## THOR 5<sup>th</sup> Female Biofidelity Evaluation in Gold Standard Sled Test Condition

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**Abstract** THOR 5<sup>th</sup> percentile female dummy was evaluated in a well-controlled 30 km/h frontal impact test condition that utilized a 9g deceleration and 3-point force-limited restraint. The pelvis and lower extremities were constrained in order to study the upper torso kinematics and thoracic deflections. BioRank scores were calculated using the NHTSA BioRank method. The biofidelity evaluation results showed "good" to "excellent" biofidelity for the dummy responses in head, spine and pelvis kinematics, and thorax deflections.

Keywords biofidelity, BioRank, sled, 5th percentile female dummy, THOR-05F

#### I. INTRODUCTION

Studies in the past decade showed that females not only have higher injury risks than males in motor vehicle crashes (MVCs), but also sustain different injuries [1][2][3][4]. Smaller stature and mass affect female occupant kinematics and associated interactions with restraint systems in MVCs. The odds for a belt-restrained female driver to sustain severe injuries is 47% higher than these for a belt-restrained male driver involved in a comparable crash [1]. Females have a higher risk of thoracic and spinal fractures due to belt and airbag loading [2][3], along with a higher risk of neck and lower extremity injuries [3]. Most recently it was shown that the female occupants wearing a seatbelt have 73% greater odds of being seriously injured (AIS 3+) in frontal crashes compared to belted males [4].

To address female safety in MVCs, the THOR 5<sup>th</sup> percentile female dummy, i.e., THOR-05F (Test Device for Human Occupant Restraint) was developed by the National Highway Traffic Safety Administration (NHTSA) and fabricated by Humanetics [5]. The THOR-05F was evaluated with a series of biofidelity requirements for each body segment [7]. The dummy has "good" biofidelity in each body segment with an overall BioRank score of 1.28 according to NHTSA's BioRank calculation method in 2020 [9][10]. Similarly, the THOR-50M dummy showed substantial biofidelity improvements compared to the Hybrid III anthropomorphic test device (ATD) in current regulation [6].

As part of the evaluation, THOR-05F was also tested in a frontal impact sled test condition (known as the "gold standard" condition) as defined in [11]. In this paper, the BioRank scores of this test are presented, using the most up to date NHTSA BioRank method[10].

#### **II. METHODS**

The tests were conducted by The Ohio State University (OSU) at Transportation Research Center (TRC) sled facility. The test setup followed the small female post-mortem human subject (PMHS) test procedure defined in [11]. The THOR-05F ATD was tested in a well-controlled 30 km/h frontal impact test condition that utilized a 9g deceleration and 3-point force-limited restraint. The dummy was positioned on a rigid seat with its torso and head supported by an adjustable matrix of cables to approximate the seating posture of a right-front passenger. The test setup allowed for torso and shoulder kinematic response to be comprehensively studied in a frontal crash scenario. The test setup is shown in Fig. 1. Four trials were performed on a single ATD.

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Fig. 1 Test setup for THOR-05F biofidelity evaluation

# **Restraint System**

The restraint system included a 3-point lap and shoulder belt of standard webbing using separate belt segments of adjustable lengths. The belt system did not include a retractor. The shoulder belt was routed through a low friction D-ring and down to a custom belt load limiting device. The device was developed to limit the shoulder belt loads to 2 kN tension. It was comprised of a 3/8" cell commercial grade aluminum honeycomb with seven active cells sandwiched between two aluminum plates and pulled using a cable connected to the shoulder belt on the other end, see Fig. 2. For each test, the initial shoulder belt tension was adjusted to approximately 17 N to eliminate the slacks and ensure repeatable belt initial position for OSU tests.



Fig. 2 Aluminum honeycomb sandwiched between two aluminum plates to limit shoulder belt load to 2 kN for OSU test setup.

## **Dummy Positioning and Belt Route**

The pre-test ATD positioning parameters are recorded in TABLE I. The ATD H-point was positioned such that the tibia and femur angles of around 36 and 13 degrees were achieved, respectively, to match the PMHS setup (PMHS had femur angle between 12 and 14 degrees and tibia angle between 27 and 37 degrees). Upon positioning the lower body, the torso was positioned to obtain a target value of approximately 13 degrees.

TABLE I

	THOR-05F POSITIONING ANGLES								
Test ID	Torso Angle (deg)	Femur Angle (deg)	Tibia Angle (deg)						
	(reference vertical)	(reference horizontal)	(reference horizontal)						
b12071	14.2	14.5	36.0						
b12072	14.0	13.5	37.0						
b12073	13.0	11.5	35.0						
b12074	12.2	11.8	35.0						

The shoulder belt was positioned to pass over the clavicle superiorly and exit on the lateral aspect of the pelvis inferiorly as shown in Fig. 3. The resulting pre-test shoulder belt angle and location between the D-ring and head are recorded in TABLE II.

	TABLE II					
SHOULDER BELT ANGLE MEASURED AT STERNUM FOR THOR-05F						
Test ID	θ (deg)	X (mm)				
b12071	49.1	338				
b12072	49.2	324				
b12073	48.4	354				
b12074	48.5	325				



Fig. 3 Shoulder belt route illustration diagram

Pelvis and lower extremity motion were restricted using a combination of lap belt, rigid knee bolster and footrest (Fig. 1) which were adjusted to be in contact with the knees and feet of the ATD at the time of impact.

### Instrumentation

On the sled buck, a total of six uni-axial load cells (Interface, Scottsdale, AZ, Model# 1100) mounted to the seat, one on each knee support plate, and one on the foot support plate to measure forces. Acceleration of the sled was measured by placing three linear accelerometers (Endevco, CA, Model #7231c) on the sled floor. Three seatbelt load cells (Measurement Specialties, now TE Connectivity, PA, Model #EL20) were affixed to the belt segments to measure belt forces: one each on the lap belt, the shoulder belt above the right shoulder, and the belt segment in front of the load-limiter mechanism. The dummy was instrumented with 41 channels of sensors, including all sensors from the pelvis up to the head. A complete sensor list is documented in Appendix I.

The kinematics of the ATD were studied using trajectories of several retroreflective targets obtained using a 16-camera, 1000 Hz motion capture and data acquisition system (VICON, Oxford, UK, Model Vantage). These retroreflective targets were attached to the head, posterior aspect of the spine, shoulders, anterior torso, pelvis, and knees of the ATD. Additionally, test videos were recorded at 1000 frames per second using two on-board high-speed video cameras. A FARO Arm (FARO Technologies Inc., Florida) was used to document the ATD position in three dimensions and locate the initial position of the some of the key landmarks on the ATD and sled. Points were also taken for each of the VICON markers.

#### Data Processing

Data were acquired at a sampling frequency of 20,000 Hz and in the laboratory coordinate system (LCS), with the positive x-axis directed from posterior to anterior, positive y-axis directed from left to right, and positive z-axis directed from superior to inferior, per standard SAE-J211 (2014-03). To determine time zero, the THOR-05F sled pulse was aligned with the PMHS sled pulse, giving a priority to the rising period. The time corresponding to the PMHS sled pulse time zero was used as the time zero for the THOR-05F tests.

The data channels were filtered with the same filter class as in the PMHS tests. In the PMHS data analysis [11], to minimize the noise, SAE CFC30 was applied to the sled load cells, and SAE CFC60 filter was applied to seat belt load cells, T1 and head accelerometers, and angular rate sensors. The IR-TRACC (Infra-Red Telescoping Rod for Assessment of Chest Compression) data was processed according to SAE J211 standard. BioRank scores were calculated after the data was filtered.

## Additional data

An additional three THOR-05F tests were conducted at The University of Virginia (UVA), under the same test conditions and on the same sled buck as the original PMHS tests. These test data (available in the NHTSA Biomechanics Database) were included in this paper for comparison. The details of UVA tests can be found in the test report published in NHTSA Biomechanics Database.

Both UVA and OSU tests used similar test method and setup. The test identification numbers for the OSU and UVA test series are summarized in TABLE III. The sled test pulses, including PMHS and dummy tests, are shown in Fig. 4.

SUMMARY OF TEST IDS AND TEST FACILITIES								
Test Facility		Test IDs						
OSU	b12071	b12072	b12073	b12074				
UVA	b12820	b12821	b12822					



Fig. 4 Sled pulse with SAE J211 filter CFC60

### **BioRank Calculation**

Data were quantitatively compared to PMHS corridors defined in [11]. The corridors were based on ten PMHS tests conducted on 5<sup>th</sup> percentile female specimens. ATD BioRank scores were calculated according to the NHTSA method [9], which was recently updated [10]. In this updated method, the dummy data is aligned in time with the biofidelity corridor mean data and then the BioRank score B is defined as DCAD/CCSD (Dummy Cumulative Absolute Difference / Cadaver Cumulative Standard Deviation). The dummy phase shift (DPS), i.e., the time shift of the dummy data curve for DCAD calculation, is recorded for reference. BioRank scores were calculated after the data was filtered. The biofidelity categories are summarized in TABLE IV.

		TABLETV					
BIOFIDELITY RANKING BASED ON BIORANK SCORES							
BioRank Score	B ≤ 1.0	1.0 < B≤2.0	2.0 < B≤3.0	3.0 < B			
Biofidelity	Excellent	Good	Marginal	Poor			

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Since the tests conducted in both OSU and UVA used the same dummy (serial number ED7441), BioRank scores were calculated with an average of all tests from both test facilities together.

### **III. RESULTS**

BioRank scores are summarized in TABLE V through TABLE XIII in this section, and data plots are documented in Appendix II. Due to the limited space, only B scores are presented for some cases in this section. The B scores along with dummy phase shift information are provided in Appendix III.

TABLE V summarizes the BioRank scores for all accelerations. The overall average of the BioRank scores for all accelerations is 0.79, which corresponds to "excellent" biofidelity.

	BIORANK B SCORES OF ACCELERATIONS									
	Hea	d Accelera	ation	T1	Accelerat	ion				
Test ID	Х	Y	Z	Х	Y	Z	Test			
b12071	0.78	0.93	1.58	0.40	0.60	0.67	0.83			
b12072	0.73	0.94	1.07	0.41	0.59	0.61	0.73			
b12073	0.58	0.90	1.53	0.37	0.61	0.52	0.75			
b12074	0.66	0.77	1.63	0.39	0.82	0.51	0.80			
b12820	1.08	1.13	0.89	0.75	0.94	0.59	0.90			
b12821	0.86	0.95	0.92	0.54	0.71	0.62	0.77			
b12822	0.88	0.89	0.92	0.55	0.70	0.68	0.77			
						Average	0.79			

TABLE V

Full B scores and DPS can be found in Appendix III.

The head angular velocity BioRank scores are shown in TABLE VI. The overall average BioRank for the head angular biofidelity is 0.46, corresponding to "excellent" biofidelity.

	TABLE VI										
	BIORANK B SCORES AND DPS OF HEAD ANGULAR VELOCITY										
		Head Angular Velocity									
		Х		Y		Z					
Test ID	В	DPS(s)	В	DPS(s)	В	DPS(s)	В				
b12071	0.39	0.0344	0.29	-0.0075	0.69	0.0505	0.46				
b12072	0.52	0.0829	0.26	-0.0082	0.44	0.0505	0.40				
b12073	0.36	-0.0403	0.20	-0.0052	0.78	0.0610	0.45				
b12074	0.52	-0.0413	0.18	-0.0063	0.93	0.0784	0.54				
b12820	0.57	-0.032	0.22	0.0034	0.58	0.0309	0.46				
b12821	0.61	0.0829	0.20	-0.0005	0.55	0.0237	0.45				
b12822	0.59	0.0829	0.25	0.0005	0.52	0.0202	0.45				
						Average	0.46				

The BioRank scores for belt loads are shown in TABLE VII. The overall belt BioRank score is 1.23, corresponding to "good" biofidelity.

TABLE VII BIORANK B SCORES AND DPS OF SHOULDER RELT AND LAR RELT									
Linner Shoulder Belt Lower Shoulder Belt Lon Belt Test									
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Test ID	В	DPS(s)	В	DPS(s)	В	DPS(s)	В		
b12071	1.61	-0.0042	2.00	-0.0026	1.42	-0.0027	1.67		
b12072	1.38	-0.0051	1.60	-0.0078	1.96	0.0018	1.65		
b12073	0.80	-0.0038	1.29	-0.0050	2.42	-0.0042	1.50		
b12074	1.51	-0.0054	2.07	-0.0046	2.04	-0.0055	1.87		
b12820	0.46	0.0003	0.91	0.0016	0.64	0.0045	0.67		
b12821	0.50	-0.0025	0.62	-0.0025	0.68	-0.0013	0.60		
b12822	0.49	-0.0020	0.59	-0.0016	0.77	-0.0001	0.62		
						Average	1.23		

The kinematics of the dummy response were evaluated as well. The BioRank scores are summarized in TABLE VIII. The overall BioRank score of the kinematics is 0.99, corresponding to "excellent" biofidelity.

	Head	Displa	cement	T1 D	isplace	ment	T8 D	isplace	ment	Pelvi	s Displ	acement	
Test ID	Х	Y	Z	Х	Y	Z	Х	Y	Z	Х	Y	Z	Test
b12071	2.56	0.33	1.09	0.98	0.38	2.32	0.91	1.23	1.70	1.53	0.23	0.46	1.24
b12072	1.86	0.55	1.13	0.87	0.41	1.29	0.86	1.34	0.84	1.35	0.29	0.55	1.07
b12073	1.60	0.45	1.02	0.88	0.37	0.46	0.93	1.27	0.18	1.12	0.25	0.55	0.89
b12074	1.62	0.57	1.07	0.97	0.34	0.36	1.11	1.36	0.29	1.05	0.26	0.24	0.94
b12820	0.15	1.45	0.35	0.39	0.24	0.33	0.58	1.12	1.05	0.33	0.24	1.93	0.97
b12821	0.42	0.86	0.36	0.83	0.20	0.17	0.12	0.84	0.82	0.24	0.06	1.51	0.89
b12822	0.36	1.17	0.40	0.83	0.29	0.37	0.11	0.43	0.87	0.25	0.07	1.49	0.92
												Average	0.99

TABLE VIII BIORANK B SCORES OF HEAD, T1, T8 AND PELVIS DISPLACEMENTS

DPSs are listed in Appendix III.

The BioRank scores for the THOR-05F thorax deflection are summarized in TABLE IX. The overall BioRank score for the thoracic deflections is 1.00, corresponding to "excellent" biofidelity.

BIORANK B SCORES OF THE THORAX DEFLECTIONS (IR-TRACC MEASUREMENTS)												
Test ID	UL Dx	UL DY	UL Dz	UR Dx	UR Dy	LL Dx	LL Dy	LL Dz	LR Dx	LR Dy	LR Dz	Test
b12071	0.54	0.56	0.27	0.62	0.82	1.47	0.71	1.14	2.93	1.02	1.35	0.99
b12072	0.53	0.58	0.28	0.78	0.79	1.36	0.65	1.09	2.87	1.01	1.41	0.98
b12073	0.58	0.59	0.31	0.87	0.79	1.31	0.64	1.05	2.82	1.00	1.31	0.97
b12074	0.56	0.58	0.29	0.65	0.80	1.39	0.67	1.08	2.82	1.01	1.30	0.96
b12820	0.39	0.49	0.55	1.04	0.81	1.61	0.64	1.08	2.95	0.88	1.78	1.05
b12821	0.42	0.50	0.48	0.95	0.84	1.61	0.63	1.04	2.95	0.86	1.79	1.03
b12822	0.41	0.48	0.45	0.96	0.84	1.58	0.64	1.04	2.93	0.86	1.77	1.02
										А	verage	1.00

TABLE IX BIORANK B SCORES OF THE THORAX DEFLECTIONS (IR-TRACC MEASUREMENTS)

Notes: 1) UL – Upper Left, UR – Upper Right, LL – Lower Left, LR – Lower Right

2) DPSs are listed in Appendix III.

The BioRank for each category is summarized in TABLE X. The overall BioRank score, an average of scores for all categories, is 0.89, corresponding to "excellent" biofidelity.

OVERALL BIORANK SCORES OF ALL CATEGORIES					
Test	BioRank Scores				
Accelerations	0.79				
Angular Velocities	0.46				
Kinematics	0.99				
Thorax Deflections	1.00				
Shoulder and Lap Belt	1.23				
Overall BioRank	0.89				

TABLE	X	

Looking at the average BioRank by body region, the head showed good biofidelity in head accelerations, angular velocities and kinematics. The average BioRank of the head alone is 0.79, corresponding to "excellent" biofidelity, see TABLE XI.

				<b>BIORANK</b>	<b>3</b> SCORES C	F THE HEA	D			
	Head	l Accelera	ations	Head A	Angular V	elocity	Head	Displace	ment	Head
Test ID	Х	Y	Z	Х	Y	Z	Х	Y	Z	
b12071	0.78	0.93	1.58	0.39	0.29	0.69	2.56	0.33	1.09	0.96
b12072	0.73	0.94	1.07	0.52	0.26	0.44	1.86	0.55	1.13	0.83
b12073	0.58	0.90	1.53	0.36	0.20	0.78	1.60	0.45	1.02	0.82
b12074	0.66	0.77	1.63	0.52	0.18	0.93	1.62	0.57	1.07	0.88
b12820	1.08	1.13	0.89	0.57	0.22	0.58	0.15	1.45	0.35	0.71
b12821	0.86	0.95	0.92	0.61	0.20	0.55	0.42	0.86	0.36	0.64
b12822	0.88	0.89	0.92	0.59	0.25	0.52	0.36	1.17	0.40	0.66
								A	verage	0.79

TABLE XI
ANK <b>B</b> SCORES OF THE HEAD

DPSs are listed in Appendix III.

The overall BioRank score of the spine is 0.69, corresponding to "excellent" biofidelity, see TABLE XII.

					TABLE XI	I				
		В	IORANK RI	MS SCORES	OF THORA	ACIC AND LU	JMBAR SPI	NE		
	T1 .	Accelerat	ion	T1 [	Displacem	nent	T8 [	Displacem	nent	Spine
Test ID	Х	Y	Z	Х	Y	Z	Х	Y	Z	
b12071	0.40	0.60	0.67	0.98	0.38	2.32	0.91	1.23	1.70	1.02
b12072	0.41	0.59	0.61	0.87	0.41	1.29	0.86	1.34	0.84	0.80
b12073	0.37	0.61	0.52	0.88	0.37	0.46	0.93	1.27	0.18	0.62
b12074	0.39	0.82	0.51	0.97	0.34	0.36	1.11	1.36	0.29	0.68
b12820	0.75	0.94	0.59	0.39	0.24	0.33	0.58	1.12	1.05	0.66
b12821	0.54	0.71	0.62	0.83	0.20	0.17	0.12	0.84	0.82	0.54
b12822	0.55	0.70	0.68	0.83	0.29	0.37	0.11	0.43	0.87	0.54
								A	verage	0.67

The BioRank score for the thorax displacement and spine are 1.00 and 0.67 respectively, both corresponding to "excellent" biofidelity, see TABLE IX and TABLE XII. The BioRank score of the pelvis is 0.67, corresponding to "excellent" biofidelity, see TABLE XIII.

	TA	BLE XIII		
	ΒΙΟΡΑΝΚ Β	SCORES OF	PELVIS	
	Pel	vis Displac	ement	Test
Test ID	Х	Y	Z	
b12071	1.53	0.23	0.46	0.74
b12072	1.35	0.29	0.55	0.73
b12073	1.12	0.25	0.55	0.64
b12074	1.05	0.26	0.24	0.52
b12820	0.33	0.24	1.93	0.83
b12821	0.24	0.06	1.51	0.60
b12822	0.25	0.07	1.49	0.60
			Average	0.67

## **IV.** DISCUSSION

THOR-05F ATD sled tests from two labs were quantitatively compared to small female PMHS biofidelity corridors for a well-controlled 30 km/h frontal impact test condition. The dummy segment BioRank scores showed "excellent" biofidelity with B scores of 0.79, 0.67, 1.00 and 0.67 for head, spine, thorax, and pelvis respectively. The four repeated tests showed qualitatively good repeatability. The lab-to-lab data also compared well

qualitatively.

Accelerations for head and T1 had a combined average BioRank score of 0.79, corresponding to "excellent" biofidelity. Plots of the PMHS corridors and the ATD trials can be seen in Appendix II. Head CG x-acceleration was well within the biofidelity corridor. Head CG y-acceleration was well within the corridors during the initial loading period but did not replicate the negative peak and the following positive peak of the biofidelity corridor. Head z - acceleration went up faster than the biofidelity corridor but matched the peak of the biofidelity corridor mean. T1 x-, y- and z-accelerations matched the PMHS corridors. One of the seven tests showed higher peak T1 y-acceleration, which most likely was caused by test setup variation.

Head angular velocities had an average BioRank score of 0.46, corresponding to "excellent" biofidelity. Head x- and y- angular velocities were within the PMHS corridors. Head z-angular velocity varied between the four repeated tests conducted. The neck cable in THOR-5F is not straight [5] and friction between the cable and the guidance bushing may have contributed to the inconsistency. It was also observed the tests conducted at UVA had consistent, but lower magnitude, head z-angular velocity.

Thorax deflection for all IR-TRACC positions had an average BioRank score of 1.00, corresponding to "excellent" biofidelity. For the upper left IR-TRACC location, thorax deflections in the x-, y- and z-directions were nearly within the biofidelity corridors. It was noticed the upper left IR-TRACC z-deflection went upward (negative) in the OSU tests, but downward (positive) in the UVA tests. These differences most likely are caused by the shoulder belt routing difference between the two labs. For the upper right IR-TRACC location, thorax x-deflection followed the biofidelity corridor closely though it has a slightly lower peak value than the biofidelity corridor. Thorax y- and z- deflections had relatively low magnitudes compared to the biofidelity corridor peak values. It was observed that the biofidelity corridors are wide in the y- and z-deflections, reflecting a large variation in human specimens. For the lower left IR-TRACC location, the thorax x- and y- deflection were well within the biofidelity corridors. The thorax x-deflection had a higher peak value than the biofidelity corridor. The thorax z-deflection had a higher peak value than the biofidelity corridor. The thorax z-deflection had a higher peak value than the biofidelity corridor. The thorax z-deflection had a different pattern than the biofidelity corridors though a majority of the responses stayed within the corridors. The y- and z-deflection peak values were lower than the peak of the corridors. For the lower right IR-TRACC position, the thorax x-, y- and z-deflection peak magnitudes were much lower than their corresponding corridors. Most likely the diagonal belt was away from the lower right IR-TRACC measurement location.

The displacements for the head, T1, T8, and pelvis had an average of BioRank score of 0.99, corresponding to "excellent" biofidelity. Differences were observed between OSU and UVA tests. The head x-displacement reached a higher peak value than the biofidelity corridor in the OSU tests, but followed the biofidelity corridor well for the UVA tests. The head y-displacement followed the biofidelity corridor well in the OSU tests, but had much lower magnitudes in the UVA tests. In the z-direction, the head displaced downward faster than the biofidelity corridor in the OSU tests, but followed the corridor well in the UVA tests. The T1 x-displacement was within the biofidelity corridor for both OSU and UVA tests and was very comparable between the two labs. The T1 y-displacement stayed within the biofidelity corridor very well for data from both test labs though two tests from OSU showed higher displacement. For the T8 x-, y- and z-displacement, all tests followed the biofidelity corridor, and the OSU tests had higher magnitudes than UVA tests. The pelvis y-displacement was very comparable between the two labs.

The belt load overall BioRank score was 1.23, corresponding to "good" biofidelity. For the upper shoulder belt load, the OSU tests followed the biofidelity corridor well, while the UVA tests had much higher magnitudes. The lower shoulder belt loads were very comparable between the two labs and all tests followed the corridors closely. For the lap belt load, the tests from UVA followed the corridor well, while the tests from OSU had lower magnitudes.

The results were visually inspected for any BioRank score that seemed irrational. A few biofidelity corridors were wide due to the large variation of PMHS test results, which resulted in low BioRank scores for the ATD tests Wide corridors tend to provide good dummy BioRank scores despite an ATD response that may not follow the mean PMHS response target well. Examples include the head angular velocity in x-direction with an average B score of 0.51 (Fig. 5, left) and the lower right thoracic y-deflection, with an average B score of 0.81 (Fig. 5, right). The selection criteria for the biofidelity ranking parameters should be reviewed in the future. Some critical parameters that are used for injury predictions may need to have higher priority in biofidelity assessment.

Weighting factors were considered in the past [12]. The correlation between the dummy BioRank score and the injury risks certainly worth investigating in the future.



Fig. 5 Examples of wide corridors: head angular velocity in x-direction and upper right thorax y-deflection (solid black – PMHS upper and lower boundaries, solid dash – PMHS mean)

### V. CONCLUSIONS

The evaluation of THOR-05F in the gold standard test condition showed the dummy kinematics overall had "excellent" biofidelity with an average BioRank score of 0.80. The dummy head kinematics showed "excellent" biofidelity with a BioRank score of 0.77. The spine kinematics and the thorax deflections showed a BioRank score of 0.68 and 1.00 respectively, both in "excellent" biofidelity. The pelvis kinematics showed "excellent" biofidelity with a BioRank score of 0.67. The shoulder belt response showed "excellent" biofidelity. The lap belt response showed "good" biofidelity. In this study, no distinction was given to the parameters that are typically used for injury predictions.

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		Sensor Information
Data Channel	Channel Description	Make
1	EVENT TRIGGER	
2	SLED G LONG.	ENDEVCO
3	SLED G LONG. REDUNDANT	ENDEVCO
4	BRAKE PRESSURE	INTERFACE
5	FOOT PLATE LOADCELL	INTERFACE
6	LEFT KNEE PLATE LOADCELL	INTERFACE
7	RIGHT KNEE PLATE LOADCELL	INTERFACE
8	SEAT PLATE LOADCELL (ANTERIOR)	INTERFACE
9	SEAT PLATE LOADCELL (POSTERIOR LEFT)	INTERFACE
10	SEAT PLATE LOADCELL (POSTERIOR RIGHT)	INTERFACE
11	BELT LOADCELL (Front of the load-limiter) - Redundant	MEASUREMENT SPECIALITIES
12	SHOULDER BELT LOADCELL (Above right shoulder) - Primary	MEASUREMENT SPECIALITIES
13	LAP BELT LOADCELL	MEASUREMENT SPECIALITIES
14	HEAD CG ACCEL X	MSI
15	HEAD CG ACCEL Y	MSI
16	HEAD CG ACCEL Z	MSI
17	T1 ACCEL X	MSI
18	T1 ACCEL Y	MSI
19	T1 ACCEL Z	MSI
20	T8 ACCEL X	MSI
21	T8 ACCEL Y	MSI
22	T8 ACCEL Z	MSI
23	MID STERNUM ACCEL X	MSI
24	T12 ACCEL X	MSI
25	T12 ACCEL Y	MSI
26	T12 ACCEL Z	MSI

### APPENDIX I

27	PELVIS ACCEL X	MSI
28	PELVIS ACCEL Y	MSI
29	PELVIS ACCEL Z	MSI
30	HEAD ANGULAR RATE SENSOR X	DTS
31	HEAD ANGULAR RATE SENSOR Y	DTS
32	HEAD ANGULAR RATE SENSOR Z	DTS
33	CLAVICLE LOAD CELL SD3 LEFT X LATERAL	HUMANETICS
34	CLAVICLE LOAD CELL SD3 LEFT X MEDIAL	HUMANETICS
35	CLAVICLE LOAD CELL SD3 LEFT Z LATERAL	HUMANETICS
36	CLAVICLE LOAD CELL SD3 LEFT Z MEDIAL	HUMANETICS
37	CLAVICLE LOAD CELL SD3 RIGHT X LATERAL	HUMANETICS
38	CLAVICLE LOAD CELL SD3 RIGHT X MEDIAL	HUMANETICS
39	CLAVICLE LOAD CELL SD3 RIGHT Z LATERAL	HUMANETICS
40	CLAVICLE LOAD CELL SD3 RIGHT Z MEDIAL	HUMANETICS
41	IR-TRACC ASSY UPPER THORAX LEFT	HUMANETICS
42	POT Y UPPER THORAX LEFT	HUMANETICS
43	POT Z UPPER THORAX LEFT	HUMANETICS
44	IR-TRACC ASSY UPPER THORAX RIGHT	HUMANETICS
45	POT Y UPPER THORAX RIGHT	HUMANETICS
46	POT Z UPPER THORAX RIGHT	HUMANETICS
47	IR-TRACC ASSY LOWER THORAX RIGHT	HUMANETICS
48	POT Y LOWER THORAX RIGHT	HUMANETICS
49	POT Z LOWER THORAX RIGHT	HUMANETICS
50	IR-TRACC ASSY LOWER THORAX LEFT	HUMANETICS
51	POT Y LOWER THORAX LEFT	HUMANETICS
52	POT Z LOWER THORAX LEFT	HUMANETICS
53	ABDOMEN PRESSURE SENSOR RIGHT	Transpolis
54	ABDOMEN PRESSURE SENSOR LEFT	Transpolis



This section contains all time history plots. The black solid lines are upper and lower boundary of the PMHS corridors. The black dash lines are mean of the PMHS corridors.











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APPENDIX III

This appendix contains the BioRank B scores and dummy phase shifts (DPS).

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Head Acceleration Y Z	r z	Z			×	T1 A	cceleratio Y	۲	Z	Test
S(s) B DPS(s)		в	DPS(s)	в	DPS(s)	в	DPS(s)	в	DPS(s)	В
103 0.93 0.0360		1.58	0.0054	0.40	-0.0099	0.60	-0.0057	0.67	-0.0121	0.83
074 0.94 0.0355		1.07	0.0086	0.41	-0.0097	0.59	-0.0049	0.61	-0.0075	0.73
068 0.90 0.0368		1.53	0.0060	0.37	-0.0077	0.61	-0.0142	0.52	-0:0030	0.75
076 0.77 0.0332	•••	1.63	0.0055	0.39	-0.0045	0.82	-0.0205	0.51	-0.0027	0.80
004 1.13 0.0476	-	0.89	0.0106	0.75	-0.0005	0.94	-0.0005	0.59	-0.0025	06.0
001 0.95 0.0469		0.92	0.0077	0.54	-0.0032	0.71	-0.0079	0.62	-0.0033	0.77
003 0.89 0.0407		0.92	0.0091	0.55	-0.0031	0.70	-0.0026	0.68	-0.0035	0.77
									Average	0.79

ANK B S	CURES ANL		LIEAU, 11,	- () -							
	Ι	Head Di	splacement					T1 Dis	placement		
	X		Y		Z		X		Υ		Z
В	DPS(s)	в	DPS(s)	в	DPS(s)	в	DPS(s)	В	DPS(s)	В	DPS(s)
2.56	0.0027	0.33	0.0073	1.09	0.0191	0.98	0.0059	0.38	0.0879	2.32	-0.0049
1.86	0.0008	0.55	0.0083	1.13	0.0255	0.87	0.0072	0.41	0.0879	1.29	-0.0018
1.60	0.0003	0.45	0.0139	1.02	0.0292	0.88	0.0051	0.37	0.0879	0.46	-0.0066
1.62	0.0010	0.57	0.0157	1.07	0.0298	0.97	0.008	0.34	0.0879	0.36	-0.0038
0.15	0.0011	1.45	-0.0167	0.35	0.0113	0.39	0.0043	0.24	0.0612	0.33	0.0042
0.42	0.0016	0.86	-0.0165	0.36	0.0072	0.83	0.0075	0.20	0.0533	0.17	0.0007
0.36	0.0020	1.17	-0.0221	0.40	0.0093	0.83	0.0081	0.29	0.0498	0.37	0.0064
	B B 2.56 1.60 1.60 1.62 0.15 0.42 0.36	ANNE JUDICE ANNE     X   N     B   DPS(s)     2.56   0.0027     1.86   0.0003     1.60   0.0003     1.62   0.0010     0.15   0.0016     0.36   0.0020	Annocentration   Head Division     X   Head Division     B   DPS(s)   B     2.56   0.0027   0.33     1.86   0.0008   0.55     1.60   0.0003   0.45     1.62   0.0010   0.57     0.15   0.0011   1.45     0.42   0.0016   0.86     0.36   0.020   1.17	X   Y     B   DPS(s)   B   DPS(s)     1.86   0.0027   0.33   0.0073     1.86   0.0008   0.55   0.0083     1.60   0.0003   0.45   0.0139     1.62   0.0010   0.57   0.0167     0.15   0.0011   1.45   -0.0167     0.42   0.0016   0.86   -0.0167     0.36   0.0020   1.17   -0.0221	X   Y     B   DPS(s)   B   DPS(s)   B     2.56   0.0027   0.33   0.0073   1.09     1.86   0.0008   0.55   0.0083   1.13     1.60   0.0003   0.45   0.0139   1.02     1.62   0.0010   0.57   0.0157   1.07     0.15   0.0011   1.45   0.0167   0.35     0.42   0.0016   0.86   -0.0167   0.35     0.42   0.0020   1.17   -0.0221   0.40	Head Displacement   X Y Z   B DPS(s) B DPS(s) B DPS(s)   2.56 0.0027 0.33 0.0073 1.09 0.0191   1.86 0.0003 0.45 0.0139 1.13 0.0255   1.60 0.0003 0.45 0.0157 1.07 0.0298   1.62 0.0011 1.45 0.0167 0.35 0.0113   0.42 0.0011 1.45 0.0167 0.35 0.0113   0.42 0.0016 0.86 -0.0167 0.35 0.0113   0.36 0.0020 1.17 -0.0221 0.40 0.0033	Head Displacement   X Y Z   B DPS(s) B DPS(s) B DPS(s) B   1.60 0.0027 0.33 0.0073 1.09 0.0191 0.98   1.86 0.0003 0.45 0.0139 1.13 0.0255 0.87   1.60 0.0003 0.45 0.0157 1.02 0.0298 0.97   0.15 0.0011 1.45 0.0167 0.35 0.0113 0.39   0.42 0.0016 0.86 -0.0167 0.35 0.0113 0.39   0.42 0.0016 0.86 -0.0167 0.35 0.0113 0.39   0.36 0.0020 1.17 -0.0221 0.40 0.0033 0.83	Head Displacement   X Y Z X   B DPS(s) B DPS(s) B DPS(s) B DPS(s)   2.56 0.0027 0.33 0.0073 1.09 0.0191 0.98 0.0059   1.86 0.0003 0.45 0.0139 1.13 0.0255 0.87 0.0072   1.60 0.0003 0.45 0.0139 1.02 0.0298 0.97 0.0073   1.62 0.0010 0.57 0.0157 1.07 0.0298 0.97 0.008   0.15 0.011 1.45 -0.0167 0.35 0.0113 0.39 0.0043   0.15 0.0011 1.45 -0.0165 0.36 0.072 0.83 0.0043   0.42 0.0016 0.86 -0.0165 0.36 0.0072 0.83 0.0075   0.36 0.0020 1.17 -0.0221 0.40 0.0093 0.83 0.0075	Head Displacement T1 Dis   X Y Z X   B DPS(s) B DPS(s) B DPS(s) B DPS(s) B   2.56 0.0027 0.33 0.0073 1.09 0.0191 0.98 0.0059 0.38   1.86 0.0003 0.45 0.0139 1.13 0.0255 0.87 0.0072 0.41   1.60 0.0003 0.45 0.0139 1.02 0.0292 0.88 0.0071 0.37   1.62 0.0010 0.57 0.0157 1.07 0.0298 0.97 0.0043 0.34   0.15 0.0011 1.45 -0.0167 0.35 0.0113 0.39 0.0043 0.24   0.15 0.0016 0.86 -0.0165 0.36 0.0072 0.83 0.0075 0.20   0.34 0.0020 1.17 -0.0221 0.33 0.0075 0.28 0.20   0.35 0.00165 0.86 -0.0221 0.33 0.33 0.0033 0.33 0.0033 0.035	Head Displacement   T1 Displacement     X   Y   T1 Displacement     B   X   Y   X   Y     B   DPS(s)   B   DPS(s)   B   DPS(s)   B   DPS(s)     2.556   0.0027   0.33   0.0073   1.09   0.0191   0.98   0.0879     1.86   0.0008   0.55   0.0083   1.13   0.0255   0.87   0.0072   0.41   0.0879     1.60   0.0003   0.45   0.0139   1.07   0.0255   0.88   0.0072   0.34   0.0879     1.62   0.0010   0.57   0.0139   1.07   0.0298   0.97   0.0073   0.34   0.0879     0.152   0.0011   1.45   -0.0167   0.35   0.004   0.24   0.0612     0.42   0.0016   0.86   -0.0165   0.36   0.0075   0.24   0.0612     0.34   0.0021   0.34   0.0075   0.29   0.0612   0.0533   0.0233	Interview   TI Displacement     X   Y   TI Displacement     B   X   Y   X   Y     B   DPS(s)   D   DS(s)   D   DS(s)   D   DS

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		T8 Disp	placement					Pelvis D	isplacemen	it		Test
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В	DPS(s)	В	DPS(s)	В	DPS(s)	в	DPS(s)	В	DPS(s)	в	DPS(s)	в
.91	0.0056	1.23	0.0044	1.70	0.0017	1.53	0.0859	0.23	0.0617	0.46	-0.0090	1.24
.86	0.0061	1.34	-0.0007	0.84	-0.0009	1.35	0.0859	0.29	0.0611	0.55	-0.0046	1.07
.93	0.0036	1.27	-0.0091	0.18	-0.0025	1.12	0.0859	0.25	0.0513	0.55	-0.0086	0.89
.11	0.0077	1.36	-0.0053	0.29	-0.0002	1.05	0.0859	0.26	0.0502	0.24	-0.0095	0.94
.58	-0.0007	1.12	-0.0341	1.05	-0.0089	0.33	0.0107	0.24	0.0056	1.93	-0.0108	0.97
).12	0.0014	0.84	-0.034	0.82	-0.0059	0.24	0.0042	0.06	0.0059	1.51	-0.0012	0.89
0.11	0.0004	0.43	-0.0332	0.87	-0.0043	0.25	0.0071	0.07	0.0109	1.49	-0.0070	0.92
											Average	0.99

TABLE XVI BI	ORANK B	SCORES AN	DPS OF	THORAX DI	EFLECTIO	NS (IR-TRA	(ccs)					
	Ŋ	L Dx	U	, DY	Ū	L Dz	IJ	R Dx	IU	R Dy	UF	t Dz
Test ID	В	DPS(s)	в	DPS(s)	В	DPS(s)	В	DPS(s)	в	DPS(s)	в	DPS(s)
b12071	0.54	-0.0028	0.56	0.0089	0.27	0.0419	0.62	0.0040	0.82	-0.1000	0.43	-0.1000
b12072	0.53	-0.0020	0.58	0.0210	0.28	0.0408	0.78	0.0087	0.79	-0.1000	0.39	-0.0961
b12073	0.58	0.0008	0.59	0.0282	0.31	0.0408	0.87	0.0042	0.79	-0.1000	0.41	-0.0953
b12074	0.56	-0.0032	0.58	0.0268	0.29	0.0399	0.65	0.0036	0.80	-0.1000	0.41	-0.0946
b12820	0.39	0.0063	0.49	-0.0024	0.55	-0.0337	1.04	0.0049	0.81	0.0817	0.43	-0.0667
b12821	0.42	0.0032	0.50	-0.0068	0.48	-0.0877	0.95	0.0038	0.84	0.0935	0.36	-0.0777
b12822	0.41	0.0040	0.48	-0.0030	0.45	-0.0885	0.96	0.0015	0.84	0.0941	0.32	-0.0779
Notes: UL – I	Jpper L	eft, UR – L	Jpper Ri <sub>i</sub>	ght, LL – Lc	ower Le	ift, LR – Lo	wer Rig	ght				
TABLE XVI (C	ONTINUE	D)										

TABLE XVI (Co	DNTINUE	D)											
	L]	L Dx	LJ	L Dy	ΓI	L Dz	Г	R Dx	LI	۲Dy	LI	R Dz	Test
Test ID	В	DPS(s)	В	DPS(s)	в	DPS(s)	В	DPS(s)	В	DPS(s)	в	DPS(s)	В
b12071	1.47	0.0999	0.71	-0.0344	1.14	0.0999	2.93	0.0869	1.02	0.0999	1.35	-0.0604	0.99
b12072	1.36	0.0999	0.65	-0.0335	1.09	0.0999	2.87	0.0869	1.01	0.0999	1.41	-0.0582	0.98
b12073	1.31	0.0999	0.64	-0.0277	1.05	0.0999	2.82	0.0869	1.00	0.0999	1.31	-0.0700	0.97
b12074	1.39	0.0999	0.67	-0.0256	1.08	0.0999	2.82	0.0869	1.01	0.0999	1.30	-0.0607	0.96
b12820	1.61	0.0999	0.64	0.0019	1.08	0.0999	2.95	0.0869	0.88	0.078	1.78	0.0999	1.05
b12821	1.61	0.0999	0.63	0.0044	1.04	0.0999	2.95	0.0869	0.86	0.0906	1.79	0.0999	1.03
b12822	1.58	0.0999	0.64	0.0054	1.04	0.0999	2.93	0.0869	0.86	0.0885	1.77	0.0999	1.02
												Average	1.00