Pelvis Kinematics and Injuries of Reclined Occupants in Frontal Impacts

R. Richardson, M. Jayathirtha, J.P. Donlon, J.L. Forman, B. Gepner, M. Ostling, K. Mroz, B. Pipkorn, J.R. Kerrigan

Abstract A reclined seating posture is likely to become more prevalent as highly automated vehicles are introduced to roadways. Current human body model (HBM) simulations reveal a high risk of submarining in this posture due to initial rearward pitch of the pelvis. The goal of this study was to assess the kinematics and injuries of the pelvis under lap-belt loading in a reclined seating posture through post-mortem human subject (PMHS) sled tests. Five male PMHS were seated on a semi-rigid seat and reclined to a torso angle of 50 deg. The three-point seat-integrated restraint used in this study was designed to mitigate submarining in a reclined posture. The pelvises of the subjects were initially positioned to a similar angle, but the subjects exhibited variations in kinematics, including the direction of pelvis rotation (forward vs. rearward) throughout the forward excursion. Two subjects sustained pelvis fractures at the right iliac wing between the anterior superior iliac spine and the anterior inferior iliac spine. One subject submarined. The results from this study can be used to better understand potential contributing factors to pelvis injury and submarining in a reclined seating posture. Further, the data can be used to assess and improve the biofidelity of HBMs.

Keywords Pelvis, PMHS, Recline, Restraint, Submarining

I. INTRODUCTION

Highly automated vehicles may permit occupants—including the driver—to assume a reclined forward-facing posture [1][2]. Crashes with reclined occupants have a miniscule incidence but a high severity. Dissanaike et al. [3] found that only 0.3% of occupants in NASS-CDS frontal crashes (1995-2005) were fully reclined, but these occupants had a 77% higher fatality rate. McMurry et al. [4] found a similar incidence (0.1%) for belted occupants in NASS-CDS frontal crashes over 2000-2015, with a 21% greater risk of MAIS 2+ and a 69% greater risk of MAIS 3+ for belted occupants. These field studies have suggested that unfavorable seatbelt engagement may contribute to the increased risk of injury and fatality for reclined occupants. In particular, a reclined posture may increase the risk of "submarining", where the lap-belt translates superiorly over the anterior superior iliac spines (ASIS) to load the abdomen directly.

Computational studies have predicted reclined occupant kinematics using finite element (FE) human body model (HBM) simulations. Several studies report unfavorable occupant kinematics and an increased risk of submarining, mainly due to changes in optimal seatback recline angle and altered seat-belt routing paths [5-11]. The position of the pelvis relative to the car seat or the lap-belt angle with respect to the pelvis have been shown to influence submarining [12][13]. In a reclined seating posture, the pelvis and lumbar spine are initially rotated rearward, increasing the likelihood of submarining and unfavorable loading by the lap-belt. However, due to an absence of benchmarking data in the literature, HBMs have not been validated in a reclined seating posture.

In addition to submarining-related outcomes, the results from the computational studies, as well as the field data, show that traditional B-pillar-mounted 3-point belt restraint systems, designed to fit properly with upright occupants, may be less effective when used in reclined positions. To improve the shoulder belt fit with the occupant's thorax, seat-integrated restraints may be introduced in self-driving vehicle technology. Further, to mitigate the likelihood of submarining in postures such as recline, novel restraint systems including dual lap-belt pretensioners have been investigated [6][14] [17]. Additionally, it has been proposed to use double lap belt load

R. Richardson is a PhD Student in Mechanical Engineering at the University of Virginia's Center for Applied Biomechanics (phone: 434-297-8008, email: rer5xu@virginia.edu). J.R. Kerrigan is the Director of University of Virginia's Center for Applied Biomechanics and Associate Professor in the Department of Mechanical and Aerospace Engineering.

limiting in combination with a separated lap and shoulder to reduce risk of pelvic wing fractures in slouched occupant sitting position [17].

The goal of this study was to assess the kinematics and injuries of the pelvis under lap-belt loading in a reclined seating posture through the use of post-mortem human subjects (PMHS) sled tests. The results from these sled tests are analyzed here in the context of occupant kinematics and associated mechanisms of loading.

II. METHODS

Test Environment

Simulated frontal impacts were performed using a reverse acceleration sled system (1.4 MN ServoSled®, Seattle Safety, Auburn WA). The subjects were seated on a semi-rigid seat that was designed to reproduce the behavior of a real vehicle front seat and has been used in previous PMHS sled tests [15][16]. The subjects were seated in a right front seating position. A 30-g (ΔV = 51 km/h) pulse was used which has been used in previous sled tests to assess PMHS submarining [16][17] (Fig. 1.).

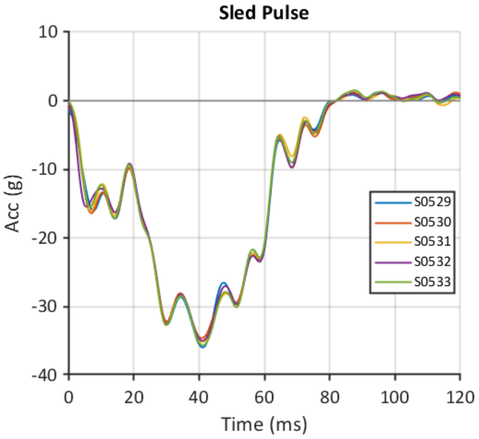

Fig. 1. Acceleration pulse used in this test series (CFC 60).

Restraint System

The subjects were restrained by a seat-integrated three-point belt equipped with dual lap-belt pretensioners and a shoulder-belt pretensioner and shoulder-belt load limiter of 3.5 kN. The anchorage points for the inboard (buckle) and outboard lap-belt were symmetric. The inboard lap-belt pretensioner, located at the buckle, fired at 3 ms. The outboard lap-belt pretensioner, located within the outboard retractor, as well as the shoulder-belt retractor pretensioner simultaneously fired at 10 ms. The belt system also included a crash locking tongue that mitigated webbing transfer from shoulder-belt to lap-belt. The D-ring in each test was positioned to approximate the position of a seatback-integrated D-ring, with an angle of approximately 12 degrees (from horizontal) as the belt leaves the shoulder in the direction of the retractor. The shoulder-belt crossed the shoulder at approximately mid-clavicle. The lap-belt was positioned by routing it over the subject's ASIS landmarks, which were estimated by palpation. The seat belt concept was developed to reduce the risk of submarining in reclined seating [14].

Restraint Instrumentation

Uniaxial belt gauge load cells were installed both on the shoulder-belt, between the subject's shoulder and the D-ring, and on the lap-belt, between the subject's right hip and the outboard retractor. Motion-capture markers were affixed to the belt at key locations relative to the subject's abdomen, including one at the center of the lap-belt (approximately center of the subject, below the umbilicus), and at the inboard and outboard locations (approximately at the subject's left and right ASIS landmarks) (Fig. A1). Markers were also installed on the outboard retractor and at the buckle.

Subjects

The PMHS were obtained and treated in accordance with the ethical guidelines established by the Human Usage Review Panel of the National Highway Traffic Safety Administration, and all testing and handling procedures were reviewed and approved by the Center for Applied Biomechanics and an institutional review board at the University of Virginia (Charlottesville, VA, USA). The PMHS were frozen until testing and screened for blood-borne pathogens including HIV and Hepatitis B and C. A full body computed tomography (CT) scan confirmed the absence of bone injury and abnormalities, and dual-energy X-ray absorptiometry (DXA) was used to measure bone mineral density (BMD), an indicator of bone quality (Table I). Four of the five subjects had approximately mid-sized male anthropometry (55 y.o. average; 178.5 cm average; 74.4 kg average) and one subject had similar stature but a lower mass (53 y.o; 175 cm; 56.7 kg).

TABLE I
Subject Details

Subject	Test No.	Age	Cause of Death	Height (cm)	Weight (kg)	BMD (g/cm2)
1	S0529	66	Dementia	175	74.4	1.065
2	S0530	53	Glioblastoma	175	56.7	1.357
3	S0531	72	Sepsis	185	73.9	1.133
4	S0532	25	Gun-shot wound	174	75.0	1.221
5	S0533	55	Myocardial Infarction	180	74.4	1.009

Positioning

The subjects were reclined to a torso angle of approximately 50 deg by measuring the angle between three different locations on the subject's torso with respect to the vertical: (i) a line connecting the H-point (palpated greater trochanter) to the acromion (mean±SD: 46.5±1.1 deg), (ii) a line connecting T11 and L3 (55.8±2.4 deg) and (iii) the sternum (50.6±8.4 deg). The angles for (i) and (ii) were measured using a large set of calipers placed over the surface of the subject, while the angle for (iii) was taken using an inclinometer positioned on the subject's sternum [18]. The subject was positioned using three tethers that were routed through overhead bars on the buck [19]. Pre-test computational simulations of this test condition showed no interaction of the occupant's torso with the seatback during the forward excursion. The minimal profile and placement of these tethers allowed for full visibility of posterior instrumentation. At the start of the impact pulse, a triggered mechanism released the tethers. Due to the sensitivity of submarining occurrence to variations in the pelvis position, the pelvis angle was selected based on targets developed from tests with reclined volunteers [20]. The pelvis angle was defined as the angle of the line connecting the average of the left and right ASIS to the pubic crest (PC) in the sagittal plane with respect to the anterior horizontal [21] (Fig. 2). A typical seated pelvis (Nyquist) angle is generally greater than 90 deg, and a greater pelvis angle corresponds to a reclined, rearward-rotated pelvis [22].

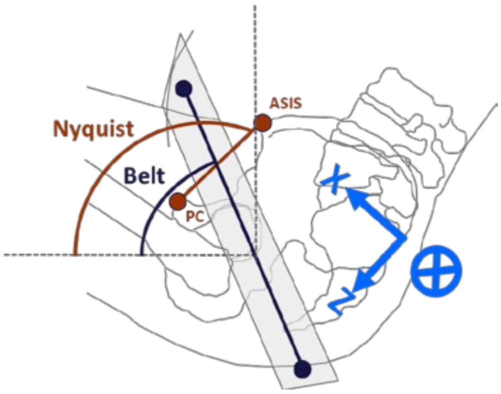

Fig. 2. Definitions of lap-belt and pelvis (Nyquist) angles. The Nyquist angle is shown in brown. The belt angle, shown in dark blue, is defined as the line connecting the center of the lap-belt to either the outboard retractor or the inboard buckle points with respect to the horizontal. The blue axes correspond to the pelvis local coordinate system (Y-axis going into the page).

The initial positions of the local coordinate systems for each of the body segments that were tracked with 3D motion tracking are tabulated in the Appendix (Table AI).

Pelvis Instrumentation

Kinematic data were collected at 1000 Hz using an optoelectronic motion capture system consisting of 20 cameras (Vicon TX^{TM}, VICON, Centennial, CO, USA) that tracked the position of retro reflective spherical markers in a calibrated 3D space lying within the cameras' collective field of view. Four-marker clusters were secured posterior to the pelvis, affixed at the left and right posterior superior iliac spines (PSIS) to facilitate the determination of the position and orientation of the corresponding bone using a rigid body assumption and coordinate transformations at each time step [19]. The local coordinate system of the pelvis generally conformed to the occupant coordinate system defined in in SAE J211 (positive X = anterior motion; positive Y = motion to the occupants' right; positive Z = inferior motion) (Fig. 2). The origin of the pelvis was between the posterior superior iliac spines (PSIS).

Two Micro-Measurements ® C2A-06-062WW-350 strain gauge rosettes were affixed to the lateral surface of each iliac wing between the ASIS an anterior-inferior iliac spine (AIIS) landmarks. The resulting in-plane maximum and minimum principal strains were computed, when possible, based on the three axes in each rosette.

III. RESULTS

Pelvis and Lap-belt Initial Positioning

The motion-capture markers rigidly attached to the pelvis bone and the lap-belt allowed for the replication of the initial (pre-impact) position of the lap-belt with respect to the pelvis in 3-D space (Fig. 3). Subjects exhibited initial pelvis (Nyquist) angles from 155-178 deg with Subjects 2 and 5 pitched most rearward (178 deg and 172 deg) and Subject 4 pitched most forward (155 deg) (Table II). Initial lap-belt angles (defined in Fig. 2) were 56-66 deg (inboard) and 60-74 deg (outboard) (Table II). While the anchorage points for the inboard and outboard lap-belt were symmetric, the buckle (inboard side) was initially positioned or "pulled" more rearward than the outboard retractor due to tension from the shoulder-belt. This led to a smaller angle at the inboard side. Soft tissue depth, measured from the ASIS midpoint to the lap-belt center, was around 83 mm for all except Subject 3 (142 mm).

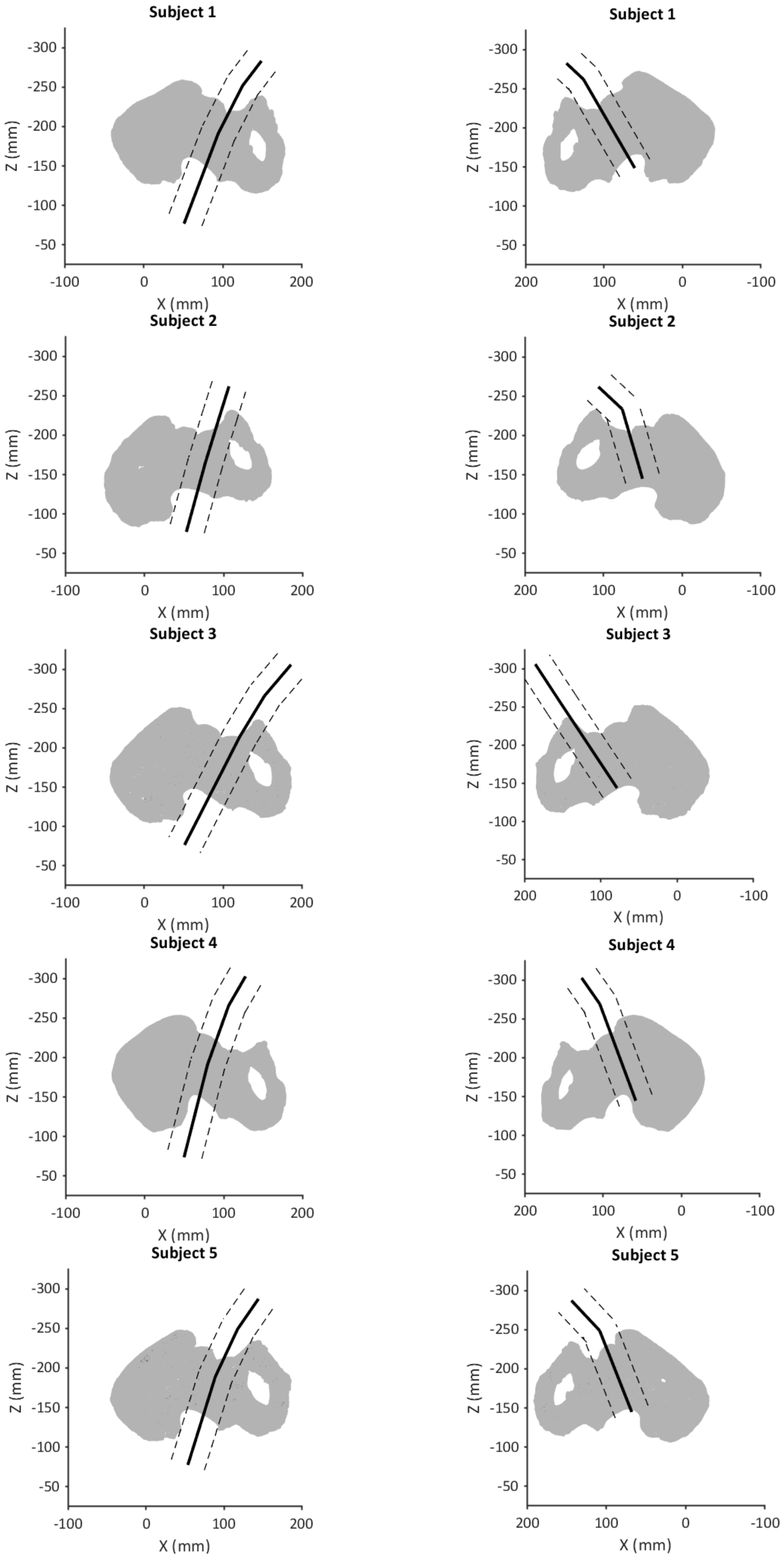

Fig. 3. Initial position of the pelvis and lap-belt in the buck coordinate system, viewed from the outboard (left column) and inboard (right column) sagittal planes. The solid black line connects the motion-capture markers placed in the center (width-wise) of the lap-belt. The dashed line approximates the edges of the lap-belt. The grey pelvis outline represents each subject's corresponding pelvis, reconstructed from the subject's CT-scan.

TABLE II
PELVIS, LAP-BELT, AND ABDOMEN MEASUREMENTS

Subject	**Pelvis (Nyquist) Angle (deg)**	**Inboard Belt Angle (deg)**	**Outboard Belt Angle (deg)**	**Soft Tissue Depth (mm)**
1	166	57	65	81
2	179	64	74	82
3	168	56	60	142
4	160	66	71	82
5	170	62	66	86

Kinematics

All subjects exhibited grossly similar kinematics in the sagittal plane (Fig. A2). The four midsize subjects showed consistent pelvis forward displacement with an average maximum of 148 mm, while Subject 2 (the lower-mass subject) displaced far less with a maximum of 33 mm (Fig. 4). The pelvis rotated forward in all tests except that with Subject 5 which had a neutral or slightly rearward rotation of 2-3 deg (Fig. 5).

The pelvis mount of Subject 3 interacted with the seat-pan at 30 ms and bent upwards. While this did not affect the subject's motion and only slightly affected the measured displacements, the pelvis pitch for this subject is accurate only up to 30 ms.

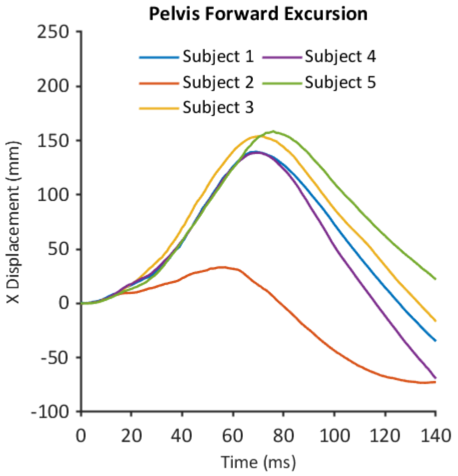

Fig. 4. Pelvis forward displacement with respect to the vehicle.

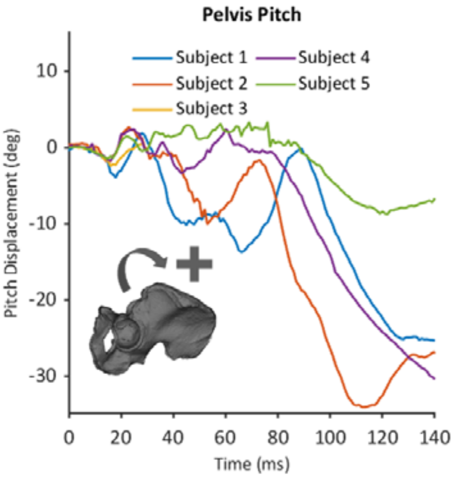

Fig. 5. Change in pelvis pitch with respect to the vehicle. A negative value represents a forward rotation.

The five subjects showed consistent trends in lap-belt angle time-history, although the lower-mass subject (Subject 2) rotated less (-15 deg) than the average of the other four subjects (-29 deg) (Fig. 6). The peak lap-belt angle occurs approximately at the same time as peak pelvis forward excursion.

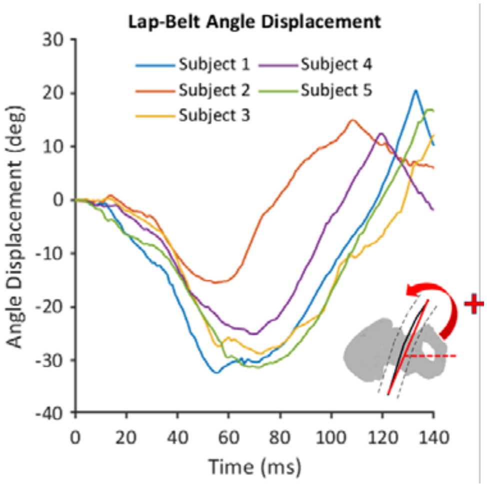

Fig. 6. Change in outboard lap-belt angle.

Pelvis Injuries and Submarining

Subjects 1 and 3 exhibited pelvis fractures at the right iliac wing between the ASIS and AIIS landmarks (Fig. 7). The injuries were identified from post-test CT-scans and confirmed by autopsy. These injuries were coded using the Abbreviated Injury Scale (AIS) and were both coded as AIS-2 as the posterior arch and remainder of the pelvic wing remained intact (Table A2).

Timing of injury was identified by the strain gauge rosettes affixed to the lateral surface of the iliac wing between the ASIS and AIIS landmarks. The strain time history from gauges on the right iliac wing of Subject 1 indicated a sharp drop in strain beginning at approximately 60-65 ms due to the sensor being displaced from the fracture that happened at this time (Fig. 8). The lap-belt force at the time of fracture was 7.8 kN. Subject 3 exhibited fracture at approximately 53-58 ms (lap-belt force of 6.6 kN), which was indicated simultaneously with a peak in strain and drop in lap-belt force. Subjects 2 and 4, who did not sustain pelvis fractures had peak lap-belt forces of 4.6 kN and 8.3 kN.

Subjects 1, 2, 3, and 5 all sustained injuries at the lower-level of the sacrum. Subject 1 exhibited a fracture at the S3-S4 level; Subject 2 exhibited a fracture at S5; Subject 3 exhibited a fracture at S4; and Subject 5 exhibited a fracture at S3 (Table A2).

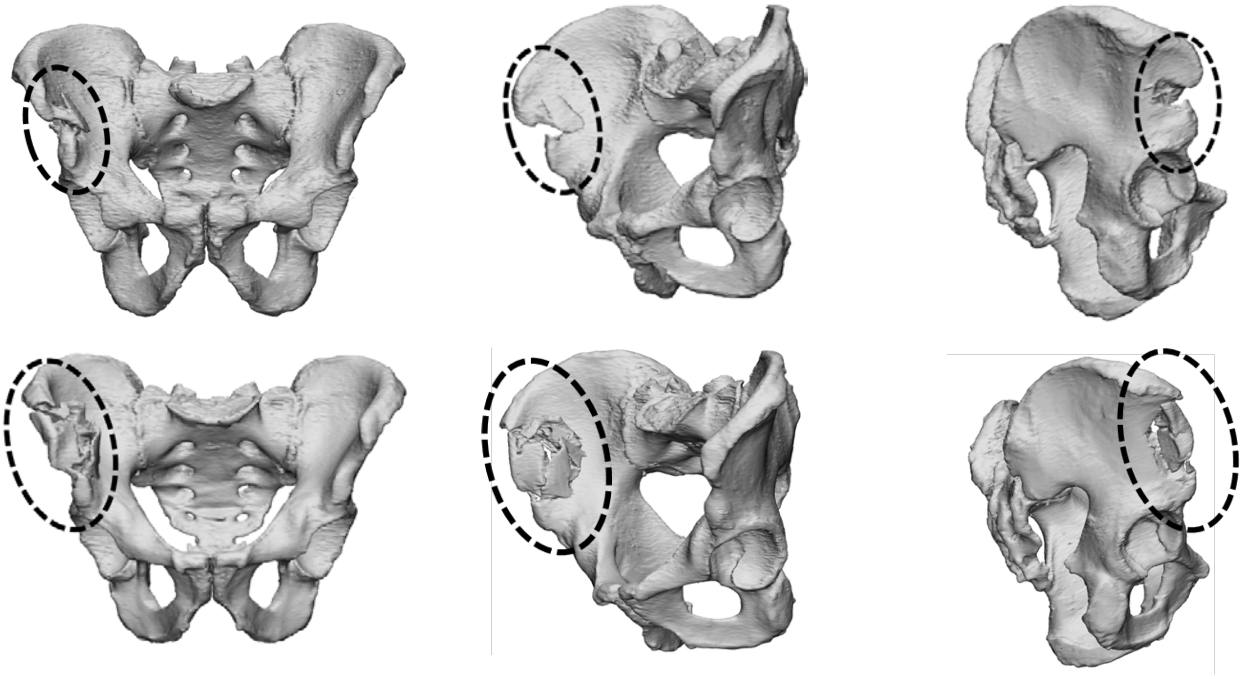

Fig. 7. Reconstructed pelvis CT-scans from Subject 1 (top row) and Subject 3 (bottom row), showing the fractures at the right iliac wing between the ASIS and AIIS landmarks in both of these subjects.

Subject 5 submarined at the inboard (buckle) side (left iliac wing) at approximately 60 ms, indicated by a simultaneous peak in strain at the left iliac wing and drop in lap-belt force at this time (Fig. 8). The lap-belt force just prior to submarining was 7.6 kN. High-speed video was focused at Subject 5’s pelvis during the submarining event (Fig. A4).

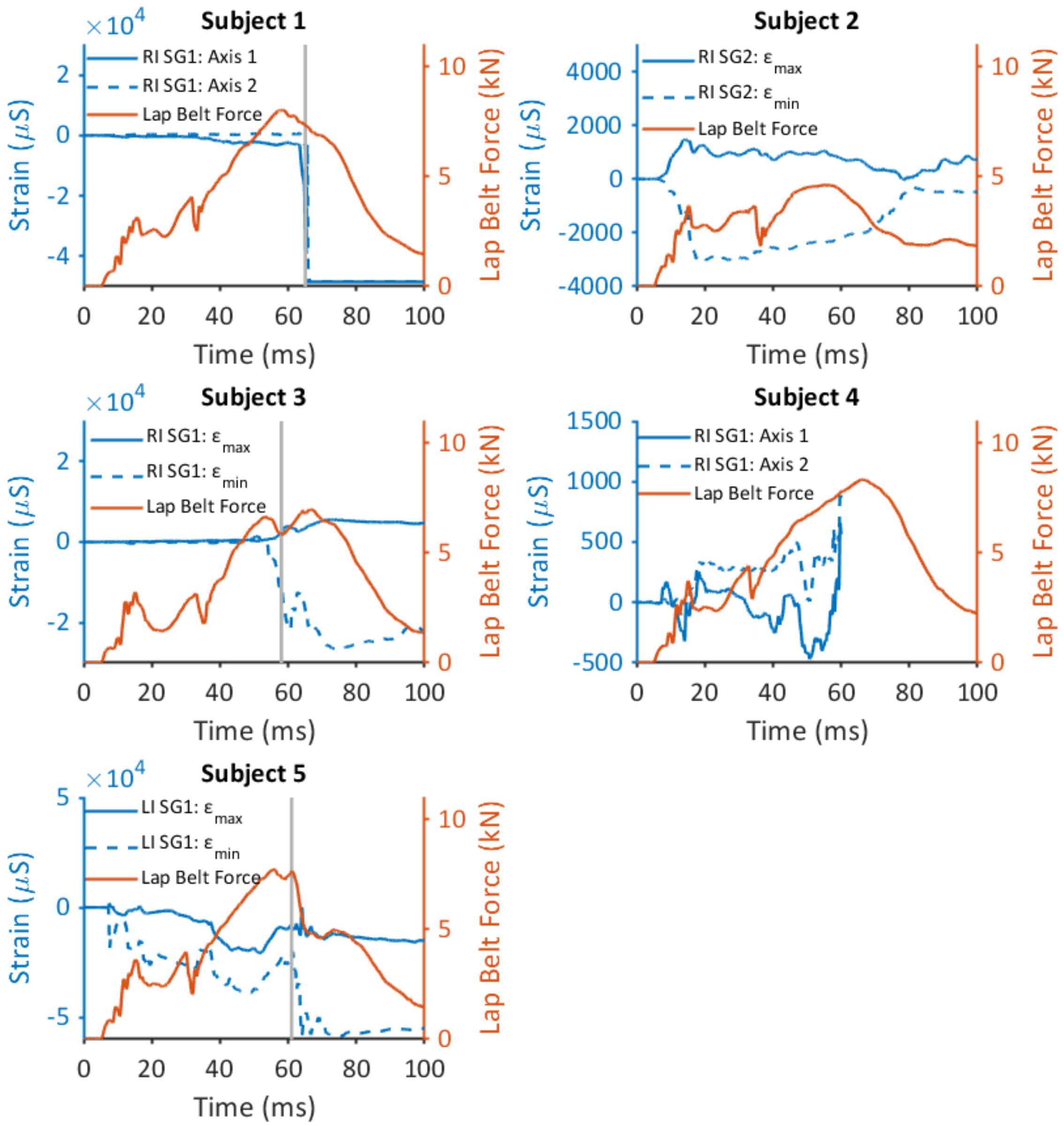

Fig. 8. Strain gauge signals (left axes) and outboard lap-belt forces (right axes) for all five subjects at either the lateral right iliac wing ("RI") or left iliac wing ("LI"). For subjects 1 and 4, the third axis of the strain gauge rosette failed. Subject 4's sensor detached at 60 ms.

The motion-capture markers rigidly attached to the pelvis bone and attached to the lap-belt allowed for the replication of the lap-belt position with respect to the pelvis at the time of injury in Subjects 1 and 3 at the outboard side (65 ms and 55 ms, respectively) (Fig. 9). The solid black line represents the belt segment between the outboard lap-belt retractor and the outboard motion-capture marker placed on the lap-belt, superior to the retractor. During the forward excursion, the subjects' soft tissue occluded the markers at the center of the lap-belt, limiting 3-D tracking. The red dashed arrow represents a projected lap-belt path based on the angle between the retractor and outboard marker. The length of this arrow, representing the connection between the outboard marker and the center of the lap-belt, is based on the soft-tissue depth (between the center of the ASIS landmarks and the center of the lap-belt) at a time just after the pretensioning (Fig. A3.). Tracking pelvis displacement in the X-direction for Subject 3 was still accurate despite the pelvis mount interaction that occurred at 30 ms; this subject's pelvis is shown at the X-position at time 55 ms (time of fracture) with the pitch angle measured just prior to the mount interaction with the seat at 30 ms. For Subject 5, the lap-belt position with respect to the pelvis was replicated at the time before (50 ms) and just after (65 ms) submarining (Fig. 9). Subjects 1 and 3 fractured near the time of peak pelvis forward excursion. Subjects 2 and 4 are shown at peak pelvis forward excursion (58 ms and 72 ms) for comparison.

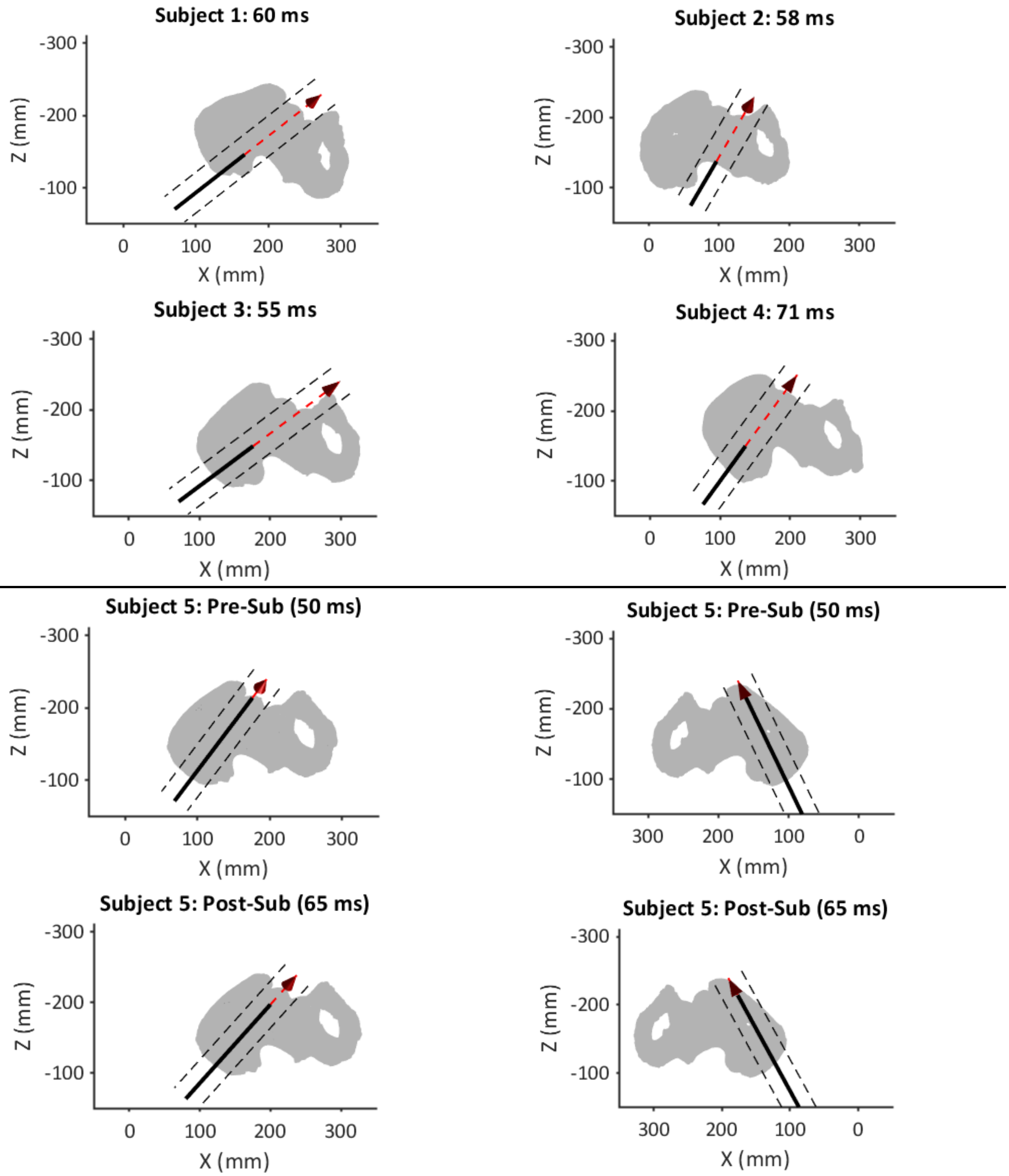

Fig. 9. Lap-belt position and pelvis orientation with respect to the vehicle at times of interest. Subject 1: At time of fracture (60 ms, OB). Subject 2: At time of peak excursion (58 ms, OB). Subject 3: At time of fracture (55 ms, OB); note that pelvis position is accurate but pelvis orientation is estimated. Subject 4: At time of peak excursion (71 ms, OB). Subject 5: Pre-submarining (50 ms) and post-submarining (65 ms) in both inboard and outboard views. The red dashed line indicates the estimated belt path when motion-capture markers on the belt were occluded.

TABLE III
PELVIS, LAP-BELT, AND ABDOMEN MEASUREMENTS AT TIME OF EVENT (OB = outboard; IB = inboard)

<table>
<tr><th>Subject</th><th colspan="2">Pelvis (Nyquist) Angle at Event (deg)</th><th colspan="2">Difference in Pelvis Angle
(Event Angle – Initial Angle)</th><th colspan="2">Belt Angle (deg)</th><th colspan="2">Difference in Belt Angle
(Event Angle – Initial Angle)</th></tr>
<tr><td>1</td><td colspan="2">156</td><td colspan="2">-10 (forward)</td><td colspan="2">38 (OB)</td><td colspan="2">-27 (OB)</td></tr>
<tr><td>2</td><td colspan="2">170</td><td colspan="2">-9 (forward)</td><td colspan="2">59 (OB)</td><td colspan="2">-14 (OB)</td></tr>
<tr><td>3</td><td colspan="2">X</td><td colspan="2">X</td><td colspan="2">37 (OB)</td><td colspan="2">-23 (OB)</td></tr>
<tr><td>4</td><td colspan="2">159</td><td colspan="2">-1 (forward)</td><td colspan="2">54 (OB)</td><td colspan="2">-17 (OB)</td></tr>
<tr><td rowspan="4">5</td><td rowspan="2">Pre-sub:</td><td rowspan="2">171</td><td rowspan="2">Pre-sub:</td><td rowspan="2">1 (rearward)</td><td rowspan="2">Pre-sub</td><td>53 (OB)</td><td rowspan="2">Pre-sub:</td><td>-13 (OB)</td></tr>
<tr><td>64 (IB)</td><td>2.2 (IB)</td></tr>
<tr><td rowspan="2">Post-sub:</td><td rowspan="2">173</td><td rowspan="2">Post-sub:</td><td rowspan="2">3 (rearward)</td><td rowspan="2">Post-sub:</td><td>48 (OB)</td><td rowspan="2">Post-sub:</td><td>-18 (OB)</td></tr>
<tr><td>61 (IB)</td><td>-0.6 (IB)</td></tr>
</table>

IV. DISCUSSION

Analysis of Pelvis Loading and Outcome Variability

Five midsize male PMHS were subjected to frontal impact tests in a forward-facing reclined posture. Two of the PMHS sustained fractures of the right anterior iliac wing, and one other PMHS submarined.

The observed fractures may have been due to the belt angle relative to the pelvis. Initially, the two PMHS who sustained fractures (Subjects 1 and 3) had pelvis angles near the average but the lowest (most horizontal) belt angles of all the subjects. Then, at the time of fracture, these two PMHS retained the lowest (most horizontal) belt angles as compared to the other PMHS (Fig. 9). The two fractured PMHS may also have attained the lowest (most forward pitched) pelvis angles at the time of fracture: Subject 1 certainly did (Nyquist angle of 156 deg at 60 ms), and Subject 3 may have (rotation data was lost after 30 ms). This combination of a forward-pitched pelvis and a belt angle more closely aligned with the acceleration vector may have increased the effective load of the lap-belt on the pelvis and loaded the pelvis in a direction of structural or material weakness. The peak lap-belt loads for Subjects 1 and 3 were 7.8 kN and 6.6 kN. Subject 4 had the highest lap-belt force (8.5 kN) and was likely uninjured due to this subject's young age and high BMD. Subject 5 had a lap-belt force of 7.6 kN prior to submarining; this subject may have fractured if this loading remained on the ASIS during the pelvis forward excursion. Subject 2 had the lowest lap-belt force of 4.6 kN; this low force, in combination with a small pelvis forward excursion and the subject's high BMD, likely contributed to the result of no injuries.

The observed submarining may also have been due to the belt angle relative to the pelvis. Initially, the PMHS who submarined (Subject 5) had a near-average pelvis angle and a belt angle only slightly higher (more vertical) than the average. However, immediately before submarining, the pelvis attained the highest (most rearward pitched) angle (171 deg at 50 ms), while retaining the same belt angle on the inboard side as initially (Fig. 9). The rearward rotation of the pelvis, in the absence of a concomitant change of belt angle, may have permitted the lap-belt to slide over the pelvis. Additionally, the submarining was observed to occur on the inboard (buckle) side of the pelvis. The asymmetric submarining may have been due to the asymmetric belt geometry, where the initial inboard belt angle was 5 deg lower than the initial outboard belt angle (Table 2).

All subjects except Subject 4 sustained sacral fractures. It is unknown whether or not these fractures occurred during the forward excursion or during rebound. Sacral fractures have been seen in sled tests with upright PMHS [17].

Two subjects (2 and 4) sustained neither ASIS fracture nor submarining. This suggests that these two PMHS experienced biomechanically favorable loading of the pelvis. For Subject 4, this may have been due to the combination of the highest (most vertical) belt angle (66 deg) and the lowest (most forward-pitched) pelvis angle (160 deg) initially. Subject 4 may also have had a higher tolerance for pelvis injury, as it was considerably younger than the other four subjects: this subject also was the only one to not sustain sacral fractures. For Subject 2, it is likely that the absence of ASIS fracture and submarining was due to the lower mass of the PMHS: Subject 2 displaced much less farther than the other subjects. This agrees with past studies, which have suggested that heavier occupants (e.g. obese) may be more likely to submarine than lighter occupants [15][23]. Nonetheless, these two subjects demonstrate the possibility of restraining the pelvis without causing ASIS fracture or submarining.

Recommendations for Future Research

Like the current study, past studies have observed ASIS fractures due to lap-belt loading [13][16][17][22][24]. However, these studies used various test conditions. Therefore, there is a need for future research into the tolerance of the pelvis (ASIS) under belt loading as a function of restraint design parameters (belt angle, belt load, recline angle, seat design etc.). Further, the results of the current study suggest a potential alteration to the current restraint design, incorporating a lap-belt load limiter to reduce injury risk. This system was successfully tested as a counter measure to pelvis fractures in a past study investigation slouched occupant sitting position [17] and further investigated by using 5 kN lap belt load limiter in two different set-ups; a rear seat set-up with lap belt anchorage more rear ward and one front seat set-up with lap belt anchorage more forward. Despite similar test condition and lap belt forces at approximately 5-6 kN all the PMHS in the rear seat set-up sustain pelvis wing fractures but none of the PMHS in the front seat set-up [16].

Similarly, past studies have examined the likelihood of submarining as related to belt angle and belt load [22][25]. However, more physical tests (e.g. with PMHS) in reclined postures are needed to expand previous research and to validate the predicted sensitivity of submarining to intrinsic occupant factors in expected reclined postures [9].

The connection of these two research foci – pelvis injury tolerance and submarining sensitivity – may suggest specific restraint design goals. For example, the results of the present study suggest the existence of a "sweet spot": a combination of lap-belt angle and lap-belt load, which may avoid both submarining and ASIS fracture. However, an optimum such as this may be highly sensitive to slight variations in intrinsic factors—external geometry, mass, pelvis geometry, soft tissue distribution, etc. Thus, identification and evaluation of proposed restraint designs for the future vehicle fleet may also require a comprehensive sensitivity study to relate uncontrollable intrinsic factors to controllable extrinsic factors.

V. CONCLUSIONS

The following conclusions can be drawn from this study:

- While the subjects exhibited similar gross kinematics (with the exception of Subject 2, who was lighter mass), the pelvis rotation differed between subjects; this rotation differed despite a similar initial pelvis angle and anthropometry among subjects
- Two subjects sustained pelvic (ASIS) fractures, which may have been due to a more horizontal lap-belt angle and a forward-pitched pelvis combined with a high lap-belt force
- One subject submarined, which may have been due to a rearward-pitched pelvis relative to the lap-belt angle or due to the subject’s pelvis bone geometry; another subject, with a similar rearward-pitched pelvis, may also have submarined but the lighter mass resulted in a subsequent lower amount of pelvis forward excursion, not permitting the lap-belt from sliding over the ASIS
- Future work should identify restraint design targets for reclined and upright occupants which avoid both submarining and ASIS fractures

VI. ACKNOWLEDGEMENT

We would like to acknowledge all those involved in the design, preparation, and execution of the sled tests at the University of Virginia’s Center for Applied Biomechanics. We would also like to acknowledge our sponsor, Autoliv Development AB, Sweden, for their support in this project.

VII. REFERENCES

[1] Ostling M, Larsson A. Occupant activities and sitting positions in automated vehicles in China and Sweden. *Enhanced Safety of Vehicles 26th Conference,* 2019, Eindhoven, The Netherlands.

[2] Jorlöv, S., Bohman, K., & Larsson, A. Seating positions and activities in highly automated cars–a qualitative study of future automated driving scenarios. In *International Research Conference on the Biomechanics of Impact*, 2017.

[3] Dissanaike S, Kaufman R, Mack CD, Mock C, Bulger E. The effect of reclined seats on mortality in motor vehicle collisions. *Journal of Trauma,* 2008, 64(3):614-619.

[4] McMurry TL, Poplin GS, Shaw G, Panzer MB. Crash safety concerns for out-of-position occupant postures: A look toward safety in highly automated vehicles. *Traffic Injury Prevention,* 2018, 19(6):582-587.

[5] Forman J, Lin H, Gepner B, Wu T, Panzer M. Occupant safety in automated vehicles. *Japan Society of Automotive Engineers*, 2018, Pacifico Yokohama, Japan.

[6] Gepner B, Draper D, Mroz K, Richardson R, Ostling M, Pipkorn B, Forman JL, Kerrigan JR. Comparison of human body models in frontal crashes with reclined seatback. *IRCOBI Conference Proceedings,* 2019, Florence, Italy.

[7] Ji P, Huang Y, Zhou Q. Mechanisms of using knee bolster to control kinematical motion of occupant in reclined posture for lowering injury risk. *International journal of crashworthiness*, 2017, 22(4):415-424.

[8] Lin H, Gepner B, Wu T, Forman J. Effect of seatback recline on occupant model response in frontal crashes. *Short communication presented at IRCOBI Conference,* 2018, Athens, Greece.

[9] Rawska K, Gepner B, Kulkarni S, Chastain K, Zhu J, Richardson R, Perez-Rapela D, Forman J, Kerrigan JR. Submarining sensitivity across varied anthropometry in an autonomous driving system environment. *Traffic Injury Prevention,* 2019, 20(2):123-127.

[10]Song D, Tarriere C, Mack P, Avaste FL. Finite element simulation of the occupant belt interaction chest and pelvis deformation belt sliding and submarining. *37th Stapp Car Crash Conference*, 1993, San Antonio, TX.

[11]Thorbole CTC. Dangers of seatback recline in a moving vehicle: how seatback recline increases the injury severity and shifts injury pattern. *ASME 2015 International Mechanical Engineering Congress and Exposition*, 2015, Houston, TX.

[12]Leung, Y. C., Tarrière, C., Fayon, A., Mairesse, P., Delmas, A., & Banzet, P. A comparison between part 572 dummy and human subject in the problem of submarining. SAE Transactions, 1979, 3537-3556.

[13]Luet C, Trosseille X, Drazetic P, Potier P, Vallancien G. Kinematics and dynamics of the pelvis in the process of submarining using PMHS sled tests. *SAE Technical Paper,* 2012, 22-0011.

[14]Ostling M, Sunnevang C, Svensson C, Kock HO. Potential future seating positions and the impact on injury risks in a Learning Intelligent Vehicle (LIV). *VDI-Tagung Fahrzeugsicherheit Conference 11,* 2017, Berlin, Germany.

[15]Trosseille X, Petit P, Uriot J, Potier P, Baudrit P, Richard O, et al. Reference PMHS sled tests to assess submarining of the small female. *Stapp Car Crash Journal,* 2018, 62:93-118.

[16]Uriot J, Potier P, Baudrit P, Trosseille X, Petit P, Richard O, et al. Reference PMHS sled tests to assess submarining. *SAE Technical Paper,* 2015, 22, 0008.

[17]Uriot J, Potier P, Baudrit P, Trosseille X, Richard O, et al. Comparison of HII, HIII and THOR dummy responses with respect to PMHS sled tests. *Proceedings of IRCOBI Conference*, 2015, Lyon, France.

[18]Richardson R, Jayathirtha M, Chastain K, Donlon J-P, Forman J, Gepner B, Ostling M, Mroz K, Shaw G, Pipkorn B, Kerrigan J. Thoracolumbar Spine Kinematics and Injuries in Frontal Impacts with Reclined Occupants. *Traffic Injury Prevention*, (*Accepted*, 2020).

[19]Richardson R, Donlon J-P, Chastain K, et al. Test methodology for evaluating the reclined seating environment with human surrogates. *Enhanced Safety of Vehicles 26th Conference*, 2019, Eindhoven, The Netherlands.

[20]Reed MP, Ebert SM. Effects of Recline on Passenger Posture and Belt Fit. UMTRI-2018-2 Technical Report.

[21]Nyquist, Gerald W., and Lawrence M. Patrick. Lumbar and pelvic orientations of the vehicle seated volunteer. *SAE Transactions,* 1976, 2610-2621.

[22]Uriot, J., Baudrit, P., Potier, P., Trosseille, X., Petit, P., Guillemot, H., ... & Vallancien, G. Investigations on the belt-to-pelvis interaction in case of submarining. *SAE Technical Paper*, 2006,22:0003.

[23]Forman, J., Lopez-Valdes, F. J., Lessley, D., Kindig, M., Kent, R., & Bostrom, O. The effect of obesity on the restraint of automobile occupants. In *Annals of Advances in Automotive Medicine/Annual Scientific Conference*, 2009, 53:25.

[24]Shaw, G., Lessley, D., Ash, J., Acosta, S., Heltzel, S., Riley, P., ... & Crandall, J. Pelvic restraint cushion sled test evaluation of pelvic forward motion. *Traffic injury prevention*, 2018, 19, 3:250-255.

[25]Kim, T., Park, G., Montesinos, S., Subit, D., Bolton, J., Overby, B., ... & Kim, H. Abdominal characterization under lap belt loading. In *24th Enhanced Safety of Vehicles Conference,* 2015, Gothenburg, Sweden, 13.

VIII. APPENDIX

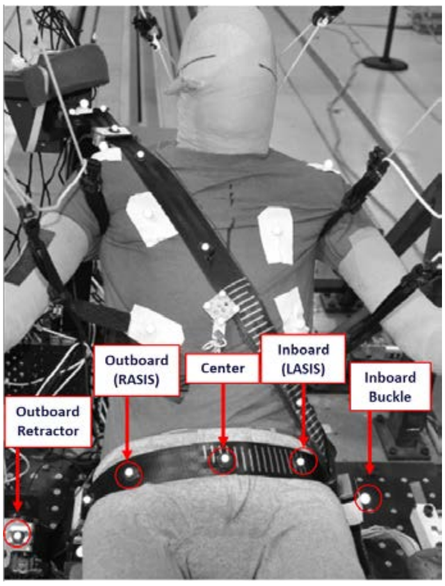

Fig. A1. Lap-belt motion-capture marker locations and descriptions.

TABLE AI
PMHS POSITION DATA

Measurement Point	Definition	X (mm)	Y (mm)	Z (mm)	SD X (mm)	SD Y (mm)	SD Z (mm)
Origin of Coordinate System	Seat edge right side	3196,7	-	461,7	-	-	-
Head Top	-	3472,0	-	1264,0	50,1	-	33,6
Head Origin Position	Midpoint btw L/R zygomatic processes	3512,5	-	1137,6	26,7	-	32,1
Head Angle (deg)	Midpoint btw L/R zygomatic process to midpoint btw eye orbits	33,6			2,6		
T1 Origin Position	Center of vertebral body	3467,3	-	996,3	23,1	-	15,1
T8 Origin Position	Center of vertebral body	3421,4	-	844,3	8,0	-	12,2
T11 Origin Position	Center of vertebral body	3374,2	-	787,5	4,4	-	15,9
L1 Origin Position	Center of vertebral body	3320,9	-	744,1	3,1	-	22,6
L3 Origin Position	Center of vertebral body	3255,0	-	701,7	14,0	-	5,9
Pelvis Origin Position	Midpoint btw L/R PSIS	3187,7	-	574,7	9,1	-	11,3
Pelvis Angle (deg)*	Angle of the vector from pubic symphysis to midpoint btw L/R ASIS with respect to the vertical	74,3			8,7		
Pelvis Angle (deg)*	Angle of the vector from midpoint btw L/R PSIS to midpoint btw L/R ASIS with respect to the horizontal	66,5			7,2		
Right Knee Position	Center lateral epicondyle	2658,7	-	750,9	19,9	-	28,2
Left Knee Position	Center lateral epicondyle	2660,2	-	754,1	7,0	-	28,6
Right Heel Position	-	2419,7	-	350,9	1,9	-	7,5
Left Heel Position	-	2418,8	-	351,2	5,4	-	12,5
Sternum	Midpoint btw L/R 4th rib insertion points	3299,3	-	928,8	20,8	-	15,5
HP Center btw R and L*	Midpoint btw L/R hip points	3078,0	-	642,7	1,4	-	3,3

*Data from S0531 not included in pelvis measurements

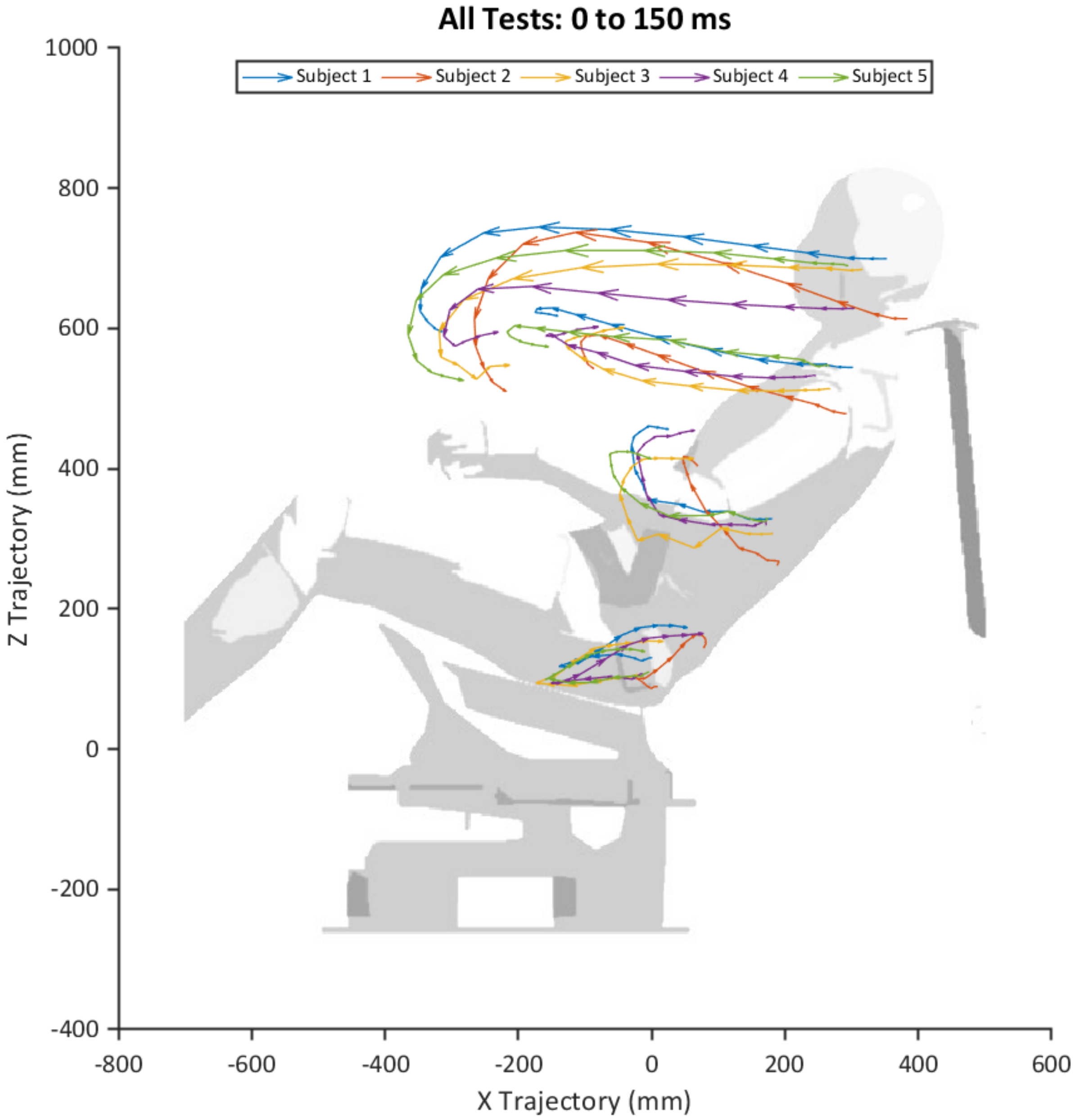

Fig. A2. Global X- and Z-trajectories of the five PMHS from 0 to 150 ms.

TABLE AII
PELVIS INJURY DETAILS

Subject	Injury Description(s) [from post-CT, pelvis]	AIS Code(s) [AIS15]	AIS Injury Descriptor
1	*"Comminuted displaced fracture of the right anterior iliac wing involving both the anterior superior and inferior iliac spine. Severely comminuted transversely oriented fracture of the sacrum at the S3-S4 level."*	856151.**2**	Pelvic ring fracture, posterior arch intact; isolated fracture not destroying the integrity of the pelvic ring
2	*"Anteriorly displaced comminuted fracture of the coccyx with a comminuted fracture of the S5 vertebral body"*	856151.**2**	Pelvic ring fracture, posterior arch intact; isolated fracture not destroying the integrity of the pelvic ring
3	*"Comminuted displaced and apex medially angulated fracture of the anterior right iliac wing extending from the anterior inferior iliac spine to the anterior superior iliac spine. Minimally displaced fracture of the central aspect of the S4 vertebral body with buckling of the anterior aspect of the vertebral body."*	856151.**2**	Pelvic ring fracture, posterior arch intact; isolated fracture not destroying the integrity of the pelvic ring
4	None	No Code	N/A
5	*"Apex posterior angulated fracture of the mid S3 vertebral body extending through the posterior elements with minimal displacement."*	856151.**2**	Pelvic ring fracture, posterior arch intact; isolated fracture not destroying the integrity of the pelvic ring

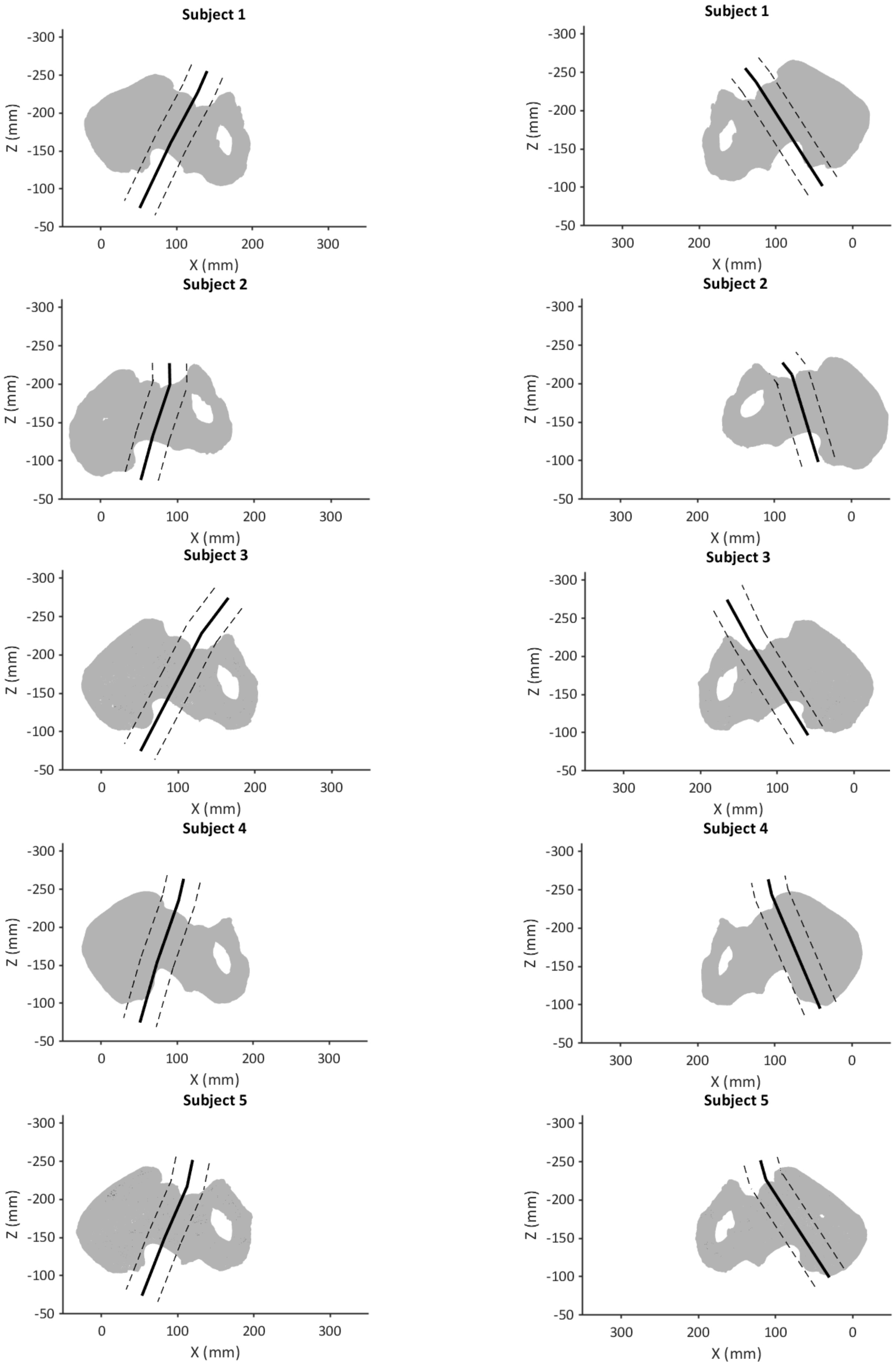

Fig. A3. Lap-belt position and pelvis position and orientation after pre-tensioning.

Fig. A4. Video stills of Subject 5 submarining