Biofidelity Evaluation of THOR-AV 50th Percentile Male Dummy with a 60° Reclined Semi-rigid Seat

Z. Jerry Wang, Olivier Richard, Matthieu Lebarbé, Jérôme Uriot

Abstract THOR-AV, a modified THOR 50th percentile male dummy, was evaluated for its biofidelity in a 60° reclined semi-rigid seat. The sled test pulse had a delta velocity of 50 km/h and a peak acceleration of approximately 35 g. BioRank scores (BRS) were calculated using the latest method from the National Highway Traffic Safety Administration to provide an objective assessment of the dummy's biomechanical responses. The BRS score for the restraint system was 1.34, indicating good biofidelity. The BRS scores for the head, spine, and pelvis were 0.61, 1.28, and 1.77, respectively, corresponding to excellent, good and good biofidelity, respectively. The overall average BRS score for the THOR-AV was 1.25, classifying it as having good biofidelity.

Keywords Anthropomorphic test device, biofidelity, BioRank, semi-rigid seat, THOR-AV

I. INTRODUCTION

Reclined seating has become increasingly popular in vehicles equipped with automated driving systems (ADS) and zero-gravity seats, particularly in the unique Chinese automotive market. The zero-gravity seat was first studied by the National Aeronautics and Space Administration (NASA) in the 1970s to help astronauts adapt to the physical demands of spaceflight and was later included in NASA Standard 3000 in the 1980s [1][2].

Unlike a regular reclining chair, where the legs remain down while the torso leans back, a zero-gravity chair elevates the legs above heart level. This positioning distributes weight more evenly across the body, reducing stress caused by gravity. While reclined and zero-gravity seating may be safe under vertical loading conditions [3], the effectiveness of automobile restraint systems in protecting occupants during crashes has not been thoroughly evaluated.

Existing crash test dummies, designed for upright seating postures with a 25° torso angle, were evaluated to determine whether they could be adapted to represent occupant postures in reclined seats [4]. It was found that the THOR 50th percentile male dummy (THOR-50M) has limitations and is not fully representative of a reclined occupant [4]. To address this deficiency, THOR-AV, a modified version of the THOR-50M, was developed. The THOR-AV features a newly designed neck that has demonstrated better biofidelity than the necks of both the THOR and Hybrid III dummies [5]. Additionally, it includes an updated pelvic bone, pelvis flesh, and abdomen, reflecting the latest human pelvic bone anthropometry defined in [6].

The dummy was tested at seatback angles of 25° and 45° for evaluation, demonstrating good to excellent biofidelity [7-8]. It was also assessed in a rearward-facing position under frontal crash pulses, where it exhibited good biofidelity as well [9]. Baudrit *et al*. conducted a PMHS test with a 60° seatback angle [10], providing valuable information for further evaluation of the THOR-AV in highly reclined seating positions.

The objective of this study is to evaluate the biofidelity of the THOR-AV 50th percentile male dummy in a 60° seatback semi-rigid seat under a 50 km/h full frontal crash test pulse as defined in [10].

II. METHODS

In this study, the THOR-AV was tested on a semi-rigid sled, as detailed in [10] for the PMHS test. The test results were analysed and overlaid with PMHS data presented in [10]. BioRank scores were calculated using the NHTSA BioRank method described in [11] and [12] to provide an objective biofidelity rating.

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Test Method

A sled buck was composed of a semi-rigid seat, a reclined seatback, and a footrest, developed in [13], to mimic the mechanical response of a production seat in a frontal impact. The semi-rigid is composed of two plates, namely the seat pan at the rear and the Anti-Submarining Ramp (ASM Ramp) at the front (Fig. 1), that can rotate around a transverse (Y) axis and which rotation stiffness is controlled by springs. Compared to [13], the seat used in this research was modified with several enhancements, which had no impact on the semi-rigid seat mechanical response during loading phase for PMHS tests [10]. The plate rotation locking systems used for the rebound phase was replaced with a hydraulic damping system, which was activated shortly after the backward rotation of the plates. In addition, the ASM ramp included stoppers to prevent excessive rotation during the loading phase. The seatback was reclined to 58° relative to the vertical and covered with two 50 mm-thick layers of foam. In [10] and the present study, the first foam was rigid (white in Fig. 1), and the second one, onto which rested the back of the tested subjects, was soft (yellow in Fig. 1). In the present study the rigid foam was composed of Ethafoam™ 180 material, with a density of 16 kg/m³. The footrest consisted of a rigid plate positioned at 35° relative to the vertical. Both the buck and the footrest were bolted to the sled. The test buck with the THOR-AV mounted is shown in Fig. 1.

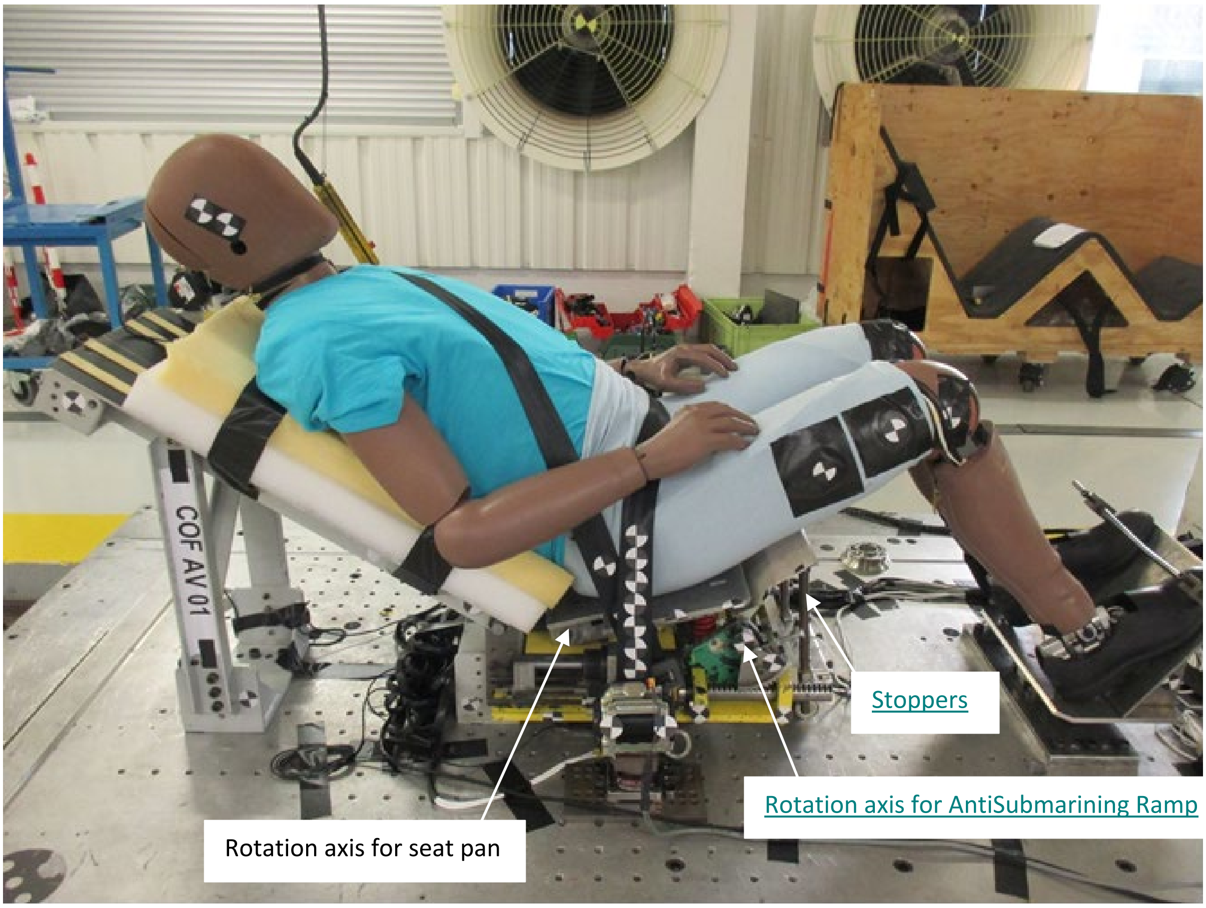

Fig. 1. THOR-AV test set-up in reclined semi-rigid seat.

The geometry of the test set-up, including the coordinates of the joints and footrest, was maintained to be the same as in the PMHS test, which is documented in detail in [10]. The sled impact speed was 50 km/h, with a peak acceleration of approximately 35 g and a duration of around 100 ms. The time history of the sled pulses for the three repeated tests of THOR-AV are shown in Fig. 2.

The THOR-AV was configured to represent 60° reclined angle, summarised in Table I, where the pelvis tilt sensor angle is the target angle from the ATD design layout. The THOR-AV head angle was adjusted to be approximately perpendicular to the seatback plane.

TABLE I
THOR-AV CONFIGURATION FOR 60° RECLINED SEATS

Torso Angle	Pelvis tilt sensor Angle	Lower spine pitch position	Upper spine pitch position (°)
60°	44.8°	+15° from neutral, red mark of THOR-AV lumbar joint	0°

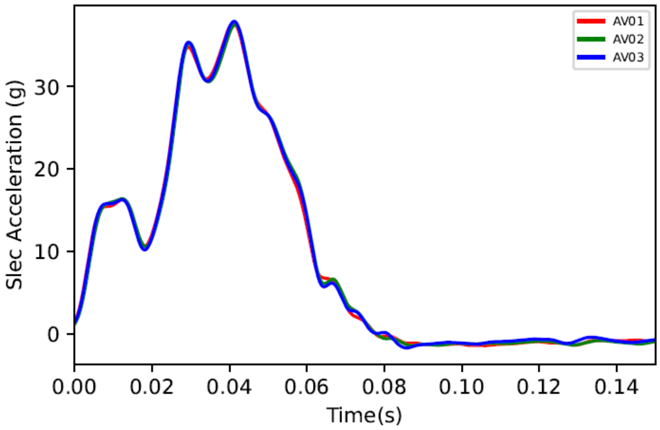

Fig. 2. Sled test pulses.

Three repeated tests were conducted with THOR-AV. The test IDs of the series are summarised in Table II.

TABLE II
THOR-AV TEST MATRIX

Test #	Test 1	Test 2	Test 3
Test ID	AV01	AV02	AV03

Dummy positioning

THOR-AV followed the PMHS positioning procedure used in [10]. Tilt sensors and hip joint (H-point) coordinates for THOR-AV were recorded and summarized in Table III.

TABLE III
TILT SENSORS AND H-POINT DATA FOR THOR-AV POSITIONING

Test ID		AV 01	AV 02	AV 03
Head (°)	X	1	0	1.9
	Y	45	46.1	45.2
Pelvis (°)	X	0.6	0.5	1
	Y	54	52.3	51.5
Upper Thorax (°)	X	1	1.1	0.7
	Y	44.7	45	44.5
Middle Thorax (°)	X	0.1	0.5	0.2
	Y	69.5	69.7	69
Lower Thorax (°)	X	-0.1	0.1	-0.2
	Y	56.8	57.1	56.3
Head CG (mm)	X	-485	-492	-494
	Z	-614	-607	-609
H-point (mm)	X	107	103	97.5
	Z	-182	-176	-175

Instrumentation and Data Processing

The data were collected with 20,000 Hz sampling rate. The data were all filtered according to SAE J211 (or ISO 6487). The data channels analysed in this study was summarized in Table IV. The rotations for the head and pelvis were calculated by integrating their corresponding angular velocity data. The displacements were measured with high-speed video analysis and the rotations were integrated from angular velocity measured at the corresponding locations or video analysis. All video analysis were conducted with TackReport software (Orme, France). Video targets were placed on THOR-AV skin to track the head and pelvis H-point. For the head, the targets were glued at the points projected laterally in y-direction from the centre of gravity. For the pelvis, two targets were glued onto each femur lateral aspects (see Fig. 1), and a hip joint trajectory estimate was derived from these targets, at each side. The video camera recorded the test event at 1000 frame per second speed. For all sensor-measured and video-tracked data, the time 0 corresponded to the time when the CFC180-filtered sled pulse curve first crossed the 0.1g threshold.

TABLE IV
LIST OF THE DATA CHANNELS FOR BIORANK SCORE CALCULATIONS

	Data Channel	Instrumentation
Restraint	Seat pan force Fx	
	Seat pan force Fz	
	Seat pan y-rotation	
	Seat anti-sub ramp y-rotation	
	Upper shoulder belt force (B3)	
	Lower shoulder belt force (B4)	
	Lap belt force (B6)	
Head	Head x-acceleration	Endevco 7264C-2KTZ
	Head z-acceleration	Endevco 7264C-2KTZ
	Head y-angular velocity	DTS ARS-PRO-18k
	Head x-displacement	High speed camera (1000 fps)
	Head z-displacement	High speed camera (1000 fps)
Spine	T1 x-acceleration	Endevco 7264C-2KTZ
	T1 z-acceleration	Endevco 7264C-2KTZ
	T12 x-acceleration	Endevco 7264C-2KTZ
	T12 z-acceleration	Endevco 7264C-2KTZ
Pelvis	Pelvis x-acceleration	Endevco 7264C-2KTZ
	Pelvis z-acceleration	Endevco 7264C-2KTZ
	Pelvis x-displacement	High speed camera (1000 fps)
	Pelvis z-displacement	High speed camera (1000 fps)
	Pelvic y-angular velocity	DTS ARS-PRO-18k

BioRank Method

The U.S. National Highway Traffic Safety Administration (NHTSA) has been developing an objective method to assess dummy biofidelity [11, 12, 14-16]. In this study, the method defined in [11] and [12] was used to calculate the BioRank scores (BRS) for the THOR-AV. For the data time history alignment, minimum of dummy cumulative absolute difference over the cadaver cumulative standard deviation (DCAD/CCSD) was used as the criterion. If the dummy phase shift (DPS) time exceeds 15 ms, no shift was applied to the dummy data for the BRS calculation.

For the evaluation, the responses of the restraint system were grouped together. BRS values were calculated for each body segment of the THOR-AV, and the overall BRS was determined as the average of all body segment scores. The BRS scores and corresponding biofidelity categories are summarised in Table V [11].

TABLE V
BIORANK SCORE AND BIOFIDELITY CATEGORY SUMMARY

BioRank Scores	BRS ≤ 1.0	1.0 < BRS ≤ 2.0	2.0 < BRS ≤ 3.0	BRS > 3.0
Biofidelity	Excellent	Good	Marginal	Poor

III. RESULTS

The THOR-AV test data were plotted alongside the PMHS corridors for comparison, and BRS scores were calculated to provide an objective assessment of the THOR-AV dummy. The data were categorised into two groups: the restraint system, and the dummy. The dummy group was further divided into three body segments – head, spine, and pelvis – while the overall dummy BRS was calculated as the average of these three segments.

The seat pan force in the x- and z-directions, seat pan y-rotation, and anti-submarining ramp y-rotation data are presented in Figs 3–6. In these Figures, "#x-74x" represents PMHS test data, with the corresponding envelope corridors from [10] shown in grey, while "AV0x" represents THOR-AV test data. All subsequent plots follow the same format.

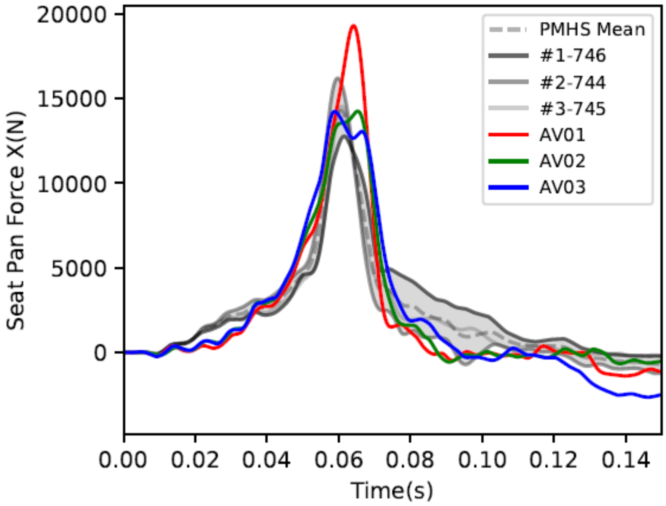

Fig. 3. Seat pan force in x-direction.

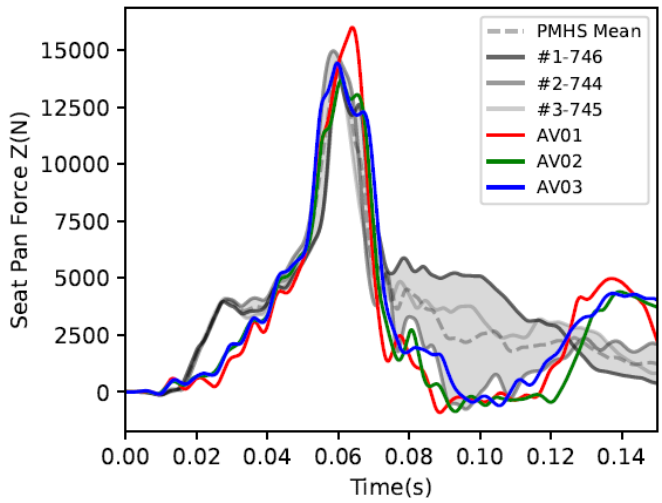

Fig. 4. Seat pan force in z-direction.

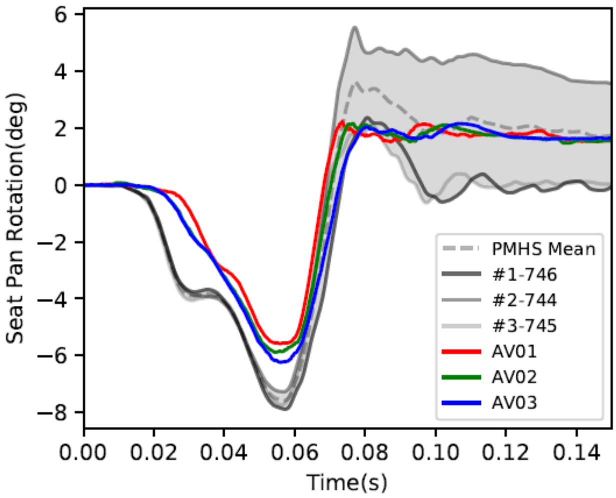

Fig. 5. Seat pan y-rotation.

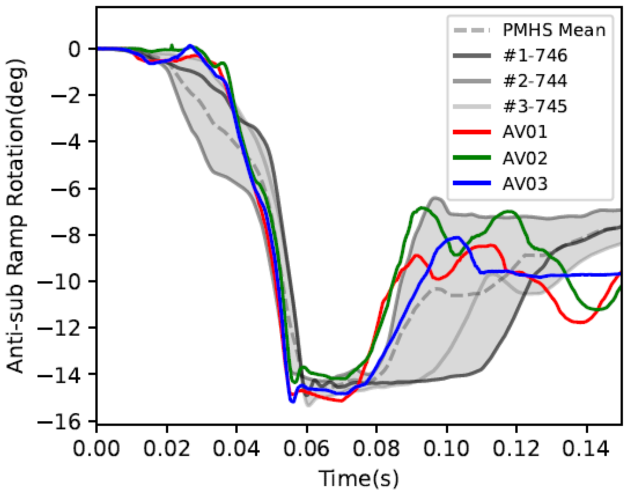

Fig. 6. Anti-sub ramp y-rotation.

The shoulder belt and lap belt forces are shown in Fig. 7 through 8.

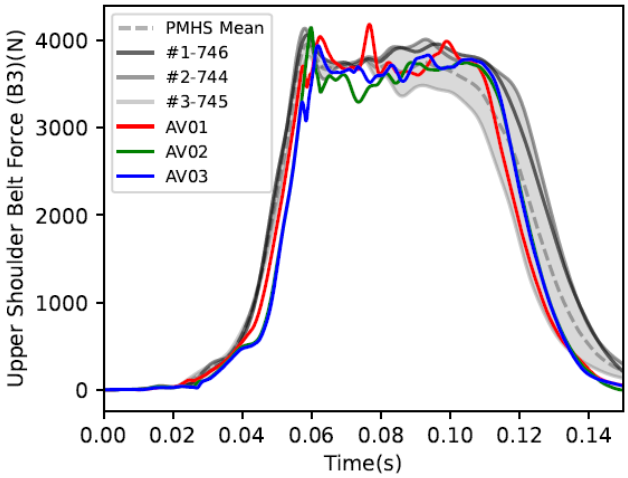

Fig. 7. Upper shoulder-belt force (B3).

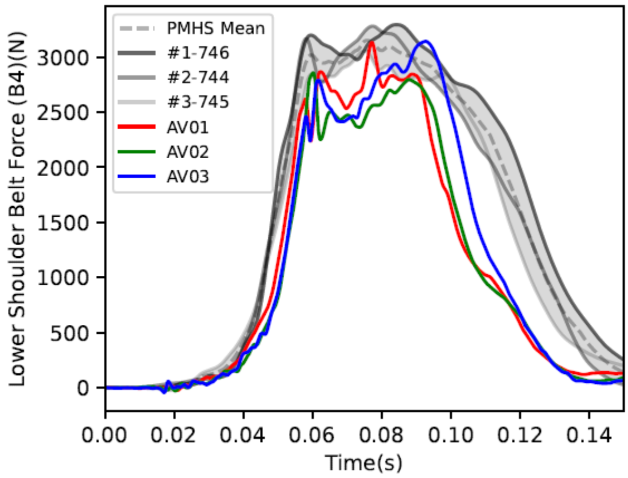

Fig. 8. Lower shoulder-belt force (B4).

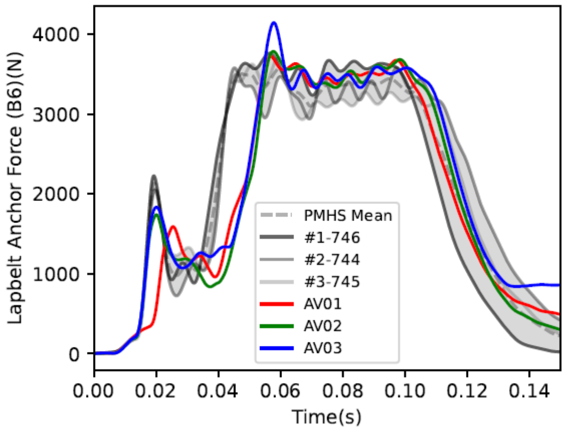

Fig. 9. Lap-belt force (B6).

The BRS scores and dummy phase shift (DPS) for the restraint system are summarised in Table VI. The average BRS values from three repeated tests are 1.41, 1.50, 0.50, 0.95 for seat pan x-force, seat pan z-force, seat pan y-rotation, and anti-sub plate y-rotation, respectively, corresponding to good, good, excellent, and excellent biofidelity, respectively. The average BRS scores for the three repeated tests of the upper shoulder belt force (B3), lower shoulder belt force (B4), and lap-belt force (B6) are 0.95, 2.74, and 1.33, corresponding to excellent, marginal, and good biofidelity, respectively. The overall average BRS score for the restraint system is 1.34, indicating good biofidelity.

TABLE VI
SUMMARY OF BRS AND DPS FOR THE RESTRAINT SYSTEM

	Seat Pan Fx		Seat Pan Fz		Seat Pan Rotation Y		Anti-sub-Plate Rotation Y		Continued below
Test ID	BRS	DPS (ms)	BRS	DPS (ms)	BRS	DPS (ms)	BRS	DPS (ms)	
AV01	1.39	-0.1	1.62	-0.9	0.57	2.1	0.91	2.5	
AV02	1.26	-0.3	1.49	-1.1	0.50	-0.1	1.19	1.6	
AV03	1.59	1.1	1.40	-0.1	0.42	-2.6	0.76	1.8	
Test Avg.	1.41	0.3	1.50	-0.7	0.50	-0.2	0.95	2.0	

TABLE VI continued

	Shoulder Belt Force (B3)		Shoulder Belt Force (B4)		Lap Belt Force (B6)		Total BRS Avg.
Test ID	BRS	DPS (ms)	BRS	DPS (ms)	BRS	DPS (ms)	
AV01	0.91	-1.1	2.69	-1.3	1.09	-4.8	
AV02	1.01	-2.1	3.10	-2.4	1.07	-0.9	
AV03	0.95	-2.6	2.43	-3.0	1.82	-1.5	
Test Avg.	0.95	-1.9	2.74	-2.2	1.33	-2.4	1.34

THOR-AV head resultant acceleration and head y-rotation are shown in Fig. 10 - 11.

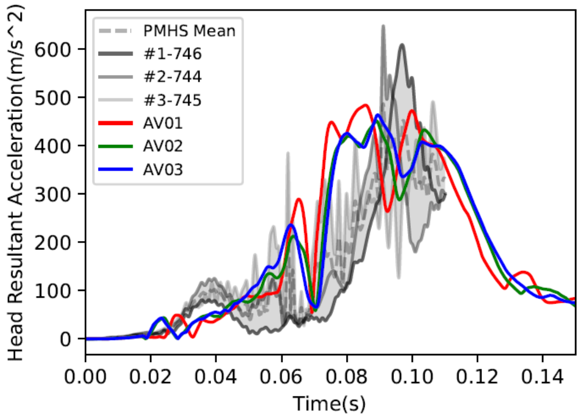

Fig. 10. Head resultant acceleration.

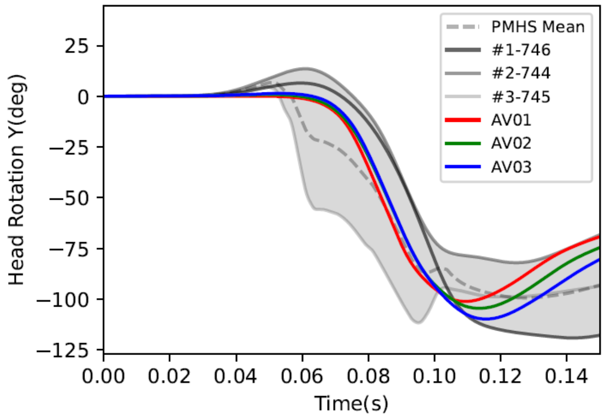

Fig. 11. Head y-rotation.

The head y-rotation, x-displacement and z-displacement are shown in Fig. 12 - 13.

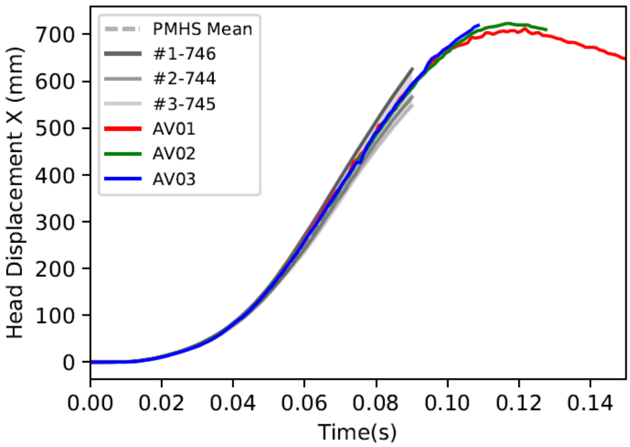

Fig. 12. Head x-displacement.

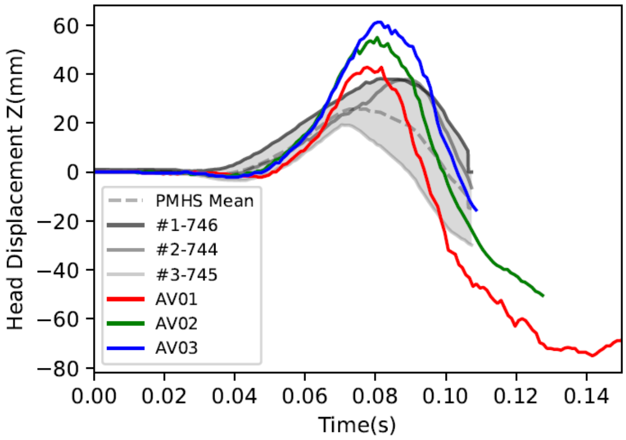

Fig. 13. Head z-displacement.

The BRS scores and DPS for THOR-AV head are summarized in TABLE VII. The average BRS scores for head resultant acceleration, y-rotation, x-displacement and z-displacement are 0.80, 0.56, 0.13, 0.97, all corresponding to excellent biofidelity. The overall average of head BRS score is 0.61, corresponding to excellent biofidelity.

TABLE VII
SUMMARY OF BRS SCORES AND DPS FOR THOR-AV HEAD

	Head resultant acceleration		Head y-rotation		Head x-displacement		Head z-displacement		Total BRS Avg.
Test ID	BRS	DPS (ms)	BRS	DPS (ms)	BRS	DPS (ms)	BRS	DPS (ms)	
AV01	0.86	10.3	0.62	0.8	0.15	0.6	0.82	4.5	
AV02	0.72	8.9	0.54	-1.4	0.12	0.3	0.91	0.6	
AV03	0.81	11.4	0.52	-1.5	0.13	0.4	1.17	-2.9	
Test Avg.	0.80	10.2	0.56	-0.7	0.13	0.4	0.97	0.7	0.61

The T1 and T12 spine resultant accelerations are shown in Fig. 14 - 15.

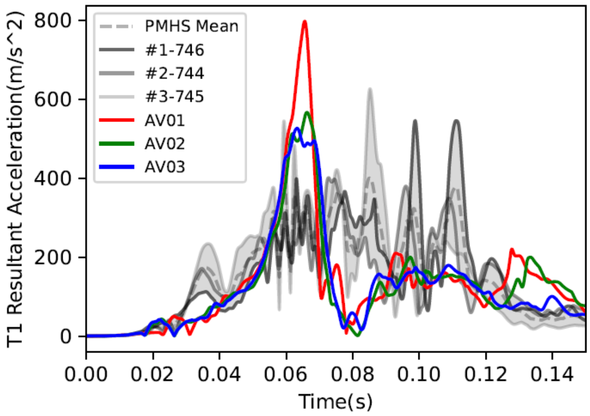

Fig. 14. T1 resultant acceleration.

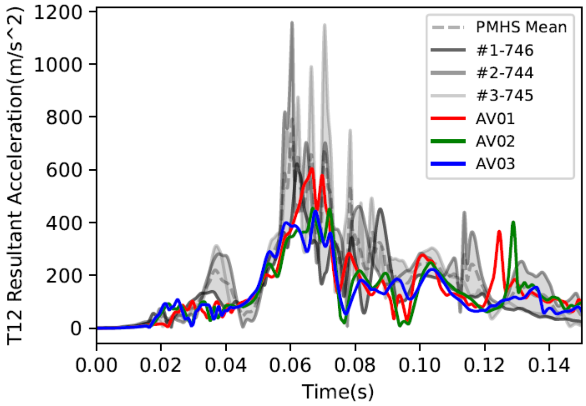

Fig. 15. T12 resultant acceleration.

The average BRS scores of the three repeated tests for T1 and T12 are summarised in Table VIII. The BRS scores for T1 and T12 resultant accelerations are 1.57 and 0.98, corresponding to good and excellent, respectively. The overall BRS score of the spine is 1.28, corresponding to good biofidelity.

TABLE VIII
SUMMARY OF T1 AND T12 BRS SCORES AND DPS

	T1 resultant acceleration		T12 resultant acceleration		Total BRS Avg.
Test ID	BRS	DPS (ms)	BRS	DPS (ms)	
AV01	1.73	-2.9	0.96	1.0	
AV02	1.60	-2.4	1.02	-0.1	
AV03	1.37	-2.4	0.97	2.5	
Test Avg.	1.57	-2.5	0.98	1.1	1.28

The pelvis resultant acceleration, y-rotation, x- and z-displacement are shown in Fig. 16 - 19.

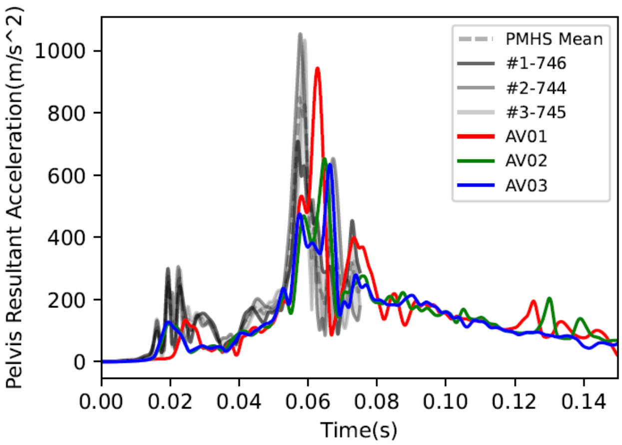

Fig. 16. Pelvis resultant acceleration.

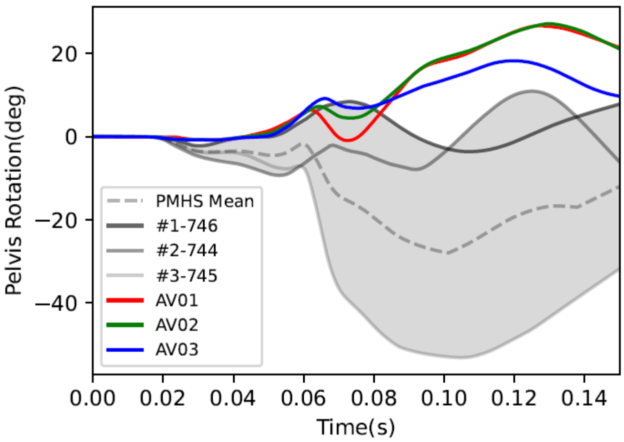

Fig. 17. Pelvis y-rotation.

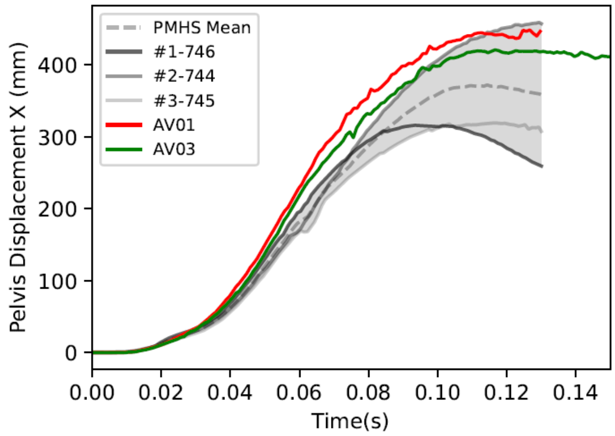

Fig. 18. Pelvis x-displacement.

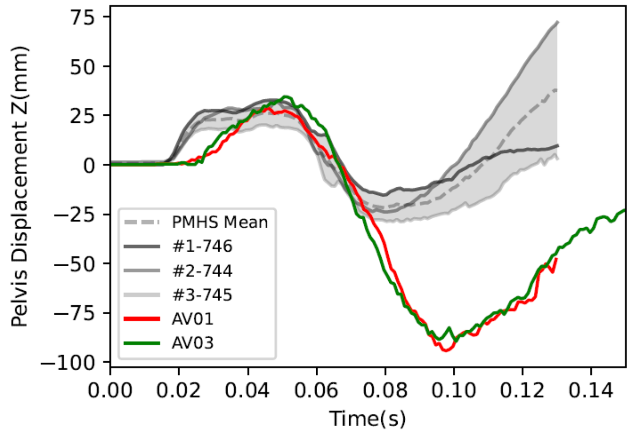

Fig. 19. Pelvis z-displacement.

The BRS scores and DPS for pelvis resultant accelerations, y-rotation, x- and z-displacements are summarised in Table IX. The average BRS scores from the three repeated tests are 1.34, 1.40, 0.90, and 3.46 for pelvis resultant acceleration, y-rotation, x- and z-displacement, corresponding to good, good, excellent, and poor biofidelity, respectively. The overall average BRS score for the pelvis is 1.77, indicating good biofidelity.

TABLE IX
SUMMARY OF BRS SCORES AND DPS OF THE PELVIS AND FEMUR ACCELERATION AND ROTATIONS

	Pelvis resultant acceleration		Pelvis y-rotation		Pelvis x-displacement		Pelvis z-displacement		Total BRS Avg.
Test ID	BRS	DPS (ms)	BRS	DPS (ms)	BRS	DPS (ms)	BRS	DPS (ms)	
AV01	1.18	-4.6	1.49	0.0	1.07	7.7	3.41	0.0	
AV02	1.41	-4.5	1.48	0.0	NA	NA	NA	NA	
AV03	1.43	-1.1	1.23	0.0	0.73	6.3	3.52	0.0	
Test Avg.	1.34	-3.4	1.40	0.0	0.90	7.0	3.46	0.0	1.77

NA = data lost in the test AV02.

The THOR-AV body segment and overall BRS scores are summarised in Table X. The BRS scores for the head, thoracic spine, and pelvis are 0.61, 1.28, and 1.77, respectively, all corresponding to good biofidelity. The average BRS score for all body segments is 1.25, indicating good biofidelity.

TABLE X
BRS SCORE SUMMARY OF THOR-AV BODY SEGMENTS AND OVERALL AVERAGE

	Head	Thoracic Spine	Pelvis	Overall
BRS Scores	0.61	1.28	1.77	1.25

IV. DISCUSSION

It was observed that the seat pan forces in the x- and z-directions had higher peaks in the first test (@63 ms), while were consistent with lower peaks in the second and third tests, as shown in Fig. 3 and Fig. 4. Sled pulses were inspected and no difference among the three repeated tests were observed, see sled pulse overlay in Fig. 2. Examining the dummy positioning, the head CG and Pelvis H-point XZ coordinates were within a 10 mm square window for the three tests, which was fairly repeatable, and the pelvis initial Y-tilt within a 3 degrees window (54, 52.3, and 51.5, respectively for AV01, AV02, and AV03). All tests induced a large pelvic excursion with a potential hard contact onto the ASM ramp due to the reach of the stoppers. Fig. 6 shows similar ASM ramp rotation signals during the loading phase for the three tests, with the stoppers being reached during 20 ms, from 58 ms to 78 ms approximately. This time window includes the peak force time of AV01 (63 ms). The pelvis y-rotation signals (fig. 17) are also very close for the three tests until 63 ms approximately. So, we may suspect a stronger pelvis/ASM ramp hard contact at 63 ms for AV01 compared to the other two tests, that cannot be explained in light of the available data. FE-simulation could help figuring out if variations in the pelvis initial position and orientation can induce a particular presentation of the pelvis with respect to the ASM ramp during the loading phase, that is prone to harder contact.

For the seat pan rotation, it was noted that the rotation in the THOR-AV test had an approximate 10ms delay compared to the PMHS tests, as shown in Fig. 5. This delay may be due to the stiffer dummy flesh, which may not deform as easily as the PMHS flesh under gravity. It was also observed that the dummy sat approximately 25 mm taller than PMHS due to the less compressed pelvis flesh. The ischium of the PMHS could be much closer to the seat than the dummy due to the gravity compression, resulting in faster engagement with the seat pan. The anti-submarining plate engagement and rotation magnitudes were very similar between the THOR-AV and PMHS tests.

The lap belt force of THOR-AV matched the PMHS response pattern closely (see Fig. 9). A separation of THOR-AV lap belt response from the PMHS was observed, which most likely caused the difference in flesh compression in front of the ASIS.

Submarining was analyzed from video analysis, there was no submarining for the THOR-AV in all three repeated tests, matching the PMHS test results.

There are limitations in this study. The targets on the pelvis skin for pelvis displacements may not be accurate because the skin is not rigidly coupled with the bone and can deform too. The version of the THOR-AV evaluated did not have the cavity in the pelvis flesh that was created for proper pelvis flesh compression for today's dummy version. Finite element modeling for this change was carried out later with the updated pelvis flesh, however, the results from FE analysis are not reported in this paper, and no repeated physical test with the new pelvis flesh was conducted in this test condition yet.

V. CONCLUSIONS

The THOR-AV 50th percentile male dummy was evaluated in a large, reclined seatback with an angle of 60°. BRS scores were calculated for both the restraint system and the dummy. The BRS score for the restraint system is 1.34, indicating good biofidelity. The BRS scores for the head, spine, and pelvis are 0.61, 1.28, and 1.77, respectively, corresponding to excellent, good and good biofidelity, respectively. The overall average BRS score for the dummy is 1.25, indicating good biofidelity.

VI. ACKNOWLEDGEMENTS

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