Variability in Body Shape, Superficial Soft Tissue Geometry, and Seatbelt Fit Relative to the Pelvis in Automotive Postures—Methods for Volunteer

Citation for the original published paper (version of record):
Forman, J., Booth, G., Mergler, O. et al (2024). Variability in Body Shape, Superficial Soft Tissue Geometry, and Seatbelt Fit Relative to the
Pelvis in Automotive Postures—Methods for Volunteer Data Collection With Open Magnetic Resonance Imaging. Journal of Biomechanical Engineering, 146(3).
http://dx.doi.org/10.1115/1.4064477

ASME Journal of Biomechanical Engineering
Online journal at:
https://asmedigitalcollection.asme.org/biomechanical

Jason Forman
Center for Applied Biomechanics,
University of Virginia Center for Applied Biomechanics,
4040 Lewis and Clark Dr.,
Charlottesville, VA 22911

Gabrielle Booth
MEA Forensic Engineers & Scientists,
11151 Horseshoe Way,
Richmond, BC V7A 4S5, Canada

Olivia Mergler
Center for Applied Biomechanics,
University of Virginia Center for Applied Biomechanics,
4040 Lewis and Clark Dr.,
Charlottesville, VA 22911

Sarah Romani
University of British Columbia,
2222 Health Sciences Lane,
Vancouver, BC V6T 1Z3, Canada

Honglin Zhang
University of British Columbia,
798 - 2635 Laurel Street,
Vancouver, BC V5Z 1M9, Canada

Carolyn Roberts
MEA Forensic Engineers & Scientists,
23281 Vista Grande Drive,
Laguna Hills, CA 92653

Gunter P. Siegmund
University of British Columbia,
798 - 2635 Laurel Street,
Vancouver, BC V5Z 1M9, Canada;
MEA Forensic Engineers & Scientists,
3281 Vista Grande Drive,
Laguna Hills, CA 92653

Bengt Pipkorn
Autoliv Research and Chalmers University,
Wallentinsvägen 22 Vargarda,
Västergötland 44793, Sweden

Peter Cripton
School of Biomedical Engineering,
University of British Columbia,
2222 Health Sciences Mall,
Vancouver, BC V6T 1Z3, Canada

Variability in Body Shape, Superficial Soft Tissue Geometry, and Seatbelt Fit Relative to the Pelvis in Automotive Postures—Methods for Volunteer Data Collection With Open Magnetic Resonance Imaging

Variability in body shape and soft tissue geometry have the potential to affect the body's interaction with automotive safety systems. In this study, we developed a methodology to capture information on body shape, superficial soft tissue geometry, skeletal geometry, and seatbelt fit relative to the skeleton—in automotive postures—using Open Magnetic Resonance Imaging (MRI). Volunteer posture and belt fit were first measured in a vehicle and then reproduced in a custom MRI-safe seat (with an MR-visible seatbelt) placed in an Open MR scanner. Overlapping scans were performed to create registered three-dimensional reconstructions spanning from the thigh to the clavicles. Data were collected with ten volunteers (5 female, 5 male), each in their self-selected driving posture and in a reclined posture. Examination of the MRIs showed that in the males with substantial anterior abdominal adipose tissue, the abdominal adipose tissue tended to overhang the pelvis, narrowing in the region of the Anterior Superior Iliac Spine (ASIS). For the females, the adipose tissue depth around the lower abdomen and pelvis was more uniform, with a more continuous layer superficial to the ASIS. Across the volunteers, the pelvis rotated rearward by an average of 62% of the change in seatback angle during recline. In some cases, the lap belt drew nearer to the pelvis as the volunteer reclined (as the overhanging folds of adipose tissue stretched). In others, the belt-to-pelvis distance increased as the volunteer reclined. These observations highlight the importance of considering both interdemographic and intrademographic variability when developing tools to assess safety system robustness. [DOI: 10.1115/1.4064477]

Manuscript received February 28, 2023; final manuscript received November 14, 2023; published online January 29, 2024. Assoc. Editor: Francisco Jose Lopez Valdes.

Introduction

Human variability affects automobile safety in many ways. Aging increases injury risk through increased fragility, especially in the thorax [1–3]. Obesity affects the body mass that must be decelerated during a collision and affects the ability of a restraint system to engage with strong parts of the skeleton [4–6]. Other effects of human variability may be quite subtle, affecting interactions between restraint systems and the vehicle interior in manners that are not always intuitive. For example, females tend to be at greater risk than males for ankle fractures in frontal collisions when belted [3]. This may be at least partially affected by fundamental differences in body shape between males and females. Females tend to have a lower center of gravity and increased adipose tissue concentrated around the gluteofemoral region, which may adversely affect interaction between the lap belt and pelvis, potentially leading to increased risk of submarining and greater loading of the lower extremities [7,8]. Also, breast tissue may introduce more slack in the belt system and thus contribute to greater forward excursion. By understanding the nature and effects of occupant variability, we gain insight into the factors that affect injury causation in collisions, equipping us to better identify countermeasures to continue improving vehicle safety. This insight can aid in the understanding of residual injury mechanisms and inform factors that should be included in injury prediction for assessing safety system robustness (e.g., human body models representing a range of occupants [9–12]).

As noted above, one of the dimensions of occupant variability is body habitus (shape and/or size). Body habitus is often described in highly simplified anthropometric measures such as height, weight, and Body Mass Index (BMI). Even within persons of similar height, weight, and BMI; however, there can be a wide range of body shapes. Some people with a relatively high BMI can be quite muscular, with less adipose tissue than their BMI would suggest. Others can have a large amount of adipose tissue, distributed around their body in various ways. There tend to be some systematic differences in body shape among different segments of the population, reflecting differences in how the body mass tends to be distributed. In general, females tend to exhibit more of a gynoid adipose tissue distribution, with a relatively consistent layer of subcutaneous adipose tissue and more mass concentrated around the hips, pelvis and upper thighs [7]. Also, the presence of breast tissue is more pronounced in females than males on a population basis. Males tend to exhibit an android adipose tissue distribution, with increased visceral adipose tissue in the abdomen, a more variable superficial layer of adipose tissue, and generally less adipose around the hips and pelvis. As a result of differences in soft tissue distribution (both adipose and muscle), males tend to have a proportionally higher center of gravity than females [8]. These factors can all potentially affect a person's interaction with the restraint system during a collision, affecting the overall kinematics (e.g., via the relationship between the body center of gravity and the locations of the external restraint loads) as well as the engagement of the restraint system with the strong parts of the skeleton, affected by the intervening soft tissue on both the initial position and dynamic interaction of the belt relative to the skeleton.

Recognizing the potential importance of reflecting body shape in our injury prediction tools, several studies have sought to quantify variations in body shape in the population and how those variations affect belt fit. A large body of work has been produced by researchers at the University of Michigan Transportation Research Institute, quantifying external body shape and belt fit for volunteers under a range of postures [13–15]. Such studies have provided estimates of skeletal posture and belt fit relative to the skeleton largely via external palpation, and have provided valuable information on how body shape differences between females and males can affect belt routing and fit [16]. Others have complemented this work using various radiology tools to directly observe skeletal posture and belt fit. This has included volunteer studies using planar X-ray [17,18] and computed tomography (CT) [19]. While each method provides valuable increments of information, each also carries its own limitations. The studies using planar X-ray are limited to two-dimensional views of belt fit relative to the skeleton [17,18]. The recent study with upright CT was limited in the postures that they could study, where the "seated" posture was more upright than a typical automotive posture due to the geometric constraints of the upright CT [19].

Though not necessarily a technological limitation, most previous research gravitated toward the traditional practice of reporting results in terms of averages, even when describing differences in the population. For example, there persists a tendency to describe body shapes in terms of the "average" body shape for a particular segment of the population (e.g., the "average" body shape for a female of a particular height, weight, age, and BMI [20]). While describing average body shapes across different population segments is an important step, it is also important to consider the breadth of variations in body shape about those averages.

In this study, we sought to complement past volunteer body shape studies using an imaging tool that can aid in filling gaps in knowledge that remain – specifically, Upright Open Magnetic Resonance Imaging (MRI). Unlike traditional MRI, Open MRI is configured to allow the person being scanned to take a wide array of postures, including supine, standing, or seated. It is commonly used to study musculoskeletal geometries during weight bearing postures. As it is nonionizing, Open MRI does not carry radiation exposure concerns like X-ray or CT. It is also well-suited to capturing border distinctions of different soft tissues, including muscle, fat, and visceral tissue. The goals of this study were to develop methods to quantify body shape, skeletal geometry, and belt fit relative to the skeleton in real driving postures using a simulated automobile seating environment built inside an Open MRI machine. Those methods were then used to perform preliminary pilot data collection with a sample of ten volunteers.

Methods

Volunteer posture and belt fit were first measured in an actual vehicle and then reproduced in a custom MRI-safe seat replica placed in an Open MR scanner. Ten subjects (5M, 5F; mean age = 32.2 ± 4.8, range 25–56 years; mean BMI 24.6 ± 3.3, range 21.5–30.6; Table 1) were recruited and gave their informed consent. Volunteer height was limited to 6 ft to maintain clavicle visibility in the MR images. This study was approved by the University of British Columbia's Clinical Research Ethics Board.

Prior to entering the vehicle, a series of 92 anthropometric measurements were taken of the volunteers. These measurements included the distance from the ground (or a platform for seated measurements) of selected skeletal features and the body circumference at these locations. The skeletal landmarks were verified via palpation each time an anthropometric or postural measurement was taken. The postures and belt fits of each volunteer were measured in an actual vehicle to serve as references to recreate a driving postures and belt fit for the volunteer in the Open MRI. The in-vehicle positioning trials were performed in the driver's seat of a 2017 Acura TLX. Measurements were taken with each volunteer in their self-selected upright posture in the driver seat (seat position was also self-selected), and in a predetermined reclined posture (50-degree seatback angle).

At the start of the self-selected upright posture trial, the seatback and seat base were in their forward-most angle and position, respectively, since this position prohibited the volunteer from sitting in the seat and necessitated that the volunteer adjust the seat. The seat base was set to 12 degrees from the horizontal, the angle of the nonadjustable seat base of the MR replica. The volunteer was then asked to adjust the seat to a comfortable driving position (without changing the seat base angle) and don the seatbelt as they typically would. The seat position along the horizontal track, D-ring location, and head restraint height were recorded.

The posture of the volunteer was established by measuring the positions of skeletal landmarks in the seat-based reference plane. Additionally, the self-selected seatback angle, angles of pertinent

Table 1 Volunteer age, sex, anthropometry, and self-selected upright seatback angle characteristics

Subject ID	Sex	Age	Height (cm)	Weight (kg)	BMI	Self-selected upright seat back angle (°)
3	M	25	182	101	30.6	20
7	F	27	165	64.1	23.5	20
4	M	31	186	96.7	28.0	20
8	F	34	171	63.0	21.5	20
5	F	24	163	74.1	27.9	10
9	F	41	179	67	20.9	16
6	M	30	174	69.8	23.1	20
12	F	56	158	57.5	23.0	10
14	M	52	155	57.5	23.9	10
15	M	56	188	94.5	26.7	20

body segments, and the location of the lap belt and shoulder belt relative to select skeletal landmarks (e.g., distance between the shoulder belt and the xiphoid process) were measured.

In addition to the self-selected upright automotive posture, trials were also performed for each volunteer in a reclined posture. While a reclined posture deviates from typical automotive postures in today's vehicles, it is being widely contemplated that reclined postures may become increasingly common with higher degrees of vehicle automation [21]. As a result, there has been substantial recent interest in extending occupant protection research to reclined postures, with one of the foundational questions lying in the effect of recline on skeletal posture and belt fit [13]. After the measurements were taken in the upright posture in our in-vehicle trials, the volunteer was then asked to sit comfortably and as still as possible in a reclined posture with a 50-degree reclined seat back angle. For vehicles specifically designed to accommodate reclined occupants, it is likely that the shoulder belt will consist of a belt-in-seat configuration, where the D-ring is mounted to the seatback allowing the shoulder belt to maintain engagement with the shoulder as the seatback reclines [22]. To represent this condition for the reclined trials, the shoulder belt was rerouted through a three-dimensional (3D)-printed surrogate D-ring clamped to the head restraint posts and designed to have a geometry representing a belt-in-seat D-ring. Similar positioning and belt-fit measurements were recorded for the reclined posture as for the self-selected seat angle. The measurements taken for the self-selected and reclined postures were then used to recreate the automotive postures and belt fits for each volunteer within the Open MRI.

A nonferromagnetic seat was constructed for safe use in the Upright Open MRI (Paramed MROpen EVO, ASG Superconductors, Genoa, Italy; with a gap width of 56 cm). The MR-safe seat was constructed to represent the external geometry of the real vehicle seat that the volunteers were seated in during the in-vehicle trials (using as many of the components from an Acura TLX seat as possible). The MR-safe seat allowed adjustability in seatback angle, head restraint height, "D-ring" location, and vertical and horizontal seat back position (Fig. 1). The seat back was constructed to be as thin as possible to minimize the distance between the MRI U-coil and the subject, and did not include the seatback wings that provided lateral body support in the actual seat. The front of the seat base was angled 12 degrees up from the horizontal, and the height of the seat base was minimized to allow for the lowest positioning of the volunteer in the MR and the maximum range of volunteer heights to be measured. A seat belt made of standard automotive webbing material was marked with three continuous lines of Vitamin E tablets that were adhered to the belt to make the belt's edges and centerline visible in the MR images. A 372-gram weight was hung over an MR safe support bar to represent the belt tension provided by the seat belt retractor (based on initial spring tension measurements from a real retractor).

A T1-weighted gradient field echo sequence was developed to provide clear visualization of bony landmarks, the border between

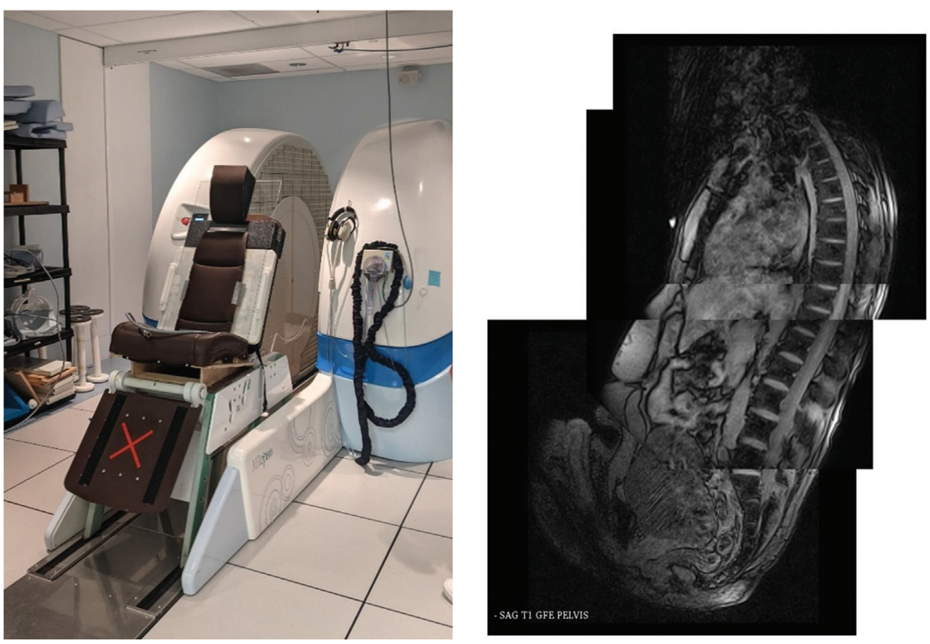

Fig. 1 Left: MR-safe automobile seat mockup within the UBC Open MRI (seatbelt not shown). Right: Example of registered composite image of a male volunteer in their self-selected upright driving posture, at the midsagittal plane.

bone and soft tissue, and the Vitamin E capsules on the belt, while keeping the scan time short enough to minimize motion artifact. A series of 5 scans (imaged both sagittally and axially) were taken to image the body from the femoral shaft to the clavicles. These 5 scans had sufficient overlapping skeletal anatomy to allow for image registration and had sufficient resolution to identify skeletal landmarks. The parameters of the sequence are as follows: TR/TE = 890/8 ms, acquisition matrix 224×160, FOV 38 cm, slice thickness 4 mm, gap 2 mm, 48 slices, NEX = 1, imaging time 5 min.

Each participant was scanned in two postures: their self-selected driving posture and a reclined posture with the seatback angled to 50 degrees. The MR replica seat was adjusted to reflect the self-selected seat back angle, head rest height, and D-ring location that the volunteer selected in the in-vehicle session. Then, the volunteer was positioned in the replica seat using the measurements taken in the in-vehicle session. Specifically, the locations of the patella, left and right ASIS, trochanters, 10th rib, acromion, and intertragal notch were prioritized during the postural repositioning (including the angles formed by connecting combinations of these points). For the seat belt positioning, the location and distance from the left and right ASIS, suprasternal notch, and the xiphoid process were prioritized during repositioning.

A series of MR coils were placed at each of the scan locations of interest. A 1-channel large flexible coil was positioned to cover the pelvis region and two scans were taken using this coil: one for posterior pelvis covering up to L3 and the gluteal tissue and another for the anterior pelvis covering the pelvis area, a portion of the femoral shaft, superficial abdominal adipose tissue, and the Vitamin E capsules on the lap belt. A 1-channel small flex coil was placed at the navel/L3–L4 level and a single scan was taken to cover the sacrum to T10, and a portion of the Vitamin E capsules on the shoulder belt at this level. A 3-channel u-coil was used to image posterior aspect of the upper thorax, from T10 to T1 or C spine, depending on the height of the participant. After the first four scans were completed, a fourth 1-channel flexible surface coil was placed on the chest of the participant for the upper thoracic anterior scans to capture the sternum, a portion of the clavicles, and the upper shoulder belt (Fig. 2). Once the coils and the participant were positioned in the scanner, the participant was asked to keep still while the chair was adjusted vertically and horizontally to center the interested anatomy at the scanner center for imaging.

Each coil was used to generate a set of images in the region of the coil. After scanning, the images collected from each coil were combined with the images collected from the adjacent coils to generate a combined composite set of images spanning from the pelvis to the shoulder. An image registration process was developed and methods for digitizing spinal, pelvic, and sternal landmarks were established using 3D Slicer software[1]. Landmark registration was manually conducted using 8–10 overlapping anatomical points observed in common between each overlapping pair of scans. Anatomical landmarks were then digitized in 3D to quantify the position, orientation, and shape of the pelvis, spine, sternum, and visible portions of the clavicles. The digitized pelvis landmarks included the ASIS, posterior superior iliac spine (PSIS), pubic symphysis, ischial tuberosities, and multiple points on each acetabulum (for calculation of the spherical acetabulum centers). The position and orientation of each vertebra were digitized by capturing the four corners of each vertebral body in the midsagittal plane. Points digitized on the sternum included the sternal notch, the inferior-most point on the xyphoid process, and interim points on the lateral borders of the sternal body. In addition to the skeletal landmarks, points were digitized on the lap and shoulder belts. This was accomplished by capturing the coordinates of the Vitamin E tablets placed along the belt's centerline, top edge, and bottom edge (note: the center of the tablets were digitized—thus the reported coordinates are offset from the belt location by $1/2$ of a tablet height). These discrete digitized points were used to interpolate the curvilinear path of the belt in 3D space via linear interpolation between nearest points. Combined with the digitized skeletal landmarks, this belt geometry was used to calculate the distance between the belt system and pertinent strong points on the skeleton, such as the distance between the lap belt and the ASIS of the pelvis. This was measured as the resultant of the anterior–posterior distance and superior–inferior distance between the belt edge and the ASIS, in the sagittal plane intersecting with the ASIS.

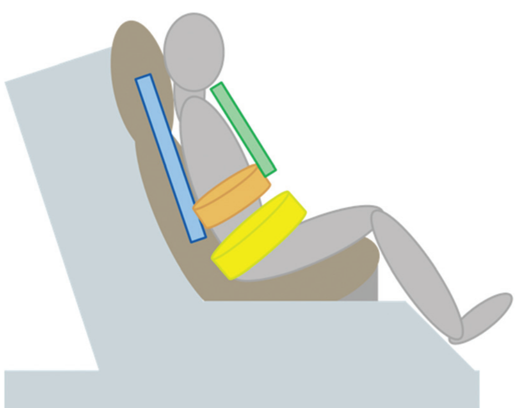

Fig. 2 Illustration of MRI coil placement. Coils were placed to allow capture of multiple overlapping scans, with minimal interim movement of the volunteer. From bottom to top: Yellow—large flex coil around the pelvis. Orange—small flex coil around the lumbar spine and abdomen. Blue—U-coil for the posterior upper torso. Green—flat flex coil for the anterior upper torso.

Results

Ten volunteers were scanned—five males and five females. The volunteer characteristics (age, height, and weight) are listed in Table 1. The self-selected seatback angles in the upright driving posture ranged from 10 deg to 20 deg in the in-vehicle sessions.

The volunteers exhibited a range of body shapes and skeletal postures. Figure 3 shows registered composite images from the midsagittal plane of the volunteers. Some volunteers exhibited a range of kyphosis and lordosis in the spine (e.g., volunteers 3, 9, and 12), whereas other volunteers had little or no kyphosis or lordosis, except in their upper thoracic spine (e.g., volunteers 4, 6, and 7). Some volunteers maintained similar relative vertebral alignments in their reclined scans (volunteer 4 in Fig. 4), whereas others reconfigured their spines when reclined (volunteer 5 in Fig. 4).

The volunteers also exhibited different external body shapes. In some cases, differences in body shape were associated with BMI. For example, volunteer 4 (male, BMI 28.0) had the second-to-largest BMI of the cohort and one of the largest abdominal depths relative to their chest depth. This relationship was not universal, however. The subject with the highest BMI (volunteer 3, also male, BMI 30.6) had a more uniform distribution of mass in his torso, with an abdominal depth (distance from the posterior surface of the back to the anterior surface of the abdomen) that was similar to his chest depth. Some differences were also observed in the general body shape between the males and females. Whereas the males tended to have a more uniform distribution of mass in their torso (with similar abdominal and chest depths), the females tended to have more of their soft tissue concentrated lower around their abdomen and pelvis (with a greater abdomen depth relative to their sagittal-plane chest depth, not including breast tissue).

Differences were also observed in the local geometry of the soft tissue, particularly around the lower abdomen and pelvis near the lap belt interface (Fig. 5). Some volunteers exhibited an inhomogeneous depth of superficial adipose tissue around the lower abdomen and pelvis, where the depth of adipose tissue was noticeably greater on anterior surface of the abdomen, reducing to near zero depth directly in front of the ASIS (e.g., volunteer 4, Fig. 5). In those cases, the

[1]www.slicer.org

superficial tissue anterior to the abdomen tended to hang down in front of the ASIS when the subject was in the upright posture, pushing the initial position of the lap belt forward relative to the ASIS. This pattern of adipose tissue was particularly apparent in the male volunteers. In other cases, the adipose tissue exhibited a more uniform distribution, with the superficial adipose tissue layer extending in a continuous fashion over the ASIS (e.g., volunteer 5, Fig. 5). This also affected the lap belt location relative to the ASIS, with a continuous depth of adipose tissue between the lap belt and the ASIS. This pattern of adipose tissue geometry was particularly apparent in female subjects.

The differences in adipose tissue distribution also affected the changes in belt position that occur when the volunteers reclined. For subjects with the android adipose tissue distribution, the soft tissue overhanging the ASIS tended to get pulled back as the torso rotated rearward, lessening the amount of soft tissue between the belt and the ASIS (thus also drawing the belt closer to the ASIS). In contrast, for subjects with the gynoid soft tissue distribution, the more-uniform layer of adipose tissue remained in place between the lap belt and the pelvis even when the subjects reclined.

In addition to those qualitative observations, quantitative measures of the changes in pelvis angle and lap belt to pelvis distance between the two volunteer postures (upright versus reclined) were captured (Table 2). When moving from the upright to the reclined posture, the pelvis rotated rearward by an average of $62 \pm 14\%$ of the seatback rotation (male and female combined). A wide amount of variation was observed in the lap-belt-to-ASIS distance when moving from upright to reclined. In some cases, the lap belt drew closer to the ASIS (as indicated by a negative change in distance in Table 2), whereas in other cases, the lap-belt-to-ASIS distance increased (as indicated by a positive change in distance). As a result, the mean changes tended to be close to zero, with a large variability as indicated by the standard deviation.

Discussion

People vary in many ways. This complicates vehicle and restraint designers' work in optimizing protection for vehicle occupants. Some aspects of this variability can be described in terms of simple measures such as height, weight, and BMI. Other aspects of

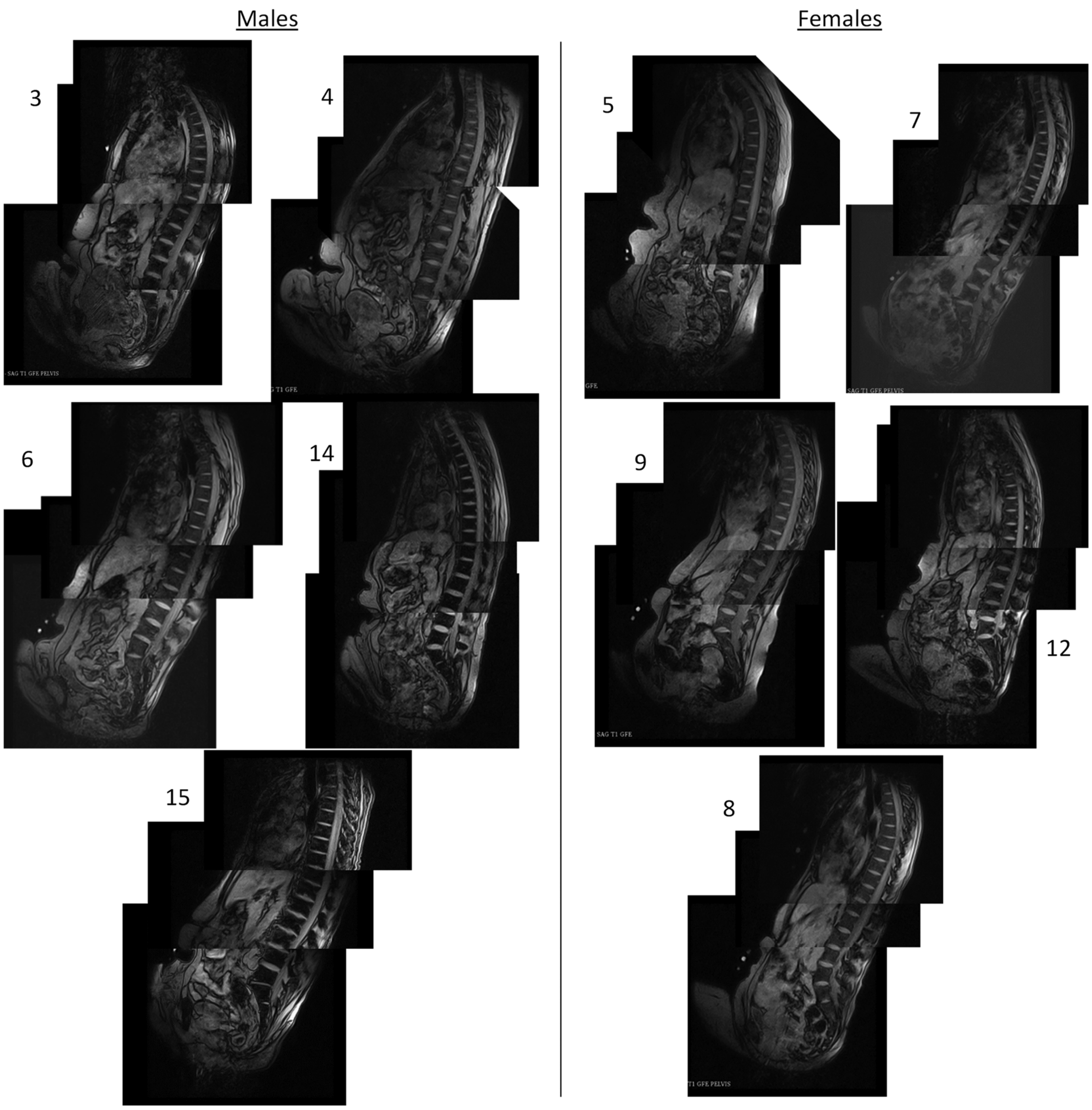

Fig. 3 Composite registered images at the midsagittal plane, with the volunteers in their self-selected upright driving postures. Note the substantial variations in spinal curvature and morphology of the anterior soft tissue.

Fig. 4 Examples of two volunteers, showing scans performed in their self-selected upright driving posture (left) compared to scans performed with a 50 deg seatback angle (right). Midsagittal plane.

variability defy descriptions from simple measures, or representations of average body shapes for selected heights and BMIs. Differences across people of the same height and BMI can be extreme, including gross variations in body shape or skeletal geometry. They can also be more subtle, such as variations in the

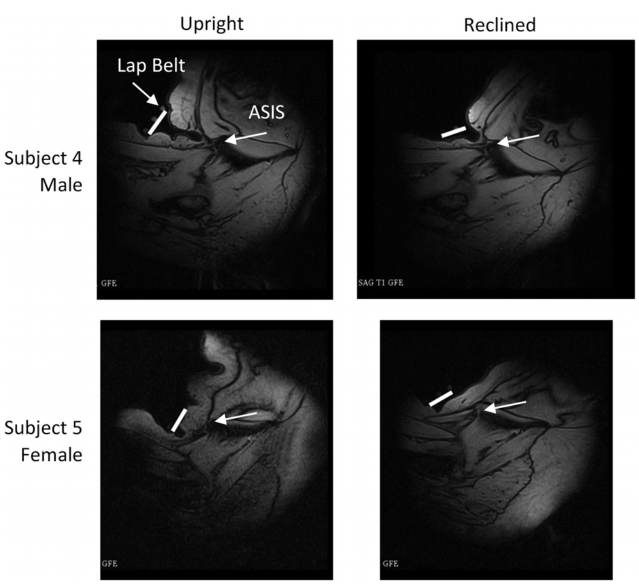

Fig. 5 Examples of adipose tissue contour directly in front of the ASIS, comparing a male subject (BMI 28, top row) to a female subject (BMI 27.9, bottom row) in their self-selected upright driving postures (left column) and their reclined postures (right column). The Anterior Superior Iliac Spines (ASIS) are noted by the arrows. Note that subject 4 (male) had very little adipose tissue directly in front of the ASIS, with a fold created by the abdominal adipose tissue overhanging the ASIS. In contrast, subject 5 (female) had a more uniform layer of adipose tissue, including a contiguous layer between the lap belt and the ASIS.

local distribution of adipose tissue overlying strong parts of the skeleton. Each of these may affect the body's interaction with a restraint system. The gross distribution of soft tissue affects the location of the body's center of mass, likely influencing overall kinematics. The depth of the soft tissue influences the location of the belt and the amount of material between the belt and the skeleton, both likely influencing the local engagement of the belt with the skeleton.

This study developed a method to observe both the gross and subtle dimensions of interpersonal variability, and how they affect belt fit relative to the pelvis, through direct observation with Open MRI. Substantial variations were observed already in this pilot study, including variations in the skeletal geometry such as the curvature of the spine, and future work will include quantification of some of this variation. Some of this variation was due to differences in the self-selected seatback angle across volunteers, but some was due to natural variations in spinal curvature across volunteers. Spinal curvature likely affects the nature of loading of the spine, particularly in cases where there are substantial compressive loads applied to the spine during an automotive crash. Though the effect on injury tolerance is not entirely clear, the spinal curvature can change the mode of failure of the spine from direct compressive failure (with a spine of lesser curvature) to a failure mode more akin to buckling (with a spine of greater curvature [23,24]). Further work is needed to investigate how these differences affect fundamental injury tolerance of the spine, especially in cases that are prone to elevated compressive load (such as frontal crashes in reclined postures [25]).

This study also provides a preliminary view of the variability that can be present in external body shape and adipose tissue distribution, and how it can affect the proximity of the belt relative to the skeleton. When a noticeable layer of superficial tissue was present, the females tended to exhibit a continuous layer of adipose tissue directly in front of the ASIS (as opposed to a nonuniform layer that thins in front of the ASIS as observed in the males). Beyond these systematic differences, however, substantial variations were also observed within both the male and female cohorts. These variations manifested in the wide variability in lap-belt-to-ASIS distance, as well as wide variations in the effect reclining that seat had on lap-belt-to-ASIS distance. Many past studies investigating the consequences of anthropometry variation in the population have focused on "average" body shapes developed from statistical shape models that vary by height, BMI, age, and sex [e.g., 9–12, 20]. Describing body shapes based on "averages" removes substantial information on the variability that remains even within narrow demographic bands of height, BMI, age, and sex. Considering that injury occurs in rare cases, potentially affected by a confluence of different sources of variability present in each specific case, removing information by describing "average" body shapes may blind us to the specific characteristics that lead to injury in some few people but not others. Instead, care should be taken to quantify not just average internal and external body shapes but also the variability present about those averages. This study is just one step in collecting such data—the volunteers in this study represented a convenience sample for pilot data collection, with differing BMIs and ages across the male and female cohorts examined. The next step in data collection (ongoing now) will include filling gaps in the BMI's and ages in the male and female datasets, to provide more direct points of comparison for the adipose tissue distributions described above. Extending further to quantify variability across the population will require substantially more data collection beyond even this ongoing work, potentially using a combination of high-detail methods such as those developed here in parallel to coarser methods that can facilitate larger sample sizes.

While the data presented in this paper are limited to select qualitative observations and quantitative measures, the larger body of information collected in these volunteer scans will prove invaluable for efforts to develop occupant injury prediction models capturing variability in the population. Specifically, the internal and external body shape geometries may be used to modify

Table 2 Changes in pelvis angle and lap-belt-to-ASIS distance observed between the upright and reclined postures

	Subject	Change in seatback angle (°)	Change in pelvis angle (°)	Change in pelvis angle: % of change in seatback angle	Lower belt edge to ASIS distance: Resultant avg., upright[a] (mm)	Lower belt edge to ASIS distance: Change with recline (mm)
Male	3	30	19	63%	NA[b]	NA
	4	30	13	42%	108	−28
	6	30	25	83%	84	+35
	14	40	21	52%	95	+22
	15	30	19	63%	97	−20
	Mean	*32*	*19*	*61%*	*96*	*+2*
	Std. Dev.	*4.5*	*4.4*	*15%*	*9.6*	*31*
Female	5	40	16	40%	63	NA
	7	30	25	83%	44	−19
	8	30	20	65%	55	+10
	9	34	20	59%	77	+11
	12	40	25	63%	96	−33
	Mean	*35*	*21*	*62%*	*67*	*−8*
	Std. Dev.	*5.0*	*3.9*	*15%*	*20.1*	*22*

[a]Resultant lap-belt-to-ASIS distance (average of left and right) in the upright posture. All other measurements indicate the change that was observed between the upright and reclined postures.
[b]NA: Not available due to obscured measurement in the MRI images.

computational human body models (HBMs) to capture both the gross and local variability aspects observed here. Some aspects of the body shape variability will likely be challenging to reflect in HBMs. For example, the undulations and over-hanging of superficial adipose tissue observed in some subjects may be challenging to implement in HBMs through traditional morphing techniques, as the wide variations in local tissue depth would inevitably result in large amounts of model mesh distortion. Reflecting these variations in adipose tissue geometry in HBMs may require foregoing current morphing techniques, and instead may require remeshing the model's adipose tissue to best suit the specific geometry being targeted.

Lastly, this study presents the first cohort of data collection with volunteers seated in an automotive posture in an Open MRI. While the data process is time intensive (requiring a total of approximately 10 h from each volunteer), the protocol provides a depth of 3D geometry data, obtained without the risk of exposure to ionizing radiation, that is not feasible to collect through other means. This protocol provides detailed 3D visualization of the external body shape, skeletal position, adipose tissue geometry (both superficial and visceral), organ geometry (including the major vasculature such as the aorta), and belt fit relative to the skeleton—effectively providing an anatomic atlas for each volunteer from the pelvis to the upper torso. While such detailed anatomical information is readily available for supine postures, there are few (if any) studies that have attempted to gather this depth of information in realistic automotive postures [17–19]. Recent approaches with upright CT scans, while valuable in their own right, were limited in the postures that they could attain by the geometric constraints of the CT scanner (effectively requiring the volunteers to sit with an erect posture [19]). Similarly, though X-Ray-based approaches provide great flexibility in posture, they are limited to capturing a two-dimensional planar image, often with limited fidelity to discern distinct tissues [17,18]. The Open MRI approach provides an ability to capture high fidelity, 3D information, including fine detail on distinct tissues. The main limitation of the Open MRI approach lies in the practical challenges of the time and cost needed for each set of scans. As a result, the Open MRI approach should not be considered a replacement for other methods that can provide a higher throughout with lower detail (including methods based on external surface scanning and manual palpation). Instead, we could encourage the field to think about how these various methods may be combined to build upon each other, each filling gaps in information ranging from highly detailed individual geometries to coarser views across a much larger sample size. The challenge now is to figure out how to put these pieces together to develop tools that can aid in injury prediction in the population.

This paper provides a preliminary view of the information that may be gained—continuing work will include interrogating the scans to extract further qualitative and quantitative information on the nature of occupant variability by age, sex and anthropometry, and the variability that remains within those demographic groups. Future work should also include comparing to external body shape information collected via other methods (e.g., laser scan) to contextualize the implications of the compromises that were required in the development of our MRI-safe seat (e.g., the removal of the lateral seat bolsters). Finally, unlike other imaging techniques, the Open MRI system also provides a unique imaging opportunity that is nonionizing, with no known risks for exposure (beyond magnetic safety protocols). This opens the door to large-scale volunteer data collection, limited only by the time/expense associated with the scans (which can be substantial). Our continuing work will include more data collection targeting volunteers filling in gaps in combinations of age, sex, and BMI that remain following the cohort presented here. Given the relative ubiquity of Open MRI systems in public and private institutions, combined with the minimal risk associated with such systems (with adherence to proper safety protocols), we would encourage others to seek opportunities to utilize such systems for parallel data collection to develop a base of data describing variations in body shape across the population.

Conclusion

Methods were developed to quantify variations in body shape, soft tissue geometry, skeletal geometry, and belt location relative to the skeleton in real automotive postures using Open MRI. Data were collected with 10 volunteers (5 females and 5 males) in two postures: their self-selected upright driving posture, and a reclined posture. Substantial qualitative and quantitative differences were observed across the volunteer group. In the males with substantial anterior abdominal adipose tissue, the adipose tissue depth tended to narrow in the region of the ASIS of the pelvis, and the abdominal adipose tissue tended to overhang the ASIS under gravity. In contrast, in the females with noticeable superficial adipose tissue, the adipose tissue depth around the lower abdomen and pelvis was more uniform, with a more continuous layer superficial to the ASIS. For skeletal geometry—substantial variations were observed in the curvature of the spine in both the upright and reclined postures, including a large amount of variability in the lordosis in the lumbar spine across the volunteers. For both the males and females, the pelvis rotated rearward by an average of approximately 62% of the change in seatback angle as the volunteers reclined. Lastly, quantitative measurements were captured describing the distance between the lap belt and the ASIS. This also exhibited a large amount of variability, affected by differences in the amount and geometry of the superficial adipose tissue. Because of this variability, in some cases the lap belt drew nearer to the pelvis as the volunteer reclined (e.g., as the overhanging folds in abdominal adipose tissue stretched out). In others, the lap belt to pelvis distance increased as the volunteer reclined. These observations highlight the extreme amount of variability that is present in both external body shape and internal anatomy not only across the sexes, but also for people of similar age, sex, height, and weight. These dimensions of both interdemographic and intrademographic variability should be considered when developing tools to assess safety system robustness for a diverse population.

Acknowledgment

We would especially like to thank the study volunteers for their time and patience, which have produced an invaluable contribution to advance injury prevention for a diverse population.

Funding Data

- Autoliv Research.

Data Availability Statement

The authors attest that all data for this study are included in the paper.

References

[1] Kent, R., Henary, B., and Matsuoka, F., 2005, "On the Fatal Crash Experience of Older Drivers," Annual Proceedings/Association for the Advancement of Automotive Medicine, Association for the Advancement of Automotive Medicine, Boston, MA, Vol. 49, p. 371.

[2] Forman, J. L., and McMurry, T. L., 2018, "Nonlinear Models of Injury Risk and Implications in Intervention Targeting for Thoracic Injury Mitigation," Traffic Inj. Prev., **19**(sup2), pp. S103–S108.

[3] Forman, J., Poplin, G. S., Shaw, C. G., McMurry, T. L., Schmidt, K., Ash, J., and Sunnevang, C., 2019, "Automobile Injury Trends in the Contemporary Fleet: Belted Occupants in Frontal Collisions," Traffic Inj. Prev., **20**(6), pp. 607–612.

[4] Kent, R. W., Forman, J. L., and Bostrom, O., 2010, "Is There Really a "Cushion Effect"?: a Biomechanical Investigation of Crash Injury Mechanisms in the Obese," Obesity, **18**(4), pp. 749–753.

[5] Forman, J., Lopez-Valdes, F. J., Lessley, D., Kindig, M., Kent, R., and Bostrom, O., 2009, "The Effect of Obesity on the Restraint of Automobile Occupants," Annals of Advances in Automotive Medicine/Annual Scientific Conference, Association for the Advancement of Automotive Medicine, Baltimore, MD, Oct. 5–7, Vol. 53, p. 25.

[6] Reed, M. P., Ebert-Hamilton, S. M., and Rupp, J. D., 2012, "Effects of Obesity on Seat Belt Fit," Traffic Inj. Prev., **13**(4), pp. 364–372.

[7] Ley, C. J., Lees, B., and Stevenson, J. C., 1992, "Sex-and Menopause-Associated Changes in Body-Fat Distribution," Am. J. Clin. Nutr., **55**(5), pp. 950–954.

[8] Janssen, I., Heymsfield, S. B., Wang, Z., and Ross, R., 2000, "Skeletal Muscle Mass and Distribution in 468 Men and Women Aged 18–88 yr," J. Appl. Physiol., **89**(1), pp. 81–88.

[9] Larsson, K. J., Pipkorn, B., Iraeus, J., Forman, J., and Hu, J., 2022, "Evaluation of a Diverse Population of Morphed Human Body Models for Prediction of Vehicle Occupant Crash Kinematics," Comput. Methods Biomech. Biomed. Eng., **25**(10), pp. 1125–1155.

[10] Hu, J., Zhang, K., Reed, M. P., Wang, J. T., Neal, M., and Lin, C. H., 2019, "Frontal Crash Simulations Using Parametric Human Models Representing a Diverse Population," Traffic Inj. Prev., **20**(sup1), pp. S97–S105.

[11] Hu, J., Zhang, K., Fanta, A., Jones, M., Reed, M., Neal, M., Wang, J. T., Lin, C. H., and Cao, L., 2017, "Stature and Body Shape Effects on Driver Injury Risks in Frontal Crashes: A Parametric Human Modelling Study," IRCOBI Conference, Antwerp, Belgium, Sept. 13–15, pp. 656–667.

[12] Shi, X., Cao, L., Reed, M. P., Rupp, J. D., and Hu, J., 2015, "Effects of Obesity on Occupant Responses in Frontal Crashes: A Simulation Analysis Using Human Body Models," Comput. Methods Biomech. Biomed. Eng., **18**(12), pp. 1280–1292.

[13] Reed, M. P., Ebert, S. M., and Jones, M. L., 2019, "Posture and Belt Fit in Reclined Passenger Seats," Traffic Inj. Prev., **20**(sup1), pp. S38–S42.

[14] Reed, M. P., Ebert, S. M., and Hallman, J. J., 2013, "Effects of Driver Characteristics on Seat Belt Fit," Stapp Car Crash J., **57**(57), pp. 43–57.

[15] Jones, M. L. H., Ebert, S. M., Varban, O., Hu, J., Reed, M. P., Weerappuli, P., Sundarajan, S., and Barbat, S., 2021, "Effect of Class I–III Obesity on Driver Seat Belt Fit," Traffic Inj. Prev., **22**(7), pp. 547–552.

[16] Jones, M. L. H., Ebert, S., Hu, J., and Reed, M. P., 2017, "Effects of High Levels of Obesity on Lap and Shoulder Belt Paths," Proceedings of the 2017 International Research Council on Injury Biomechanics (IRCOBI) Conference, Antwerp, BE, Sept. 13–15.

[17] Yamagata, H., Nishida, N., Izumiyama, T., Asahi, R., Koike, M., Mihara, A., Imajo, Y., et al., 2022, "A Radiographic and Physical Analysis of Factors Affecting Seat Belt Position in Sitting Car Seat," Sci. Rep., **12**(1), p. 10732.

[18] Izumiyama, T., Nishida, N., Yamagata, H., Asahi, R., Chen, X., Ohgi, J., Sugimoto, S., and Fukushima, M., 2022, "Analysis of Individual Variabilities for Lumbar and Pelvic Alignment in Highly Reclined Seating Postures and Occupant Kinematics in a Collision," IRCOBI, Porto, Portugal, Sept. 14–16.

[19] Tanaka, Y., Nakashima, A., Feng, H., Mizuno, K., Yamada, M., Yamada, Y., Yokoyama, Y., and Jinzaki, M., 2022, "Analysis of Lap Belt Fit to Human Subjects Using CT Images," SAE Paper No. 2021-22-0004.

[20] Zhang, K., Cao, L., Fanta, A., Reed, M. P., Neal, M., Wang, J.-T., Lin, C.-H., and Hu, J., 2017, "An Automated Method to Morph Finite Element Whole-Body Human Models With a Wide Range of Stature and Body Shape for Both Men and Women," J. Biomech., **60**, pp. 253–260.

[21] McMurry, T. L., Poplin, G. S., Shaw, G., and Panzer, M. B., 2018, "Crash Safety Concerns for Out-of-Position Occupant Postures: A Look Toward Safety in Highly Automated Vehicles," Traffic Inj. Prev., **19**(6), pp. 582–587.

[22] Matsushita, T., Saito, H., Sunnevång, C., Östling, M., Vishwanatha, A., and Tabhane, A., 2019, "Evaluation of the Protective Performance of a Novel Restraint System for Highly Automated Vehicles (HAV)," International Technical Conference on the Enhanced Safety of Vehicles, Eindhoven, The Netherlands, June 10–13.

[23] Nightingale, R. W., McElhaney, J. H., Camacho, D. L., Kleinberger, M., Winkelstein, B. A., and Myers, B. S., 1997, "The Dynamic Responses of the Cervical Spine: Buckling, End Conditions, and Tolerance in Compressive Impacts," SAE Paper No. 3968-3988.

[24] Myers, B. S., and Winkelstein, B. A., 1995, "Epidemiology, Classification, Mechanism, and Tolerance of Human Cervical Spine Injuries," Crit. Rev.™ Biomed. Eng., **23**(5–6), pp. 307–409.

[25] Richardson, R., Donlon, J. P., Jayathirtha, M., Forman, J. L., Shaw, G., Gepner, B., Kerrigan, J. R., Östling, M., Mroz, K., and Pipkorn, B., 2021, "Kinematic and Injury Response of Reclined PMHS in Frontal Impacts," SAE Paper No. 2020-22-0004.