Preliminary Impact and Injury Response of Varied Anthropometry PMHS in Frontal Sled Tests

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ABSTRACT

Robust restraint system design requires effectiveness across varied anthropometries. Biofidelity reference datasets of post-mortem human surrogates (PMHS), a necessary component of informing and assessing restraint system design, exist for the mid-size males and small females, but there is limited research for other anthropometries such as the mid-size females and obese populations. The goal of this study was to evaluate the kinematic and injury response of mid-size female, elderly mid-size female, obese female, and obese male PMHS in upright frontal impacts in a simplified restraint environment. The test condition in this study was a full-frontal 30 km/h impact. The test fixture consisted of a rigid seat, knee bolster, foot pan, a custom 3 kN shoulder belt force limiter, and separate shoulder and lap belts. Twelve tests were performed with PMHS of varied anthropometries: three per occupant type (mid-size female, elderly mid-size female, obese female, and obese male). The restraint environment limited the movement of the lower extremities, isolating the thoracic response. Shoulder belt lengths and positioning varied by occupant type. Peak shoulder belt force values ranged between 2.8 and 4.4 kN. Differences in soft tissue distribution (including the hips, abdomen, and breasts) affected both the pre-test path of the shoulder belt on the thorax and the belt's subsequent motion relative to the thorax during the test. Rib fractures were observed across all four occupant types ranging from zero to 19 fractures. Occupant anthropometry affected the impact and injury response of the PMHS in this study, demonstrating the breadth of the population over which restraint system robustness is required.

INTRODUCTION

Despite advances in automotive safety that have significantly reduced fatality in the United States, injury is still a prevalent outcome of motor vehicle crashes (Kahane, 2015; Forman et al., 2019; Brumblelow et al., 2022). Risk of thoracic injury varies within the population and factors such as age, sex, and obesity could all have an impact on individual risk of injury. It is imperative that restraint systems are robust across all populations. Incorporation of occupant variability into injury prediction tools may lead to increases in the robustness of safety systems. Human Body Models (HBMs) have the potential to capture a wider range of population variability compared to physical testing. However, reference biomechanical data is vital to the validation and subsequent use of HBMs for injury risk prediction.

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The Gold Standard 2 (GS2) testing condition has been used previously to evaluate thoracic response of mid-size male and small female post-mortem human surrogates (PMHS) (Montesinos-Acosta et al., 2016; Shaw et al., 2017). This condition is highly simplified and limits motion of the lower extremities to isolate the thoracic response and shoulder belt interaction of the occupant. Other anthropometries, such as mid-size females, elderly mid-size females, and obese occupants have seen limited study in this regard. Mid-size female PMHS have been tested in recline (Shin et al., 2023) but have not been evaluated in upright seating configurations. The thoracic response of elderly female PMHS has been evaluated in a driver-side vehicle-like environment (Kang et al., 2017). Frontal impacts of obese subjects have been conducted in a rear seat environment (Forman et al., 2009, Kent et al., 2010), as well as in upright and reclined postures at varying severities seated on a semi-rigid seat (Somasundaram et al., 2022; Yoganandan et al., 2023).

The goal of this study was to evaluate the impact and injury response of mid-size female, elderly mid-size female, obese female, and obese male PMHS in an upright frontal impact with a simplified environment.

METHODS

Subject Information

Twelve tests were performed with PMHS in four occupant categories: mid-size female (50F), elderly mid-size female (e50F), obese female (ObF), and obese male (ObM). Target for elderly classification was defined as older than 70 years old. Target for obese classification was defined as a BMI between 30 and 39. Three tests per occupant type were performed (Table 1). All subjects were acquired and handled with the approval of and in accordance with the policies and procedures of the University of Virginia Institutional Review Board for Human Surrogate Use. All donors were screened and negative for blood-borne pathogens. A whole-body computed tomography (CT) scan was completed for each donor to confirm the absence of pre-test injury.

Table 1: Test Matrix

PMHS ID	Occupant Type	Age	Height (cm)	Weight (kg)	BMI	Sled No.
1118F	50th%ile Female	55	160	65	25	UVAS0963
1129F	50th%ile Female	59	158	62	22	UVAS1002
1137F	50th%ile Female	67	155	55	23	UVAS1001
1110F	Elderly 50th%ile Female	80	163	59	22	UVAS0960
1139F	Elderly 50th%ile Female	72	166	46	17	UVAS0998
1164F	Elderly 50th%ile Female	84	158	48	19	UVAS1003
1117F	Obese Female	69	160	79	31	UVAS0964
1124F	Obese Female	68	163	100	38	UVAS0963
1133F	Obese Female	72	158	80	32	UVAS0999
976M	Obese Male	60	185	135	39	UVAS0961
1101M	Obese Male	66	183	97	29	UVAS0965
1140M	Obese Male	58	188	110	31	UVAS1000

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Test Set Up

All tests were performed in the Gold Standard 2 condition (Figure 1; Montesinos-Acosta et al., 2016). The PMHS were seated on a flat rigid seat, and their feet were secured into an inclined footpan. A rigid knee bolster was secured in contact with the knees of the PMHS. The restraint consisted of separate shoulder and lap belt segments. The lap belt was rigidly secured at the anchor locations. The shoulder belt was routed through a surrogate D-Ring and attached to a custom force limiting device. The force limiter was configured to deliver a nominal 3 kN force limit for all occupant types. A Seattle Safety reverse acceleration servo sled (1.4 MN ServoSled®, Seattle Safety, Auburn, WA, USA) achieved a repeatable delta-V of 30 kph and a 9 G trapezoidal acceleration (Montesinos-Acosta et al., 2016).

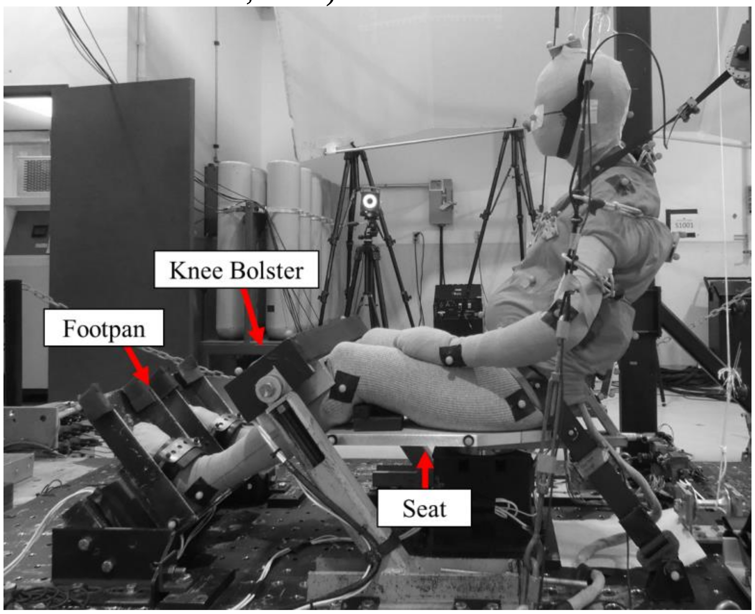

Figure 1: Gold Standard 2 sled set up featuring a mid-size female occupant (1137F).

Specimen Preparation and Instrumentation

All specimens were surgically instrumented with sensor mounts at 10 locations. Five locations posteriorly (head, T1, T8, L2, and pelvis) and five locations anteriorly (sternum and bilateral 4th and 8th ribs). All anterior instrumentation was installed with care to minimize anterior soft tissue disruption. No mastectomies were performed for female subjects to keep breast tissue intact. Bras were used to support breast tissue to facilitate realistic positioning when seated upright. Subject specific measurements were taken pre-test to identify subject specific bra size and bras had minimal padding and no underwire, similar in design and material to those used in the past for tests with mid-size female PMHS in recline (Shin et al., 2023). The same brand and type of bra was used for all female subjects.

Seven of the twelve PMHS in this study had a requisite supplier-performed amputation to one of their upper extremities. In cases of amputation at the elbow joint (n=3), where the full humerus was intact, no additional modifications were made. In cases of mid-humerus amputation (n=4), a potting cup was attached to the humerus and a threaded rod with mass at the end was

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attached to restore weight and length to the upper extremity. Weight was approximated using the intact upper extremity to define upper and lower bounds, with target total added mass being the average of the measurements.

Data from load cells, accelerometers, and angular rate sensors were collected at 10,000 Hz. Boundary loads of the test condition were measured by load cells in the seat, knee bolster channels, and the footpan. Belt forces were measured by seat belt tension load cells at four locations along the belt (upper shoulder belt, lower shoulder belt, pre-D-Ring belt, and lap belt). High-speed video was recorded by three off-board high-speed video cameras recording at 1000 frames per second. Each PMHS was instrumented with six-degree-of-freedom acceleration and angular rate sensors at the head, T1, T8, L2, and pelvis mount locations. Motion capture data was captured using a 3-D motion tracking system (Vicon TX™, Oxford, UK) at 1000 Hz. Motioning tracking arrays of four markers each were attached to the 10 surgically implanted mounts to track occupant motion during the impact. Additional motion tracking markers were attached to locations on the surface of the occupant and buck to track soft tissue, the buck structures, and extremity motion. If applicable, data were filtered in accordance with channel frequency class (CFC) recommendations of the Society of Automotive Engineers Recommended Practice J211 (SAE, 2014).

Subject and Belt Positioning

Symmetric positioning targets were derived from previous tests with mid-size male PMHS in the same condition (Shaw et al., 2009, Montesinos-Acosta et al. 2016). Due to differences in occupant stature, priority positioning targets were defined as hip (H-Point) location, femur angle, and gross torso posture (Table 2). The lap belt was secured low and tight across the lap of the PMHS. The shoulder belt was positioned targeting crossing the PMHS at mid-sternum and mid-clavicle. The vertical and lateral position of the D-Ring was adjusted per occupant to achieve similar positioning of the belt across the clavicle and sternum, and a shoulder belt take off angle of 30 degrees.

Table 2: Positioning targets and measurements (mean ± std.) reported per occupant type

Measurement	Target	50F	e50F	ObF	ObM
H-Point (mm)	0 ± 5	0.75 ± 2.4	1.0 ± 2.2	1.2 ± 5.7	1.9 ± 2.9
Femur Angle (°)	7 ± 3	8.5 ± 0.86	8.2 ± 1.5	7.3 ± 0.58	8.3 ± 0.76
Tibia Angle (°)	35 ± 3	34 ± 1.2	34 ± 1.6	34 ± 2.1	34 ± 1.0
Torso Angle (°)	62 ± 3	63 ± 1.3	62 ± 1.0	64 ± 2.0	65 ± 2.3
Shoulder Belt Take-Off Angle (°)	30 ± 1	30 ± 0.28	30 ± 0	30 ± 0	30 ± 0.58

Due to differences in upper extremity lengths, the shoulder belt was positioned such that the belted shoulder in all cases had a full-length extremity. If the PMHS had an amputation on the left arm, the right shoulder was belted and vice versa. In cases where both upper extremities were intact, the occupant was belted on the right shoulder. To convert the belted shoulder, the sled set up was mirrored in its entirety to ensure anchor locations and belt positions were comparable between the two belted conditions. Six tests were run with the right shoulder belted and six tests were run with the left shoulder belted.

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Kinematic Analysis

The locations of the anatomic landmarks at the head, T1, T8, L2, and pelvis were defined using local coordinate systems (Shaw et al., 2009). Motion tracking data of the arrays on the occupant allowed for the motion of the occupant to be tracked in 3D space throughout the impact. All coordinate systems were defined in accordance with the SAE J211 (SAE, 2014).

RESULTS

Shoulder Belt Position

Anterior soft tissue and breast tissue influenced the initial positioning of the shoulder belt (Figure 2). Positioning targets were defined as crossing at mid-clavicle and mid-sternum, and the D-Ring and force limiter lateral location were adjusted per occupant. However, in cases of more anterior soft tissue for the obese occupants, the shoulder belt shifted inboard towards the neck of the occupant resulting in a shallower frontal angle of the belt.

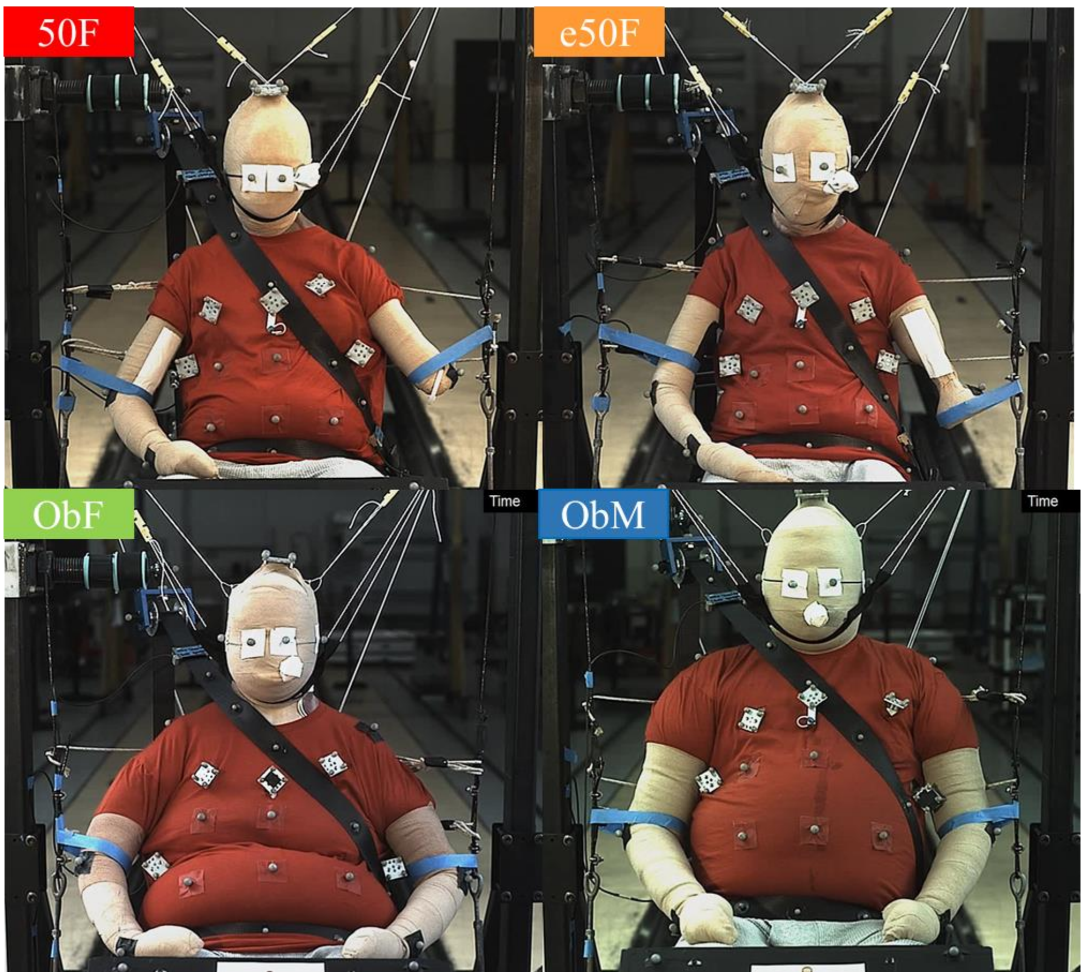

Figure 2: Initial shoulder belt position for a representative occupant for all four PMHS occupant types. Mid-size female (top left) and elderly mid-size female (top right) images mirrored for comparison.

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Shoulder Belt Force

The shoulder belt effectively arrested the forward motion of the PMHS in all twelve tests. Upper shoulder belt forces exhibited the nominal 3 kN force limit achieved by the force limiter with peak shoulder belt forces between 2.7 and 3.7 kN for eleven of the twelve tests, with a plateau around 3 kN (Figure 3). During UVAS0961 (ObM), the force limit was higher, peaking around 4.4 kN due to internal binding of the force limiting device during that test.

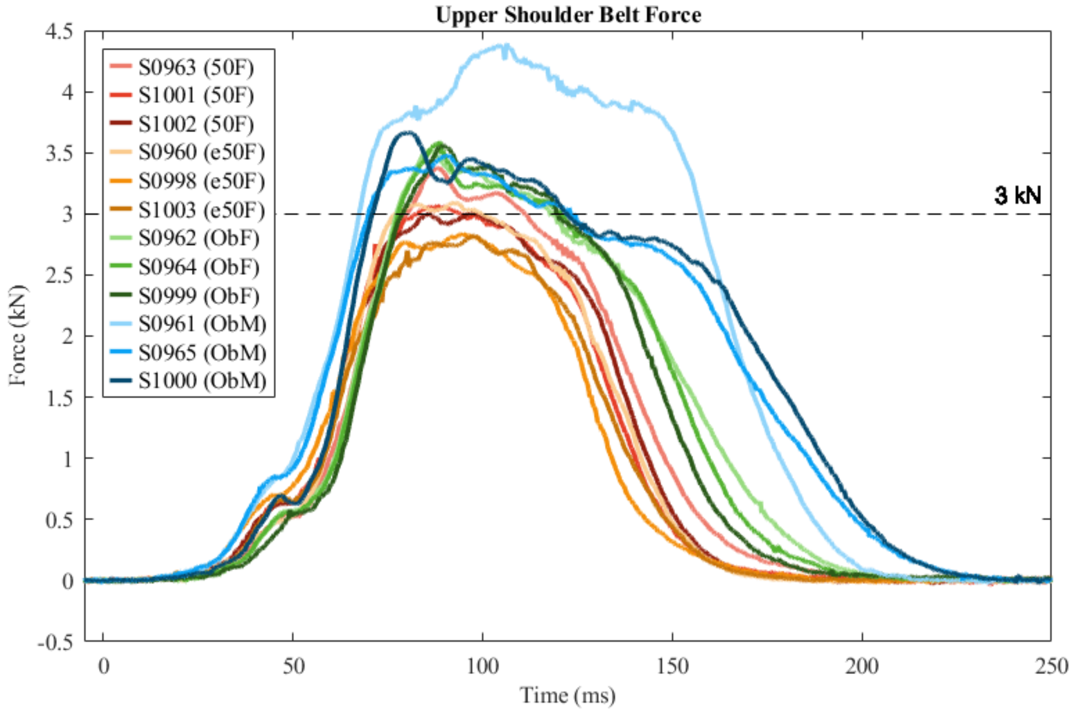

Figure 3: Upper shoulder belt force (CFC600 filter) measured by a tension load cell placed between the shoulder of the PMHS and the D-Ring

Occupant Kinematics

From off-board high-speed video views, the motion of all four occupant types was similar. Throughout the impact, the occupant flexed forward and the head moved forward and towards the belted shoulder (Figure 4).

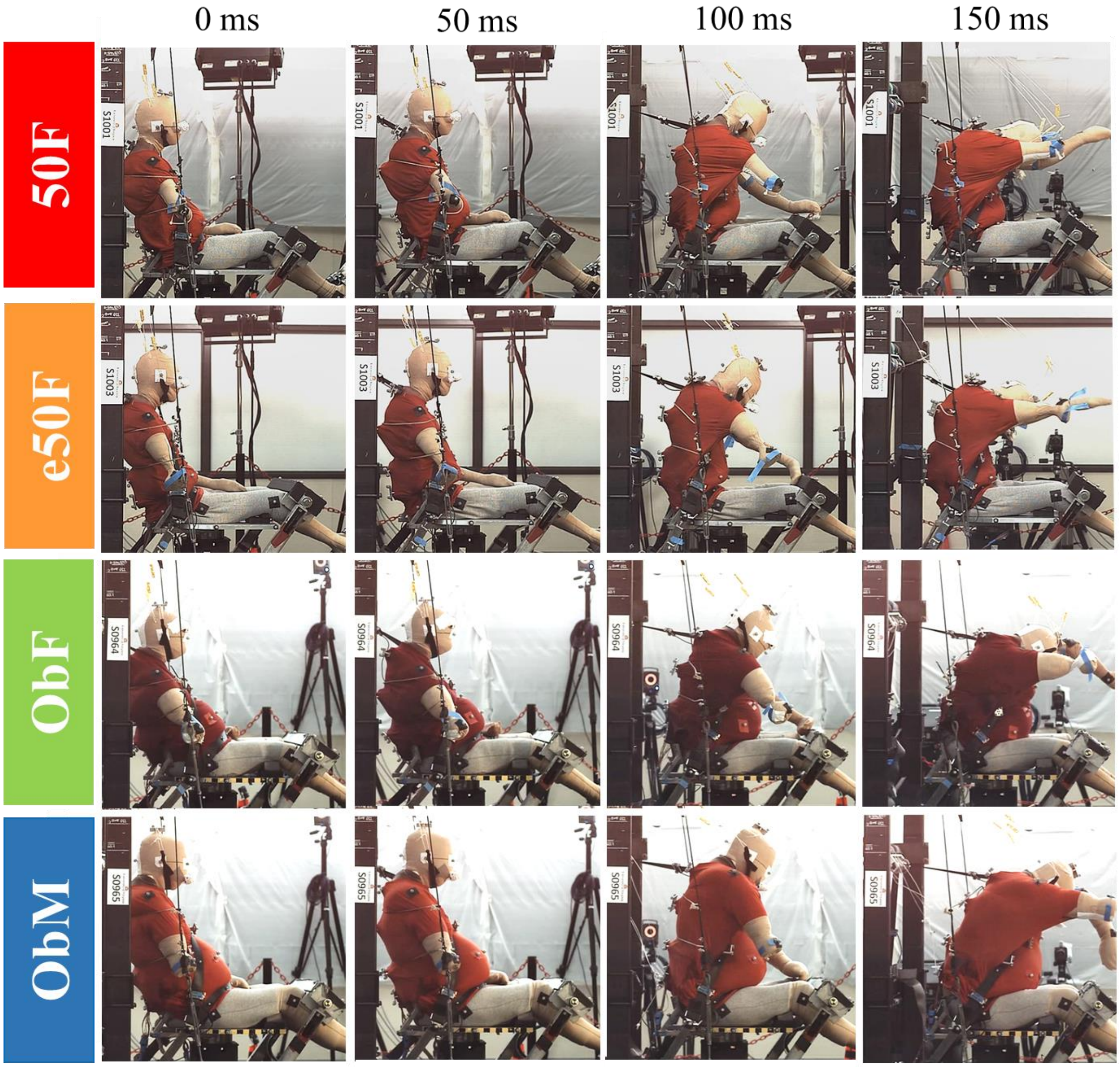

Figure 4: High-speed video stills from off-board cameras for all four occupant types: mid-size female (1st row), elderly mid-size female (2nd row), obese female (3rd row), and obese male (4th row).

The trajectories of the anatomic landmarks for all four occupant types exhibited a similar kinematic trend (Figure 5). The vertical lines in Figure 5 indicate the average forward head excursion for each occupant type. The obese occupants exhibited greater forward excursion of the head compared to the mid-size female and elderly mid-size female occupants. Head forward excursion for the obese female and male occupants exceeded the mid-size female occupants by approximately 70-170 mm. H-Point location was generally consistent across PMHS, and the restraint environment effectively limited motion of the pelvis.

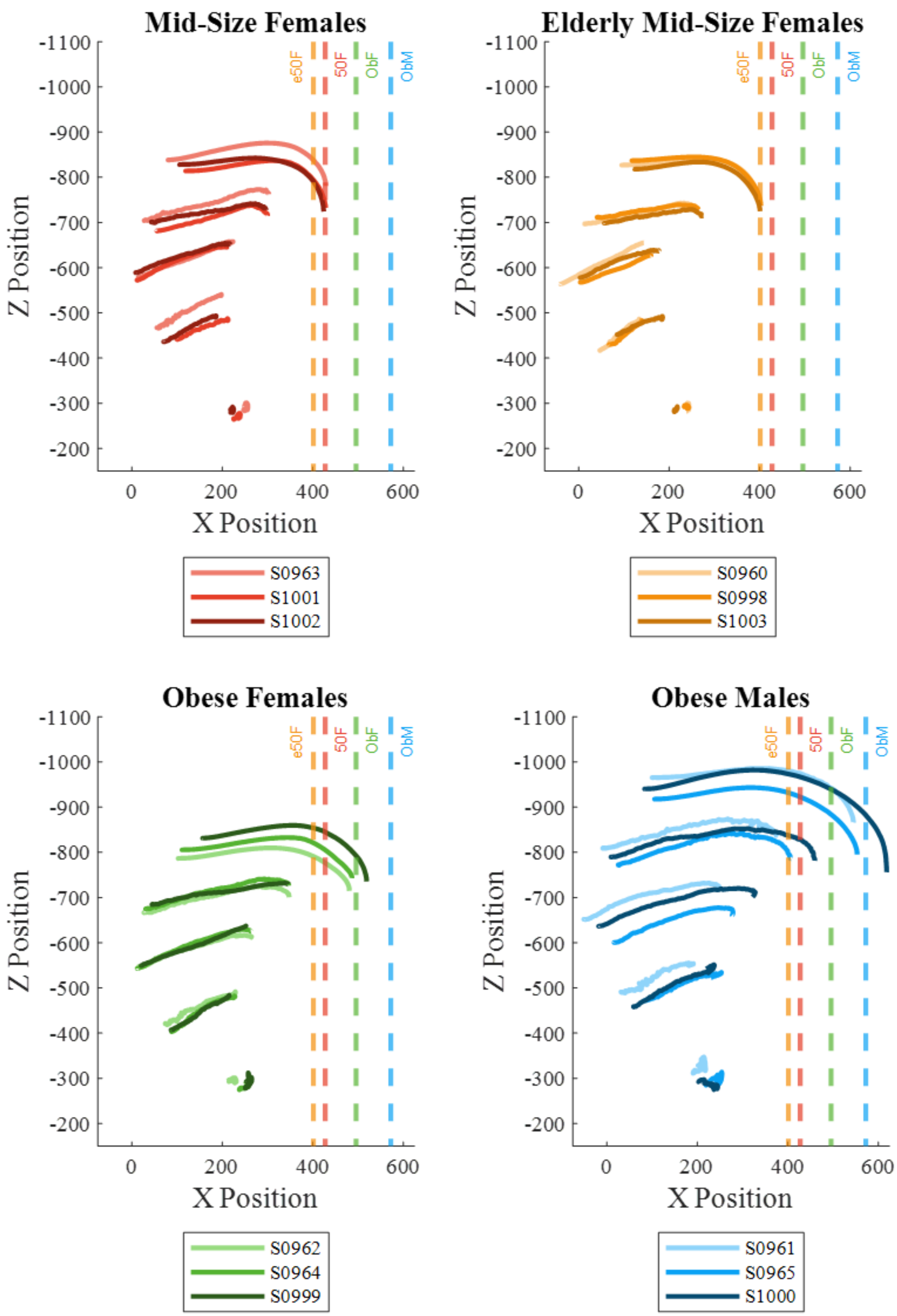

Figure 5: Sagittal (X-Z) plane projection of occupant motion of the head, T1, T8, L2, and pelvis (top to bottom in each graph) as the occupant flexes forward

Injury Outcomes

Fractures to the ribs and/or sternum were observed on post-test CT and during dissection for all twelve PMHS. Rib fracture totals ranged from zero to 19 fractures (Table 3). A classification of an AIS 3+ rib fracture injury is associated with three or more fractures to the rib cage (AAAM 2018). Rib fracture totals in ten of the twelve tests were considered to be AIS 3+, with the exception of two of the obese males, one of which had only two rib fractures and one of which had zero. All twelve PMHS had at least one sternum fracture.

Table 3: Ribcage Fracture (Fx) Totals

PMHS ID	**Sternum Fx(s)**	**Rib Fx(s)**	**AIS* 3+ Rib Fx?**
Mid-Size Females			
1118F	1	9	**Yes**
1129F	2	4	**Yes**
1137F	2	7	**Yes**
Elderly Mid-Size Females			
1110F	1	9	**Yes**
1139F	1	14	**Yes**
1164F	1	14	**Yes**
Obese Females			
1117F	1	13	**Yes**
1124F	1	3	**Yes**
1133F	1	19	**Yes**
Obese Males			
976M	1	5	**Yes**
1101M	1	2	No
1140M	1	0	No

*Abbreviated Injury Scale (AAAM 2018)

DISCUSSION

Variability in occupant shape was highlighted by the PMHS in this set of tests. For the female subjects the presence of breast tissue, while realistically supported by a bra, affected routing of the belt around the mid-sternum target. For the obese subjects, the presence of anterior soft tissue caused the belt to shift inboard and superiorly towards the neck of the PMHS. This inboard shift was also observed in a volunteer study with obese subjects (Reed et al., 2012). In contrast to many studies that have performed mastectomies on female occupants, this set of PMHS demonstrate the importance of maintaining realistic PMHS shape due to soft tissue, as it can affect shoulder belt positioning, and subsequently interaction.

For all twelve tests, the custom force limiting device was configured to the same position; however, there is some variance in peak and plateau shoulder belt forces (Figure 3). Generally, the shoulder belt force measured scaled with mass, with heavier occupants experiencing a greater shoulder belt force. In the case of UVAS0961 (ObM), where the force limit peaked at 4.4 kN, the PMHS still exhibited the greatest forward excursion despite the higher force limit. The subject in

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UVAS0961 was also the heaviest PMHS in this set of twelve. The two tests that did not fully engage the 3 kN limit (2.8 kN peaks) were the two elderly mid-size PMHS that were lighter than the mid-size female target mass (46 and 48 kg versus 65-79 kg target), but within the target range for stature (155-170 cm). The shoulder belt engagement timing is generally consistent across the occupant types, with small variations likely related to PMHS stature.

The kinematic trend of all four occupant types was similar, evidenced by the high-speed video (Figure 4) and calculated spine motions (Figure 5). The obese females and obese males experienced greater forward excursion compared to the mid-size female PMHS. This is consistent with obese PMHS tests in a rear seat environment, whereas compared to non-obese, the obese subjects exhibited greater forward excursion and torso flexion (Kent et al. 2010). Larger mass was also associated with larger excursions in upright frontal impacts at two severities with a semi-rigid seat (Somasundaram et al., 2022).

Rib fractures ranged from zero to 19 fractures across the occupant types, and each PMHS had at least one sternum fracture. Across the three female occupant categories (mid-size, elderly mid-size, and obese), all three PMHS had three or more fractures to the rib cage resulting in an AIS 3+ injury classification (AAAM 2018). Only one obese male subject had an AIS 3+ rib fracture. Comparing to previous tests in the GS2 condition, small female PMHS had five cases of AIS 3+ rib fracture out of five tests, with two cases of sternum fracture with a 2 kN force limit (Shaw et al., 2017). Previous GS2 tests with mid-size male PMHS had two of five cases with AIS 3+ rib fractures and only one case of sternum fracture with a 3 kN force limit (Montesinos-Acosta et al., 2016). In three tests of obese PMHS at 32 kph (comparable to GS2's 30 kph) with PMHS seated on the semi-rigid seat, all three PMHS had more than three rib fractures and a sternum fracture (Somasundaram et al., 2022). In two tests in a rear seat environment, obese male PMHS had two and seven rib fractures respectively, one case of which was AIS 3+ and one which was not. In the same condition with non-obese PMHS rib fractures ranged in number from two to 17, suggesting there was not a significant difference between obese and non-obese (Forman et al., 2009).

The occupant groups from this set of Gold Standard 2 tests (mid-size female, elderly mid-size female, obese female, and obese male) have seen limited study. The GS2 configuration is intentionally designed to be simple, rigid, and repeatable by nature to isolate the thoracic response of belted occupants. Information about shoulder belt loading, anterior soft tissue interaction, and spinal biofidelity can be leveraged from this dataset as a critical first step in validation data for human body models for varied anthropometries. This study highlights initial findings from twelve whole body PMHS impacts focusing on sagittal spine kinematics, shoulder belt positioning and forces, and rib fracture totals. Future work should investigate the relationship between anterior soft tissue and the shoulder belt in further detail. Additionally, this dataset could be leveraged to understand chest deflection of mid-size female and obese occupants. Rib fracture totals were reported in this study, but further work could examine rib fracture patterns and evaluate how representative the observed rib fracture totals are of real-world crash data.

CONCLUSIONS

Twelve frontal impact sled tests were performed on PMHS from four occupant categories: mid-size female, elderly mid-size female, obese female, and obese male. Overall kinematics were similar across all occupant types with obese occupants exhibiting greater forward excursion. Breast tissue and anterior soft tissue influenced shoulder belt positioning. Rib fractures were observed in eleven of twelve tests, and all twelve PMHS had at least one sternum fracture. These preliminary findings are part of a larger effort to quantify thoracic response for varied anthropometries for use in validation of human body models, restraint evaluation, and injury prediction tools.

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