Biomechanical Responses of THOR-AV in a Semi-Rigid Seat that Mimics the Front and Rear Seat of a Midsize Car

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Abstract The THOR-AV prototype was designed as an immediate tool for the industry to test the restraint systems for autonomous driving system (ADS) equipped vehicles. In this study, the THOR-AV was evaluated for its responses in the traditional front seat and rear seat configurations. The National Highway Traffic Safety Administration's (NHTSA) latest BioRank method was used to objectively assess the THOR-AV biofidelity. The interaction between THOR-AV and the restraint system in the front and rear seat configurations had BioRank scores (BRS) of 1.54 and 1.64 respectively, both corresponding to *good* biofidelity. THOR-AV responses had BRS scores of 0.84 and 0.77 for the front seat and rear seat respectively, both corresponding to *excellent* biofidelity. Overall, the THOR-AV interaction with the restraint system had a combined BRS score of 1.59, corresponding to *good* biofidelity. The THOR-AV responses had a front and rear seat combined BRS score of 0.80, corresponding to *excellent* biofidelity. It was observed that the THOR-AV prototype submarined slightly earlier than post-mortem human subjects. Design changes were explored using the THOR-AV finite element model. The revised design improved the pelvic bone geometry and pelvis flesh compression, the dummy pelvis kinematics and submarining time.

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

I. INTRODUCTION

Vehicles equipped with an automated driving system (ADS) have been advancing dramatically in the last decade. With most of the fundamental issues solved in recent years, there are still challenges to overcome for the technology to be part of daily public life. There are many perceived occupant seating choices in these vehicles equipped with ADS technology. Studies have shown that occupants can sit in many non-traditional postures, including reclined a seated posture for resting, rearward facing posture to face another occupant for social engagement, or seats dialogically or facing each other side way as well [1-2], though the future regulation may limit the vehicle seat design options for occupant safety. The long-term goal for ADS-equipped vehicles is to reduce human errors, and eventually reduce or ideally eliminate fatalities and injuries. However, until the ADS technology matures, it is expected that a mixture of ADS-equipped vehicles and human drivers would co-exist in the foreseeable future.

In current regulations, the safety testing only mandates the upright seated postures with the torso angle at 25° approximately as recommended by the vehicle manufacturer. Safety testing of occupant seated postures in a reclined seat, rearward facing, and oblique impact are not required. It is unknown if the 3-point belt system in today's vehicle fleet would be able to restrain the occupants effectively in reclined seated postures and provide similar occupant protection benefit as in the upright seated postures. The preliminary evaluations showed that the Test device for Human Occupant Restraint (THOR) dummy cannot be configured to represent the human properly in reclined seated postures [3]. It is also expected that the occupant has a higher risk of submarining in a reclined seated posture. To improve the seated posture and submarining responses, THOR-AV, a modified THOR was developed. The THOR-AV dummy has a new neck design that improves its biofidelity in torsion and oblique impact tests over THOR and H-III 50th percentile male dummies[4]. It has an updated pelvic bone geometry that better represents the human. It also has a redesigned abdomen that uses abdomen pressure twin sensors (APTS),

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replacing the abdomen Infra-Red Telescope Rod for assessment of Chest Compression (IR-TRACC) which are frequently damage in testing. The THOR-AV design was intended for use in both the upright (25° seatback angle) and the reclined (45° and 60° seatback angles) postures.

In this study, the THOR-AV dummy was evaluated in a semi-rigid seat that present the front and rear seat configurations with the seatback angle at 22° as defined in [5]. In the PMHS study of [5], four average male cadavers were tested in the front seat configuration, and the average age, weigh and stature were 79 years, 75kg and 173 cm respectively. Another four average male cadavers were tested in rear seat configuration, and the average age, weight and stature were 85 years, 69 kg and 170 cm respectively. The corridors developed in [5] were used in this study to evaluate the THOR-AV biofidelity.

II. METHODS

A prototype THOR-AV conversion kit was installed on an existing THOR dummy for its biofidelity evaluation. The semi-rigid seat used in [5] was used for the dummy evaluation tests. The test results were evaluated with NHTSA's recent BioRank method to provide an objective biofidelity rating [7]. Humanetics Innovative Solutions, Inc. (Humanetics thereafter, Farmington Hills, Michigan, USA) also developed a finite element (FE) model of a THOR-AV in parallel. The FE model (Pam-Crash) was used to explore the options to improve the submarining responses. The design changes from the FE analysis results have been summarized in this paper.

THOR-AV Dummy Design

The THOR-AV dummy was developed to address a few potential issues based on Humanetics' communications with industry experts, i.e., a) dummy seated postures in reclined seated postures, b) dummy responses in reclined seated postures, especially submarining behaviors, and c) dummy neck responses in torsion and extension (rearward facing). To provide a reasonable solution in a short time, THOR was chosen as the base dummy for modifications since it is the most advanced dummy available and has superior biofidelity to the Hybrid III 50th male dummy [6].

A new neck was developed for THOR-AV by [4]. This new design improved the neck torsion responses. For simplicity and improved repeatability in testing, the THOR-AV neck design removed the external front and rear cables, which also improved durability in rearward facing sled tests [7]. The neck design is shown in Fig. 1.

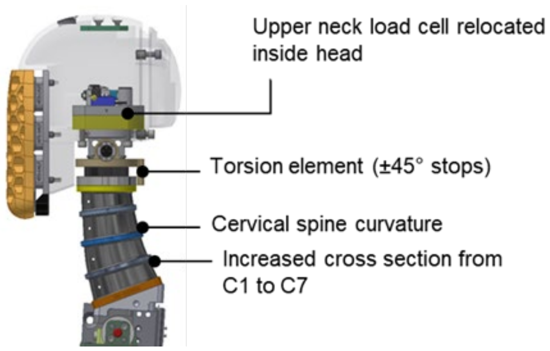

Fig. 1. THOR-AV 50M neck design.

The THOR-AV pelvis design was updated to reflect human pelvic bone geometry according to [14] as the geometry of the pelvic bone can affect the pelvis engagement with the seat and the submarining responses. The lumbar was redesigned to increase its flexibility and improve the upper torso kinematics. APTS sensors were designed into the abdomen to replace the THOR abdomen IR-TRACCs to address the durability concern. An abdomen insert was designed to attach to the main abdomen to fill a gap generated when the dummy is reclined. Coupling features were introduced between pelvis flesh and pelvic bone, and pelvis flesh and thigh flesh to mitigate flesh separation during the crash test. The pelvis/lumbar/abdomen design is shown in Fig. 2.

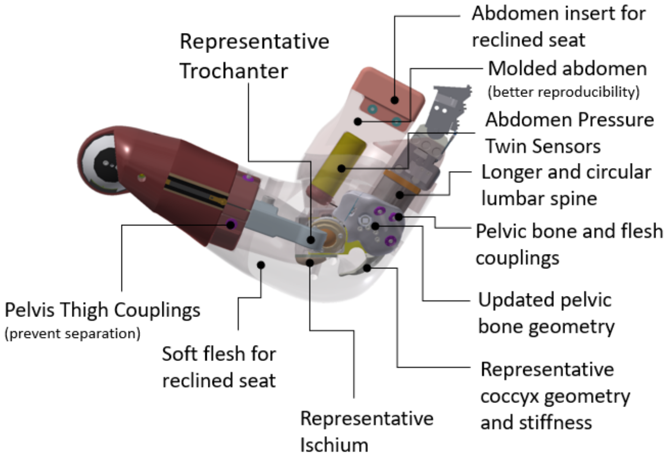

Fig. 2. Design of THOR-AV 50M pelvis, thigh, abdomen and lumbar.

Sled Test Setup

The same sled, semi-rigid seat and belt system as defined in [5] were used in this study, see Fig. 3. The semi-rigid seat consists of an aluminum rigid plate with 380 mm width pivoted at its rear edge. Two sets of the spring were fixed under the front of the plate to provide a two-slope stiffness law. A second aluminum plate, which was pivoted at the front edge of the seat pan plate, represents the anti-submarining ramp. It was connected to a spring system to provide the appropriate stiffness. As described in [4], the stiffness of the springs of both the seat pan and the anti-submarining ramp were adjusted to mimic the properties of a front seat and rear seat, respectively. The rear seat was softer than the front seat. The anti-submarining ramp angle in the rear seat was 22° less tilted with its pivot point at 30 mm downward than in the front seat. The back rest consists of a rigid support and a polyurethane foam pad covered by a textile fabric. The rigid support was set at 22° from the vertical and the foam pad had dimensions of 30 cm wide, 47.5 cm high, 10 cm thick. An expanded polypropylene pad with dimensions of 23 cm wide, 12.5 cm high and 6.6 cm thick was placed behind the pelvis. The lap and shoulder belts were 45 mm wide with an elongation of 9% at 10 kN, the inboard and outboard lap belt forces were limited to 5 kN. The upper shoulder belt was limited to 7 kN. No pre-tensioner was present in the tests.

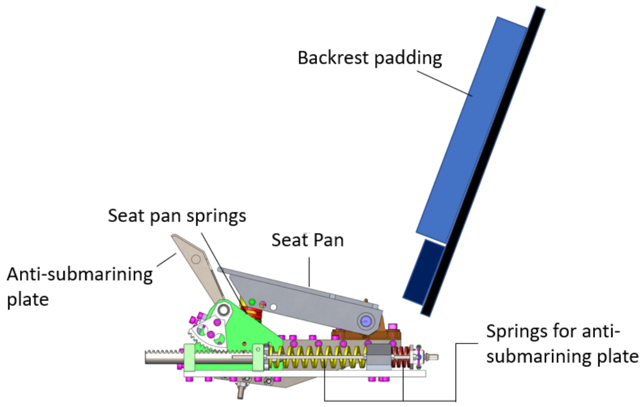

Fig. 3. Seat configuration for sled test setup.

The sled pulse had a delta velocity of 14 m/s or 50 km/h, shown in Fig. 4. The same pulse was used for testing in both front and rear seat configurations.

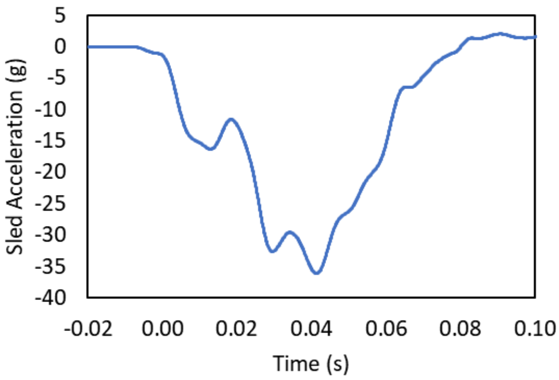

Fig. 4. Sled pulse for testing in both front and rear seat configurations.

Test Matrix

Three repeated tests were conducted for THOR-AV in each configuration. The test numbers are summarized in TABLE I.

TABLE I
THOR-AV TEST MATRIX

Configuration	Test 1	Test 2	Test 3
Front Seat	SUB_BIO_AV_01	SUB_BIO_AV_02	SUB_BIO_AV_03
Rear Seat	SUB_BIO_AV_04	SUB_BIO_AV_05	SUB_BIO_AV_06

THOR-AV Finite Element Model

A THOR-AV FE model in Pam-Crash (version v0.5) was developed in parallel to the dummy development. The FE model shared many components with THOR, which were validated extensively in the THOR model. The new component FE models were validated with certification test data. The buttock responses were validated with an impact test to the buttock by a 20.18 kg mass probe. The model was used to explore options to improve THOR-AV pelvis responses and its submarining time.

BioRank Method

NHTSA has developed a biofidelity evaluation method to objectively rank the biofidelity of a dummy by providing a BioRank Score (BRS). The first method was published by [7], followed by numerous enhancements [10-12]. The most recent updates were done by [11]. The BRS and biofidelity relationships are summarized in TABLE II. The dummy phase shift (DPS) reflects the phase shift between the dummy test data and the PMHS mean time history data and it is recorded in millisecond. The DPS was not included in the BRS calculation, but monitored only.

TABLE II
BIORANK SCORE RANGE AND BIOFIDELITY CORRELATION

BRS 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 time history of each evaluated parameter was overlaid with its corresponding PMHS corridor defined in [5], see Fig. A1 through Fig. A15 in the Appendix. THOR-AV responses were evaluated with the BRS score. The seat load measurements and the dummy body segments were grouped in a way as defined in [12]. The seat load scores were evaluated as a group. Components of the seat load and restraint system scores are shown in Fig. 5. The dummy response scores were grouped by head, spine, pelvis, and thorax. The components of the dummy response BRS scores are shown in Fig. 6.

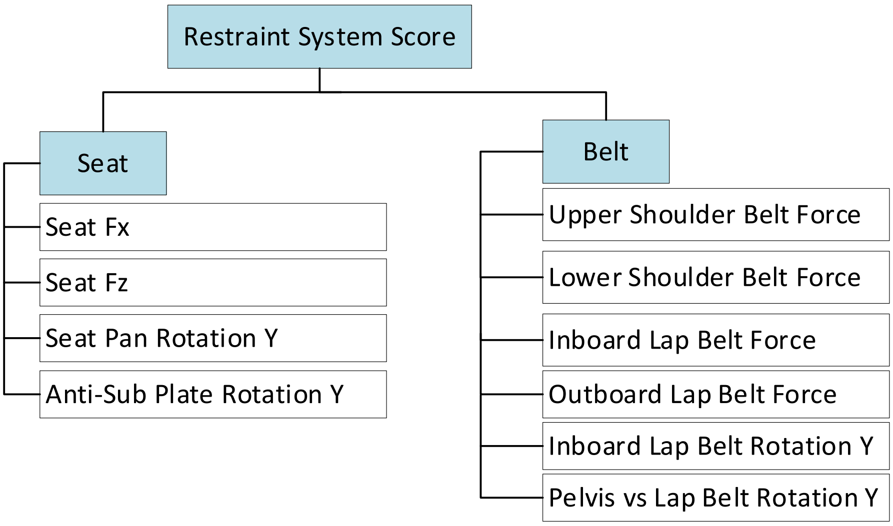

Fig. 5. Components of restraint system response BRS scores.

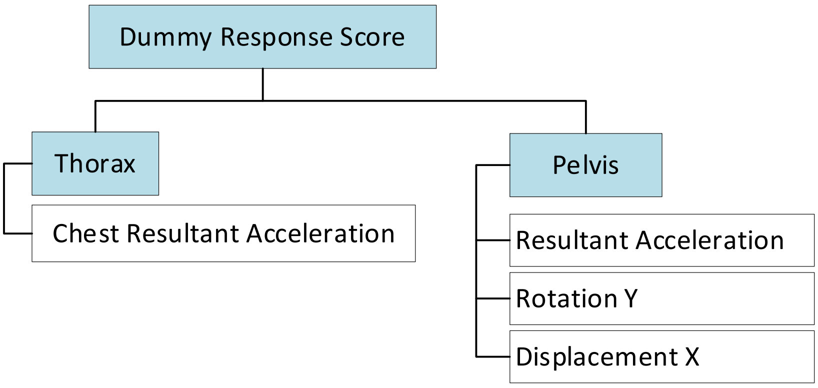

Fig. 6. Components of dummy response BRS scores.

Front Seat Biofidelity Ranking

The BioRank scores for the front seat restraint system and the THOR-AV 50M are summarized in

TABLE III. The overall seat response had a BRS score of 2.12, corresponding to *marginal* biofidelity. For the seat rotation Y, the biofidelity was *poor* with a BRS score greater than 4.0. The responses of the shoulder belt and lap belt were *excellent* with an average BRS score of 0.97. The overall BRS score for the restraint (seat and belts) was 1.46, corresponding to *good* biofidelity.

TABLE III
BIORANK SCORES AND DPS FOR FRONT SEAT CONFIGURATION

	SUBBIO_AV_01		SUBBIO_AV_02		SUBBIO_AV_03		Average	
Restraint System	BRS	DPS(ms)	BRS	DPS(ms)	BRS	DPS(ms)	BRS	DPS(ms)
Seat							2.12	-6
Seat Force X	0.69	-7.1	0.70	-6.9	0.68	-7.6	0.69	-7
Seat Force Z	NA	NA	1.68	-32.7	1.64	-15.9	1.66	-24
Seat Rot Y	4.49	-3.0	4.73	-2.9	4.48	-2.3	4.57	-3
Ant-sub Ramp Rot Y	1.78	10.0	1.41	11.3	1.45	9.8	1.55	10
Belt							0.97	-4
Upper Shoulder Belt Force	1.60	3.5	1.35	2.1	1.18	3.1	1.38	3
Lower Shoulder Belt Force	1.34	-1.6	1.49	-2.1	1.22	0	1.35	-1
Inboard Lap Belt Force	0.78	-5.5	0.92	-6.1	0.65	-6	0.78	-6
Outboard Lap Belt Force	0.75	-5.8	0.96	-6.6	0.66	-6.3	0.79	-6
Inboard Lap Belt Rot Y	1.35	-2.3	0.88	-13.5	1.30	-9.6	1.18	-8
Outboard Lap Belt Rot Y	0.80	-9.4	0.78	-7.1	1.00	-3.8	0.86	-7
Pelvis vs Lap Belt Rot Y	0.43	-2.4	0.40	-4.3	0.50	-0.5	0.44	-2

Overall Average	1.54	-5

There were limited biofidelity corridors for the dummy in [4], focusing on thoracic spine and pelvis only. The BRS scores of the THOR-AV 50M are summarized in TABLE IV. The thoracic spine T4 resultant acceleration had a BRS score of 0.80, corresponding to *excellent* biofidelity. The pelvis BRS score was 0.87, corresponding to *excellent* biofidelity as well. Overall, the THOR-AV 50M had a BRS score of 0.84, corresponding to *excellent* biofidelity.

TABLE IV
BIORANK SCORES OF THOR-AV 50M IN FRONT SEAT CONFIGURATION

	SUBBIO_AV_01		SUBBIO_AV_02		SUBBIO_AV_03		Average	
ATD	BRS	DPS(ms)	BRS	DPS(ms)	BRS	DPS(ms)	BRS	DPS(ms)
Thorax							0.80	7
T4 Resultant Acceleration	0.82	7.4	0.84	6.6	0.75	6.6	0.80	7
Pelvis							0.87	-1
Pelvis Resul. Acceleration	0.72	-5.8	0.70	-6.8	0.80	-6.6	0.74	-6
Pelvis Rotation Y	0.36	-2.9	0.33	-2.3	0.36	-1.8	0.35	-2
Pelvis Displacement X	1.41	4.6	1.75	6.3	1.41	5.2	1.53	5
Overall Average							0.84	3

Rear Seat Biofidelity Ranking

The BioRank scores for the rear seat restraint system and the THOR-AV 50M are summarized in TABLE V. The seat rotation was *poor* with BRS scores greater than 3.0. The anti-submarining ramp rotation was *marginal* with BRS scores greater than 2.0. The overall seat response was *marginal* with a BRS score of 2.19. The belt responses were in *excellent* and *good* categories. The average of the belt responses had a BRS score of 1.10, corresponding to *good* biofidelity. Overall, the restraint system responses had a BRS score of 1.64, corresponding to *good* biofidelity.

TABLE V
BIORANK SCORES OF RESTRAINT SYSTEM FOR REAR SEAT CONFIGURATION

	SUBBIO_AV_04		SUBBIO_AV_06		SUBBIO_AV_06		Average	
Restraint System	BRS	DPS(ms)	BRS	DPS(ms)	BRS	DPS(ms)	BRS	DPS(ms)
Seat							2.19	-1
Seat Force X	1.09	-0.1	1.13	0	0.96	-0.4	1.06	0
Seat Froce Z	1.50	7.7	1.45	6.7	1.59	8.4	1.51	8
Seat Pan Rotation Y	3.37	-9.3	3.51	-9.8	3.73	-10	3.54	-10
Ant-sub Ramp Rotation Y	2.64	0.0	2.64	0.0	2.65	0.0	2.65	0
Belt							1.10	-8
Upper Shoulder Belt	0.80	2	0.57	0.3	0.53	0.6	0.63	1
Lower Shoulder Belt	1.04	-2.3	1.02	-2.3	NA	NA	1.03	-2
Inboard Lapbelt	1.48	-1.9	1.45	-1.4	1.55	-1.8	1.49	-2
Outboard Lapbelt	1.57	-2.2	1.24	-1.6	1.40	-2.7	1.40	-2
Inboard Lapbelt Rotation Y	0.33	-15.4	1.91	-10.5	0.91	-21.8	1.05	-16
Outboard Lapbelt Rotation Y	0.73	-33.1	1.53	-14	1.20	-38.3	1.15	-28
Pelvis vs lapbelt rotation Y	0.42	-9.1	1.82	-0.1	0.59	-11.8	0.94	-7
Overall Average							1.64	-4

The BioRank scores for THOR-AV 50M are summarized in TABLE VI. The parameters of the PMHS tests were limited, focusing on the thoracic spine acceleration and pelvis. The thoracic spine T4 resultant acceleration had a BRS score of 1.02, corresponding to *good* biofidelity. The pelvis BRS score was 0.51, corresponding to *excellent* biofidelity. The overall THOR-50M biofidelity was *excellent* with a BRS score of 0.77.

TABLE VI
BIORANK SCORES OF THOR-AV 50M IN REAR SEAT CONFIGURATION

	SUBBIO_AV_04	SUBBIO_AV_05	SUBBIO_AV_06	Average

ATD	BRS	DPS(ms)	BRS	DPS(ms)	BRS	DPS(ms)	BRS	DPS(ms)
Thorax							1.02	-5
T4 Resultant Acceleration	1.02	-5.1	1.09	-5.1	0.96	-4	1.02	-5
Pelvis							0.51	-1
Pelvis Resultant Acceleration	0.77	-3.7	0.78	-2.2	0.82	-3.9	0.79	-3
Pelvis Rotation Y	0.42	-2.6	0.41	-2	0.35	-1.9	0.39	-2
Pelvis Displacement X	0.33	2	0.44	3.5	0.29	2	0.35	3
Overall Average							0.77	-3

Overall Biofidelity

The overall BioRank scores and DPS are summarized in TABLE VII. For front seat configuration, THOR-AV had BRS scores of 1.54 and 0.84 for the restraint system and dummy, respectively, corresponding to *good* and *excellent* biofidelity. For the rear seat configuration, THOR-AV had BRS scores of 1.64 and 0.77 for the restraint system and the dummy, respectively, corresponding to *good* and *excellent* biofidelity. Overall, THOR-AV showed *good* biofidelity for the restraint system and *excellent* biofidelity for the dummy responses.

TABLE VII
OVERALL BIORANK SCORES AND DPS FOR EACH TEST

	BRS	*DPS (ms)*
Front Seat – Restraint System	1.54	-5
Front Seat – THOR-AV	0.84	3
Rear Seat – Restraint System	1.64	-4
Rear Seat – THOR-AV	0.77	-3
Overall – Restraint System	1.59	-5
Overall – THOR-AV	0.80	0

Submarining Responses

The THOR-AV dummy did not submarine in the front test configuration and submarined in the rear seat test configuration, matching the PMHS test results in both test configurations presented in [4]. However, the THOR-AV appeared to submarine earlier than the PMHS.

In the front seat configuration test, it was observed that THOR lap belt force started to drop at approximately 62 ms, which implied the lap belt near the buckle side could slip off the ASIS, see Fig. A3 (left) and Fig. A4 (left). The lap belt slip over the ASIS could not be determined clearly from the video for THOR-AV, shown in Fig. 7 (right). For PMHS test, shown in Fig. 7 (left, sub bio 29, mass 77kg, stature 175 cm [4]), the belly tissue in PMHS helped to retain the lap belt in position positively.

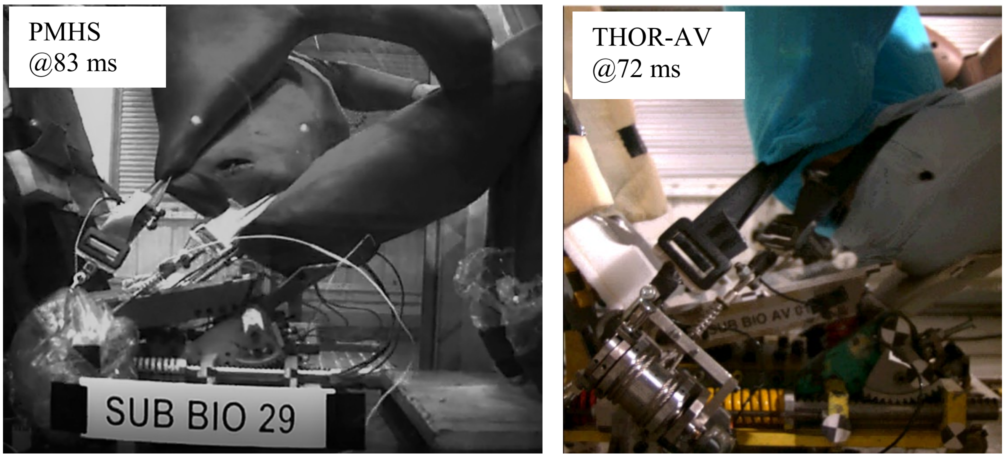

Fig. 7. Static picture from the buckle side in front seat configuration.

In the rear seat configuration test, it was observed that the THOR-AV lap belt force started to drop at approximately 58 ms, followed by a second drop near 66 ms, see Fig. A3 (right) and Fig. A4 (right). Most likely the first lap belt force drop happened when the lap belt near the buckle slipped off the ASIS and the second lap belt force drop happened when the lap belt near the anchor side slipped off the ASIS. From the video, the submarining of THOR-AV started about the same time, which was approximately 10 ms earlier than the PMHS. The static pictures when the submarining started are shown in Fig. 8 for PMHS (SUB BIO 24, mass 77kg, stature 171 cm [4]) and THOR-AV.

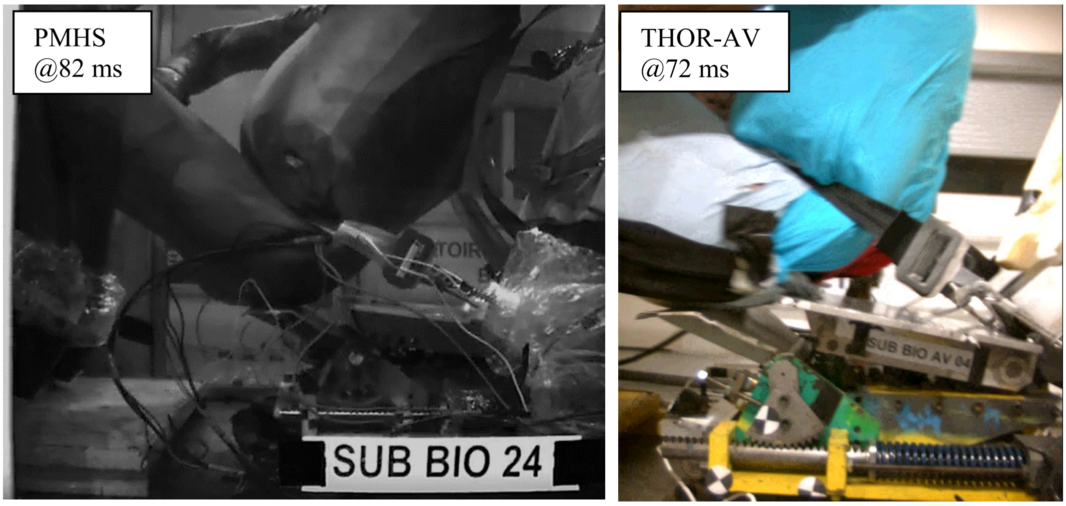

Fig. 8. Static picture of the anchor side right before the submarining started.

IV. DISCUSSION

While the NHTSA BioRank method provides an objective way to assess the ATD biofidelity, it does not offer an objective method to assess the ATD submarining responses. The submarining results were analyzed with both belt data and video analysis in this study.

Belt System Responses

The upper and lower shoulder belt forces matched the PMHS results very closely in general for both front and rear seat configurations, see Fig. A1 and Fig. A2 in the Appendix. It was noticed that the THOR-AV shoulder belt engagement lagged the PMHS shoulder belt load by 20 ms approximately. In the front seat configuration, the shoulder belt force peak magnitude of THOR-AV was slightly lower than the PMHS in upper shoulder belt force, but higher in the lower shoulder belt force. In the rear seat configuration, the upper shoulder belt force magnitude matched the PMHS well, but the lower shoulder belt force of THOR-AV was higher than the PMHS. The difference could be caused by different friction coefficients between belt/dummy and belt/PMHS.

The inboard and outboard lap belt forces reached a similar maximum magnitude between the dummy and PMHS tests, see Fig. A3 and Fig. A4. There was an approximately 15 ms delay in the front seat configuration for THOR-AV. It was observed that the dummy lap belt force dropped more in magnitude and had a lower plateau in both front and rear seat configurations. The lower plateau of lap belt was most likely caused by reduced engagement with the ASIS. The less engagement implied the pelvis may slipped under the lap belt and could cause higher pelvis forward motion and earlier submarining for the dummy.

Seat pan forces in x-direction matched well between the dummy and PMHS in front seat configuration. In the rear seat configuration, the seat pan force in x-direction was much lower than the PMHS in the loading stage (up to 70 ms approximately), see Fig. A5. Friction could be one of the causes that lead to the difference. This lower force in x-direction could lead to higher forward pelvis motion and earlier submarining of the dummy. It was observed that the seat force in z-direction for THOR-AV was lower than the PMHS in both front and rear seat configurations, see Fig. A6. The body mass of the THOR-AV was close to the PMHS, both representing an average male and should not be the cause of the difference. The lower force in z-direction could also contribute to lower friction force between the seat pan and the dummy. In addition, the thigh also carried some load for the body mass. The dummy thigh flesh (representing a 45-year-old 50th percentile male) was larger than the elderly male PMHS specimens (lost muscle for elderly), and may have carried more load distribution, which was evidenced by the higher anti-submarining ramp rotation in the test.

Seat pan rotation for THOR-AV was lower for both front seat and rear seat configurations, see Fig. A7. The lower seat-pan z-force most likely caused the lower seat pan rotation. The anti-submarining plate rotation of THOR-AV was higher than the PMHS front seat configuration, which could be caused by the thigh flesh difference between THOR-AV and PMHS specimens as discussed earlier.

Inboard lap belt y-rotation varied largely between tests, see Fig. A9. In the front seat configuration, two of the three tests followed the PMHS closely. In the rear seat configuration, the inboard lap belt y-rotation had a delay of 20 ms delay, followed by a quick rotation. The change time was consistent with the lap belt force drop time discussed earlier. The outer lap belt y-rotation matched the PMHS closely for the front seat configuration. However, it had less rotation for the rear seat configuration.

THOR-AV Responses

There were only limited data presented in [5] for the PMHS responses. The PMHS study only offered chest resultant acceleration, pelvis resultant acceleration, pelvis rotation and pelvis x-displacement as guidance for the ATD biofidelity assessment.

Chest resultant accelerations (T4) were very comparable to PMHS results in both front and rear seat configurations, see Fig. A12. At 80 ms, the chest resultant acceleration went in opposite directions between THOR-AV and the PMHS. The human spine is a very complex structure, which made it difficult to replicate in dummy design.

THOR-AV pelvis resultant acceleration matched the PMHS results reasonably in both front and rear seat configurations, see Fig. A13. The pelvis resultant acceleration was also repeatable. The pelvis rotations were well within the PMHS corridors for both front and rear seat configurations, shown in Fig. A14. THOR-AV pelvis x-displacement was higher than the PMHS corridor in front seat configuration and stayed with the PMHS corridor, shown in Fig. A15.

THOR-AV Submarining and Design Change Exploration

Submarining is defined as the lap belt becoming disengaged with the anterior superior iliac spine (ASIS) and slipping over the iliac crest. The pelvis would slip under the lap belt. The occupant submarining would increase the risk of abdomen injuries and could cause higher load to lower extremities due to the inertia from the pelvis mass. There are no objective criteria from the test that can be used to determine the exact submarining time. In this study, the lap belt data and videos were used together to estimate the THOR-AV submarining time.

As mentioned in the result section, THOR-AV matched the submarining result of the PMHS in terms submarining (rear seat configuration) or non-submarining (front seat configuration). However, it was noticed the THOR-AV submarined earlier than PMHS. Investigations were conducted to explore possible design changes to improve the pelvis submarining responses. Two parameters were visited in the study, ASIS geometry and THOR-AV hip joint height. Reference [15] published a new study of the anterior iliac wing geometries in 2020. The THOR-AV ASIS was reshaped to match the critical parameters presented in this study. It was known for a long time, that the THOR hip joint is about 20 mm higher than the 50th percentile male defined by [16] when seated. The THOR-AV prototype had similar buttock geometry to THOR, which yielded similar hip joint height. Lowest density foam was experimented with, but still failed to compress enough to match the human hip joint height specified in [16]. To address this properly, a cavity was created under the pelvis bone to maximize the buttock flesh compression bringing the hip joint height lower by 20 mm approximately to match the target hip joint height.

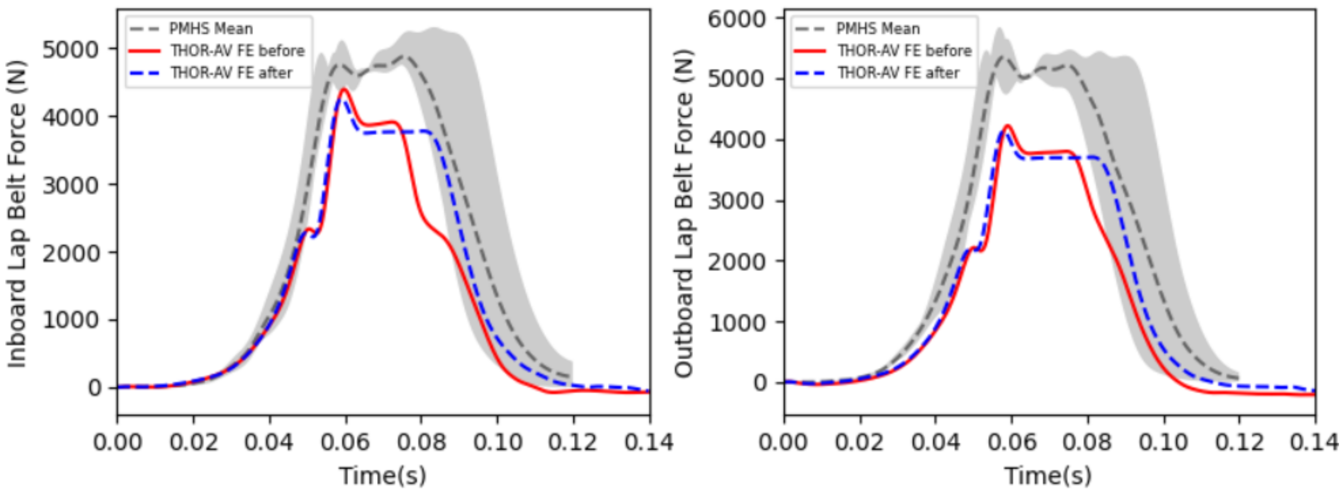

Fig. 9. Dummy engagement time with the lap belt in the front seat test configuration before and after ASIS and pelvis flesh changes from FE analysis.

Finite element simulations were conducted to quantify the improvement with the above changes. The analysis showed the ASIS geometry shape change alone had noticeable but insignificant influence on the pelvis dynamics and the submarining responses. The pelvis flesh change with the proper hip joint height contributed to the major difference and delayed the submarining time and improved THOR-AV pelvis responses. In finite element analysis, the ASIS shape and hip joint height affected the lap belt route on the dummy and improved the dummy engagement duration with the lap belt, shown in Fig. 9 for front test configuration. Similar improvement was observed in rear seat configuration. When the hip joint center was lower, which means the pelvis flesh was more compressed with its body weight, it would have less compressible flesh material for the lap belt to compress during the crash test. The less compressible flesh would provide a steadier engagement between the lap belt and the pelvis, therefore restrained the pelvis more positively. In the front seat configuration, it was observed the lap belt slipped off the ASIS on the buckle side before the changes, but stayed on the ASIS after the change, see Fig. 10. In the rear configuration, the FE analysis demonstrated the submarining start time was improved by 4 ms. The static pictures of the simulations prior to the submarining before and after the design changes are shown in Fig. 11. The FE simulation may not reflect the actual test results exactly due to limited model validation efforts but demonstrated the right direction for the improvements.

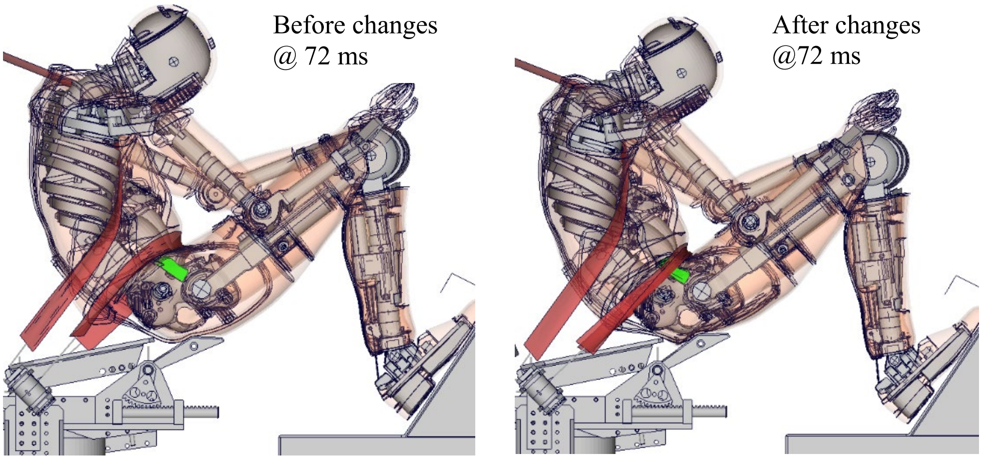

Fig. 10. Lap belt and ASIS engagement in front seat configuration before (left) and after (right) the design changes. The lap belt near the buckle side slipped over the ASIS before the changes (left) and stayed with the ASIS through the test after the changes (right). The lap belt near the anchor side stayed on the ASIS through test.

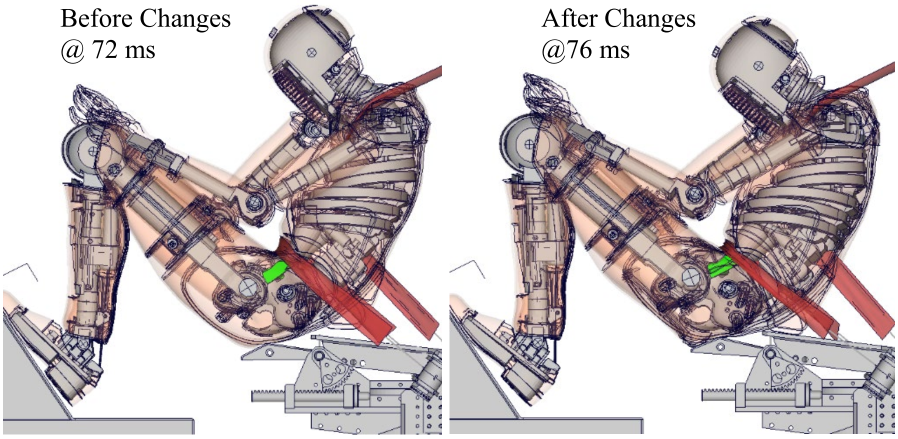

Fig. 11. Static simulation pictures of THOR-AV and lap belt engagement in rear seat configuration before (left) and after (right) the changes on the anchor side. ASIS are shown in green color.

Since the finite element analysis demonstrated both changes improved the THOR-AV submarining responses, both changes were implemented in the dummy for the next test series.

V. CONCLUSIONS

The THOR-AV dummy was designed as a tool immediately available for the industry to assess restraint systems for ADS-equipped vehicles. The dummy was designed to represent a human in both reclined and traditional upright seated postures. The evaluation of THOR-AV in upright seated postures showed good biofidelity in front seat configurations with BRS scores of 1.46 for the restraint system, 0.84 for the dummy, corresponding to *good* and *excellent* biofidelity, respectively. For the rear seat configuration, it had BRS scores of 1.57 for the restraint system, 0.77 for the dummy, corresponding to *good* and *excellent* biofidelity, respectively. Overall, the THOR-AV had BRS scores of 1.52 and 0.80 for the restraint systems and dummy responses, respectively, corresponding to *good* and *excellent* biofidelity.

The submarining responses of the THOR-AV showed higher tendency of submarining than the PMHS. Finite element analysis showed the proposed changes of the ASIS geometry and buttock flesh compression improved the submarining responses to match the PMHS submarining responses. These changes were implemented in the THOR-AV for the next evaluation test series.

VI. Acknowledgement

The authors would like to express their gratitude to FORVIA (Brières-les-Scellés, France) sled test team and CEESAR (Nanterre, France) engineering team for conducting the tests. Many thanks to Humanetics (Farmington Hills, Michigan, USA) engineering team who prepared and certified the dummy prior to the biofidelity evaluation.

VII. References

[1] Jorlöv J. Bohman K., Larsson A., Seating positions and activities in highly automated cars – a quanlitative study of future automated driving scenarios, *IRCOBI Conference Proceedings*, September 13-15, 2017, Antwerp, Belgium.

[2] Lopez-Valdes F., Jimenez-Octavio J., Bohman K., Logan D., Raphael W., Jimenez L., Koppel S., Seating preferences in highly automated vehicles are dependent on yearly exposure to traffic and previous crash experiences, *IRCOBI Conference Proceedings,* Florence, Italy, September 11-13, 2019.

[3] Forman J., Kerrigan J., Panzer M., *THOR-50M modification for reclined seating – initial assessment*, NHTSA Biomechanics Test Database: test number 12990, February 2020. https://www.nhtsa.gov/research-data/research-testing-databases#/biomechanics/12990.

[4] Wang, Z.J., Loeber B., Tesny A., Hu G., Kang Y.S., Neck biofidelity comparison of THOR-AV, THOR and Hybrid III 50th dummies, *IRCOBI Conference Proceedings*, September 8-10, 2021, online.

[5] Uriot J., Potier P., Baudrit P., Trosseille X., Petit P., Richard O., Compigne S., Masuda M., Douard R., 2015. Reference PMHS sled tests to assess submarining. *Stapp Car Crash Journal*, Vol. 59, pp 203-224.

[6] Parent, D. Craig, M., Moorhouse, K. 2017. Biofidelity evaluation of the THOR and Hybrid III 50th percentile male frontal impact andromorphic test devices, *Stapp Car Crash Journal*, Vol. 61, pp. 227-276, November 2017.

[7] Rhule H.R., Maltese M.P., Donnelly B.R., Eppinger R.H., Brunner J.K. and Bolte IV J.H., Development of a new biofidelity ranking system for anthropomorphic test devices, *Stapp Car Crash Journal*, 46th Stapp Car Crash Conference, November 2002.

[8] Rhule H., Moorhouse K., Donnelly B., Stricklin J., Comparison of WorldSID and ES-2RE biofidelity using an updated biofidelity ranking system*, 21st International Technical Conference on Enhanced Safety of Vehicles* (ESV), Stuttgart, Germany, June 2009.

[9] Rhule H., Donnelly B., Moorhouse K., Kang Y-S., A methodology for generating objective target for quantitively assessing the biofidelity of crash test dummies, *23rd International Technical Conference on Enhanced Safety of Vehicles* (ESV), Seoul, Korea, May 27-30, 2013.

[10] Rhule H., Stricklin J., Moorhouse K., Donnelly B., Improvements to NHTSA's biofidelity ranking system and application to the evaluation of the THOR 5th female dummy, *IRCOBI Conference Proceedings*, 2018, paper # IRC-18-12.

[11] Kang Y-S., Stammen J., Ramachandra R., Agnew R.M. Hagedorn, A., Thomas C., Kwon H.J., Moorhouse K., Bolte IV J.H., Biomechanical responses and injury assessment of post-mortem human subjects in various rear-facing seating configurations. *Stapp Car Crash Journal*, vol. 64 (November 2020), pp. 155-212.

[12] Hagedorn A., et al. Biofidelity evaluation of THOR-50M in rear-facing seating configurations using an updated BioRank system, *SAE International Journal of Transportation Safety* (February 2022), Special Issue: Occupant Protection & Crashworthiness for ADS-Equipped Vehicles.

[13] Wang, Z.J., Biomechanical responses of the THOR-AV ATD in rear facing sled test conditions, *SAE World Conference*, Detroit, Michigan, USA. April 2022, SAE paper # 2022-01-0836.

[14]Reed M.P., *Development of anthropometric specifications for warrior injury assessment manikin*, report number UMTRI-2013-38, October 2013.
[15]Muehlbauer J, Pfeiffer N, Puschnig M, Schick S, Bayerschen E, Peldschus S, 2020. Distribution of Anterior Iliac Wings Geometries in the Population and Comparison to Finite Element Human Body Models, 2020 *IRCOBI Conference Proceedings*, Munich, Germany (virtual).
[16]Schneider, L.W., Robbins, D.H., Pflug, M.A., Snyder, R.G., 1983. *Anthropometric Specifications for Mid-sized Male Dummy*, Vol. 2, UMTRI-83-53-2.

VIII. APPENDIX

The plots of the results in front and rear seat configurations are shown below.

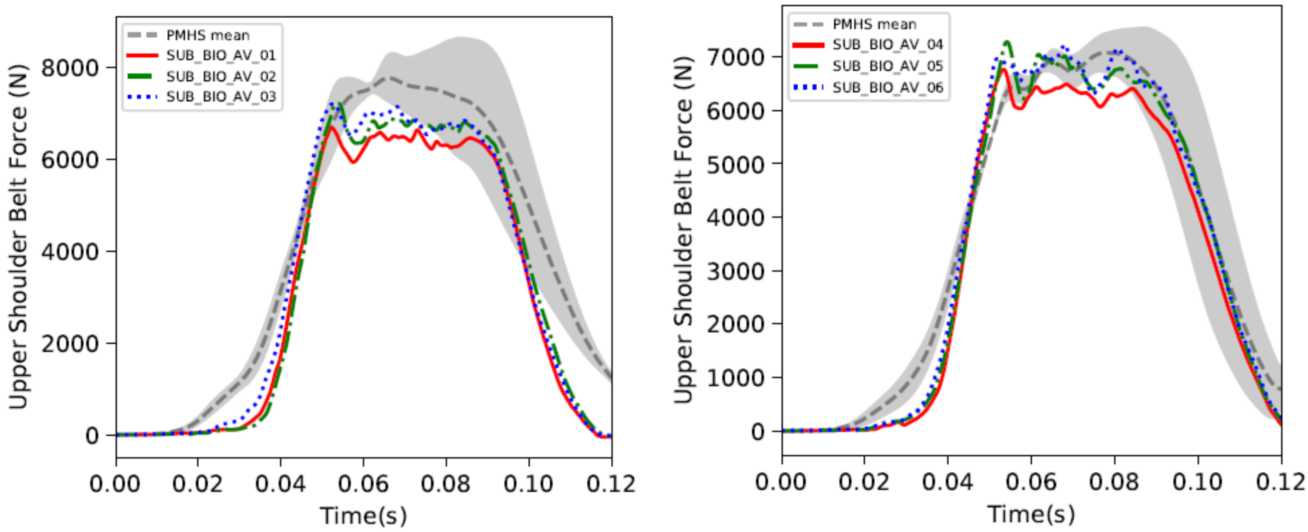

Fig. A1. Upper shoulder belt force in front seat (left) and rear seat (right) configurations.

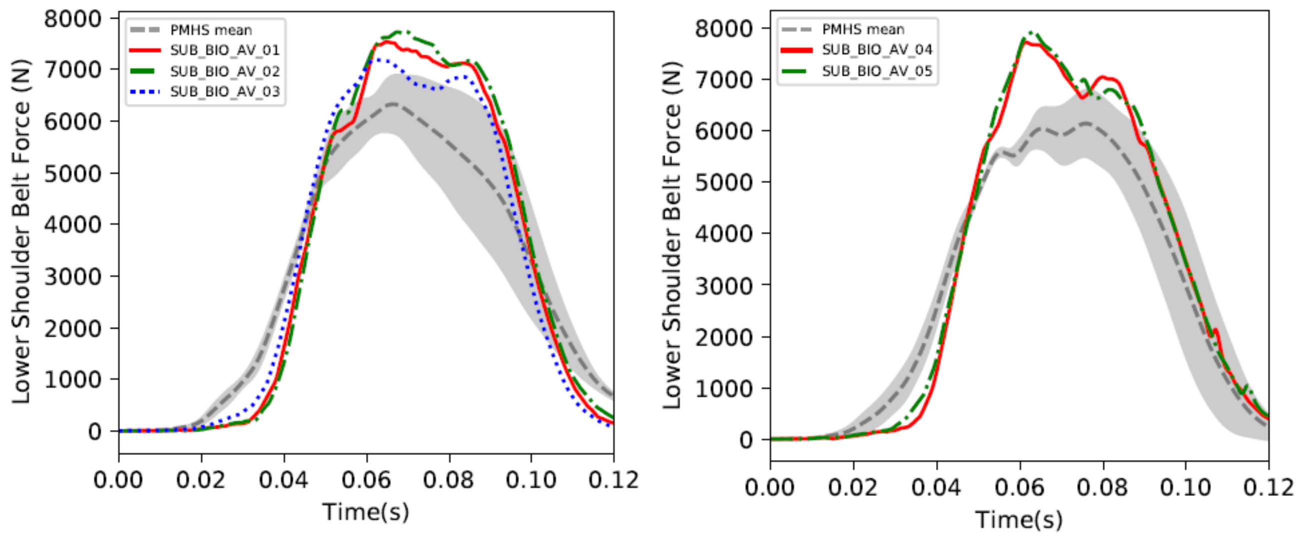

Fig. A2. Lower shoulder belt force in front (left) and rear (right) seat configurations.

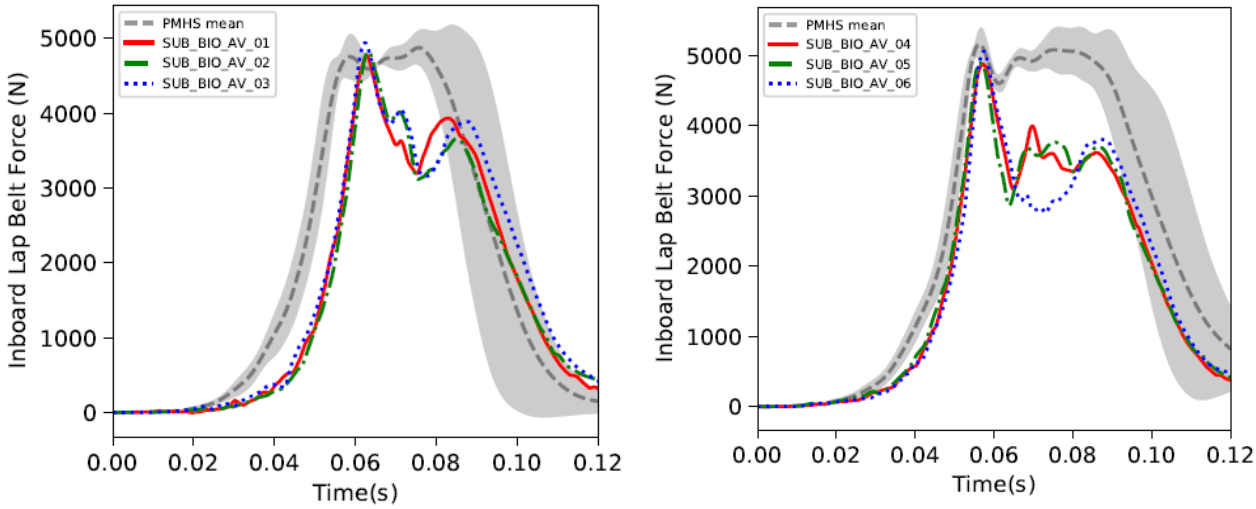

Fig. A3. Inboard lap belt force in front seat (left) and rear seat (right) configurations.

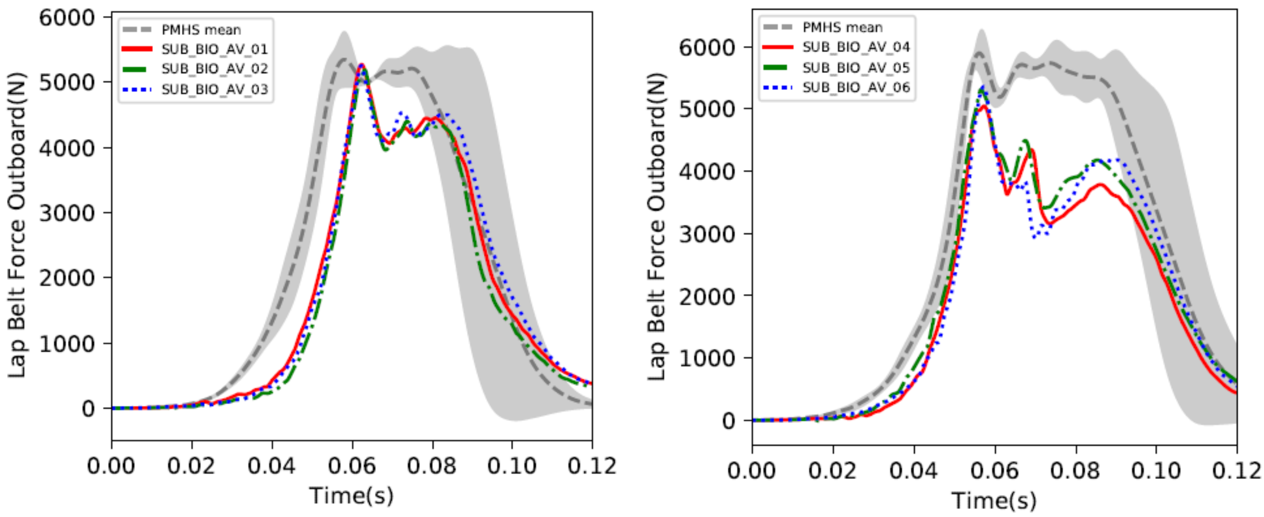

Fig. A4. Outboard lap belt force in front seat (left) and rear seat (right) configurations.

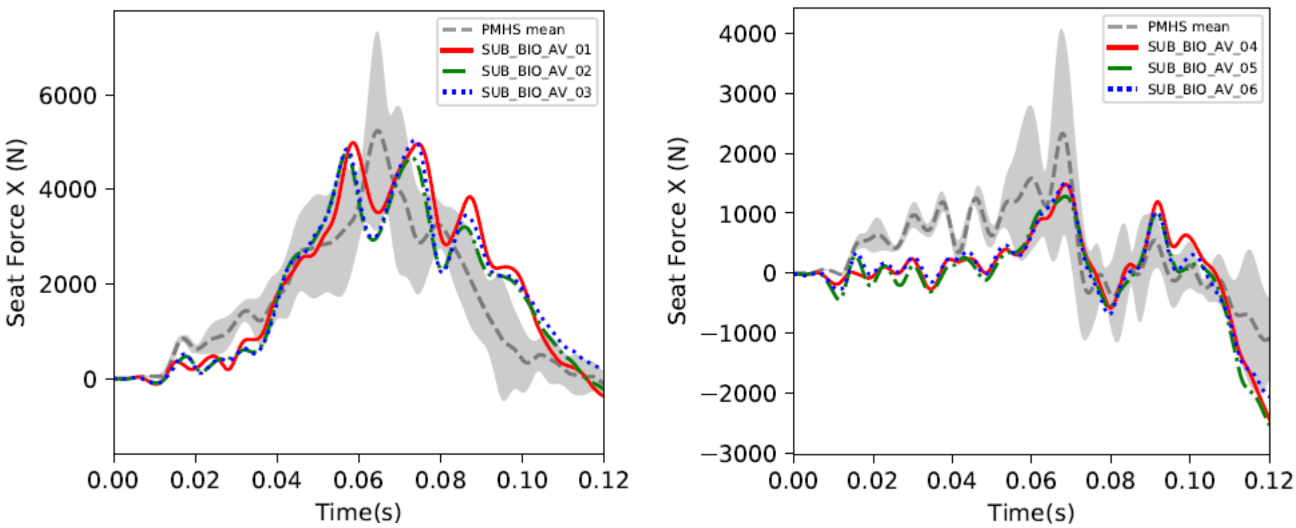

Fig. A5. Seat force Fx in front seat (left) and rear seat (right) configurations.

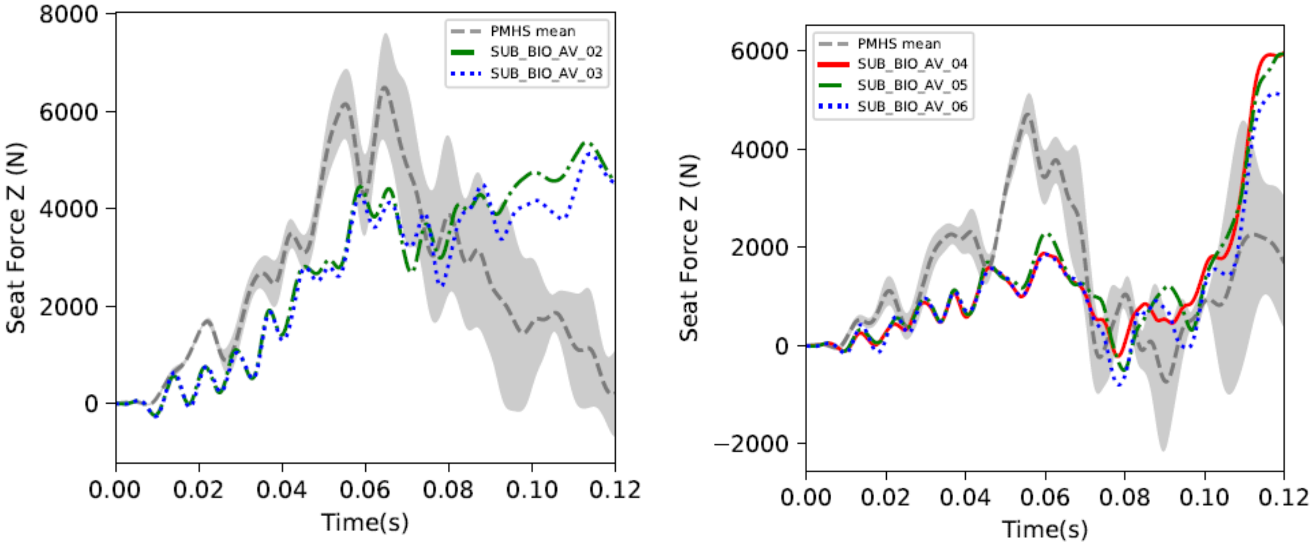

Fig. A6. Seat force Fz in front seat (left) and rear seat (right) configurations. Data lost for front seat test SUB_BIO_01.

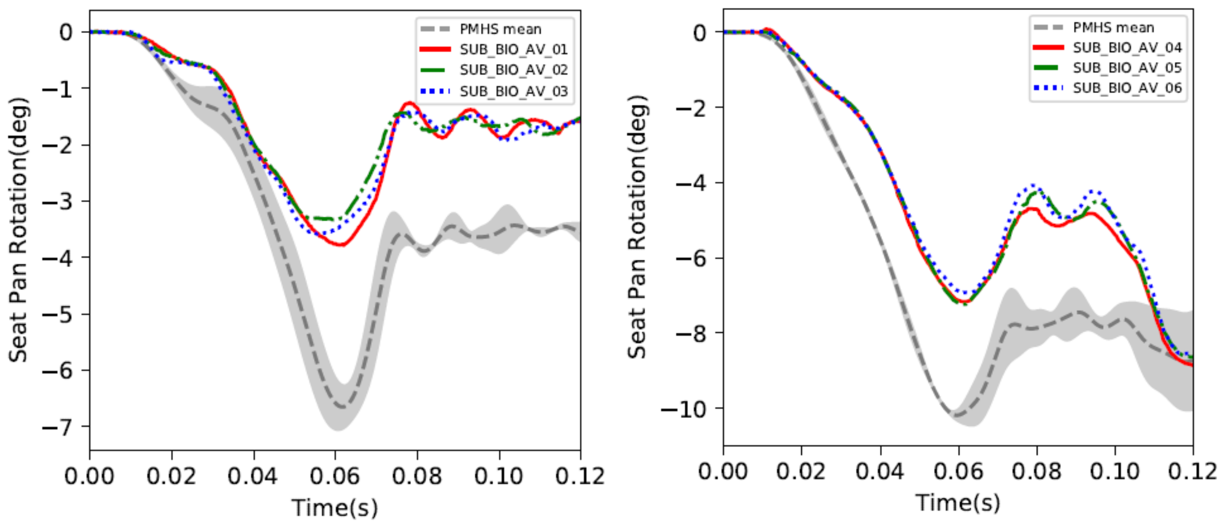

Fig. A7. Seat Rotation Y in front seat (left) and right seat (right) configurations.

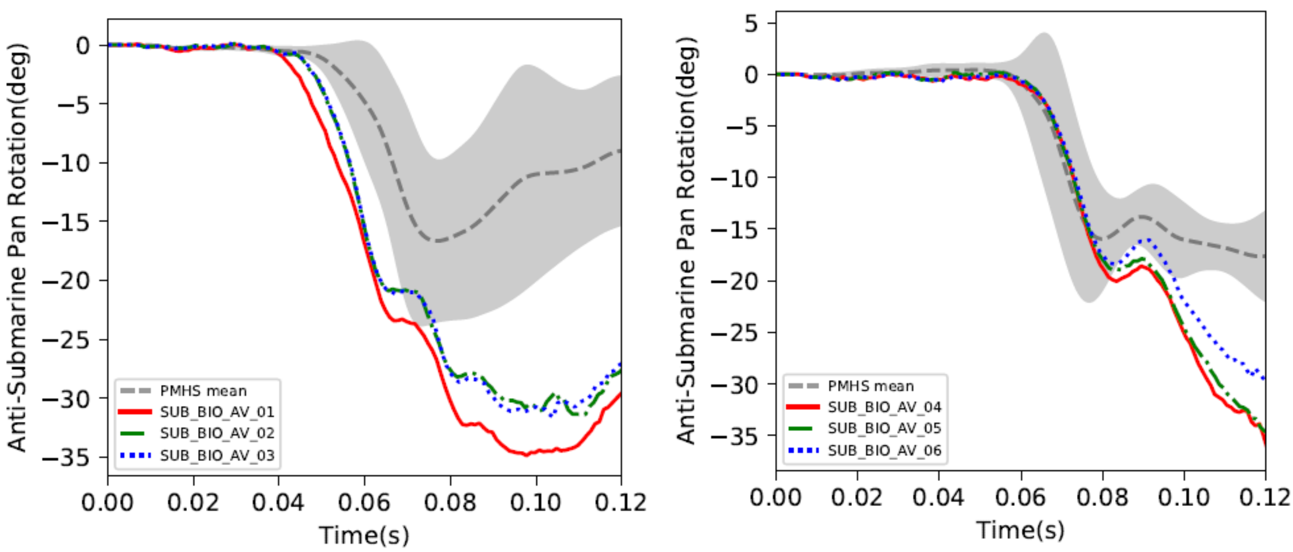

Fig. A8. Anti-submarining ramp rotation in front seat (left) and rear seat (right) configurations.

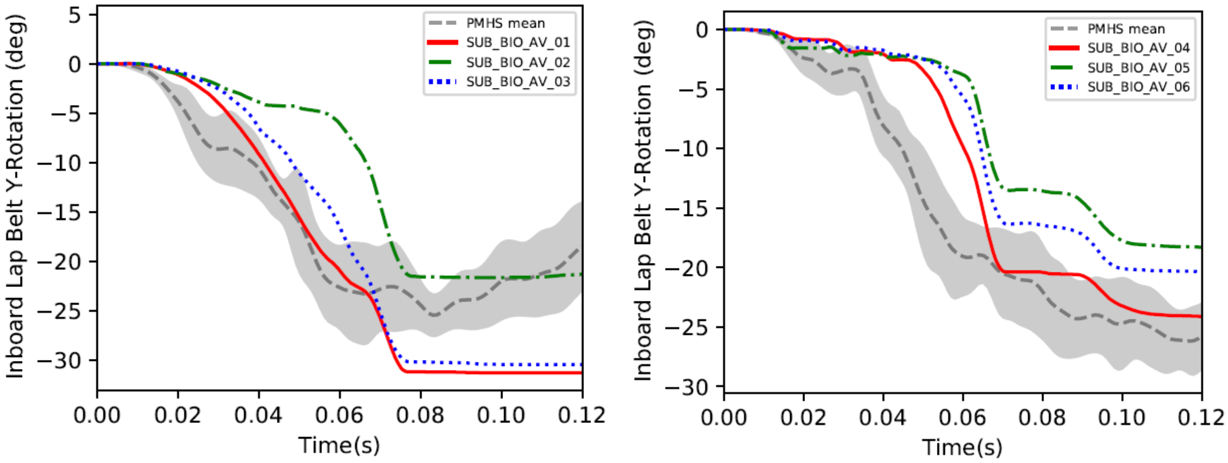

Fig. A9. Inboard lap belt y-rotation in front seat (left) and rear seat (right) configurations.

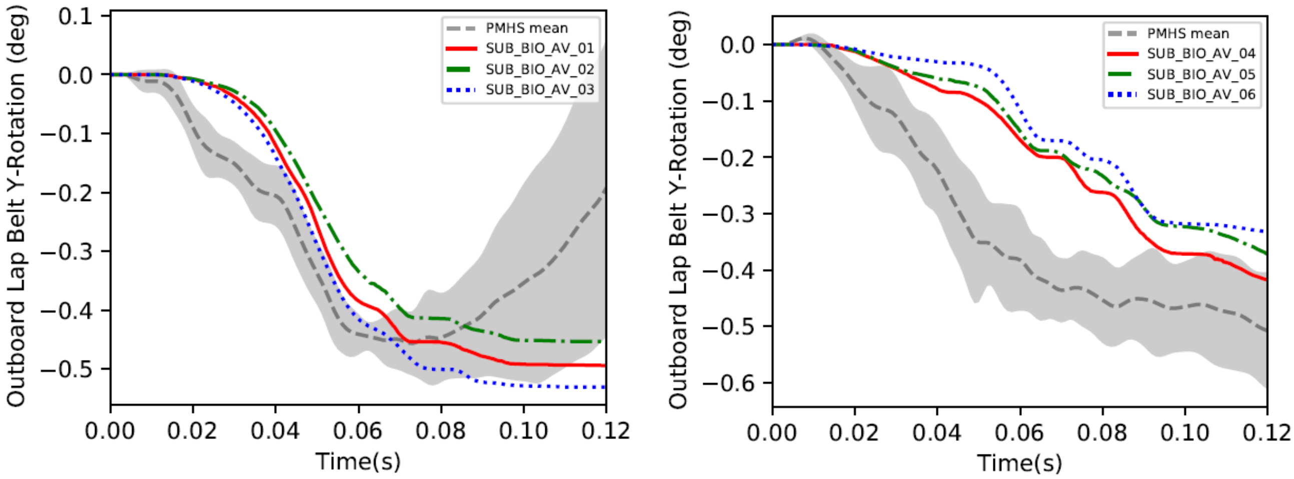

Fig. A10. Outboard lap belt y-rotation in front seat (left) and rear seat (right) configurations.

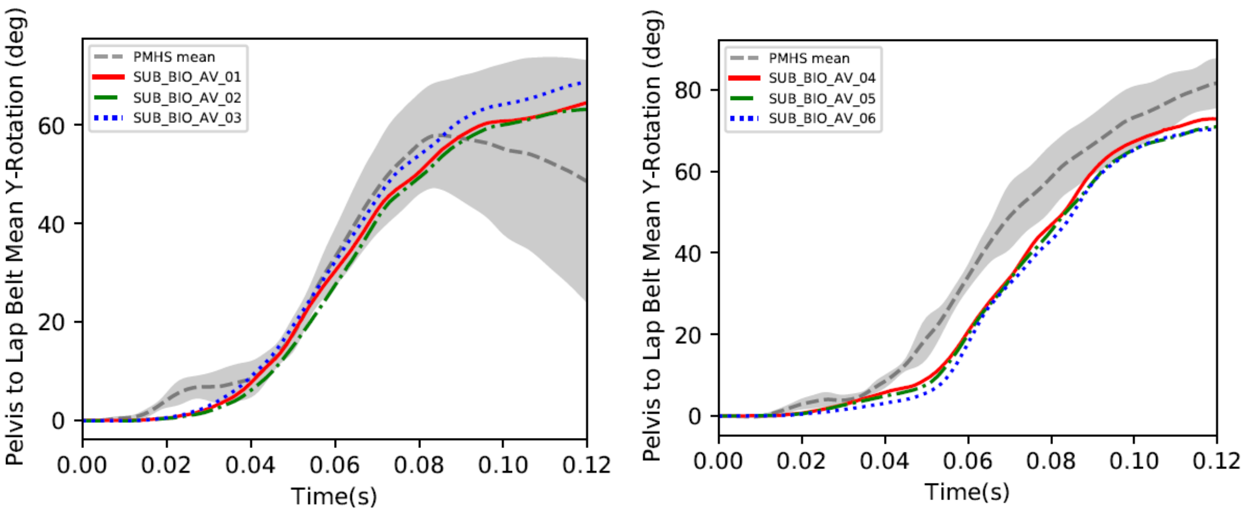

Fig. A 11. Pelvis to lap belt mean y-rotation in front seat (left) and rear seat (right) configurations.

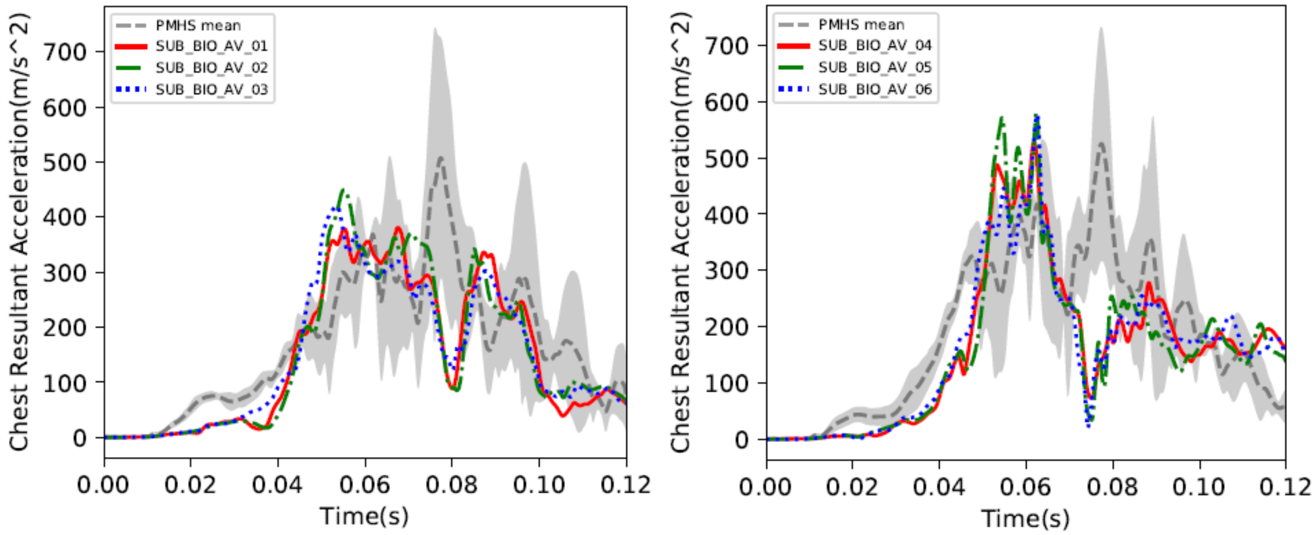

Fig. A12. Chest (T4) resultant acceleration in front seat (left) and rear seat (right) configurations.

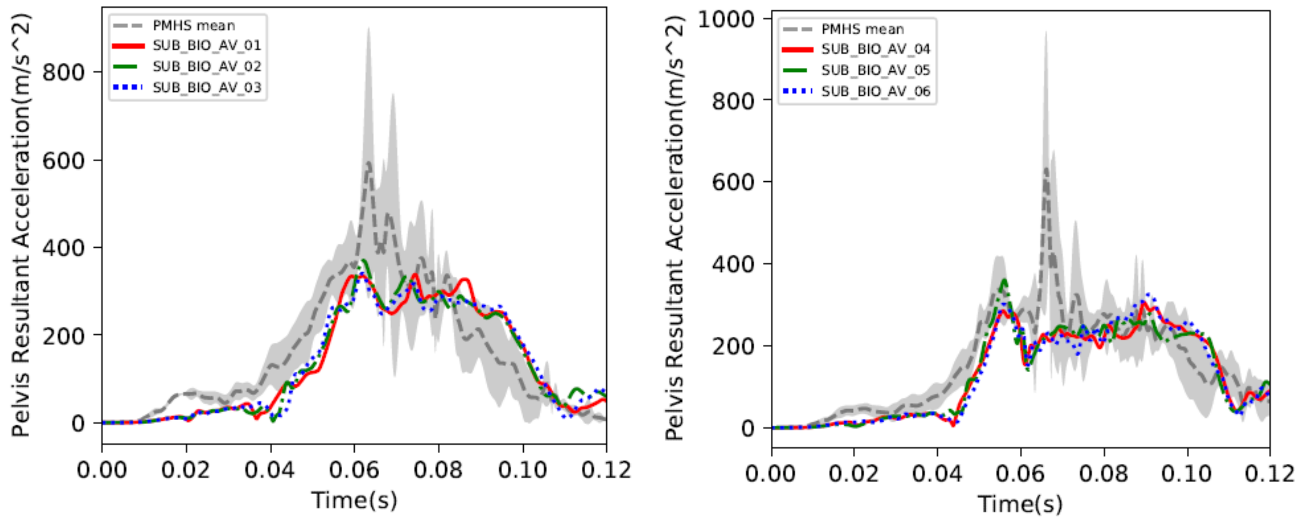

Fig. A13. Pelvis resultant acceleration in front seat (left) and rear seat (right) configurations.

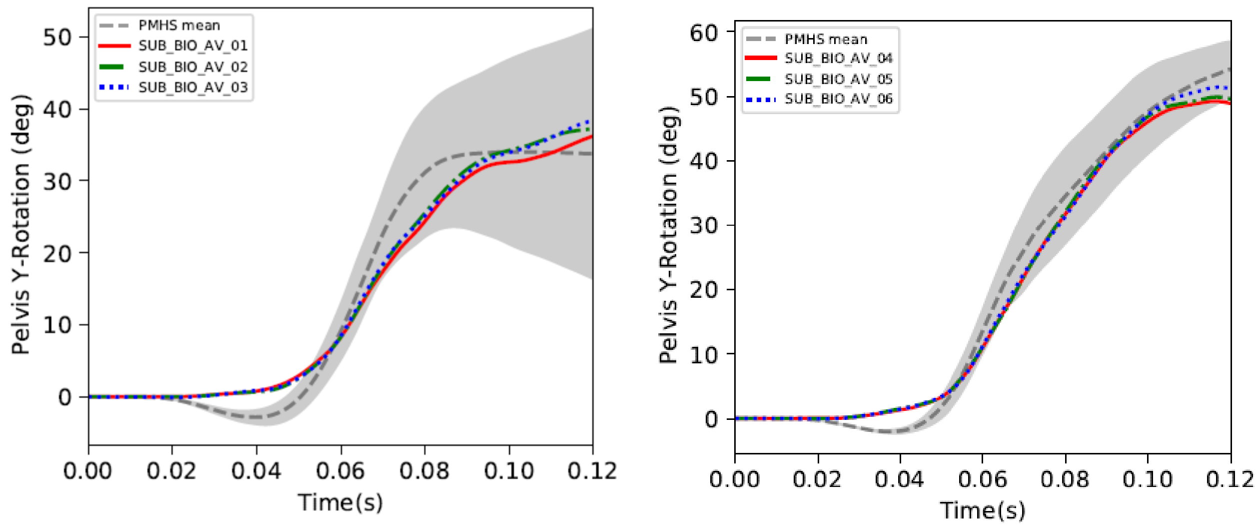

Fig. A14. Pelvis y-rotation in front seat (left) and rear seat (right) configurations.

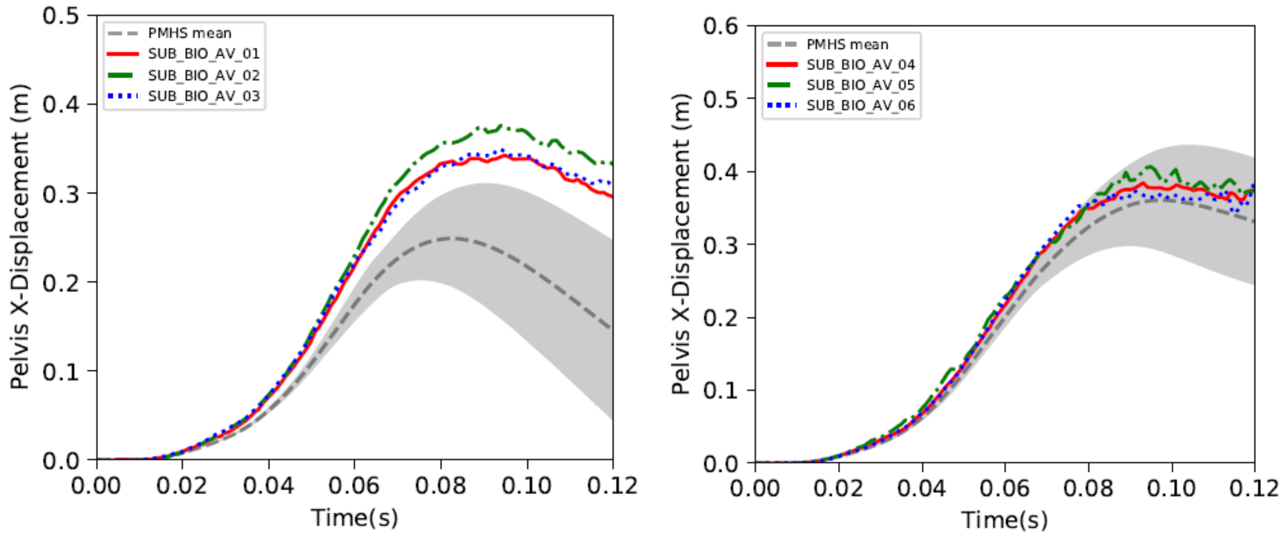

Fig. A15. Pelvis x-displacement in front seat (left) and rear seat (right) configurations.