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Xuguang Wang, Léo Savonnet, Loïc Capbern, Sonia Duprey

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Xuguang WANG (corresponding author)
Research Director
LBMC/TS2
Université Gustave Eiffel
Email address: xuguang.wang@univ-eiffel.fr

Léo Savonnet
Post-doctoral Researcher
LBMC/TS2
Université Gustave Eiffel
Email address: savonnet.leo@gmail.com

Loïc Capbern
Master student
LBMC/TS2
Université Gustave Eiffel

Sonia Duprey
Associate Professor
Université Lyon 1
sonia.duprey@univ-lyon1.fr

Conflict of Interest (several sample statements are provided below)
The authors declare no conflict of interest.

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Manuscript

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Occupational Applications

We investigated the effects of seat pan inclination and foam on the deformation of the seated buttocks using an upright MRI system. From observations among four healthy males, we found that soft tissue deformation under the ischial tuberosity (IT) could be reduced not only by using a soft cushion, but also by decreasing the shear force on the seat pan surface. These results suggest that soft tissue deformation could be used as an objective measure for assessing seating discomfort and injury risk, by accounting for the effects of both contact pressure and shear. We also confirmed that the gluteus maximus (GM) muscle displaced away from the IT once seated. As peak pressure and shear are most likely located below the IT, more realistic computational human body models in this region are needed that consider muscle sliding.

Technical Abstract

Background: A full understanding of soft tissue deformations, particularly in the gluteal region in a seated position, would be helpful for improving seat comfort and reducing the injury risk of seated people. Thanks to recent developments in medical imaging, direct observations of soft-tissue deformations under realistic loading conditions is now possible using open MRI.

Purpose: The purpose of this work was to investigate the effects of seat pan inclination and foam on the deformation of soft tissues in the gluteal region using an open MRI.

Methods: Four healthy male participants completed the experiment, in which a positional MRI scanner was used to scan the buttocks and part of the thighs. Three seating conditions were tested by varying the seat pan angle (A_SP) and cushion material while the backrest was fixed

at 22 degrees from the vertical: 1) A_SP=7° without foam (Reference); 2) A_SP=0° without foam (Shear); 3) A_SP=7° with a 50 mm thick foam on the seat pan (Foam). In addition, one configuration (Unloaded), with the buttocks being unsupported, was also scanned for comparison. After segmenting images, we calculated the volumes of the gluteus maximus (GM) muscle and subcutaneous fat in three regions of interest under the ischial tuberosity (IT) for each condition.

Results: Once seated, the GM displaced away from the IT laterally and posteriorly. For all participants, the largest tissue deformation was observed in the Shear condition, while the smallest was found in the Foam condition.

Conclusions: The present study provides quantitative data needed for validating buttock-thigh finite element models. Future work is needed to link soft tissue deformation with discomfort perception.

Keywords: Seating, Comfort/discomfort, soft tissue, deformation, biomechanics, MRI, Finite element modeling

1 Introduction

People spend more and more time seated in transportation, at home, and at an office. Comfort is not only an important sales argument for the seat manufacturers, but is also well recognized as an important health factor for sitters. Long-term sitting may lead to discomfort (De Looze et al., 2013, Hiemstra-van Mastrigt et al., 2017), and even to pressure sores for wheelchair users (Olesen et al., 2010). Despite the large number of existing seating (dis)comfort studies, there is a lack of objective methods for assessing seating discomfort. De Looze et al. (2003) proposed a conceptual model of seating comfort and discomfort based on a literature review. They suggested that stronger relationships with objective measures might exist for discomfort compared to comfort, in agreement with the model of comfort and discomfort initially proposed by Zhang et al. (1996). Among the 21 studies reviewed by De Looze et al., the following objective measures were used: sitting posture and movement shifts, muscle activities measured by EMG, pressure distribution, spinal load indirectly estimated by stature loss, and foot swelling.

Thanks to its ease of use and relatively low cost, a pressure mapping system is frequently used for objectively assessing seating discomfort. Zemp et al. (2015) reviewed studies investigating the relationships between pressure and discomfort. They concluded that the question whether contact pressure measurements are suitable for assessing seating comfort or discomfort could not yet be answered definitely, due to limited available data. More recently, Hiemstra-van Mastrigt (2017) made an extensive review on passenger seat comfort and discomfort in a human-product-context interaction. They found that there exist correlations between anthropometric variables and interface pressure variables, and that these relationships are posture dependent. However, the relationships between pressure variables and passenger comfort and discomfort are still not clear and could not be quantified due to a lack of statistical evidence.

Apart from interface pressure, other biomechanical parameters such as intervertebral disc pressure, soft tissue deformation, muscle forces, shear force at contact interface, are rarely studied, even though they are generally considered as relevant for assessing seating discomfort (see for example, Rasmussen et al., 2009 and Al-dirini et al., 2015). In particular, high shear forces on the seat may lead to large deformations of soft tissues and reduced blood flow (Goossens et al., 1994). The main reason for this lack of studies is that these biomechanical parameters cannot be easily measured experimentally. Computational human models are therefore needed to estimate these biomechanical variables indirectly. Two types of human models have been developed, deformable finite element (FE; see Savonnet et al., 2018 for a review) and rigid multi-body musculoskeletal (MSK; Rasmusen et al., 2009) models. However, these models are generally not validated under the conditions relevant for seating applications (Wang et al., 2019b).

Most existing studies on seating comfort used a real seat or an experimental seat affording little opportunity to vary design parameters (Hiemstra-van Mastrigt et al., 2017). It is therefore difficult to isolate the effects of a particular seat parameter or to examine interactions with other variables. To understand the effects of shear force, and to develop quantitative guidance regarding seat design, we recently built a multi-adjustable experimental seat equipped with force sensors to measure all contact forces (Beurier et al., 2017). We investigated the effects of seat parameters and anthropometric dimensions on preferred seat profile and contact forces (Wang et al., 2018 and 2019a). Results of this work have provided quantitative guidelines for the ergonomic design of future seats as well as data for validating computational human models, especially for providing loading boundary conditions. Further, we used both deformable FE (Savonnet, 2018) and MSK (Theodorakos et al., 2018) modeling approaches for assessing seating discomfort. Thanks to recent progress in medical imaging, it is possible to observe spine and pelvis positions and soft tissue deformation directly. Existing computational human models need to be further validated with the help of medical images in seating conditions and with

realistic boundary conditions. Relationships between biomechanical parameters and discomfort still need to be further investigated, so that objective criteria could be defined and implemented in a computerized human model.

In recent years, a few researchers have used an upright MRI system to investigate soft tissue anatomy in the buttocks during sitting, and have quantified soft tissue deformation particularly in the ischial region (Al-Dirini et al., 2015, Sonenblum et al., 2015, 2018, 2020; Call et al., 2017, Brienza et al., 2018). All of these studies, though, only focused on a single upright-seated position, and most of them studied the effects of wheelchair cushion types on tissue deformation. To our knowledge, few researchers have investigated the effects of seat design parameters and their possible interaction on tissue deformation. Thus, the main objective of the present work was to investigate, through a case study, the effects of seat pan inclination and foam (indirectly contact pressure and shear force) on the deformation of soft tissues in the gluteal region using an open MRI.

2 Methods

2.1 Participants

As a case study, four healthy male participants were recruited, and their characteristics are summarized in Table 1. The ethics committee at the Université Gustave Eiffel's (formerly the French Institute of Science and Technology for Transport, Development and Networks – IFSTTAR) approved the experimental protocol. Informed consent was obtained prior to the experiment for all participants. As the MRI system had a width of 60 cm in the scanning space, participants were selected with a relatively small BMI, which varied from 20.3 to 27.6 kg/m^2. None of the participants had metallic implants or suffered from claustrophobia.

Table 1. Age, stature, body mass, and BMI of the four participants

Participant	P1	P2	P3	P4
Age (years)	28	52	35	31
Stature (cm)	173	163	169	187
Body mass (kg)	61.2	67.3	77.6	79.8
BMI (kg/m²)	20.3	25.9	27.6	23.6

2.2 Experimental conditions

While in an upright MRI scanner (Paramed® 0.5 Tesla, Figure 1), participants were scanned in three seated positions and in one so-called 'Unloaded' position (Figure 2). The resolution of the scans was set to 3.1 mm slice thickness, and 3.1 mm slice gap. The field of view was adjusted to 300 x 300 x 150 mm in the sagittal, transversal, and coronal planes, respectively, for the left side for each acquisition. For the Unloaded condition, the buttocks and thighs were free of loading except gravity. The three seated conditions were defined by varying the seat pan angle (A_SP) and cushion material, while the back was fixed at 22 degrees from the vertical: 1) A_SP=7° without foam (Reference); 2) A_SP=0° without foam (Shear); and 3) A_SP=7° with a 50 mm thick foam on the seat pan (Foam).

The Reference configuration was defined based on our findings on the preferred seat pan angle for a given back angle using a reconfigurable experimental seat (Wang et al., 2018). We observed that people preferred a seat pan angle of about 7° for a back profile angle of 22°. In addition, we observed that reclining the seat pan angle by 7° reduced the shear force on the seat pan surface, by about 5% of body weight compared to sitting on a horizontal seat pan (Wang et al., 2019a). We thus selected a horizontal seat pan for the Shear condition, which could be considered more uncomfortable than the Reference condition. The last seating configuration was the same as the Reference in terms of seat pan and back angles, except that a foam of 50 mm thickness was added. Compared to the Reference, this 'Foam' condition was expected to have a more uniform pressure distribution and a lower peak pressure under the ischial tuberosities (ITs).

The seat pan and backrest were made of two wooden plates. The seat pan surface was 390 (length) x 500 (width) mm. We used a set of plates of different thicknesses to adjust the seat height so that participants could sit comfortably. We verified that the frontal parts of the thighs were just in contact with the seat pan. Compared to the Reference, the Shear condition should have a shear force on the seat pan surface of about 5% of body weight higher (Wang et al., 2019a). The force applied on the seat pan surface was verified after MRI scanning for the participants. They were asked to reproduce the Reference and Shear positions, out of the MRI scanning room, using our experimental seat equipped with force sensors for measuring contact forces (Table 2). For the Foam condition, foam of 50 mm thickness fully covered the seat pan plate. The foam was selected from those currently used for aircraft passenger seats. Compression tests were conducted for the foam with a sample of 5 x 5 x 7cm^3 using an Instron mechanical test machine. Quasi-static compression loading and unloading were performed (Figure 3).

For the Unloaded condition, we built a specific device providing supports for the arms, back, knees, and feet, so that participants could easily keep the desired posture with the buttocks and thighs being unsupported (Figure 2). The backrest was reclined 50° from the vertical to bear most of the body weight. We controlled the back-thigh angle (about 105°) by a goniometer, close to the Reference condition. The Unloaded condition was tested first, followed by the Reference, Foam, and Shear conditions.

Because of the limited scanning volume, we had to carry out two acquisition sequences to cover the buttocks and part of the thighs. A pre-imaging step was performed before each acquisition to ensure that the two windows of imaging overlapped, based on markers placed on the skin. Each acquisition sequence took about 8 minutes, during which participants were asked to remain immobile.

Figure 1. An overview of a participant undergoing the MRI imaging protocol

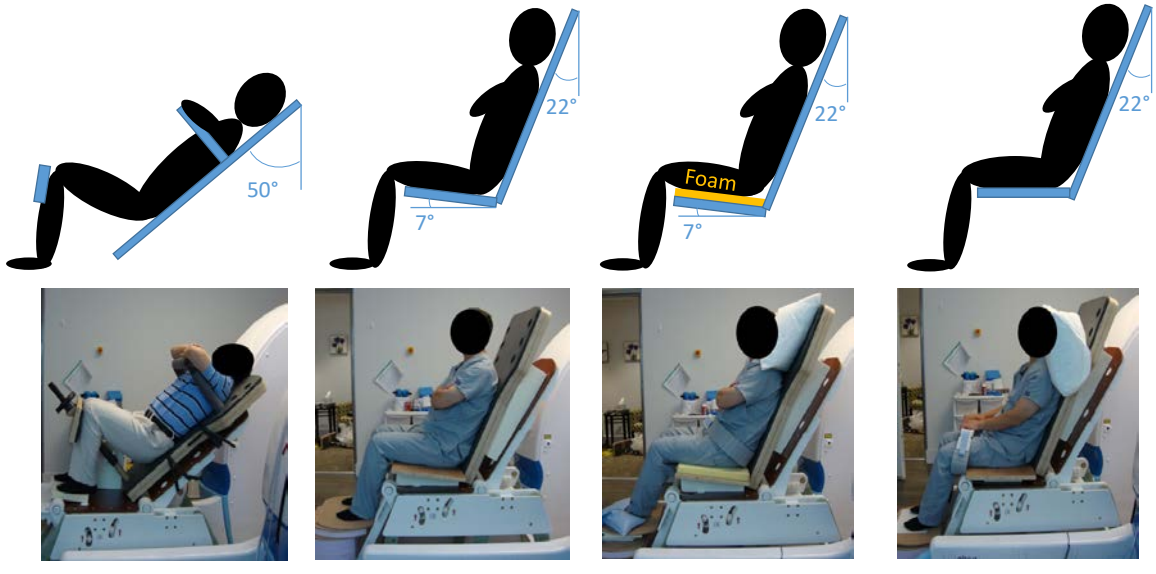


Figure 2. Illustration of the four testing conditions in the upright MRI scanner environment.

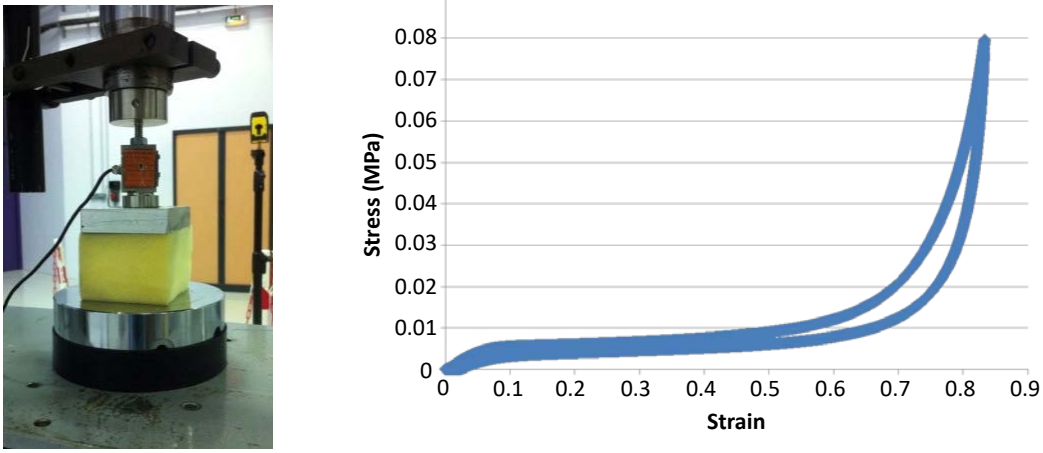


Figure 3. Foam compression testing scenario (left) and stress-strain curve (right).

Table 2. Means (standard deviations) of the shear (negative forward) and normal (negative downward) components of the forces applied on the seat pan surface in the Reference and Shear seating conditions. Measurements were repeated three times for each condition.

	Shear (N)		Normal (N)	
Participant	Reference	Shear	Reference	Shear
P1	-19.2(4.3)	-52.7(7.8)	-445.4(10.0)	-443.3(7.0)
P2	-54.4(5.5)	-76.6(4.1)	-492.6(18.0)	-469.8(2.2)
P3	-75.6(8.3)	-118.6(7.8)	-550.2(40.2)	-562.8(4.1)
P4	-74.7(4.3)	-116.2(0.4)	-545.4(5.6)	-535.8(5.2)
All	-57.2(24.6)	-88.3(30.4)	-511.7(49.1)	-500(53.3)

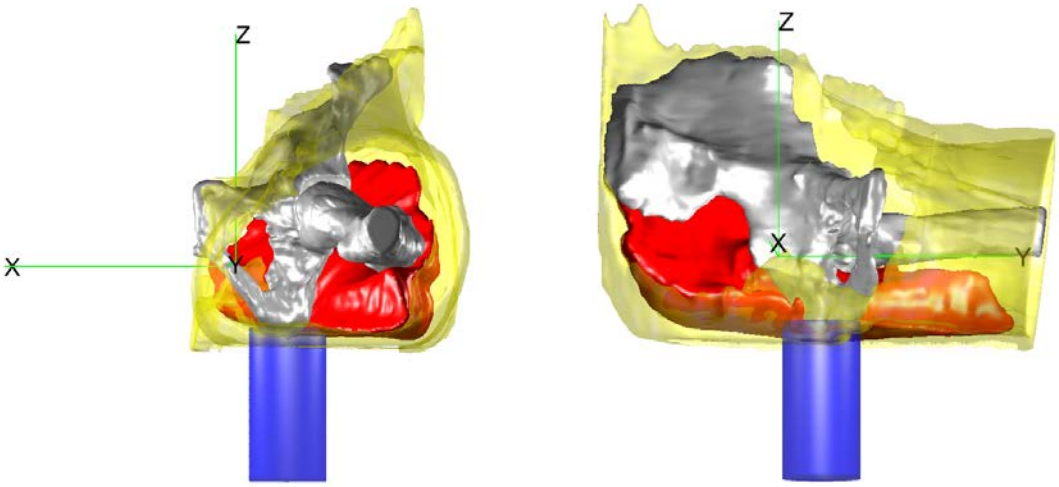
2.3 Data processing and analysis

Raw DICOM data (Digital Imaging and Communications in Medicine, the standard for the communication and management of medical imaging information and related data) were imported into the open source software 3D Slicer (www.slicer.org) for manually segmenting the pelvis, femur, gluteus maximus, and subcutaneous fat. Once segmented, 3D objects from the two scans were exported in the MRI RAS coordinate system (X = right, Y = anterior, and Z = superior). Objects were merged mainly by aligning the common part of the pelvis while ensuring continuity of the skin envelope in contact with the seat, and re-meshed using the open source software Meshlab (https://www.meshlab.net/). We defined three regions of interest (ROIs) using three cylinders with diameters of 50, 20, and 10 mm. These cylinders were similar to those

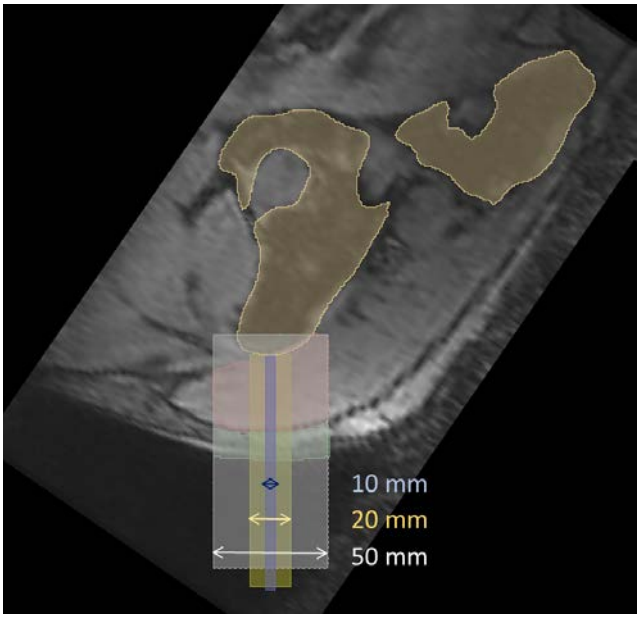
proposed by Sonenblum et al. (2015), who argued that the size of the IT is approximately 50 mm long and anterio-laterally orientated. We also defined two ROIs with smaller diameters (10 and 20 mm) for a better focus on the region underneath the ITs. For the three seating positions, the cylinders were perpendicular to the seat pan hard surface and centered at the ischium point closest to the seat (Figure 4). Compared to the horizontal (x-y) plane in the MRI coordinate system, the seat pan surface had respective angles of 7° and 0° in the Reference (also for Foam) and Shear conditions (Figure 2). The cylinders were positioned such that the external circle of the upper surface was in contact with the ischium. For the Unloaded condition, which had no seat pan, the same ROIs as for Reference were used by aligning the pelvis. Volumes and mean thicknesses of the bone, gluteal muscle, fat, and other tissues inside the ROIs were calculated using a custom Matlab (R2020b) tool.

To quantify tissue deformation, we calculated tissue volume reduction in a ROI under the IT in the three seated conditions with respect to the Unloaded condition, similar to the approaches used by Brienza et al. (2018) and Sonenblum et al. (2015, 2018):

$$\text{Tissue Volume Reduction (R)} = \left(1 - \frac{Tissue\ Volume_{loaded}}{Tissue\ Volume_{unloaded}}\right) \times 100\%$$



(a)



(b)

Figure 4. (a) Region of interest (ROI) characterized by a cylinder, illustrated for 50mm ROI of Participant #1 in the Reference sitting condition. Three cylinders of 100 mm in length and 50, 20, and 10 mm in diameter were used. Cylinder axes were perpendicular to the seat pan surface and centered at the ischium point closest to the seat. Cylinders were positioned so that the external circle of the upper surface was in contact with the ischium. (b) Three ROI illustrated with an MRI image in the sagittal plane for the Unloaded condition.

3 Results

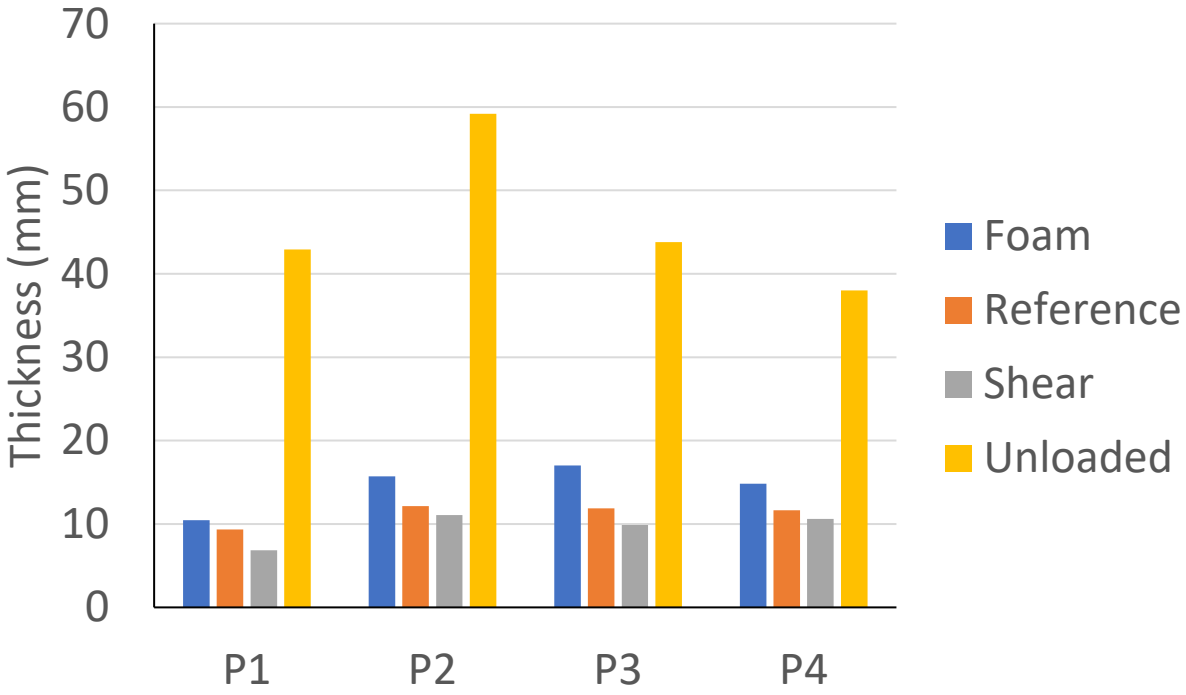
The four participants had quite different compositions of soft tissues in the ROI as shown in results from the Unloaded condition (Table 3). Mean bulk tissue thicknesses in the 50 mm ROI were 49.3, 61.2, 48.0, and 46.5 mm, and the percentages of the gluteus maximus (GM) muscle were 55.1, 13.4, 8.4, and 27.1% respectively for participants P1 to P4. For the two narrower ROIs (20 and 10 mm), P2 and P3 had almost no GM below the IT.

In the three-seated positions (Table 4), mean bulk tissue thicknesses in the 50mm ROI were reduced to 18.9, 17.3, and 16.1 mm on average across participants in the Foam, Reference, and Shear conditions, respectively, representing reductions of tissue volume (R) of 62.4, 65.5, and 68.1% with respect to the Unloaded condition. The Shear condition had the highest deformation, followed by the Reference and Foam condition. These differences were particularly obvious for the 10 and 20 mm ROIs below the IT (see Figure 5 for 10mm ROI). The

same trend was observed for all participants. Moreover, no GM was wrapped around the IT in the 10 and 20 mm ROIs once seated, even for P1 and P4, who each had an appreciable amount of the IT covered by the GM in the Unloaded condition. By visualizing the displacement of the GM from both 3D reconstructions (Figure S1 in Supplemental materials) and segmented MRI images (Figure S2 in Supplemental materials), it appears that the GM moved laterally and posteriorly.

Table 3. Volume and mean thickness of bulk tissue (T_tissue) under the ischium in the three ROI as well as the percentages of fat tissue, gluteus maximus mucle (GM), and other tissues in the Unloaded condition

Participant	ROI	Bulk tissue volume (mm^3)	T_tissue (mm)	Fat (%)	GM (%)	Others (%)
P1	50	96728.3	49.3	32.9	57.4	9.7
	20	13769.7	43.8	27.6	71.4	1.0
	10	3371.9	42.9	28.0	72.8	-0.8
P2	50	120060.4	61.2	64.6	13.5	21.9
	20	18786.6	59.8	68.4	4.3	27.3
	10	4647.4	59.2	68.8	0.2	31.0
P3	50	94179.4	48.0	71.8	8.6	19.6
	20	13979.3	44.5	88.0	0.0	12.0
	10	3440.0	43.8	83.8	0.0	16.2
P4	50	91224.1	46.5	46.1	28.8	25.1
	20	12326.9	39.2	40.8	33.8	25.4
	10	2985.5	38.0	39.6	37.2	23.2
All	50	100548.0	51.2	53.8	27.1	19.1
	20	14715.6	46.8	56.2	27.4	16.4
	10	3611.2	46.0	55.0	27.5	17.4



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288 **Figure 5. Mean bulk thickness under the ischium in the 10 mm ROI for the four test conditions**

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Table 4. Mean thickness of the bulk tissue (T_tissue) under the IT in the three ROIs as well as percentages of fat tissue, gluteus maximus muscle (GM), and tissue volume reduction (R in %) for the three seating conditions.

		Foam				Reference				Shear			
Participant	ROI	T_tissue (mm)	Fat (%)	GM (%)	R (%)	T_tissue (mm)	Fat (%)	GM (%)	R (%)	T_tissue (mm)	Fat (%)	GM (%)	R (%)
P1	50	15.5	64.2	15.1	68.5	13.9	68.2	10.7	71.8	14.8	60.9	6.4	69.9
	20	11.1	73.6	0.0	74.7	11.3	71.3	0.0	74.3	7.7	72.2	0.0	82.3
	10	10.5	69.1	0.0	75.6	9.3	75.0	0.0	78.3	6.8	79.7	0.0	84.1
P2	50	18.6	51.2	0.0	69.6	15.6	56.3	0.0	74.4	15.2	52.4	0.1	75.1
	20	15.6	43.9	0.0	73.8	12.8	45.0	0.0	78.6	12.1	38.7	0.0	79.8
	10	15.7	42.1	0.0	73.4	12.1	48.7	0.0	79.5	11.1	37.7	0.0	81.3
P3	50	20.5	60.3	5.0	57.3	19.6	61.6	0.0	59.2	15.8	66.8	3.7	67.0
	20	16.6	64.3	0.0	62.7	12.8	48.8	0.0	71.2	10.7	60.2	0.0	76.0
	10	17.0	63.5	0.0	61.2	11.9	51.7	0.0	72.9	9.9	55.8	0.0	77.4
P4	50	21.0	52.3	6.2	54.8	20.3	55.9	0.0	56.4	18.5	67.5	0.8	60.2
	20	15.6	52.3	0.0	60.2	12.6	45.3	0.0	68.0	11.2	71.9	0.0	71.4
	10	14.8	54.0	0.0	61.0	11.6	44.3	0.0	69.4	10.6	71.6	0.0	72.1
All	50	18.9	57.0	6.6	62.4	17.3	60.5	2.7	65.5	16.1	61.9	2.7	68.1
	20	14.7	58.5	0.0	67.9	12.4	52.6	0.0	73.0	10.4	60.7	0.0	77.4
	10	14.5	57.2	0.0	67.8	11.2	54.9	0.0	75.0	9.6	61.2	0.0	78.7

4 Discussion

4.1 Summary of main observations

The present work aimed to investigate how seating condition affects soft tissue deformation under the IT using an upright MRI system. The largest tissue deformation was observed in the Shear condition, while the smallest was found in the Foam condition among all participants. Though these findings were expected, to our knowledge, this is the first time that the effect of shear force on tissue deformation was quantified directly. Compared to the Reference condition with a seat pan angle of 7°, the Shear condition had a horizontal seat pan with the same backrest inclination. Reducing the seat pan angle to 0° resulted in a forward shear force of 31 N higher on average (an increase of 54.4% over 57.1N) (Table 2), while the force normal to the seat pan surface was slightly affected proportionally (a difference of 12 over 512 N on average). As peak pressure and peak shear stress are likely to be located under the IT, our results show that a higher shear led to a higher soft tissue deformation. Of course, reducing peak pressure using a soft cushion could also lead to a smaller tissue deformation as observed in the Foam condition.

4.2 Comparison with past studies

Due to the differences in the methods used for defining the regions of interest (ROIs) as well as in the experimental conditions, it is difficult to compare the results directly between different studies. Our study is the first investigating the effects of both seat pan angle and cushion, while all others kept the same seat pan inclination. We used the vertical cylinders of different diameters with their axes being perpendicular to the seat pan surface as ROIs, similar to the two cylindrical ROIs of 50 and 10mm defined by Sonenblum et al. (2015). In other words, the ROIs in the present work were not fixed to the pelvis. Alternatively, we could define a ROI with respect to the pelvis and apply it to all test conditions. However, due to the difference in seat

pan angle, a ROI with its axis perpendicular to the seat pan surface in the Reference condition will no longer be perpendicular in the Shear condition. As we were interested in the region between the IT and the seat, we preferred the first method for defining ROIs. Brienza et al. (2018) used an ROI with a rectangular section, which was defined based on the specific geometric characteristics of each IT for each participant in each condition. In two more recent studies by Sonenblum (2018, 2020), an oblique plane of 50 mm long parallel to the IT was used to define the ROI. Al-Dirini et al. (2015) also quantified the deformation of the gluteal soft tissues during sitting. They estimated tissue thickness under some landmarks directly from raw MRI images without 3D reconstructions. However, as identifying anatomical landmarks from MRI images is not easy, results may be operator dependent.

Concerning the Unloaded condition (also called ‘non-weight bearing’), participants here were instructed to maintain a desired sitting posture in a reclined position with the help of upper arm, knee, and foot supports (Figure 2), similar to the approach used in Al-Dirini et al. (2015). Compared to the unloaded conditions proposed by Sonenblum et al. (2015) and Brienza et al., (2018), our Unloaded configuration had an advantage in that the buttocks and thighs were fully unsupported with a position close to a normal sitting. Sonenblum et al. (2015) cut a hole on the seat pan and only the region beneath the IT was unsupported. Brienza et al. (2018) adopted a lying supine position with the thighs oriented vertically. Effects of gravity on soft tissues were better considered in our Unloaded position. However, when looking at the pelvis femur angle from the 3D reconstructions (Figure S1 in Supplemental Materials), it is much smaller in the Unloaded condition than in the three seated ones, though we controlled the back thigh angle close to the Reference condition. One reason could be that loading from the seat makes the pelvis rotate posteriorly, as already observed by Keegan (1953) from X-ray images in 1950s.

In terms of soft tissue thicknesses and their composition under the IT, results from the present study are comparable to past studies. For an upright sitting position corresponding to wheelchair use, Sonenblum et al. (2015) observed, from 4 able-bodied and 3 individuals with

spinal cord injury, mean values of 21 and 14 mm, respectively, for fat and the GM in the Unloaded condition and 14 and 1 mm in the Foam condition in the 10 mm cylindrical ROI. No GM was observed in the 10 mm ROI except for one able-bodied participant. The mean bulk tissue thicknesses in the 10 mm region were about 35 and 15 mm for the Unloaded and Foam conditions if tissues other than fat and the GM muscle are neglected. We found 46 and 14.5 mm in the 10 mm cylindrical ROI for Unloaded and Foam condition from 4 able-bodied males, and no GM was present for any of the participants. In their study comparing three wheelchair cushions across 4 full-time wheelchair users, Sonenblum et al. (2018) found that the bulk tissue thickness in an oblique plane of 50 mm ROI under the ischium varied from 8 to 25mm depending on participant and cushion, with a reduction of bulk tissue thickness up to 60%. For the Foam condition in the present study, it varied from 15.5 to 21 mm in the 50 mm cylindrical ROI with a thickness reduction from 54.8 to 69.6%. In a more recent study with 35 participants, Sonenblum et al. (2020) found results comparable to their previously published pilot studies. In addition, they observed that wheelchair users had thinner tissue under the ischium than did able-bodied individuals.

Our results confirm the findings by several researchers (Sonenblum et al., 2015, 2018, 2020; Brienza et al., 2018) that the tissues beneath their ITs are composed predominantly of fat and connective tissue in a seated position. This outcome suggests that sitting on soft or hard surfaces displaces the GM laterally and posteriorly away from the IT. In a seated position, the loading on the body contributes to the displacement of the GM muscle from the IT. This was clearly observed for Participant 1, who had a percentage the GM muscle of 55.1% in the 50mm ROI for the Unloaded condition (Table 3). Once seated, the GM percentages reduced to 10.2, 2.1, and 5.3% respectively in the Reference, Foam, and Shear condition (Table 4). For the two narrower ROIs (20 and 10mm) beneath the IT, no presence of the GM was observed for any of the four participants in any of the three seated conditions. In the work by Al-Dirini et al. (2017), participants were scanned in a semi-recumbent posture using a ‘tunnel’ MRI system. It seemed

that these authors did not observe the absence of the GM muscle under the IT event for the weight bearing condition, probably due to a difference in posture. The ischial point closest to the contact surface was likely located more posteriorly than the more upright sitting postures studied here.

4.3 Implications for assessing seating discomfort and injury risk

As explained above, three seating conditions were defined based on the findings from our previous studies using a reconfigurable experimental seat (Wang et al., 2018, Wang et al., 2019a). We observed that the Reference condition with a seat pan angle (A_SP) of 7° was preferred for the backrest inclination tested in the present work, compared to the Shear configuration with A_SP equal to 0°. An analysis of perceived seating discomfort ratings (Wang et al., 2018) confirmed that the preferred seating condition (Reference) had a lower discomfort rating than the seating condition with a horizontal seat pan (Shear). One explanation could be that the shear force on the seat pan was reduced. The Foam configuration was the same as the Reference in terms of seat pan and back angles, except that 50 mm thick foam was added. Compared to the Reference, the Foam condition should have created a more uniform pressure distribution and a smaller pressure under the ITs. Though we did not ask the participants to rate the three seating configurations here, we can reasonably assume that the Foam condition was the least uncomfortable, followed by Reference and Shear. In addition to the reduction of soft tissue deformation by decreasing contact pressure, the current results seem to support that reducing shear on the seat pan surface decreases soft tissue deformation under the IT. Lowering soft tissue deformation can certainly reduce pressure injury risk, as sustained deformations of soft tissues due to mechanical loading are the cause of initial cell death and tissue damage that ultimately may result in pressure injuries (Gefen et al., 2021). Our findings support the idea of using soft tissue deformation as an objective measure for assessing seating discomfort and injury risk, as this measure could account for the effects of both contact pressure

and shear. It could be useful when a finite element human model is used for assessing seating discomfort and risk based on soft tissue deformation. Future work is needed, though, to establish criteria based on soft tissue deformation for discomfort and injury assessment.

4.4 Implications for human body modeling

The present work was mainly motivated by the need for data to validate finite element human body models for assessing seating discomfort. As already pointed out by Sonenblum et al. (2015, 2018), finite element models of the buttocks, used to evaluate wheelchair cushions and pressure ulcer risk, often depict gluteus maximus coverage under the ischium as more than 50%. From our recent review on the finite element models of the thigh-buttock complex (Savonnet et al., 2018), none of the models used in the 27 selected papers explicitly considered the GM muscle sliding around the ITs. As peak pressure and shear are most likely located around the ITs, more realistic modeling in this region is needed that considers muscle sliding.

4.5 Limitations

We would like to point out several limitations in the current work. As a case study, only four healthy males participated in the experiment. With such a limited number of participants, the findings observed in the present study only give an indication for future studies. As individual characteristics such as soft tissue composition affect deformation, results are unlikely to generalize to people with different body characteristics. In addition, only one foam type was studied, and thus the effects of cushion characteristics should be investigated in the future. Another limitation is related to the MRI imaging system. With the size of scanning window being limited, we used two acquisition sequences to cover the buttock and major part of the thigh, and each sequence lasted about eight minutes. During the two sequences, we asked participants to do their best to keep the same sitting position. Small postural change during one sequence and between two sequences was unavoidable, making it difficult to merge data of two acquisitions. Lastly, this study considered only static sitting with arms crossed and not externally supported.

Typically, sitting can be dynamic while doing sedentary tasks. Results could be substantially different if tasks are considered. Moreover, usually, arms are partially or fully supported by the table or armrests and a different trunk posture may also be adopted. This may lead a different loading on the buttocks and thighs. Effects of different sitting postures need to also be studied in the future.

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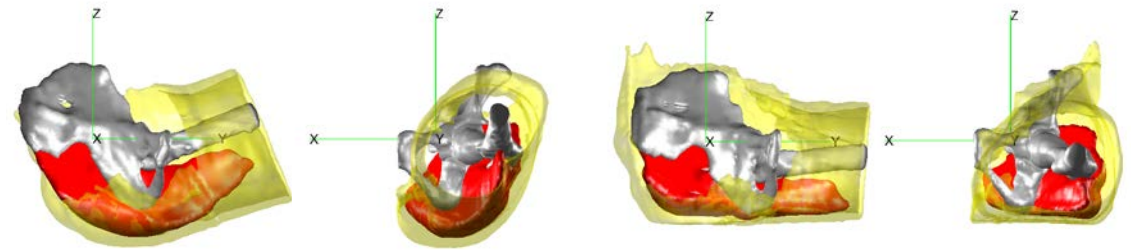
Supplemental materials



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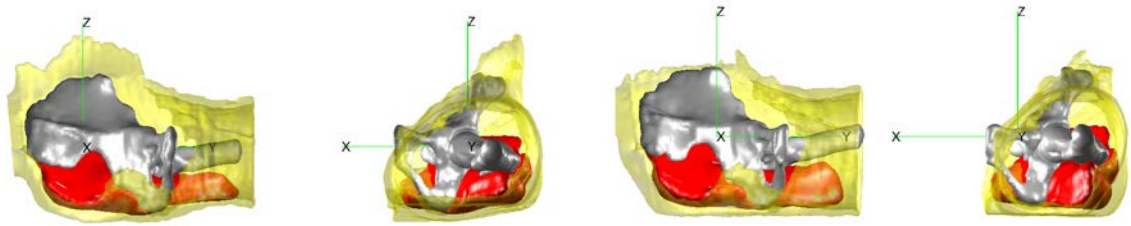

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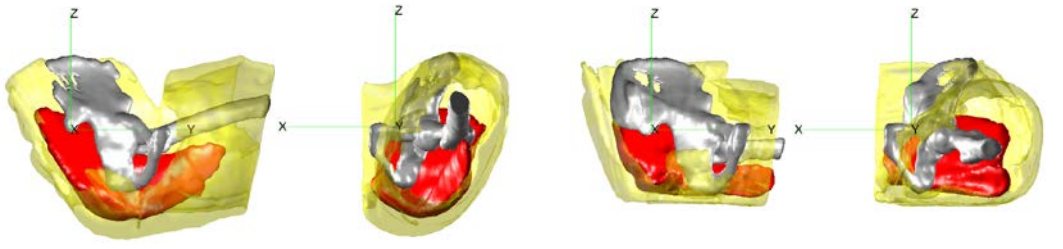

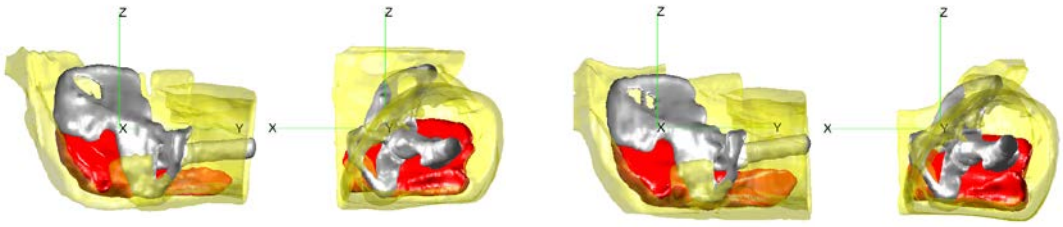

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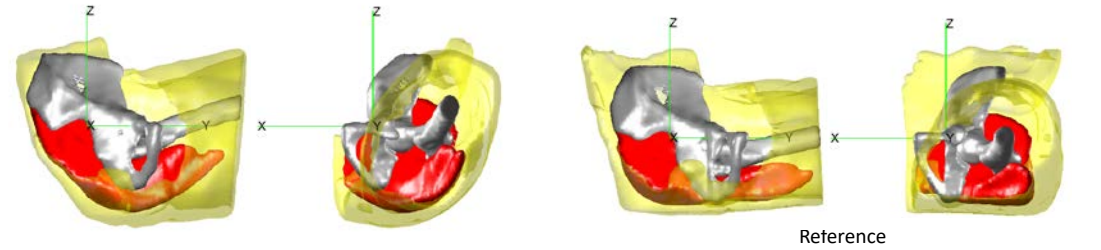

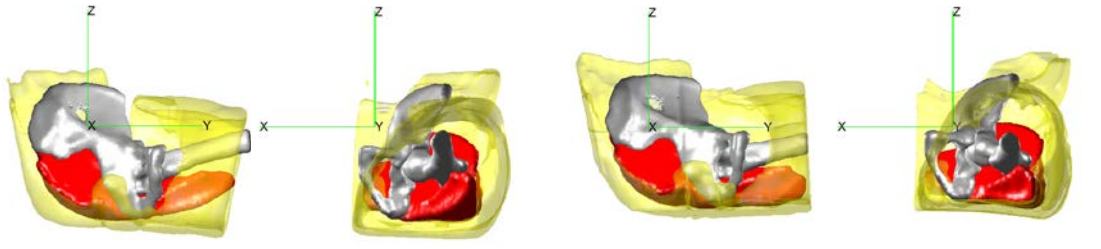

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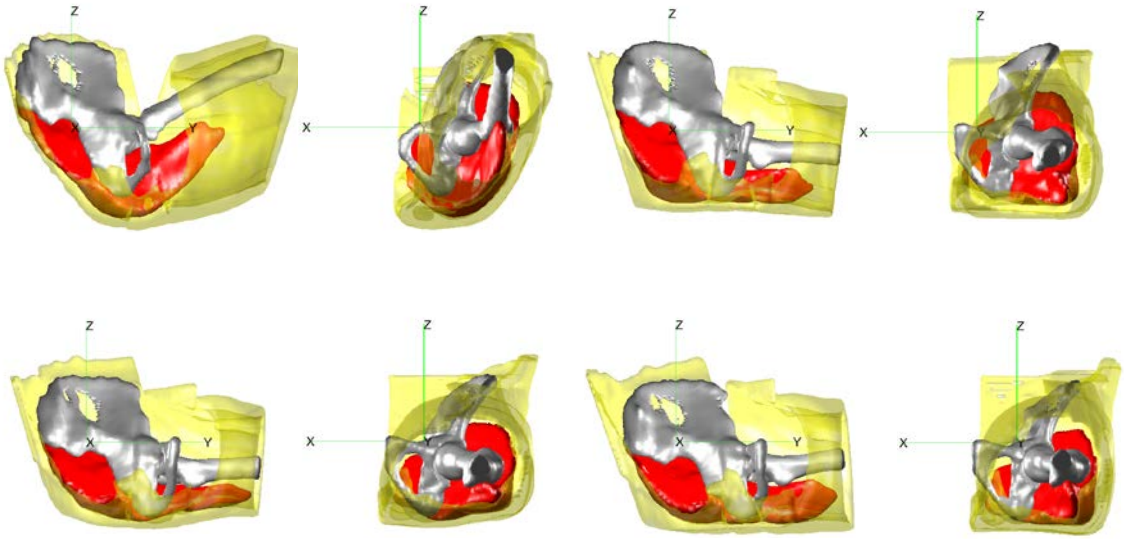

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507 **Figure S1: Reconstructed 3D representations of the pelvis, femur, GM, and fat in a seat coordinate system**
508 **with the x-y plane parallel to and z perpendicular to the seat surface for the four participants. For the**
509 **Unloaded condition, which had no seat pan, the 3D reconstructions are transformed so that its pelvis is**
510 **aligned with that of the reference configuration.**

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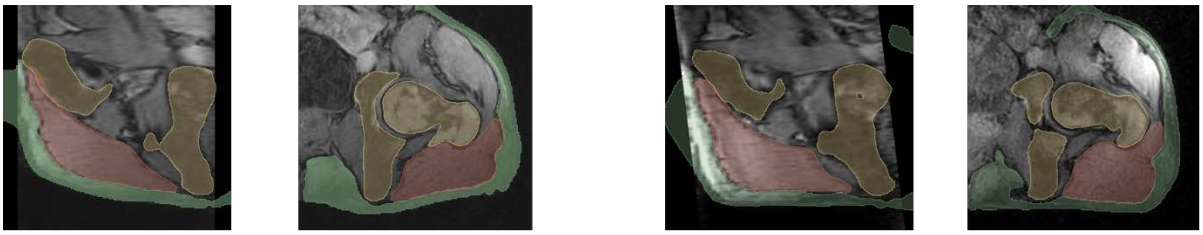
Unloaded Reference

Subject 1



Foam Shear

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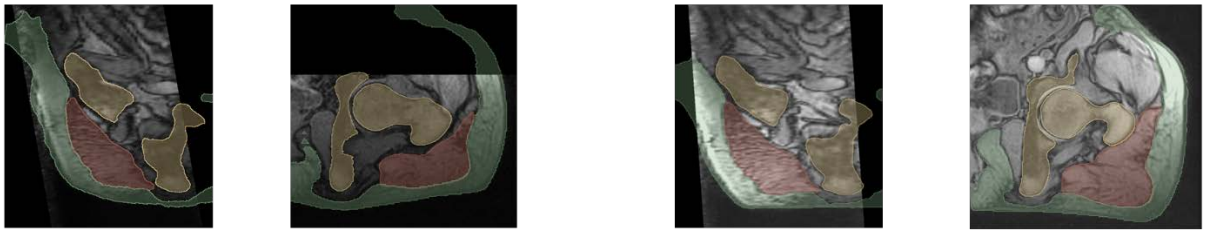

Foam Shear

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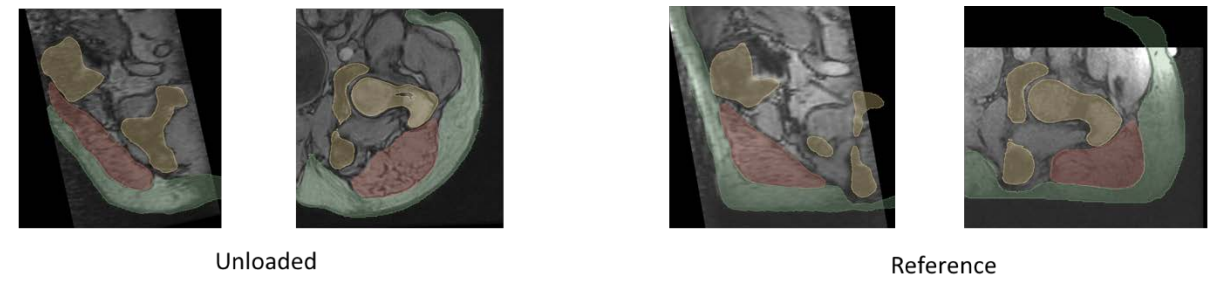

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522 **Figure S2: MRI Slices of the IT in the frontal and sagittal planes with segmentation (yellow: pelvis, green: fat,**
523 **red: muscle) for the four participants. The frontal plane is perpendicular to the seat pan surface. For the**
524 **Unloaded condition which had no seat pan, a rigid transformation is applied so that its pelvis is aligned with**
525 **that of the Reference configuration.**

526

527