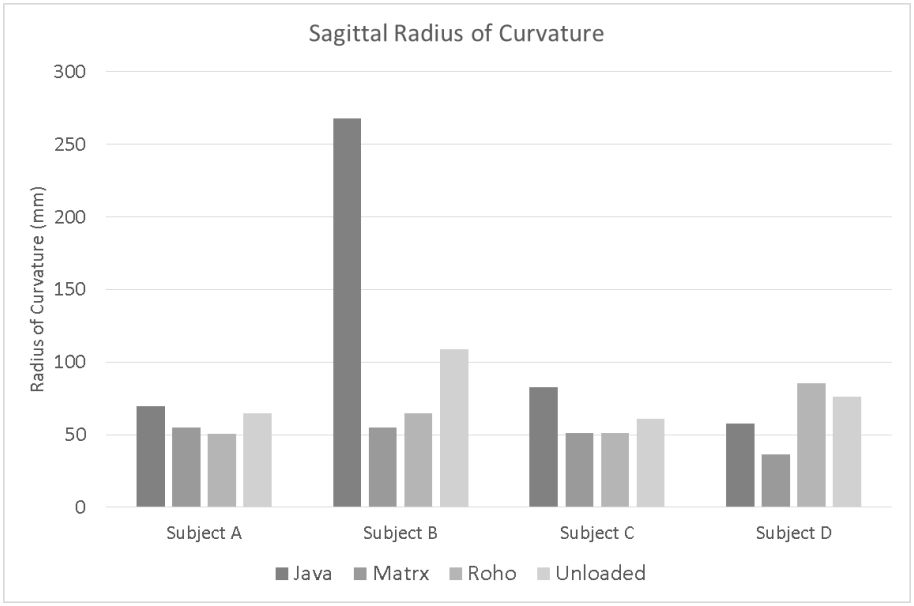

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230 *Figure 8. Radius of curvature of the skin beneath the ischium in the sagittal plane.*

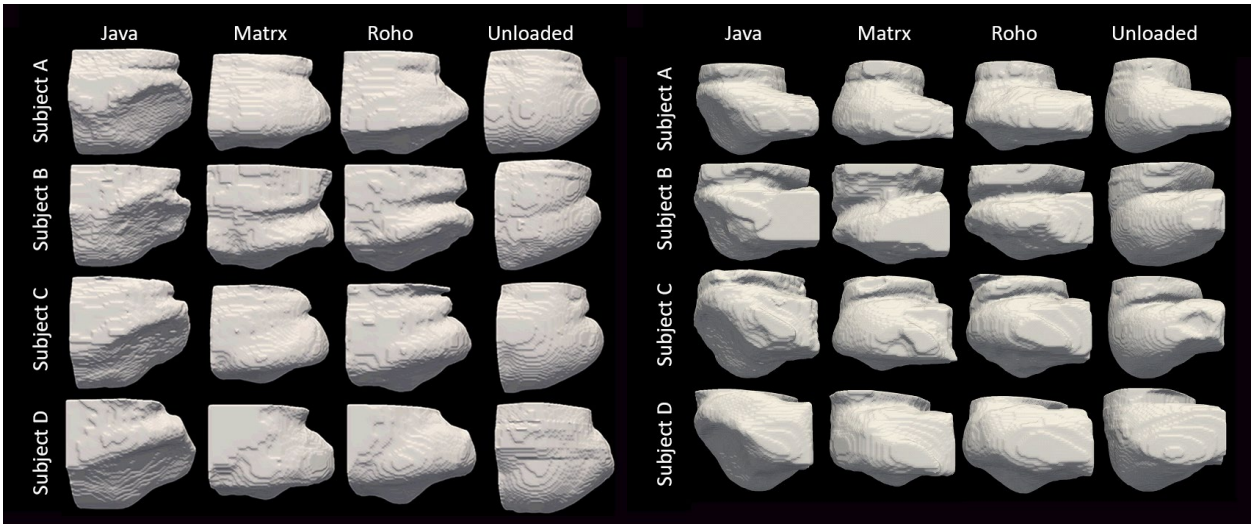
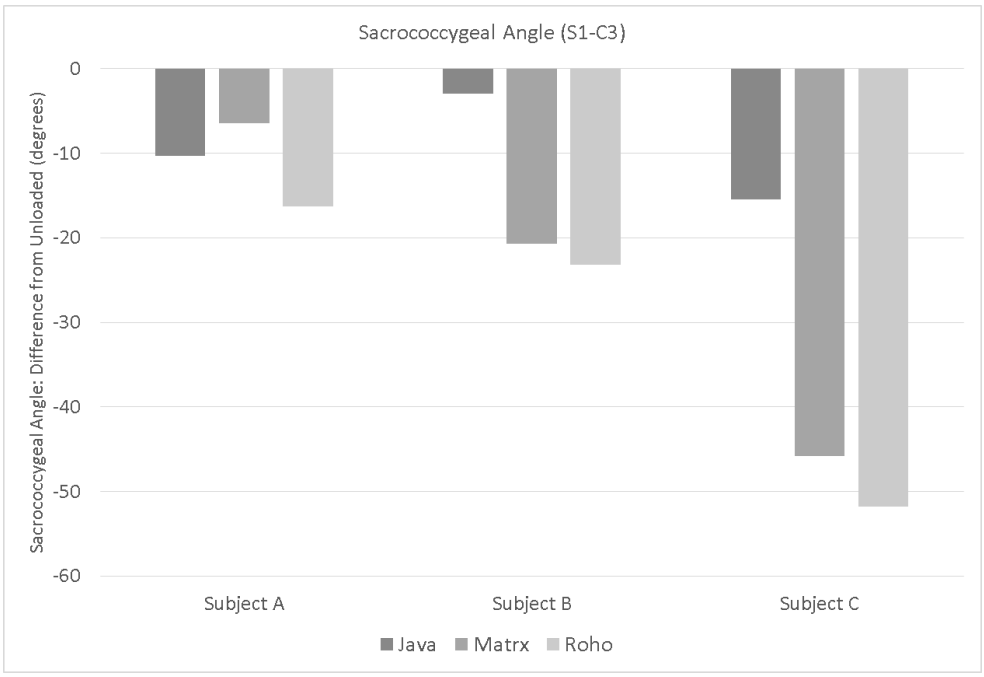


Figure 9. 3D Renderings of skin from the right half of the buttocks pictured from the lateral coronal view (Left) and posterior (Right). Note that flat edges in the lateral view depict the end of our field of view (e.g., Subject I on Java) and do not reflect the actual shape of the lateral tissue.

Sacral Loading

S1 was only visible in 3 participants because an artifact interfered with the image at the level of S1 in the fourth, so sacro-coccygeal angle was only reported for these 3 participants. When sitting in a loaded condition, the angle between the sacrum and coccyx was reduced on all cushions, but angle changes were greatest on the Roho HP. This is illustrated for Subject B in Figure 11.



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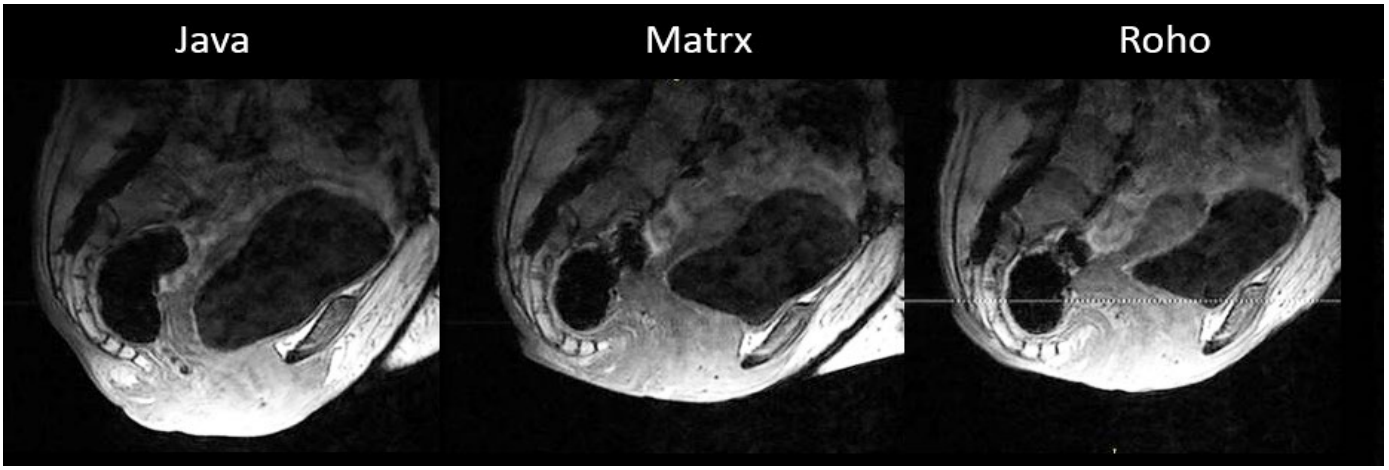
242 *Figure 10. Change in Sacro-coccygeal angle compared with unloaded.*



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244 *Figure 11. Mid-sacrum coronal slices for Subject B demonstrate the differences in coccyx orientation during sitting on different*

245 *surfaces.*

246 ## Interface Pressure Results

247 Peak Pressure Indices (PPIs) varied from 50 to 290 mmHg, with the lowest PPIs experienced while

248 participants were seated on the Java, and the greatest on the Matrx Vi (Figure 12). While higher

pressures often corresponded with increased deformation, that pattern was not always the case within nor across individuals (Figure 13).

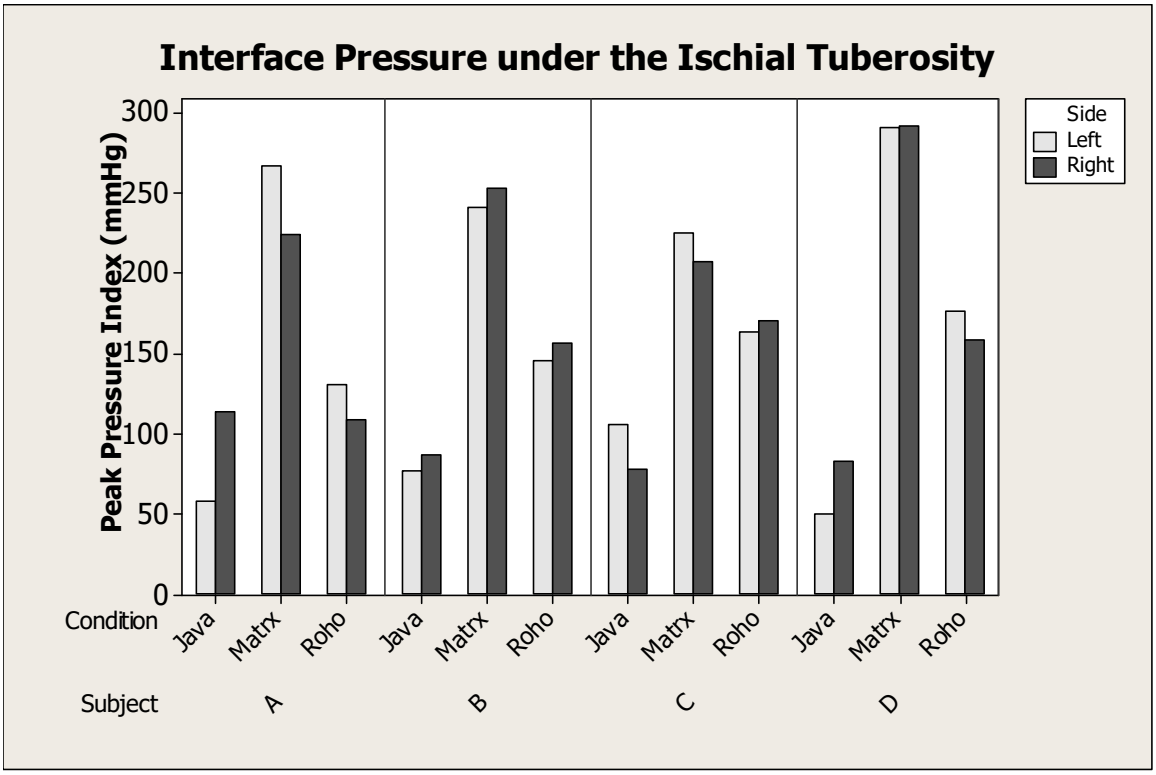

Figure 12. Interface pressure measured under the ischial tuberosities.

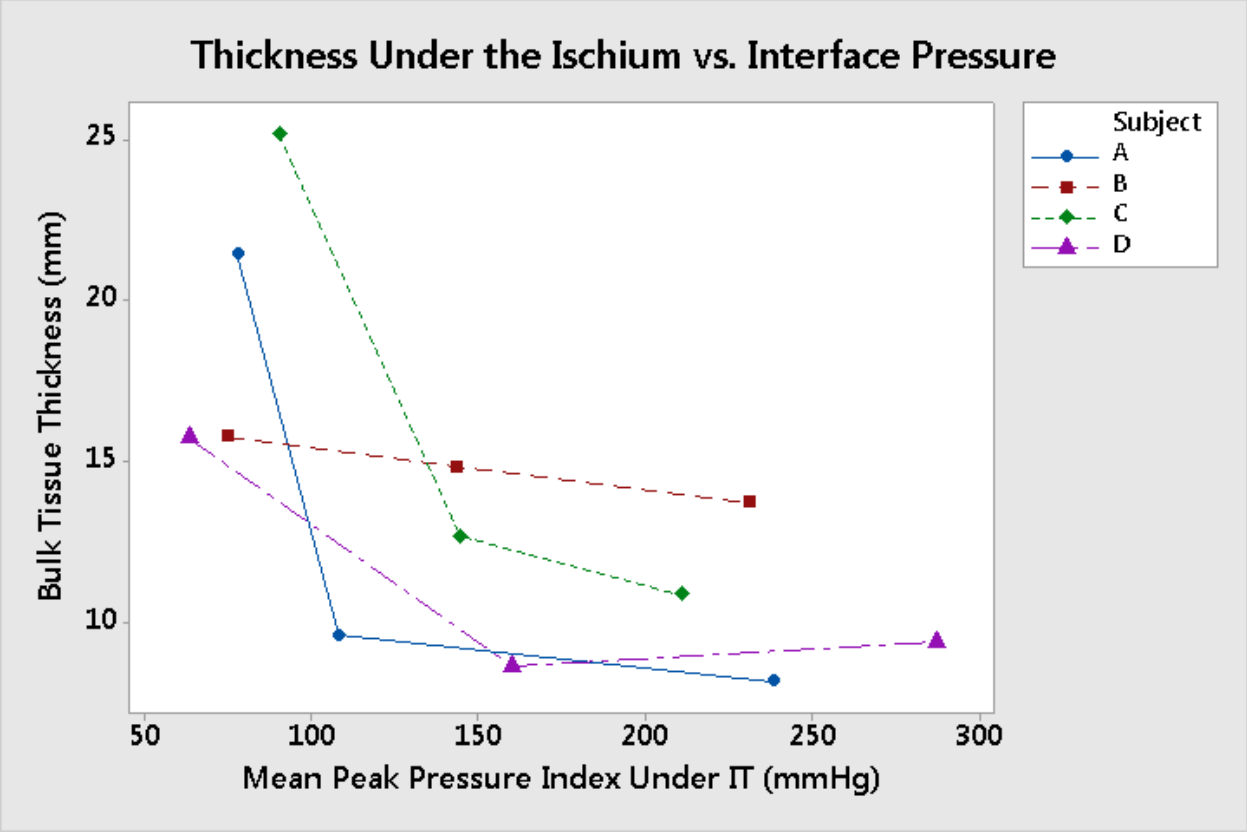

Figure 13. Relationship between tissue deformation and interface pressure under the ischium.

Overall Mechanisms of Support Across Cushions

The unloaded and loaded buttocks tissue obtained a different shape on each loading condition, as visible in the sagittal and coronal views presented in Figure 9.

Roho HP

The Roho cushion is an example of an air cell design, in which air redistributes between a matrix of connected cells in response to buttocks loading, resulting in envelopment of the buttocks. This design seeks to increase contact area and minimize pressure gradients. Cushions with similar designs include the Standard Contour Cushion by Star Cushion and the Pressure Equalization Pad by Ongoing Care Solutions, Inc.

Immersion of the buttocks into the Roho HP, or deflection of the Roho HP under load, was set by the investigators by adjusting the inflation level of the cushion. However, final measurements of the distance from the most inferior point of the buttocks to the seat base varied from 1.7 to 3.0 cm, corresponding to immersion values of 7.8-9.1 cm. The corresponding envelopment is visible in Figure 9, where the discontinuity in the surface contour represents the edge of envelopment. The inferior adipose and skin wrapped around the peak of the ischium, as evident by the decreased radius of curvature compared with unloaded (Figure 7 and Figure 8). Bulk tissue beneath the ischium changed in thickness by 2-2.5 cm compared with unloaded, displacing in the superior, posterior and lateral directions. Surrounding tissue was loaded from all directions around the ischium. Similarly, tissue around the greater trochanter was loaded at an angle for most participants. While the gluteus maximus did not wrap beneath the ischium during unloaded sitting, it displaced in the superior and lateral

directions when seated on the Roho HP (Figure 5). This is shown in Figure 5 as the red gluteus maximus being visible to the right and above the peak of the ischial tuberosity.

Matrx Vi

The Matrx Vi is a contoured foam cushion that uses multiple layers of different foam stiffnesses, including a viscoelastic layer, that seeks to envelop the buttocks and distribute loading based on compression of the foam layers. Many different manufacturers distribute contoured foam cushions with differing contours and material selections. The Comfort Acta-Embrace is an example of a similar cushion.

Because the Matrx Vi is a contoured cushion, less deflection of the cushion is expected for an equivalent amount of buttocks immersion compared with a flat cushion. Consistent with that, deflection of the Matrix under load was much smaller than on the Roho, with values ranging from 2.8-4.3 cm. Envelopment is visible in Figure 9. Similar to the Roho, the ischium sinks into the cushion, resulting in soft tissue wrapping closely around the ischium, with decreased radius of curvatures compared with unloaded. Unlike the Roho HP, however, loading seems to be mostly vertical, with the tissue posterior and anterior to the ischial region taking on a flat shape. The greater trochanter was loaded by a flat surface for most participants. Compared to the unloaded condition, the gluteus maximus compressed and deformed superiorly and laterally, and as in the other conditions, was not loaded by the ischium.

Java

The Java is designed to support load differently than immersion and envelopment based cushions such as the Roho HP and Matrx Vi. Instead, the Java takes an orthotic approach, using a balance of loading and off-loading characteristics. Consequently, the shape of the deformed buttocks looks different than on the Roho HP and Matrx Vi, with a large flat segment of skin and soft tissue in the gluteal region where the posterior-lateral supporting component of the Java cushion supports and deforms the tissue immediately inferior to the posterior iliac crest (Figure 9). Deformation is also noted at the posterior

proximal thigh just distal to the greater trochanters. In addition to supporting load at the posterior-lateral region and at the proximal thigh, tissue deformation beneath the greater trochanter suggests support of body weight there as well, in similar amounts to the other cushions. Despite complete offloading in 3 of 4 participants, tissue under the ischium still experiences deformation, with 23-60% deformation of bulk thickness. Adipose tends to displace in postero-medial and superior directions. Radius of curvatures tend to be greater (flatter) when seated on the Java compared with enveloping cushions. When seated on the Java, participants' gluteus maximus was deformed forward or anterior to cover a greater portion of the inferior-posterior portion of the ischium (Figure 5). Consequently, the presentation of the gluteus maximus was most similar to that of the unloaded buttocks when seated on the Java, but for most participants, even on the Java the gluteus maximus was still not loaded by the ischium.

Discussion

Comparison to Previous Work

As the scope of previous research regarding seated buttocks tissue deformation continues to grow, some consistent findings are noted. Foremost is the lack of muscle under the ischium, observed as little to no gluteus maximus present under the peak of the ischial tuberosity (12, 17, 18). This finding continues to suggest that finite element models depicting considerable muscle coverage are not consistent with actual anatomy (21, 22).

Bulk tissue deformation has been observed in the approximate range of 30-70% in people with spinal cord injuries across previous studies (17) (18). These results are fairly consistent with the current study, as was the variation noted across participants and surfaces. Based on these findings, the goal of ongoing

and future work must be to determine clinical characteristics of participants that will help in predicting the individual's response to sitting on different cushions.

Interface pressure mapping is a clinical tool used to evaluate clients as they sit upon one or more cushions. In 2007, Gefen and Levine published an article on why using interface pressure was a poor choice (23) and in 2009 Oomens, et. al also wrote about the importance of internal strain over interface pressure (24). We believe that IPM has clinical utility during seating evaluations. IPM can be used to identify cushions that poorly redistribute pressure, as indicted by high pressure magnitudes or asymmetry. The results of the present study and prior work corroborate that opinion. Results reflected a nonlinear relationship between interface pressure and tissue thickness which differed across participants. Figure 13 indicates that at higher pressures, corresponding buttock tissue thicknesses are smaller. This response is predicted by theoretical tissue mechanics, and illustrates that the tissues under the ischium can 'bottom-out' or reach maximum deformation at different interface pressures, depending on the individual. This result is similar to those found in previous studies. Sonenblum et. al, found a fairly wide range of individual tissue compliance in 35 persons with spinal cord injury (25). Using a tissue probe capable of measuring force and deflection, a 4.2 N force induced between 3.5 and 15.2 mm of tissue deflection, which represented between 64-96% of maximum deflection before the tissue bottomed out. Brienza, et al (26) found a relationship between IPM and tissue stiffness using a computerized support surface capable of controlling forces applies to the buttocks. In a cohort of persons with SCI, the results indicated that higher pressures were associated with higher stiffness. The authors inferred that greater tissue deformation resulted from the higher pressures and resulted in greater tissue stiffness at those loading levels. Using MRI in a recent study, Brienza et. al (17) did not find a group-wise significant relationship, and only some participants showed individual relationships between IPM and deformation. Their results support the idea that stress and strain might not be tightly correlated across cushion designs.

To better inform seating evaluations, the relationship between interface pressure and deformation should be further investigated. Because the IPM-deformation relationship appears to vary across individuals, it may be possible to use interface pressure to reflect deformation when combined with other individual characteristics such as age, diagnosis, tone, hip width, tissue thickness, and tissue compliance. Larger cohorts are needed that reflect a diversity of individual characteristics to establish clinical guidelines for IPM.

Mechanisms of Support

Wheelchair cushions use different approaches to manage body weight and reduce tissue loading and deformation at high risk areas such as the ischium, greater trochanters, and sacrum/coccyx. The Java uses an orthotic offloading approach, while Matrx Vi and Roho HP use envelopment and immersion, albeit in different manners. The results presented above on this cohort demonstrate that the orthotic, off-loading approach of the Java successfully offloaded the ischium in 3 of 4 cases, which led to reduced (but not eliminated) deformations of tissue beneath the ischium and increased deformation in the posterior-lateral region of the buttocks and the proximal thighs. The contoured foam cushion (Matrx Vi) allowed only a small amount of immersion in this population, leading to some redistribution of load across the pelvis and thighs. The air cell design of the Roho HP seeks to create a flotation effect while the individual is immersed in the air bladders. Consistent with this, the data showed loading appearing to wrap around the buttocks from multiple directions where it is enveloped in the cushion.

How tightly the tissue wraps around the ischium is in part reflected by the radius of curvature, with smaller radii beneath the ischium indicating tighter wrapping. The smallest radii of curvature were typically found in the enveloping cushion designs, although the data illustrate variability across

individuals (Figure 7 and Figure 8). Despite this variability, Figure 9 demonstrates some consistency in shape of the seated buttocks within each cushion, reflecting the cushion's shape compliance.

Biomechanical Risk

The study population was hand-picked to represent individuals with high risk buttocks that are difficult to support. Between the significant muscle atrophy and hypotonicity, and changes to the tissue compliance that are not documented in this study, there is not much tissue available to support the ischium. As the result of the reduced tissue quantity and quality, the pelvis nearly collapses through the soft tissue. Despite the lack of support for the pelvis and significant atrophy, however, only two of the four participants have experienced pressure ulcers. Further investigation is warranted to explain this. It is also worth exploring the possibility of deep tissue damage existing without concurrent visible changes. It is important to remember that amongst individuals who qualify for a skin protection wheelchair cushion, varying levels of biomechanical risk will be seen and loading conditions on the cushions presented are likely to differ considerably. In fact, even amongst these 4 participants, some considerable differences were noted in changes in tissue thickness, radius of curvature, and overall loading.

Wheelchair Cushion Shape Compliance

Wheelchair cushion shape compliance describes the ability of a cushion to support body mass without deforming the buttocks. Of course, when seated on any wheelchair cushion, the body will experience some deformation. Therefore, it becomes important not only to measure deformation, but to define shape compliance in a manner that considers the tissue responses across all of the high-risk regions in sitting. For example, deformation of tissue under the ischium was smallest for the Java, but all three cushions had comparable deformation under the greater trochanter. Similarly, tissue deformation under

391 the ischium was often greater on the Matrx Vi than the Roho HP, but the change in angle at the sacrum
392 (reflecting increased loading) was greater on the Roho HP than the Matrx Vi.

393 ## Sacrum and Coccyx Loading

394 This is the first study to report on the tissue response to sitting at the sacrum and coccyx. In general,
395 pressure ulcers are more prevalent at this region than at the ischium (27, 28), so the response is
396 important to investigate. Tissue deformation is difficult to assess in this region, so instead we chose to
397 look at the change in angle of the sacro-coccygeal joint. As the angle decreases and the coccyx inverts,
398 greater localized strains will be applied to the soft tissue present in the region. Figure 10 and Figure 11
399 demonstrate that the angle changes varied according to both cushion and subject. It is notable,
400 however, that participants were seated upright in a relatively neutral posture. Sacral loading and
401 deformation would likely change in a more slouched posture.

402 ## Clinical Implications for seating

403 Understanding the deformation of the seated buttocks in this study provides some clinical insight. First,
404 the results demonstrate that in every sitting condition there is some deformation present at the
405 ischium, but that the regions of greatest deformation tend to vary. Paying attention to those regions is
406 important. Significant loading of the sacrum and coccyx occurs, even in upright sitting.

407 The relationship between interface pressure and deformation was not linear nor consistent. However,
408 clinically speaking, interface pressures still have value. As mentioned previously, the areas of greatest
409 deformation are important and can often be identified using interface pressure mapping. Furthermore,
410 in the cases presented, most of the very high interface pressures still corresponded with higher tissue
411 deformation. While the deformation response depended on far more than interface pressure, in a
412 clinical setting, observation of relatively high peak pressures at high risk bony prominences may

encourage the seating professional to adjust and or pursue a more effective sitting surface, especially if skin redness has been noted.

Finally, achieving optimal seating conditions, even with expert skills was still challenging. Roho inflation was not always correct on the first try, nor was proper offloading on the Java always achieved on the first try. This leads to the question of how individuals maintain appropriate adjustment and how they position themselves on the cushions. Future work should investigate how cushion performance is maintained over time and how it varies according to posture, particularly individuals' typical sitting postures and activities, which are likely to differ from that supported in the test conditions described. Cushions need to perform well in a variety of conditions.

Limitations

As a case series of only 4 individuals, this study was not designed to draw broad, generalizable conclusions about cushion performance, but instead was designed to inform future studies to that end. As mentioned, the cohort of individuals was limited, as all had a very similar presentation and because deformation is dependent on individual characteristics, results are unlikely to generalize to individuals with different body types or diagnoses. Furthermore, individuals were scanned in relatively neutral postures, and as mentioned previously, cushion performance in other postures and during other activities should also be investigated. The duration of loading on cushions was approximately 15-20 minutes, so cushions with viscoelastic or temperature sensitive properties such as the Matrx Vi may deform further over time, allowing for increased immersion and possibly even bottoming out. Finally, this subset of cushions was selected because they represented different strategies of managing body weight. However, many cushion designs were not explored and would benefit from further study.

Conclusion

This was the first study to describe how different wheelchair cushion designs impact overall buttocks tissue deformation during sitting. The results highlighted the fact that all cushions deformed tissue somewhere, and that cushion design impacts how and where tissues deform. Shape compliance is a construct that can be used to describe performance, but it must first be defined. Future investigation of cushion designs needs to consider deformations at the ischium, coccyx, and trochanter. Parameters to describe deformation at these locations should be multi-planar and represent changes to the amount and shape of tissue. They may include: average thicknesses over a region of interest, radii of curvature of the skin, and the sacro-coccygeal angle to describe sacral loading. Three dimensional visualizations of the tissue response provide greater insight to the measurements. Finally, the results of this study highlighted the importance of individual characteristics on buttocks response to load, even within persons at high risk. Tools to evaluate individuals' biomechanical risk are necessary for optimizing wheelchair cushion prescription.

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