Basic research

3D anatomy and deformation of the seated buttocks

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KEYWORDS
MRI; Sitting; Anatomy; Tissue deformation; Pressure ulcer

Abstract  Aim: To describe the 3D anatomy and deformation of the buttocks during sitting. Materials and methods: The buttocks of 4 able-bodied individuals and 3 individuals with spinal cord injury were scanned sitting in a FONAR Upright MRI. T1-weighted Fast Spin Echo scans were collected with the individuals seated on a custom wheelchair cushion to unload the ischial tuberosities (ITs) and seated on a 3 inch foam cushion. Multi-planar scans were analyzed, and the muscle, bone and adipose tissue was manually segmented for 3D rendering and analysis of the quantity, geometry, and location of tissues. Results: The gluteus maximus was positioned lateral and posterior to the IT, covering the inferior portion of the IT for only 2 able-bodied participants. Adipose thickness directly under the IT did not differ by diagnosis, nor did it have a consistent response to loading. However, the envelopment of the IT by the surrounding adipose tissue was much greater in two of the participants with spinal cord injuries. These two subjects also had the most curved skin surface as the tissue wrapped

Abbreviations: SCI, spinal cord injury; IT, ischial tuberosity; FE, finite element; GM, gluteus maximus; ROI, region of interest; DTI, Deep tissue injury.

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around the IT. Tissue strains around the ischium were most visible in the adipose and connective tissue. The gluteus maximus displaced and distorted upwards, posterior and lateral, away from the inferior IT.

Conclusions: Multi-planar imaging is necessary to investigate anatomy and deformation of the buttocks. 5 out of 7 participants did not sit directly on muscle. The tissue beneath their ITs was predominantly composed of fat and connective tissue, suggesting that these tissues might be most vulnerable to injury.

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1. Background

Sitting for extended periods is common across many populations, with reports of healthy adults sitting for more than 6 h per day [1,2]. But for individuals who use wheelchairs as their primary mobility device, sitting times have been measured as upwards of 10–12 h per day [3–5]. These individuals typically have reduced mobility and sensation, and therefore they are at increased risk of tissue breakdown and pressure ulcer development. In fact, more than 50% of individuals with spinal cord injury (SCI) experience skin breakdown at some point in their lives [6–8], adversely impacting their quality of life [9,10], and burdening the health care system with significant treatment costs [11].

Pressure ulcers, by definition, result from localized tissue loading that causes a series of pathophysiological responses to deformation. The precise mechanisms by which internal loading and physiological responses lead to pressure ulcers (PUs) are not known, however current evidence suggests that damage can result directly from the deformation [12,13], or from impairment to blood flow caused by deforming tissue under load [14,15]. Individuals with SCI can exhibit much greater deformation during sitting due to changes to buttocks tissue mass and compliance [16–19]. The range of tissue properties in persons with SCI may, in fact, reflect a spectrum of PU risk within this high-risk group.

In Sonenblum et al. [20], we introduced the concept of Deformation Resistance. “Deformation Resistance can be defined as the intrinsic characteristic of an individual’s soft tissues to withstand extrinsic applied forces.” In order to develop a method for measuring Deformation Resistance, and later determining individualized risk, we first need to understand the loaded anatomy, as well as the types of deformations experienced during sitting.

An understanding of buttocks tissue deformation during sitting is also important for supporting Finite Element (FE) analyses of the buttocks. FE analysis is a powerful computational tool that can facilitate investigation of more conditions than possible with direct measurement. Furthermore, it is a tool that can assist in estimating tissue’s mechanical properties and identifying the individual parameters that have the greatest influence on an individual’s Deformation Resistance. FE has been applied to characterize sitting mechanics and evaluate wheelchair cushion designs [17,21–30]. Unfortunately, FE models present in the literature do not reflect actual variations in buttocks anatomy because that information is not available in the literature, thereby limiting the external validity of existing FE models. Furthermore, validation of existing FE models requires a complete 3D assessment of deformation under load, which has not been studied.

Therefore, the overall objective of this paper was to describe the 3D anatomy and deformation of the buttocks during sitting. The project employed 3D, seated Magnetic Resonance Imaging (MRI) and image segmentation and analysis of 7 individuals’ buttocks to describe the 3D shape, size, location and distribution of tissue underneath the pelvis, and to determine how these changed between an unloaded condition and seated on foam.

2. Methods

2.1. Subjects

We sought to study a small but diverse subset of individuals. The 7 subjects, described in Table 1 (4 able-bodied and 3 subjects with a spinal cord injury) were recruited for their diversity, convenience, and availability. Only one of the participants, Subject G, had a history of pelvic pressure ulcers (contralateral to the imaged side). Institutional Review Board approval was received from the local institution and informed consent was acquired from the recruited participants.
2.2. Test environment

Participants were scanned in two seated conditions: an "IT Unloaded" posture and seated on flat foam. In the "IT Unloaded" condition, all surface contact and normal loading were removed from the ischial tuberosities (ITs), but other parts of the neighboring tissue were loaded as necessary to manage the subjects' body weight in a seated posture. Subjects A, B, C, and G were scanned on a contoured foam cutout, which unloaded the ITs but supported the body weight on the greater trochanters. Subjects D, E, and F were supported by a stiff foam underneath the thighs, which off-loaded both the ITs and the trochanters.

For the loaded condition, participants were scanned while seated on a piece of 3'' flat foam (high resilience 45 indentation load deflection (ILD) foam). This foam is commonly used in seat and wheelchair cushions and was selected to provide a stable sitting surface during the loaded scan. Able-bodied subjects sat themselves on the relevant cushion. Participants with SCI transferred into an MRI-compatible transfer chair (Fig. 1) for transport into the scanner area and up the ramp, and then transferred onto the cushion. Seated stability was augmented from the lateral proximity of the MRI magnets as well as a horizontal support bar positioned in front of the subject on which they could rest their arms.

2.3. Scan protocol

The scans were collected using a T1-weighted Fast Spin Echo protocol previously described in Ref. [20]. Scans included 60 contiguous sagittal slices of 3 mm thickness, and a 350 mm field of view.

2.4. Data processing

Raw DICOM scans were imported into Analyze AVW v11.0 for review and segmentation of the pelvis, gluteus maximus (GM), and subcutaneous fat. Semi-automated segmentation was performed under the supervision of an experienced radiographer (JC). Segmentation of tissue on scans of this resolution does not allow for separate segmentation of skin, so the skin is included within the subcutaneous fat segmentation when visible. Point clouds of the 3D segmented surfaces of the bones,

### Table 1  Subject characteristics.

<table>
<thead>
<tr>
<th>Subject ID</th>
<th>Gender</th>
<th>Age</th>
<th>Weight (lbs)</th>
<th>Diagnosis</th>
<th>Unloading method</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>F</td>
<td>32</td>
<td>115</td>
<td>a/b</td>
<td>Contoured foam cutout</td>
</tr>
<tr>
<td>B</td>
<td>M</td>
<td>52</td>
<td>209</td>
<td>a/b</td>
<td>Contoured foam cutout</td>
</tr>
<tr>
<td>C</td>
<td>M</td>
<td>53</td>
<td>185</td>
<td>a/b</td>
<td>Contoured foam cutout</td>
</tr>
<tr>
<td>D</td>
<td>F</td>
<td>23</td>
<td>117</td>
<td>a/b</td>
<td>Thigh support</td>
</tr>
<tr>
<td>E</td>
<td>M</td>
<td>18</td>
<td>105</td>
<td>SCI — C6/C7 Complete</td>
<td>Thigh support</td>
</tr>
<tr>
<td>F</td>
<td>M</td>
<td>43</td>
<td>190</td>
<td>SCI — T12 Incomplete</td>
<td>Thigh support</td>
</tr>
<tr>
<td>G</td>
<td>M</td>
<td>56</td>
<td>260</td>
<td>SCI — T12 Complete</td>
<td>Contoured foam cutout</td>
</tr>
</tbody>
</table>

Fig. 1  MRI compatible tools to assist with transfer into the Upright scanner. A) Elevating transfer chair. B) Ramp, platform, and grab bar in the scanner. C) "IT Unloaded" cushion with a contoured cutout. D) "IT Unloaded" cushion that also unloads the greater trochanters.
muscles, and fat were exported for further analysis in Matlab 14.0.

2.5. Data analysis

Analysis was completed in Analyze 11.0 (review, registration, and muscle properties) and Matlab R2014a (remaining measurements). In order to describe the anatomy of the buttocks during sitting, we performed multi-planar qualitative review of the scans. The "IT Unloaded" and foam scans were manually registered in 3D to align the pelvises for comparison. The volume and surface area of the segmented GM was exported from Analyze 11.0. Additionally, we identified the tissue within two regions of interest (ROI) underneath the peak of the IT, defined as the lowest point of the ischium (Fig. 2). The ROI were vertical cylinders with diameters of 50 mm and 10 mm. The 50 mm ROI was selected based upon the size (approximately 50 mm long) and anterio-lateral orientation of the IT [31,32]. The percent of gluteus coverage (%GlutCoverage) was defined as the percent of the 50 mm ROI covered by at least 2 mm of GM. The radius of curvature of the superficial skin surface within the 50 mm ROI was calculated in the sagittal and coronal planes. The best fit radius of curvature of a contour was computed using a least squares fit to identify the center of the best fit circle, where the inverse of the radius was the radius of curvature [33]. The average tissue thickness underneath the peak of the IT was measured in the 10 mm region.

3. Results

Coronal and Sagittal MRI images for each of 7 subjects seated on foam illustrate the wide variety in seated buttocks anatomy (Fig. 3). The sagittal views show the ischium projecting inferior from the acetabulum. Slight differences in the ischial projection may be attributed to slight differences in pelvic tilt or anatomical variation. The sagittal views highlight the anterior-posterior projection of the GM (highlighted in red) and the hamstrings and adductor magnus which originate from the anterior aspect of the ischium. Both views highlight differences in the location of the GM and differences in the thickness of the skin and subcutaneous tissue underneath the IT.

3.1. Gluteus maximus

The GM varied considerably in volume across the 7 subjects, with a mean (SD) of 677 cm$^3$ (325 cm$^3$) (Table 2). The able-bodied male subjects (B & C) had the greatest muscle volume. Respective volumes of two able-bodied women and two men with SCI (subjects D & F and subjects A & E) were also similar. Subject G showed considerable atrophy with a muscle volume 60% less than other subjects. The surface areas of the GM were highly correlated with the volumes (correlation coefficient $r = 0.958$, $p < 0.001$), and averaged 751 cm$^2$ (157 cm$^2$). Muscle shape varied considerably, including a thick, flat gluteus (e.g., Subject B), very thin, highly atrophied gluteus (Subject G), and some more curved glutei that wrapped around the femur (Subjects E, F) (Fig. 3).

The GM was typically positioned lateral and posterior to the IT, although the location of the GM varied widely across the 7 subjects, and its position did not appear to be a function of the muscle volume. In both the "IT Unloaded" and loaded conditions, Subjects A and C presented with an appreciable amount of the IT covered by the GM. In both subjects, sitting on foam displaced the GM away from the IT, reducing the GM coverage from 97% to 48% for Subject A and 87% to

Fig. 2 The 50 mm region of interest (ROI) includes the most heavily loaded tissue underneath the IT, and the 10 mm ROI describes the region just beneath the peak of the IT. The 50 mm ROI is also highlighted in red on the pelvis (inferior medial views) to describe what region of the pelvis is included in the ROI.
64% for Subject C. Subjects B, D, and E had minimal IT coverage with none of the muscle wrapping underneath the ITs’ most inferior aspect within the 10 mm ROI (Table 2). Subject E was the only subject with SCI who exhibited any ischial coverage by the GM.

Fig. 4 displays a 3D rendering of the segmented gluteus maximus and pelvis in order to illustrate the relationship between the GM and ischium for Subjects C and G seated on foam. In Subject C, an able-bodied male, the GM covers the body of the ischium including the tuberosity and is largely positioned posteriorly and lateral to that bony prominence. The GM of Subject G, a male with SCI, rests entirely posterior and lateral to the ischium. It is not loaded by the ischium as he sits upon the foam cushion.

3.2. Adipose tissue and skin

As with the GM, considerable variation was observed in the quantity and distribution of subcutaneous fat under load. Fat and skin thickness directly under the peak of the IT averaged 13 mm (9 mm) (Table 2), but Subject B was the only person with a thickness greater than 15 mm. The average loaded thickness was 10 mm for the other six subjects. The shape of the skin under the ischium in both seated conditions is described by the radius of curvature (Fig. 5). When seated on foam, the radii of curvature of Subjects A & B increased (i.e., became flatter). In distinction, the other subjects exhibited a decrease in the radii of curvature when the buttocks was loaded. That is, their tissue conformed around the ischium and formed a more curved shape compared to the IT unloaded condition. Subjects F and G, the two men with T12 spinal cord injuries, had the smallest radius of curvature, or the sharpest curved skin when seated on foam.

The envelopment of the IT by the surrounding adipose tissue also varied across subjects. The 3D renderings in Fig. 6 illustrate the differences in three subjects. The adipose tissue is separated from the bone by a variety of tissue types and quantities while seated (Fig. 3). For Subject B, the adipose tissue is separated from the bone by muscle, connective tissues, and fat deposits in

<table>
<thead>
<tr>
<th>Subject</th>
<th>GM volume (cm³)</th>
<th>GM surface area (cm²)</th>
<th>% Gluteus Coverage</th>
<th>Avg fat thickness in 10 mm ROI (mm)</th>
<th>Average GM thickness in 10 mm ROI (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IT unloaded</td>
<td>Foam</td>
<td>IT unloaded</td>
<td>Foam</td>
<td>IT unloaded</td>
</tr>
<tr>
<td>A</td>
<td>466</td>
<td>656</td>
<td>97</td>
<td>48</td>
<td>14</td>
</tr>
<tr>
<td>B</td>
<td>1116</td>
<td>940</td>
<td>4</td>
<td>3</td>
<td>59</td>
</tr>
<tr>
<td>C</td>
<td>1119</td>
<td>969</td>
<td>87</td>
<td>64</td>
<td>8</td>
</tr>
<tr>
<td>D</td>
<td>662</td>
<td>691</td>
<td>19</td>
<td>17</td>
<td>18</td>
</tr>
<tr>
<td>E</td>
<td>452</td>
<td>612</td>
<td>5</td>
<td>7</td>
<td>15</td>
</tr>
<tr>
<td>F</td>
<td>635</td>
<td>808</td>
<td>0</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>G</td>
<td>292</td>
<td>578</td>
<td>0</td>
<td>0</td>
<td>30</td>
</tr>
<tr>
<td>Mean</td>
<td>677</td>
<td>751</td>
<td>30</td>
<td>20</td>
<td>21</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>325</td>
<td>157</td>
<td>43</td>
<td>26</td>
<td>18</td>
</tr>
</tbody>
</table>
between the sheaths of the muscle groups, resulting in a relatively flat layer of adipose tissue, while Subjects F and G have very little muscle tissue between the bone and adipose. As a result, the adipose wraps closely around the ischium.

### 3.3. Deformation

Multi-planar comparisons of two males with similar levels of spinal cord injury (Subjects F and G) offer insight into the internal strains experienced by the buttocks tissue while sitting (Figs. 7 and 8). Both subjects experienced a significant change in shape of the tissue, especially the visceral fat and muscle surrounding the IT. Interestingly, the skin and fat directly beneath the IT of Subject F did not noticeably change between the two loading conditions, whereas Subject G experienced considerable vertical displacement underneath the IT. Yet, despite this lack of linear change in subcutaneous fat, Subject F experienced considerable deformation in the tissue surrounding the IT, as visible by the significant change in tissue shape in the coronal view (Fig. 7). The hip extensor and adductor muscles of Subject G are highly atrophied, and their space is filled with highly deformable adipose tissue anterior to the ischium (Fig. 8, Vfat). The change in projection of the common hamstring insertion (Fig. 8, HST) to a slightly more superior position from the prominence of the IT, is consistent with strain of the tissue around the ischium.

As mentioned previously, the dark spaces beneath the ischium are connective tissue and indicate these structures are directly loaded during sitting. These regions may experience deformation as well, but it is difficult to quantify at this resolution.

With respect to the GM, deformation is characterized by both displacement and distortion of the muscle. Subjects’ muscles were displaced away from the peak of the IT. Specifically, Subject F exhibits deformation to the inferior portion of the muscle, which is displaced upwards. The inferior muscle shifts anterior to the IT (Fig. 8, GM).

![Fig. 4](image1.png)  
**Fig. 4** Positioning of the gluteus maximus (blue) relative to the ischium (white) for Subjects C and G. The femur is also shown. Hidden bone is outlined in red, hidden muscle is outlined in blue.

![Fig. 5](image2.png)  
**Fig. 5** Radius of curvature of the skin under the ischium.
aspect of the GM also displaces slightly towards the posterior and lateral directions (Fig. 7), but the remainder of the muscle experiences very little change with load. The GM for Subject G, though difficult to assess in Fig. 8, undergoes very little distortion or displacement. The subjects who sit on their GM (Subjects A and C) experience more significant posterior and lateral deformations of the GM when sitting on foam (e.g., Fig. 9).

4. Discussion

This is the first study to investigate the 3-dimensional anatomical characteristics and tissue deformation of the seated buttocks across multiple people, including able-bodied and individuals with SCI.

One of the most significant observations from this study was that the tissue beneath the ITs of the participants was predominantly composed of fat and connective tissue, with little or no muscle present. This is inconsistent with the assumptions dominating the PU literature. Although the description of Deep Tissue Injury (DTI) by the NPUAP refers to the "underlying soft tissue" and contains no mention of muscle, the pressure ulcer staging illustrations present bone layered with muscle, fat and skin [34,35]. As concern over DTIs has escalated in the past decade, researchers have begun to define a DTI as damage to the muscle overlying the bone (e.g. Refs. [36,37]). In fact, much of the recent PU research has focused on internal muscle strain [27,28,38–42]. Yet the results above suggest that the muscle, particularly the GM, is often not loaded directly by the bone, and is therefore unlikely to experience the largest stresses and strains of the buttocks tissue at the ischial interface. Therefore, in addition to the...
current efforts to study muscle, PU research should address the loading on fat and connective tissue as tissues that may herald necrosis during DTI formation.

In addition to informing the future direction of pressure ulcer research, these results indicate that previous studies of buttocks tissue strain, particularly those utilizing finite element models of the buttocks need to be interpreted with caution with respect to generalizability. The published models frequently reflect the anatomy of Subject C, whose GM is directly loaded by the ischial tuberosity [21,25,39,42,43]. This anatomical presentation was found to be in the minority and was inconsistent with the anatomy of many of our subjects. In the very least, the anatomical variation identified in this study indicates that the tissues exposed to high stresses under the ischium do not involve significant muscle in 5 of the 7 subjects scanned. Furthermore, the deformations observed

Fig. 8  Comparison of the Subject G’s buttocks with the “IT Unloaded” and seated on foam. In the overlapping image, Green = unloaded and Red = Foam. GM = gluteus maximus, fat = subcutaneous fat, Vfat = visceral fat, HST = common hamstrings tendon, STL = sacrotubertous ligament.

Fig. 9  Comparison of Subject C’s buttocks with the “IT Unloaded” and seated on foam. In the overlapping image, Green = unloaded and Red = Foam. GM = gluteus maximus, fat = subcutaneous fat, Vfat = visceral fat, HS = hamstrings, AbM = abductor magnus, HST = common hamstrings tendon, OI = obturator internus, STL = sacrotubertous ligament.
in fat indicate a wide range of stiffnesses across individuals, and computational models must reflect those differences.

As this is the first study to fully investigate the 3D anatomy and deformation of the seated buttocks, there are few studies available for comparison of results. However, the results strongly support the need to use multi-planar analyses to investigate buttocks anatomy and deformation. Related studies investigated the tissue thickness directly under the peak of the IT during sitting [44,45]. While fat thickness under the peak of the IT was similar to measurements in the present study, the previous studies reported an average of 8.2 mm of muscle under the peak of the IT. This is inconsistent with our findings, as 5 of 7 participants had no gluteus muscle present directly beneath the peak of the IT (in the 10 mm ROI) when unloaded (Table 2). Although the source of the discrepancy is unknown, our results did show that analyzing a single slice of data hinders the ability to identify tissues accurately. We relied on multi-planar analysis to identify the anatomy. Furthermore, it is important to note that measuring tissue thickness underneath the IT provides an incomplete assessment of the buttocks anatomy in sitting. For example, Table 2 shows that Subjects C and G have similar thicknesses of fat directly under the peak of the IT when seated on foam (7 and 6 mm, respectively), but the distribution of that fat was very different for the two subjects (Figs. 9 and 8, respectively). One additional related study found GM volumes and differences in volume between able-bodied individuals and persons with SCI consistent with the results presented above [38].

Although the present study was not designed to quantify Deformation Resistance, it illustrates the differences in Deformation Resistance across individuals. The 3 subjects with SCI showed a disparate response to loading. Subject E demonstrated a Deformation Resistance that was similar to the 4 able-bodied subjects. On the other hand, the latter two participants with SCI appear to have much less Deformation Resistance than the able-bodied participants. Both Subjects F and G have very highly curved tissue (i.e., low radius of curvature) while seated on flat foam. They also both present with subcutaneous adipose tissue that wraps around the ischium in response to loading, as compared with Subject B whose adipose tissue remains supported by internal structures and maintains its shape. It can be inferred that the shear stresses and strains experienced by Subjects F and G are considerably greater than those experienced by other subjects, who experience more uniform deformation of the adipose tissue. Clinically speaking, Subject B has a high Deformation Resistance, and appears as if he can sit on a cushion support surface with limited risk to his tissue. Subject G, who has a history of recurrent pressure ulcers (at the contralateral IT), experiences highly non-uniform tissue deformation, which is consistent with a high risk for tissue breakdown. His cushion prescription and pressure relief regimen need to reflect that increased risk.

4.1. Limitations

This study measured 7 seated individuals. Quantitative descriptions of complex tissue strains are necessary to augment the results of this study, and are planned for future work. This study was limited to only a single loaded surface (foam) and did not investigate the deformations experienced on different cushions, nor did it investigate the influence of varied postures. It is likely that pelvic tilt (i.e., slouching versus sitting upright) will have a significant impact on the seated anatomy and tissue deformation because load will be transferred from the bony skeleton to the soft tissues differently. The influence of pelvic posture should be investigated. Unfortunately, controlling posture in the FONAR upright scanner is challenging due to the narrow space. Furthermore, complete off-loading of the buttocks while seated is problematic, because the body weight must be supported somehow. In this study we balanced the need for postural stability throughout the scan with the need to offload the tissue under the ischia and coccyx. However, it is possible that tissue surrounding the IT experienced loading. Additionally, an expanded population including individuals who are African-American and women with SCI is also needed to improve our understanding of variation in seated buttocks anatomy and deformation. With regards to the analysis method, manual segmentation is always subject to variation and user error. For this study, we addressed segmentation concerns by having all segmentations reviewed by an expert, and by intentionally selecting measurements that were not highly sensitive to changes in segmentation. However, a more automated segmentation would be a valuable addition to the processing approach.

5. Conclusions

This study illustrated the importance of using multi-planar imaging to investigate anatomy and deformation of the buttocks. Multi-planar imaging
provided the surprising result that only 2 out of 7 participants had appreciable amounts of muscle underneath their ischial tuberosities. The tissue beneath their ITs was predominantly composed of fat and connective tissue, suggesting that these tissues might be most vulnerable to injury.

Conflicts of interest
None.

References


