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ABSTRACT

Objective: This study examined the response of Post Mortem Human Subjects (PMHS) in reclined postures in frontal impacts. It aims to evaluate (1) the effect of initial lap belt position on pelvis kinematics during repeated low-speed impacts; and (2) pelvis injury outcomes and kinematics during high-speed impacts.

Methods: Two 50th-percentile female PMHS were exposed to six frontal impacts (three per subject). Each PMHS underwent two low-speed, non-injurious events (nominal delta-v: 10 km/h) followed by one high-speed, injurious test (nominal delta-v: 40 km/h). A CT scan was performed immediately after the two low-speed tests to confirm the absence of injury.s. All tests represented nominally frontal impacts. Occupants were seated on a semi-rigid seat (seat pan angle: 15°, reclined seatback angle: 45°) and restrained by a three-point seat belt system equipped with a crash locking tongue, three pretensioners (2.5 kN) and three load limiters (approximately 4 kN at the shoulder belt and 5.5 kN bilaterally at the lap belt). The shoulder belt pretensioner was activated only in the high-speed tests. In the two low-speed trials, the lap belt was first positioned immediately inferior to the Anterior Superior Iliac Spines (ASIS) and then further inferiorly on the lap of the subject to assess sensitivity to initial belt placement. Kinematics were recorded using 6-DX sensors and VICON marker clusters. A detailed autopsy was performed after the tests. Recruitment and handling of PMHS were reviewed and approved by the relevant Ethics Committee

Results: CT performed after the low-speed tests confirmed the absence of injury under the tested conditions. Submarining was not observed in any test, regardless of the delta-v. The pelvis of the PMHS rotated rearward, and the peak rotation magnitude was similar between subjects (4 deg and 6 deg, in the low-speed and high-speed tests respectively). The second PMHS peak pelvis rotation occurred after that of the first PMHS, regardless of test speed. This delay was attributed to the greater anterior adipose tissue of PMHS2 compared to PMHS1. Shoulder belt forces were comparable between the subjects, while the lap belt force experimented by PMHS2 was larger due to the subject's greater body mass. PMHS1 sustained a pelvic fracture and lumbar spine injuries. Both PMHS sustained multiple rib fractures and lower cervical spine injuries.

Conclusions: Lap-belt pretensioning appeared to reduce the influence of initial lap-belt position in both subjects, provided that the belt was initially routed inferior to the ASIS. Greater anterior pelvic soft-tissue thickness in PMHS2 delayed effective lap-belt engagement with the pelvis but did not substantially alter the magnitude of rearward pelvic rotation. No submarining was identified based on video review, belt force histories, and pelvic kinematics.

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KEYWORDS
Post Mortem Human subject tests; female occupants; reclined positions; submarining; pelvic kinematics

Introduction

Over the last 10 years, several studies have explored the potential risk associated with adopting more relaxed positions within the vehicle by modifying the inclination of the seat pan, the seat back, or both (Gepner et al. 2018; Forman et al. 2019; Richardson et al. 2020; Rawska et al. 2021; Somasundaram et al. 2024). This question is frequently addressed in the context of the adoption of highly automated vehicles and non-conventional seating positions for the occupants (Koppel et al. 2019; Lopez-Valdes et al. 2020), where the seat and the seat belt would serve as the primary occupant restraints.

Several of these studies have focused on assessing the biofidelity of existing tools like Anthropometric Test Devices (ATDs) and Human Body Models (HBMs). A common discussion point is the need of updating these surrogates so that they could adopt initial postures with increased pelvic angle or showing a direction of rotation of the pelvis compatible with that of the human (Gepner et al. 2022; Fei et al. 2024; Wang et al. 2024; 2025). This latter question has also

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prompted the need of deepening the understanding of the kinematics of the human occupant in reclined loading environments. Since 2019, a handful of studies have presented results from exposing both male and female Post Mortem Human Subjects (PMHS) of different anthropometries to frontal impacts in recline conditions (Richardson et al. 2021; Somasundaram et al. 2022; Baudrit et al. 2022; Shin et al. 2023; Lopez-Valdes et al. 2024; Somasundaram et al. 2024). Several studies have reported biomechanical differences between male and female occupants, including differences in injury tolerance, anthropometry, physiology and seat-belt fit. These differences may contribute to sex-related differences in injury patterns, including the frequency and severity of pelvic and abdominal injuries (Forman et al. 2015; Cronn et al. 2024; Mergler et al. 2025). However, the experimental literature on reclined female PMHS remains limited (reporting data from 15 subjects), particularly for studies focused on pelvic kinematics and lap-belt interaction.(Shin et al. 2023; Somasundaram et al. 2024, 2025a, 2025b). These studies have reported that reclined conditions resulted in injuries to the pelvis, sacrum and the thoracolumbar vertebrae. The proposed injury mechanism consisted of an increased compression of the lower lumbar spine and the pelvis (Richardson et al. 2020), despite some of the tests incorporated advanced seat belts designed to avoid submarining and excessive loading of the pelvic bone. To this end, lap belt systems incorporating dual pretensioners and load limiters have been used in several of the above mentioned tests. The reported increased risk of female pelvic fracture requires paying attention to the lap belt force magnitude that can be applied to the female pelvis. Recent research proposed an injury risk curve for iliac wing fractures based on the peak lap belt forces measured in sled tests. Specifically, lap belt forces between 5.5 and 6.2 kN were associated to a 50% probability of iliac wing fracture for different female anthropometries (Somasundaram et al. 2025b).

The question of whether increased seatback angle can increase the risk of submarining has been also explored in studies using HBM. Grebonval et al. found that the GHBMC male model showed that a combination of lower seat pan angle and higher pelvis angle in reclined conditions (40 degrees from vertical) resulted in large differences in terms of kinematics and predicted injury, including submarining (Grébonval et al. 2021a). Studies using the small female GHBMC model showed that increasing the recline angle above 10.9 degrees was a risk factor for submarining for female occupants in US NCAP frontal impacts. Initial lap belt position and pelvis orientation were also good predictors of submarining (Rawska et al. 2019; 2020). The use of HBM to understand submarining is an attractive alternative to experimental studies, due to the inherent difficulties of identifying submarining in PMHS tests (Somasundaram et al. 2025a). Small female HBM have been used to develop countermeasures to prevent submarining (Rawska et al. 2021) and recent studies have investigated new assessment criteria of submarining that can be used with HBM (Kalmar Gonzalo et al. 2025).

To date, the experimental studies that have tested PMHS in reclined conditions have reported very few cases of submarining (none with female PMHS). The observed submarining-like kinematics were associated with pelvic fractures and not directly to the sliding of the lap belt over the iliac wings and penetrating into the abdomen of the occupant. The current study augments the available experimental data from belted 50th percentile female PMHS seated in reclined conditions and exposed to frontal impacts. This new dataset enables the evaluation of proposed risk factors for submarining in female occupants, including initial lap-belt position, and the assessment of the iliac wing fracture risk curve in a similar, but still different, loading environment for the occupant, and to provide benchmarking data for the development of more robust female HBM.

In particular, this study aims to: discuss the effect of the initial position of the lap belt in the kinematics and dynamics of the occupant pelvis in repeated low-speed frontal impacts; and to report the kinematics of the pelvis in high-speed frontal impacts, discussing the resulting injury outcome.

Methods

Test setup

The test fixture consisted of a semi-rigid seat (Uriot et al. 2015a), a flat backrest with an adjustable headrest, a rigid pillar to support the B1 retractor and the D-ring and a rigid knee bolster. The seat consisted of two rigid plates, free to rotate around a pivot, with a resistive stiffness controlled by springs. The seat pan was initially tilted at 14.5 deg from horizontal and the Anti-SubMarining ramp (ASM ramp) was initially tilted at 32 deg from horizontal. The backrest was initially tilted at 45 deg and was used to facilitate a repeatable initial position of the test subjects. The backrest was retracted immediately before the onset of the acceleration (t=-20 ms) to facilitate visual access to the spinal instrumentation. A schematic of the test fixture is shown in the Appendix (Figure A1).

The PMHS were also restrained by a concept seat-integrated restraint system including three belt retractors, one at each of the three anchorage points (Figure A2). Each retractor was equipped with a 2-kN pretensioner and a different load limiter characteristic (B1, buckle, and B6 retractors produced an effective load limit at 4 kN, 5.5, and 5.5 kN, respectively). The buckle was equipped with a crash locking tongue to prevent webbing slippage from the shoulder belt to the lap belt or vice versa. Nominally, the shoulder belt pretensioner (B1) was fired at $t = 7$ ms, the buckle pretensioner was fired at $t = 9$ ms and the left anchor pretensioner (B6) was fired at $t = 17$ ms (times defined with respect to the onset of the acceleration, $t = 0$ ms).

A right-handed coordinate system (CS) following the SAE J211 convention was defined with origin at the midpoint of the rotation axis of the seat pan, as illustrated in Figure A3 in the Appendix. This CS, which moved with the sled, will be referred to as the Sled Coordinate System (SCS) and results are reported according to this coordinate system, unless otherwise noted.

Test subjects and instrumentation

The test subjects had the approximate anthropometry of a 50th percentile female as shown in Table 1. The PMHS were recruited, handled and tested according to the internal procedures of MOBIOS Lab, and ethical approval was received from the Ethics Committee of Universidad Pontificia Comillas. Subjects were screened to ensure the absence of preexisting injuries. All procedures were performed according to the guidelines proposed in F.J. Lopez-Valdes et al. (2024).

The head, T1, T8 and L2 vertebrae and the pelvis were instrumented with 6DX sensors (DTS) measuring linear accelerations and rotational velocities (angular rate) along three axes (20 kHz), plus clusters of reflective markers allowing to track the 3D kinematics using a VICON system (10 cameras at 1 kHz). A method based on transformation of coordinates in rigid bodies (Cappozzo et al. 2005), allowed to relate a local coordinate system (LCS) defined for each of these anatomical locations and the global coordinate system (GCS) of the laboratory. The definition of the LCS for the pelvis is included in the Appendix (Figure A6). The angle rotated by the pelvis was calculated integrating the y-component of the angular velocity expressed in the pelvic LCS. Two orthogonally oriented strain gauges were placed on the external aspect of the iliac wing, near the anterior superior iliac spine (ASIS), to document the time of fractures.

Six high-speed cameras were used to capture the motion of the PMHS at 1 kHz from different perspectives. All sensors and systems were synchronized using a common trigger time definition.

Table 1. Anthropometry and general information of test subjects.

Donor ID	Age	Stature (cm)	Weight (kg)	Cause of death	Test name	Lap belt position
PMHS1 (0058F)	86	162	58.4	Dementia	01-LS-01	High
					01-LS-02	Low
					01-HS-01	High
PMHS2 (0081 F)	56	157	66.0	Cervix cancer	02-LS-01	High
					02-LS-02	Low
					02-HS-01	High
50th female	–	162	63.0	–	–	–

Table 2. Landmark coordinates (mm) and angles (deg) achieved in the initial position.

PMHS1		01-LS-01	01-LS-02	01-HS-01
H-point L	x	32.1	35.9	41.4
	y	−78.0	−79.0	−78.4
	z	−124.5	−128.1	−128.8
H-point R	x	36.0	42.4	43.8
	y	76.3	75.1	75.9
	z	−123.7	−123.3	−127.6
Pelvic angle (H-S1L5)	y	77.9	78.5	81.0
Head angle (Frankfort/H)	y	26.1/24	34/34	33.1/30.1
PMHS2		02-LS-01	02-LS-02	02-HS-01
H-point L	x	42.2	38.5	39.5
	y	−88.7	−88.7	−86.6
	z	−126.1	−124.8	−124.2
H-point R	x	38.5	34.6	35.5
	y	83.7	83.7	85.7
	z	−128.0	−124.8	−122.7
Pelvic angle (H-S1L5)	y	80.6	80.2	78.4
Head angle (Frankfort/H)	y	29.4/29.2	29.1/29.4	29/32.4

Subject initial position, lap belt positions and test matrix

The target initial position of the subjects (Figure 1) was adopted based on a comfort study carried out with volunteers (Grébonval et al. 2021b). In this position, the target pelvic angle (defined as the angle between the line connecting the mid-point of the bilateral acetabulum and the mid-point of the L5-S1 intervertebral disk and the vertical direction) was 71 ± 10 deg. Detailed position measurements are provided in the Appendix (Tables A1 and A2), but Table 2 shows information about the actual initial pelvis position achieved in the tests.

Each subject was exposed to three tests (see Table 1). The first two were performed using a non-injurious acceleration pulse, resulting in a nominal 10 km/h delta-v (see Figure A7, Appendix). The initial position of the lap belt was modified between a high position (the upper edge of the lap belt strand was positioned as high as possible on the pelvis of the PMHS but still below the ASIS) and a low position (the upper edge of the lap belt strand was positioned as low as possible on the pelvis of the PMHS) in each of these two low-speed (LS) tests. Detailed measurements of the distance between the ASIS and a reference point on the superior edge of the lap belt corresponding to approximately the same lateral (y-axis) position of the ASIS are included in Table 3.

The third test was performed using a 40 km/h (nominally) delta-v pulse consisting of two plateaus about 12 g and

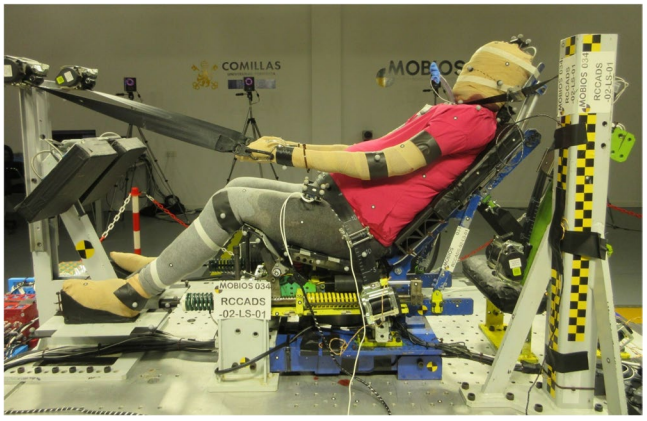


Figure 1. Initial position of PMHS2, illustrating the seat pan, anti-submarining ramp and seatback angles.

Table 3. Coordinates of ASIS bilaterally, of reference point on lap belt and magnitude of the distance between reference point and ASIS (mm).

		01-LS-01	01-LS-02	01-HS-01	02-LS-01	02-LS-02	02-HS-01
ASIS Left	x	5	8	11	8	11	8
	z	−193	−197	−196	−196	−195	−196
ASIS Right	x	4	11	8	16	20	16
	z	−198	−196	−200	−200	−197	−196
Lap belt reference left	x	42	49	23	58	76	50
	z	−190	−184	−197	−205	−192	−187
Lap belt reference right	x	21	42	17	26	58	29
	z	−190	−190	−200	−210	−195	−204
Distance	Left	19.9	32.4	14.5	65.6	87.2	62.3
	Right	36.7	44.2	11.7	77.2	90.7	69.2

Table 4. Maximum forward displacement of mid H-point, and the associated vertical displacement. Timing of maximum forward displacement.

	01-LS-01	01-LS-02	01-HS-01	02-LS-01	02-LS-02	02-HS-01
Disp X (mm)	6.4	3.2	118.9	20.7	17.6	194.2
Disp Z (mm)	−1.8	−1.5	11.4	2.5	−11.6	29.8
t (ms)	83	88	78	78	77	87

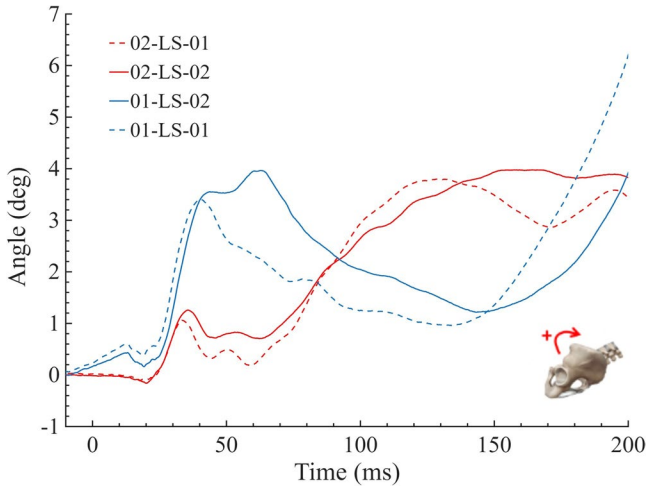


Figure 2. Time history of angle rotated by the pelvis in the low-speed tests. Dotted lines correspond to the high lap belt position while solid lines correspond to the low lap belt position.

25 g, over 90 ms (see Figure A7, Appendix). The lap belt position in the high-speed (HS) tests was chosen to be similar to the high position used in the corresponding low-speed test for the same subject (Figure A5, Appendix). The position and orientation of the seat belt retractors were kept constant throughout all the tests. The shoulder belt pretensioner was not activated in the two LS tests to avoid potential fractures of the rib cage.

Results

Kinematics

Displacement of the pelvis in the sagittal plane

Table 4 includes the peak displacement in the X SCS axis of the mid-point of the two acetabula (mid H-point), which was defined as the origin of the LCS of the pelvis, and the corresponding time. It also shows the vertical displacement in the Z axis for the same instant of time. In the LS tests, the initial lap belt position in the pelvis had minimum effect on the peak forward displacement of the mid H-point and its timing, consistently in both PMHS. PMHS2 exhibited larger forward excursions consistently in the LS and in the HS tests. The timing of the peak forward displacement was extremely consistent across the two subjects and speeds (81.8 ± 4.8 ms).

Influence of lap belt placement in pelvic rotation in LS tests

Figure 2 shows the time history of the angle rotated by the pelvis around the local Y axis (corresponding approximately with the sagittal plane) in the LS tests. The dotted lines show the kinematics corresponding to the higher position of the lap belt, while the solid lines show the results from the lower position of the lap belt. The pelvis of both subjects began rotating positively (i.e., the iliac crest rotating rearward with respect to the symphysis) at around $t = 20$ ms, shortly after the lap belt pretensioner was activated. Then, PMHS 2 showed a delay with respect to PMHS 1 in the interaction between the lap belt and the pelvis. In PMHS1, pelvic rotation reached approximately 4 degrees after the initial engagement produced by the pretensioner. This rotation caused by the lap belt loading the pelvis was observed around 70 ms later ($t = 130$ ms) in the case of PMHS2. Only in the tests with PMHS1, the lower position of the lap belt resulted in an extended interaction of the lap belt and the pelvis of the subject. The peak rotation magnitude of the pelvis under the action of the lap belt was similar for the two subjects.

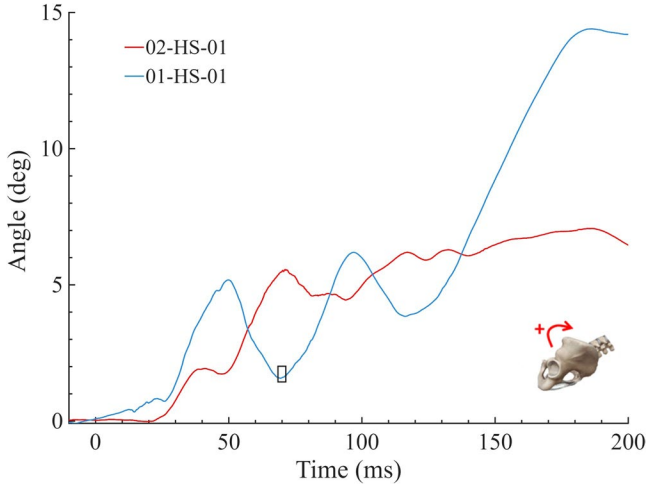


Figure 3. Time history of angle rotated by the pelvis in the high-speed tests. The timing of the pelvic fracture is indicated with a square.

Pelvic rotation in the HS tests

In the HS tests, the initial interaction between the pelvis and the lap belt is again determined by the pretensioner, starting around $t = 20$ ms (Figure 3). While the pelvic rotation in PMHS1 showed a bimodal behavior reaching a peak rotation around 6 deg (5.2 deg at $t = 50.1$ and 6.2 deg at $t = 96.9$ ms), the rotation of the pelvis of PMHS2 was more progressive and reached the peak of 5.5 deg at $t = 71.3$ ms. The valley between the two peaks in the response of PMHS1 ($t = 71.5$ ms) corresponds to the sudden change in strain observed in the right iliac wing (Figure 4), which is probably associated with the pelvic fracture identified in the autopsy. As noticed in the LS tests, the peak rotation observed in PMHS2 is delayed around 20 ms with respect to the first peak observed in PMHS1.

Analysis of submarining

Review of the onboard high-speed video, lap-belt force histories, and pelvic rotation histories did not suggest the possibility

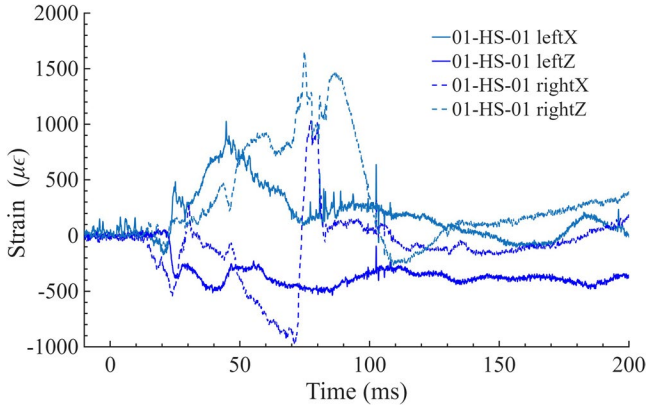


Figure 4. Time history of strain measured at the iliac wing (bilaterally) in the HS test of PMHS1.

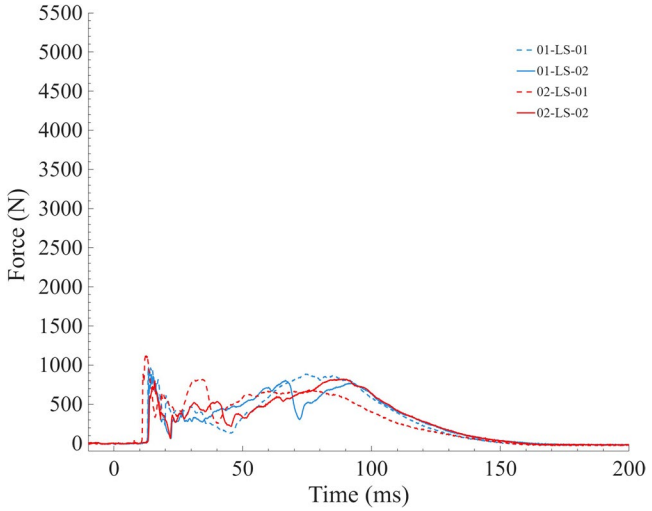


Figure 5. Time history of lap belt forces (B6) in the two low-speed tests. Dashed lines correspond to the highest position of lap belt and solid lines to the lowest one.

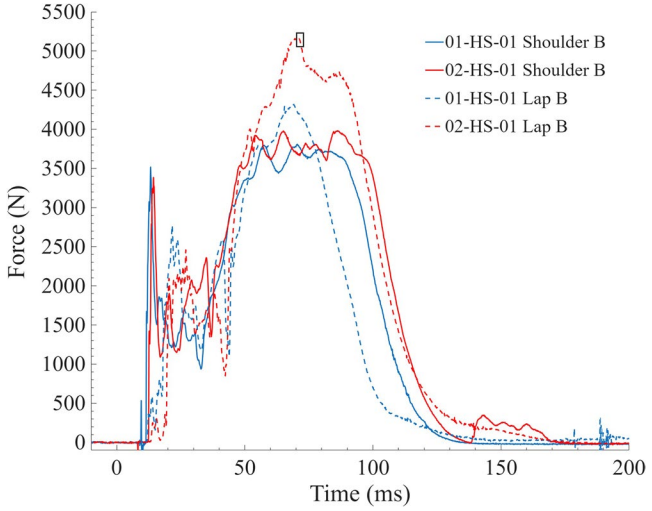


Figure 6. Time history of seat belt forces at the B3 and B6 locations in the two high-speed tests. The timing of the pelvic fracture is indicated with a square.

of submarining in the LS tests. The comparison of the lap belt forces between the two subjects and the two lap belt positions did not show any major difference, with both PMHS exhibiting approximately the same peak force around 1 kN. Fluctuations were noticed in the belt tension associated with the lower initial position of the lap belt (Figure 5).

The seat belt forces measured in the HS tests are shown in Figure 6. Both subjects exhibited a very similar response in the shoulder belt (solid lines), showing the initial 3.5 kN pretensioning and the force plateau of the load limited at approximately 4 kN. The lap belt forces showed more differences between the test subjects. First, the larger mass of PMHS2 resulted in a higher lap belt peak force in PMHS2 (5.1 kN vs 4.3 kN, both happening at around $t = 70$ ms) and in a larger time of interaction between the lap belt and the pelvis of the subject. No indication of submarining could be identified from the inspection of the lap belt forces nor from the inspection of the images captured by the onboard cameras (Appendix, Figure A8).

Table 5. Injuries found in the autopsy, including AIS 2015 code and description.

Injury	AIS	Description
PMHS1		
Rib fractures	450203.3	Rib cage, fractures without flail, any location unilateral or bilateral ≥3 ribs
C6/C7 dislocation, involving cord	610200.3	Spinal cord injury NFS as to impairment
L1/L2 disk	650699.2	Disk NFS
L2 transverse process	650620.1	Vertebra, transverse process
Ilium fractures	856151.2	Pelvic ring fracture, posterior arch intact; isolated fracture not destroying the integrity of the pelvic ring
PMHS2		
Rib fractures	450203.3	Rib cage, fractures without flail, any location unilateral or bilateral ≥3 ribs
C6-C7 IV disk	650205.3	Disk rupture
C7-T1 IV disk	650205.3	Disk rupture
Sternal fx	450804.2	Sternum fracture

Injuries

The list of injuries observed in the tests is provided in Table 5. Both subjects sustained AIS3 injuries to the thorax and AIS3 injuries to the cervical spine. Only PMHS1 sustained pelvic fractures (see Figure 7), without compromising the stability of the pelvic ring, and lumbar spine fractures.

Details about the location and distribution of rib and sternum fractures are provided in the Appendix (Figures A9 and A10).

Discussion

This work includes experimental results from frontal crash tests performed with two 50th percentile female PMHS in reclined positions. Each PMHS was exposed to three acceleration pulses: two of them were considered non-injurious (delta-v: 10 km/h), while the third one was injurious (delta-v: 40 km/h).

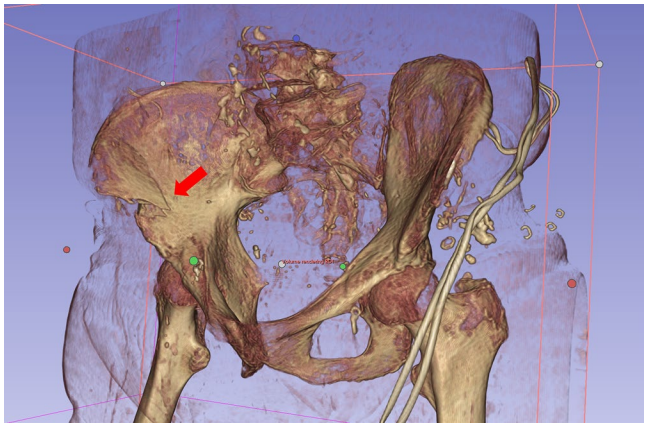


Figure 7. CT Image of the iliac wing fracture observed in the autopsy of PMHS1 (indicated by a red arrow).

The goal of the two LS tests was to analyze whether a different placement of the lap belt could result in different kinematics of the pelvis. Although it was observed that the lower position of the lap belt resulted in some oscillations of the seat belt force, there were no obvious differences in the sagittal rotation of the pelvis nor in the effective interaction of the lap belt with the subject. This finding confirms in PMHS tests that the pretensioner is capable of moving the lap belt to an equivalent initial position for as long as the lap belt is initially placed under the ASIS. Similar results were observed in the HBM study by Rawska et al. (2019), in which the lap belt pretensioner caused a downward motion of the belt, allowing it to hook on the iliac wings. While the intra-subject differences were negligible, the LS tests showed inter-subject differences in the timing of the pelvic rotation and of the peak of lap-belt forces. Even though the mass difference between PMHS1 and PMHS2 was only 7.6 kg, the amount of adipose tissue in front of the pelvis was visually greater in PMHS2. This excess of adipose tissue delayed the effective interaction of the lap-belt with the pelvis causing the rotation of the pelvis of PMHS2 to lag that of PMHS1 regardless of the lap belt initial position (Figure 2). The same delay in reaching the peak rotation angle was observed in the HS tests. A proxy measurement of the adipose tissue in front of the pelvis is given by calculating the distance between the ASIS and the so-called lap belt reference point, which is included in Table 3 and shows that the lap belt of PMHS 2 was positioned around 50 mm further from the pelvic bone.

Submarining was not observed in any of the tests, regardless of the delta-v. The rotation of the pelvis in the sagittal plane showed important differences in the HS tests, but they were likely caused by a fracture of the right iliac wing occurring at around $t = 80$ ms in PMHS1. In fact, a detailed analysis of the relative motion of the lap belt with respect to the ASIS showed that the belt strand is behind the ASIS in the X direction from that moment onwards. Despite this fracture of the iliac wing, the pelvic bone kept its integrity and the kinematics of the subject did not suggest a submarining-like motion. Video captures of the two HS tests at $t = 0$, 40, 80 and 120 ms are included in the Appendix for illustration. Interestingly, the amount of rearward rotation of the pelvis was similar between the two subjects within each speed and only around 2 deg larger in the HS tests compared to the LS tests. This relatively low rotation of the pelvis is coherent with the absence of submarining and the results observed in previous studies. Shin et al. had reported a different rotation response of the female PMHS pelvis in frontal impacts at 50 km/h, including a combination of rear- and forward rotations between $t = 20$ ms and $t = 100$ ms, and reaching rotation values up to +10 degrees (Shin et al. 2023). Although the lap belt used by Shin et al. also incorporated dual pretensioners, an important difference from the present study was that the occupants' feet were restrained, which may have contributed to the larger pelvic rotations observed in that study. The lack of submarining observed in our study is also consistent with several of the indicators for submarining discussed in Somasundaram et al. (2025a): the lack of evidence of submarining from the observation of film data, limited pelvic rotation and limited rotation of the ASM ramp. It should be also noted that we did not find any soft tissue abdominal injuries in the post-test autopsies.

Shin et al. also found fractures of the iliac wing in two out of three female subjects (although the peak lap belt forces were substantially higher than the ones found in the current study). Somasundaram et al. (2025b) proposed an iliac wing fracture risk curve for female PMHS that is supported by the results observed in our study. Peak lap belt force was 5.1 kN in PMHS1, which is close to the 5.55 kN force associated to a 50% fracture risk according to the proposed risk curve. In the case of PMHS2, who did not receive a pelvic fracture, the peak lap belt force was 4.3 kN, with an associated fracture risk between 10% and 25%. It should be noted that the lap belt used in our study incorporated bilateral load limiters. This finding suggests the need of limiting further the load on the pelvis to avoid pelvic fractures as suggested in previous research (Richardson et al. 2020; Shin et al. 2022). Regarding the forward displacement of the pelvis in the HS tests, Shin et al. reported that female PMHS peak excursions ranged between 115 mm and 170 mm, occurring at around 65 to 70 ms in all tests (in 50 km/h delta-v tests) (Shin et al. 2023). In the current study, the peak forward displacements were 118.9 and 194.2 mm and occurred slightly later, which is consistent with the incorporation of the load limiters in the lap belt.

To ensure that the repeated LS tests were not injurious, a CT scan was taken after the two initial LS tests with PMHS1 and no injuries were found in the analysis of the CT. This result is coherent with the female PMHS experiments presented in Somasundaram et al. (2024), which did not result in injuries after impacts at 15 km/h using also the semi-rigid seat. The study by Somasundaram et al. performed also experiments at 32 km/h resulting in thoracic spinal injuries and multiple rib fractures, but no fractures to the pelvis. However, the lap belt system was different from the one used in the current study. The lumbar intervertebral disk injury found in PMHS1 is consistent with injuries in the lower thoracic and lumbar areas reported in previous PMHS tests in recline positions (Richardson et al. 2020; Shin et al. 2023). The disk injuries found in the lower cervical spine of both subjects deserve attention, especially the dislocation

observed in PMHS1. These cervical injuries are likely caused by the lack of torso pitch observed in these tests and will be further investigated. Even if both subjects received multiple rib fractures, there was no flail chest found. These rib fractures are also potentially related to the lack of torso pitch that resulted in a non-effective interaction between the torso and the shoulder belt.

Although the primary focus of this study was pelvic kinematics and lap-belt loading, the thoracic injury outcomes are also relevant. Both subjects sustained AIS3 thoracic injuries despite the use of an advanced restraint system and despite the absence of submarining. This finding suggests that mitigation of submarining risk alone may not be sufficient to prevent serious injury in reclined postures. The rib fractures observed in both subjects may be related to the limited torso pitch during the impact and the resulting interaction between the torso and the shoulder belt. Therefore, future studies on reclined occupants should consider thoracic injury risk together with pelvic kinematics and submarining assessment, particularly when evaluating restraint strategies intended to control pelvis motion through lap-belt pretensioning and load limitation.

Contrary to the female PMHS tests performed by Shin et al. no sacrum fractures were found in our tests despite using a similar semi-rigid seat in both studies and even after increasing the stiffness of the ASM ramp in our case (Shin et al. 2023).

All of the above cited studies used the semi-rigid seat presented in Uriot et al. (2015b) to study the kinematics of the PMHS pelvis in reclined postures. The well defined stiffness and geometry of the seat makes it a convenient tool to facilitate the comparison between tests performed at different laboratories. In particular, this study allowed to provide an external validation of the iliac injury criterion developed in Somasundaram et al. (2025a). The simplified seat characteristics can also be easily modeled in finite element models of the tests. However, the use of the semi-rigid seat may bring some limitations to the study, as the angle and stiffness of the ASM ramp could be contributing to the pelvic and thoracolumbar injuries observed in our tests and in those reported by other authors (Richardson et al. 2020; Shin et al. 2023)

To the authors' knowledge, the current study is one of few to analyze in detail the kinematics of the female pelvis in frontal impacts in recline conditions. It provides novel data regarding the influence of the initial position of the lap belt in the kinematics and compares pelvic kinematics at LS and HS. Compared to previous studies with female PMHS, there are similarities in the injury outcomes but differences in the exact kinematics and pelvic loading, likely associated to the different lap restraint used.

The small number of individuals included in this study limits the generalization of these results to the population of 50^{th} percentile female occupants. However, as only data from 15 female subjects in reclined conditions have been reported to date, the additional data provided in the present study allow confirming previously reported findings while providing new experimental data under well-controlled and documented conditions in a slightly different load case. The present study adds two 50th-percentile female PMHS and six additional frontal impact exposures, including repeated low-speed tests on the same subjects with different initial lap-belt positions and CT confirmation of absence of injury before the high-speed test. This repeated-test design provides a controlled opportunity to examine the influence of initial lap-belt routing while reducing the confounding effect of intersubject anatomical variability. The results from the high-speed tests confirm the injury patterns observed in previous studies of reclined female occupants, but also show slightly different pelvic kinematics. In addition, the new data could be used to benchmark the kinematics of the pelvis of human body models in reclined conditions, as the restraint characteristics are different from those used in previous studies.

Conclusions

This study provides new experimental data on pelvic kinematics and belt loading for two 50th-percentile female PMHS seated in a reclined posture and exposed to repeated low-speed (10 km/h) and a subsequent high-speed (40 km/h) frontal impact. Across the low-speed tests, varying the initial lap-belt routing between a higher and lower position below the ASIS produced only limited differences in peak forward pelvis excursion and peak rearward pelvis rotation, although inter-subject differences were observed in the timing of lap-belt engagement. In the high-speed tests, both subjects exhibited rearward pelvis rotation of approximately 5–6 deg, with one subject sustaining iliac wing fracture temporally associated with an abrupt strain change and near the time of peak lap-belt loading. No submarining was identified based on synchronized video review, belt force histories, and pelvis kinematics. Both subjects sustained AIS3 thoracic injuries. These results expand the scarce dataset for reclined female PMHS and support the need for further work to (i) quantify belt-pelvis relative motion with operational submarining criteria and (ii) evaluate how subject-specific factors and restraint parameters influence lap-belt engagement and pelvic injury risk in reclined postures.

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AI Disclosure

Artificial Intelligence (AI) tools were used in the development of this manuscript. ChatGPT 5.2 was used to assist with English-language editing and with the development of MATLAB scripts for reading and plotting experimental data. In addition to traditional literature search methods, Elicit AI was also used to search for relevant literature, but all the AI-retrieved references were revised individually.

Author contributions

CRediT: **Francisco J. Lopez-Valdes**: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Visualization, Writing – original draft, Writing – review & editing; **Ema Jokubaityte**: Data curation, Investigation, Methodology, Writing – review & editing; **Manuel Valdano**: Data curation, Formal analysis, Investigation, Methodology, Writing – review & editing; **Juan M. Asensio-Gil**: Data curation, Investigation, Resources, Writing – review & editing; **Jesús R. Jimenez-Octavio**: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing – review & editing.

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