Biofidelity Evaluation of THOR 5th Percentile Female ATD

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Abstract   Three prototype anthropomorphic test devices (ATD) were fabricated in order to evaluate the biofidelity of a newly design THOR 5th percentile female ATD [1]. This paper focuses on the biofidelity responses derived from testing one of these ATDs. There were a total of twenty-three biofidelity test conditions that included the head, neck, shoulder, thorax, abdomen, knee-thigh-hip complex, and lower extremity [2]. Three repeated tests were conducted on a single ATD for each test condition. The biofidelity was objectively scored in accordance with NHTSA's Biofidelity Ranking System (BioRank) [3]. The BioRank score of each body region was less than 2.0, corresponding to "good" biofidelity and a few less than 1.0, corresponding to "excellent" biofidelity. The overall BioRank score of the dummy was 1.28, which corresponds to "good" biofidelity.

Keywords Anthropomorphic test device, biofidelity, BioRank, THOR 5th percentile female, anthropometry

I. INTRODUCTION

The Test Device for Human Occupant Restraint (THOR), an advanced frontal impact 50th percentile male ATD known as THOR-50M, was developed by the National Highway Traffic Safety Administration (NHTSA) to address the ongoing problem of fatalities and injuries in motor vehicles with modern restrains, such as airbags and force-limited seatbelts. The biofidelity and measurement/injury prediction capability of THOR-50M were substantially improved compared to the Hybrid III ATD in current NHTSA regulation [5]. A need was identified for an advanced, small stature, frontal impact ATD. Statistical studies of injuries resulting from motor vehicle crashes (MVCs) shows that female injuries differ from male injuries due to the female's anthropometry and anatomical differences, such as small size, low mass and cervical facet angles [6], which affects how female occupant kinematics and associated interactions with restraint systems in MVCs. For example, the odds for a belt-restrained female driver to sustain severe injuries were 47% higher than those for a belt-restrained male driver involved in a comparable crash [7]. The NASS-CDS data study in [6] showed that the relative risk of being seriously injured was higher in females than in males for crash severities up to 65 kph. Young adult women are more fragile than young men [8]. To address the small occupant safety need, the THOR 5th percentile female ATD (THOR-5F), was designed. The design was based on the THOR 50M with some changes and new concepts that were described in [1].

Biofidelity of a test dummy is a measure of the ATD's ability to mimic a human response in a crash environment. Biomechanical response requirements were established for the THOR-5F [2] to both guide the design of the hardware and assesse the response of the ATD. Twenty-three test conditions were identified covering the head, neck, shoulder, thorax, abdomen, knee-thigh-hip (KTH) and lower extremities. The purpose of this study is to evaluate the biofidelity of the THOR-5F ATD based on the three recently fabricated prototypes. The biofidelity was objectively scored using NHTSA's Biofidelity Ranking System (BioRank) [3].

II. METHODS

In general, the biofidelity requirements for THOR-5F were scaled from the 50th percentile male response corridors. The scaling method and the biofidelity requirements scaled for THOR-5F are summarized in [2]. The tests were conducted in accordance with what was outlined in [9] and [10]. The original papers cited in [9] and [10] were used as the main sources for the test details. A few changes to the requirements were made based on the newly available data, which are described in the relevant sections below. The available biofidelity corridors varied by test condition. Three repeated tests were conducted on a single dummy for each test condition. The data collected included the standard sensors installed in THOR-5F, such as load cells, linear accelerometers,

angular rate sensors, rotary potentiometers and InfraRed –Telescoping Rod for Assessment of Chest Compression (IR-TRACC), as well as high speed videos at 1000 frames per second. The high-speed video data was analyzed with TEMA® motion analysis software to calculate the external deflection by tracking the relative motion of two interest targets.

Head Biofidelity

The three head biofidelity test conditions were head impact, facial bar and facial disk impact. The head impact tests were conducted at Humanetics Innovative Solutions (Humanetics thereafter). The details of the critical test parameters are summarized in Table I. The force was calculated from the probe acceleration multiplied by its respective mass for each test condition.

TABLE I
SUMMARY OF HEAD TEST CONDITIONS

Test Condition	Input	Data Channel/Filter
Head	2.0 m/s, 19.2 kg mass, 152.4 mm diameter Probe center is aligned with the head center of gravity (CG) mark when head is at 29±1° forward The upper thoracic spine (UTS) joint is in "Neutral" and lower thoracic spine (LTS) joint is in "Slouch"	Probe acceleration/CFC180
Face Rigid Bar	3.6 m/s, 26.2 kg mass 25 mm diameter x 30 cm length Impact point: 43 mm below the head CG UTS joint in "Neutral", LTS joint in "Erect"	Probe acceleration/CFC180
Facial Disk	6.7 m/s, mass 10.7 kg 152.4 mm diameter, 12 mm edge radius Impact point: 61.8 mm below the head CG UTS joint in "Erect", LTS joint in Neutral	Probe acceleration/CFC180

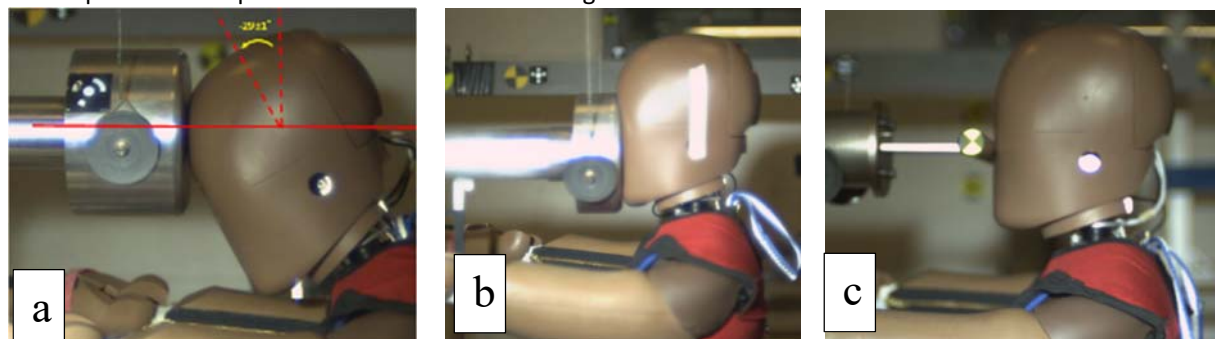The impact test setups for the head are shown in Fig. 1.

Fig. 1. Test setups for a) head impact, b) face disk impact, c) face bar impact.

Neck Biofidelity

The five neck biofidelity test conditions were neck frontal and lateral sled, neck torsion, neck flexion and lateral pendulum impact tests. The neck frontal and lateral sled tests, which were based on volunteer/Post Morton Human Subject (PMHS) tests conducted by the Naval Biodynamics Laboratory (NBDL), were considered the primary requirements because they were most relevant to the expected use of THOR-5F in vehicle crash tests. The frontal and lateral sled tests were conducted using the ATD head/neck mounted to the sled with acceleration measured at the first thoracic vertebra (T1) from the NBDL test used as sled acceleration targets, in contrast to the original study which tested the restrained full body of volunteers and PMHS on a sled.

The original NBDL restraint system was not well documented. To reduce the variation contributed by the body and restraints in testing, a head neck assembly mounted on the sled with an input equivalent to the human T1 acceleration input was desired. However, the most sleds in the field generates a square-shape pulse, but are not capable of recreating the NBDL T1 acceleration. Instead, the NBDL sled acceleration was used as an approximation in the past. In this study, the neck frontal and lateral sled tests were conducted with a Humanetics sled that has

a magnetic loading mechanism and offers the capability to program a pre-defined pulse. Therefore, the NBDL T1 pulse was programed into the sled instead of the square-shape pulse. To the authors' knowledge, it was the first time that a sled can offer the capability to match the T1 pulse in the NBDL full body volunteer/PMHS test. The test setup is shown in Fig. 2 and Fig. 3.
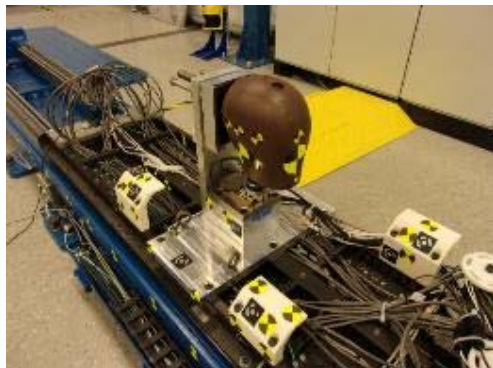

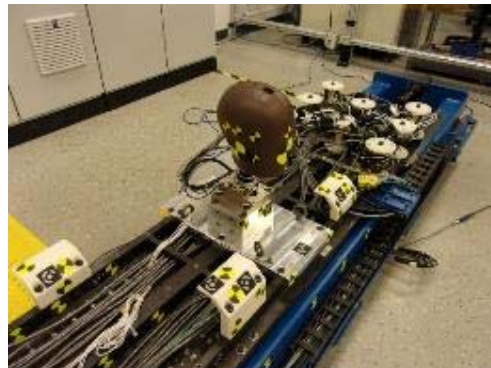Fig. 2. Setup for neck frontal sled test condition.   Fig. 3. Setup for neck lateral sled test condition.

The time zero of the raw test data was the trigger time of the sled, which does not align with the corridor time zero. To determine the time zero of the dummy data, the T1 sled pulse was aligned in time with the T1 corridor mean at 10g. The time coincident with the corridor time zero was chosen as the time zero for the test data. The displacement magnitude was adjusted so that its value at time zero matches the initial value of the corresponding corridor mean before the BioRank was calculated. The head motions, including the head linkage angle (a straight line between the head center of gravity (CG) and the occipital condyle (OC)), the neck linkage angle (a straight line between OC to the C7/T1), and the head CG motion were analyzed from the video. No filter was applied to the video data. The head linkage angle was calculated using targets placed at the head CG and the OC. The neck linkage angle could not be analyzed directly from video because a target could not be placed exactly at the T1 location (this would be on the rubber portion of the neck). Instead, the coordinates at the OC were used to calculate the neck linkage angle (see Appendix for further details).

The neck biofidelity test conditions are summarized in Table II. The neck torsion test was conducted at Duke University, using the original apparatus from the PMHS tests [11]. Since the neck pendulum test and torsion corridors were not established with the mean plus/minus one standard deviation method, the BioRank was not calculated for these test conditions. Instead, the test data was plotted against the corridors for qualitative comparison.

TABLE II
SUMMARY OF THE NECK BIOFIDELITY TEST

Test Condition	Input	Data Channel/Filter
Frontal Sled	T1 acceleration Head is horizontal with 10° wedge at the mounting base	Head accelerations Ax,Ay,Az/CFC1000 Head linkage angle*, Neck linkage angle* Head CG displacement X *and Z*
Lateral Sled	T1 acceleration Head is horizontal with 10° wedge at the mount base	Head linkage angle* Head CG displacement Y* and Z*
Torsion	500° /sec, max rotation 95°	Moment Z/CFC600, Rotation Z/CFC60
Pendulum Flexion	5.0 m/s, Part 572 pendulum	Pendulum acceleration/CFC60, angular velocity/CFC60 Upper neck moment My/CFC600, force Fx/CFC1000 Neck rear spring load cell Fz/CFC1000
Pendulum Lateral	3.4 m/s, Part 572 pendulum	Pendulum acceleration/CFC60, angular velocity/CFC60 Head angular velocity/CFC 60 Upper neck moment X/CFC600, force Y/CFC1000

* Measurement from high-speed video, no filter applied.

Shoulder Biofidelity

The three shoulder biofidelity test conditions were arm positon in 90° (arm horizontal), 135° (45° from horizontal) and 170° (80° from horizontal). The shoulder tests were conducted at The Ohio State University (OSU). The ATD torso was restrained by a sternum support that was in line with the jugular notch in a fixture rebuilt from [12]. For each arm positon, both arms were simultaneously pulled at 50N increments, up to 400N (200N per arm). The displacement in x, y and z directions were measured with a string potentiometer attached to the center of the front of the belt and the recorded for each loading point. The test conditions are summarized in Table III. Due to the anthropometry discrepancy between ATD and human volunteers, the initial data point values are quite different. To compare the motion difference, the ATD initial data point was aligned with the corridor mean initial point before the BioRank was calculated.

Table III
SUMMARY OF SHOULDER TEST CONDITIONS

Test Condition	Input	Data Channel/Filters
Arm in 90° position	Quasi-static loading, force applied up to 400N at 50N increments	Force*, Displacement*
Arm in 135° position	Quasi-static loading, force applied up to 400N at 50N increments	Force*, Displacement*
Arm in 170° position	Quasi-static loading, force applied up to 400N at 50N increments	Force*, Displacement*

* No filter applied

Thorax Biofidelity

The two thorax biofidelity test conditions were upper thorax and oblique lower thorax impact tests. The upper thorax tests were conducted by Humanetics and the lower thorax tests were conducted by OSU. A contact switch was attached to the front of the impactor to determine time zero. High-speed video was used to measure the external thoracic displacement in the upper thorax impact test with two targets, one is on the impactor and one is a rigid bracket attached to the ATD spine. The two targets were approximately on the same level to minimize the error due to the rotation. The internal displacement was projected into the horizontal direction the initial angle of the spine with the following formula. An average of the two upper thoracic IR-TRACCs displacement were used as internal thoracic displacement.

$$Dxh = Dx * \cos(-16.6 + \theta_{tilt}) + Dz * \sin(-16.6 + \theta_{tilt})$$

where

Dxh is the displacement in horizontal plane

Dx is the upper left and right IR-TRACCs displacement in x direction of the spine coordinate system

DZ is the upper left and right IR-TRACCs displacement in z direction of the spine coordinate system

The upper thoracic IR-TRACC and mid thoracic tilt sensor orientation is shown in Fig. 4 following SAE J211 sign convention.
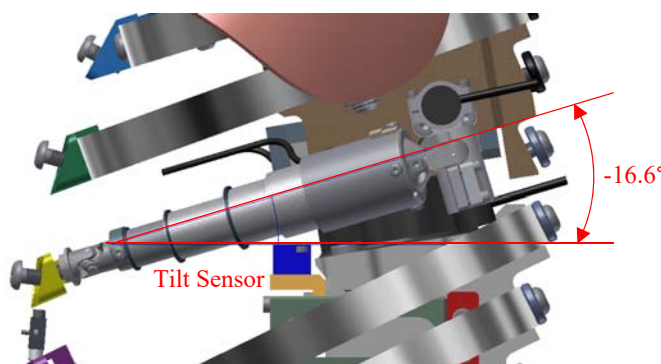

Fig. 4. Upper thoracic IR-TRACC and the thoracic spine tile sensor orientation.

A chestband was used to measure the external thoracic displacement in the lower thorax oblique tests. The chestband was wrapped around the region of the ATD corresponding to the human rib eight anteriorly. The profile

of the chestband was constructed from the strain measurement of the strain gages [14]. The maximum deflection of the chestband referencing a fixed point near the rear of the thoracic spine was used for the BioRank calculation. The test conditions are summarized in Table IV.

Table IV
SUMMARY OF THORAX TEST CONDITIONS

Test Condition	Input	Data Channel/Filters*
Upper Thorax	4.3 m/s, 14 kg mass, including 1/3 of cable harness. Probe center is aligned with the middle point of the upper two thoracic IR-TRACCs	Probe acceleration/CFC600 Internal displacement/CFC600 Rotary Pots/CFC600 External Displacement**
Oblique Lower Thorax	4.3 m/s, 14 kg mass, including 1/3 of cable harness; two pieces of 152 mm diameter x 9.5 mm thickness Rubatex® foam attached to the front of the probe; ATD was rotated +15° and -15° along z axis through T1 corresponding to UMTRI AMVO	Probe acceleration/CFC600 Chestband measurement***

* The filter class complies with SAE J211, may differ from THOR 50M qualification manual.
** Measurement from high-speed video, no filter applied.
*** Time history of the point that had maximum displacement, no filter applied

Abdomen Biofidelity

The three abdomen biofidelity test conditions were upper abdomen, lower abdomen and belt tests. The test conditions are summarized in Table V.

Table V
SUMMARY OF ABDOMEN TEST CONDITIONS

Test Condition	Input	Data Channel/Filter
Upper Abdomen	6.7 m/s, 9.0 kg steering wheel, 20° from vertical The bottom edge of the impactor is 8 mm below the ATD umbilical landmark (corresponding to human L2 level), torso upright, pelvis tilt sensor reading at 8°	Probe acceleration/CFC600 External displacement*
Lower Abdomen	6.1 m/s, 16.0 mass 25 mm diameter x 30 cm long rigid bar The tip edge of the bar is 8 mm below the ATD umbilical landmark (corresponding to human L3 level), torso upright, pelvis tilt sensor reading at 8°	Probe acceleration/CFC600 External displacement*
Abdomen Belt	Fixed back, approximately 4.5 m/s peak belt loading speed	Belt force/CFC600 Belt penetration*

* Measurement from high-speed video, no filter applied

The upper and lower abdomen tests were conducted by Humanetics. The test setups for the upper and lower abdomen impact tests are shown in Fig. 5 and

Fig. **6** respectively. Targets were placed on the impactor and a rigid bracket attached to the back of the ATD spine for external displacement measurement from the video analysis.
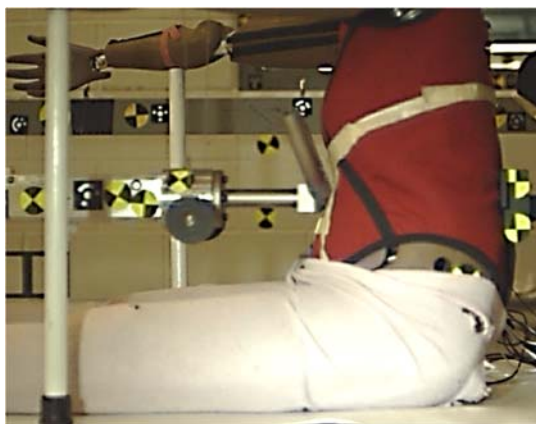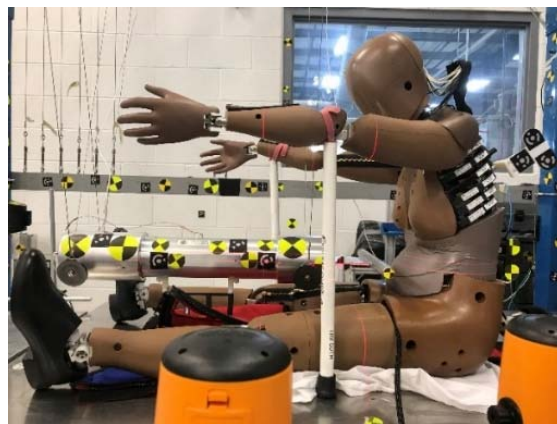
Fig. 5. Upper abdomen impact test setup.

Fig. 6. Lower abdomen impact test setup (jacket on when tested).

The belt test was conducted by OSU with a fixed-back rigid seat. The test setup is shown in Fig. 7. The initial targeted belt penetration was defined in [13]. However, due to the limitation of the current test apparatus, the abdomen belt test input loading curve was different (Fig. 8). Because of the different loading pattern, the time history responses of the ATD (force and deflection) were not evaluated relative to the PMHS in [13]. However, given similarity in overall loading rates, the force vs. deflection response was evaluated against the corridor of [9], which was scaled for the fifth female size.
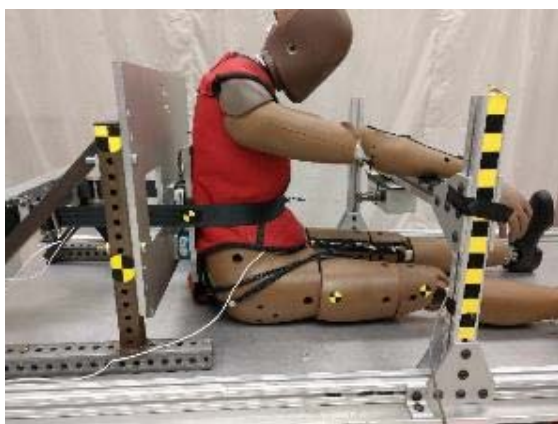
Fig. 7. The fixed-back test setup for abdomen belt test.
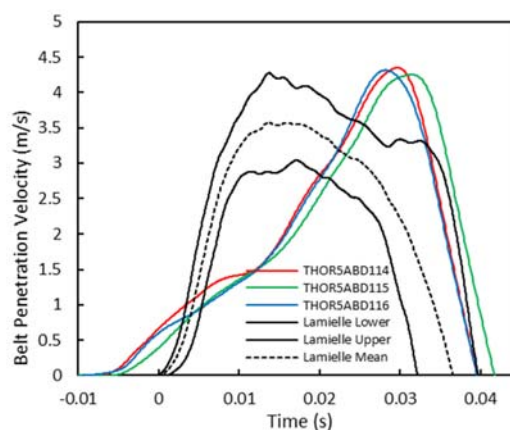
Fig. 8. Belt penetration velocity achieved in THOR-5F test, compared with Lamielle 2008 corridor.

Knee-Thigh-Hip (KTH) Biofidelity

There are three KTH biofidelity test conditions, knee slider impact, KTH isolated impact, and KTH full-body impact tests. The test was initially conducted at 2.75 m/s, which drive the force vs. deflection result far beyond the biofidelity range. To reduce the risk of potential damage to the ATD parts and instrumentation, the impact test was reduced to 2.15 m/s. It was noticed that there was not noticeable change for the force and deflection response under the two different impact velocities. The test conditions are summarized in Table VI.

Table VI
SUMMARY OF THE KTH BIOFIDELITY TEST CONDITIONS

Test Condition	Input	Data Channel/Filter
Knee Slider	2.15 m/s, 7.26 kg mass, including 1/3 of the suspension cable, 76.2 mm face diameter with 0.5 mm edge radius	String pot/CFC180 Femur force Z/CFC180
KTH Isolated	1.0 to 1.2 m/s, a platform mass impact to static guided ram 9.5 mm diameter. Hexcel and 13 floatation foam between the ram and loading platform to limit the rate of knee loading to under 300 N/ms. Deflection was measured with	Femur Force Z/CFC600 Compression*

	target 1 and 2 shown in Fig. 10, and zeroed at 100 N	
KTH full body	3.5 m/s, 255 kg impactor mass	Impactor Force/CFC600
		Acetabulum Fx/CFC600
		Femur Fz/CFC600
		Pelvis Acceleration/CFC60

* Measurement from high speed film, no filter was applied

The knee slider impact test setup is shown in Fig. 9. A femur load cell was installed to measure the femur force in z direction.
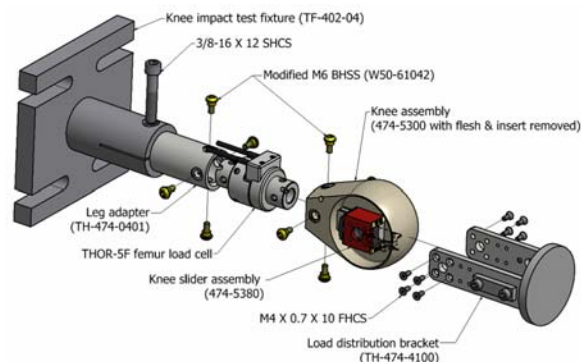

Fig. 9. Knee slide impact test setup

Both KTH isolated and full-body tests were conducted by OSU at Transportation Research Center, Inc. (TRC). The original test apparatus was no longer available for testing. Both apparatus were constructed according to the information in [15] and [16], see Fig. 10 and Fig. 11.
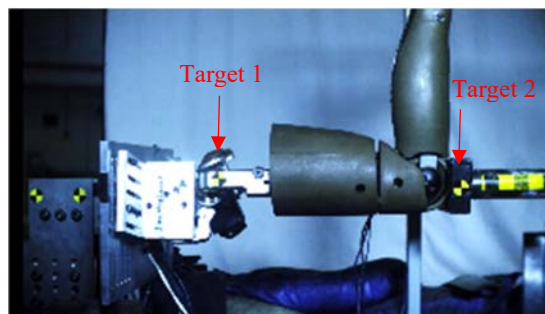
Fig. 10. Test setup for KTH isolated test condition

Fig. 11. Test setup for KTH full body test condition

Lower Extremity Biofidelity

The four lower extremity biofidelity test conditions were dorsiflexion dynamic impact, tibia axial impact, dynamic inversion and eversion tests. The test conditions are summarized in Table VII.

Table VII
SUMMARY OF THE LOWER EXTREMITY TEST CONDITIONS

Test Condition	Input	Data Channel/Filter
Dorsiflexion impact	5.0 m/s, 3.0 kg mass Impact point: 110 mm above the ankle joint center, foot was flexed to 15° in plantar flexion from vertical	Ankle rotation θy/CFC180 Lower tibia My/CFC600 Lower tibia Fx/CFC600
Tibia Axial	3.1 m/s, 28.4 kg mass	Lower tibia Fz/CFC600 Foot plate force/CFC600 Foot plate displacement*
Eversion	Impact energy to generate 1000°/s rotational velocity	Ankle rotation θx/CFC180 Lower tibia Mx/CFC600 Lower tibia Fy/CFC600
Inversion	Impact energy to generate 1000°/s rotational	Ankle rotation θx/CFC180

velocity	Lower tibia Mx/CFC600
	Lower tibia Fy/CFC600

* Measurement from high-speed video, no filter applied

The dorsiflexion impact test was conducted at Humanetics and the test setup is shown in Fig. 12. The tibia axial impact and ankle joint eversion/inversion impact tests were conducted at OSU, and the setups are shown in Fig. 13 and Fig. 14 respectively. Both fixtures were constructed according to the information of the PMHS test apparatus. The compression (foot plate displacement relative to the hip) in tibia axial impact test was measured with high-speed video.
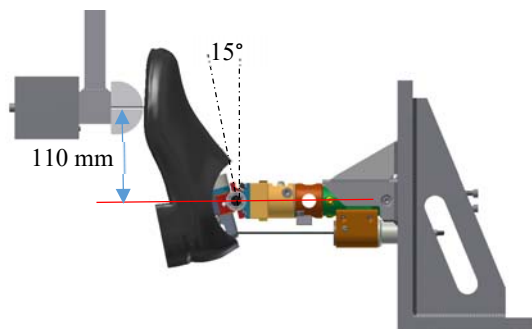
Fig. 12. Impact center for the dorsiflexion dynamic impact test
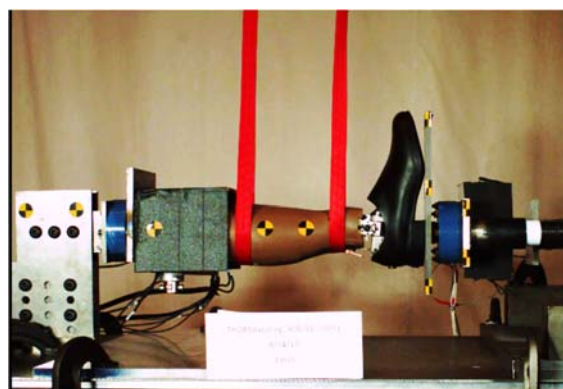
Fig. 13. Test setup for Tibia axial test conditions

Fig. 14. Test setup for inversion/eversion test conditions

For the lower tibia impact test, newer test data from small females were available to replace the biofidelity corridors defined in [2]. The PMHS test conditions for the females also used a slower impact speed of 3.1 m/s, compared to the previous defined condition. The PMHS were tested with a shore comparable to the intergrated shoe design of the ATD. The THOR 5F ATD only has one bone shaft design to represent the combined tibia and fibula load, the sum of the PMHS tibia and fibula forces was used for the BioRank evaluation. In addition, the PMHS corridor was transferred to the corresponding THOR-5F lower load cell neutral axis for biofidelity evaluation.

In order to evaluate the ATD response against the biofidelity corridor developed from PMHS test, the moment at the ankle joint center needs to be calculated. The moment at the ankle joint center for the dorsiflexion impact test was calculated with the following formula:

$$M_{ANKL} = M_{yTBLL} - 0.0864 * F_{xTBLL}$$

where 0.0864 is the distance in meters between the lower tibia load cell neutral axis and the ankle dorsiflexion pivot centerline (the upper pivot axis in THOR-5F ankle joint design), and TBLL is the **Tib**ia **L**ower **L**oadcell.

The moment at the ankle joint center for eversion and inversion impact test was calculated with the following formula:

$$M_{ANKL} = M_{xTBLL} - 0.1014 * F_{yTBLL}$$

where 0.1014 is the distance in meters between the lower tibia load cell neutral axis and the ankle

inversion/eversion pivot centerline (the lower pivot axis in THOR-5F ankle joint design), and TBLL is the **Tib**ia **L**ower **L**oadcell.

To determine the time zero for both inversion and eversion impact test, the rotation of the test data was aligned with the rotation corridor mean at 1° rotation, the time coincident with the corridor time zero was defined as the time zero of the test data.

Biofidelity Calculation

The THOR-5F biofidelity rank (BioRank) was calculated according to [3] with a Matlab® script. The biofidelity corridors used for evaluation consist of a mean plus/minus one standard deviation in order to use the biofidelity ranking technique. The new method has the following updates. The Dummy Cumulative Variance over the Cadaver Cumulative Variance (DCV/CCV) ratio was modified to the ratio of the Dummy Cumulative Absolute Difference over the Cadaver Cumulative Standard Deviation (DCAD/CCSD). To address the numerical issues encountered in the cross correlation method, repetitive shifting method was used to determine the lowest Root Mean Square (RMS) score. All data was included in the BioRank calculation instead of the upper 80%. Each data channel was evaluated against its corresponding biofidelity corridor by calculating the Shape and Magnitude (SM), Phase (P) and RMS. The RMS was used as the overall score of this data channel. All test data, including data analyzed from the high-speed videos, were resampled to 10,000 samples per second if not collected in such sampling rate before BioRank calculation.

When a biofidelity corridor consists of constant values, for example the head impact force, the P was not calculated. If the P was not calculated for an interest channel, the SM was calculated as the data was without applying the repetitive shift method. When a corridor was not time based, for example, force vs deflection and moment vs rotation corridors, the P was not calculated, and the repetitive shift was not applied to SM calculation either. In the SM calculation of force vs. deflection and moment vs. rotation, the data was resampled with 0.1 millimeter increment for deflection and 0.1° for rotation before carrying out the calculations. In case the test data does not have a full overlap with the biofidelity corridor, the BioRank was calculated up to the lower value of the maximum deflections or rotation of the test data and the corridor mean.

BioRank for each test measurement was calculated and averaged when multiple repeat tests were conducted. An average of all ranked parameters in each test is the BioRank in that test condition. An average of all test conditions for each body region is the BioRank for that specific body region. The THOR-5F overall BioRank is the average of the BioRank of all body regions. The THOR-5F body regions were defined as head, neck, shoulder, thorax, abdomen, knee-thigh-hip, and lower extremity. The biofidelity was assessed based on the BioRank scores in [4] and is summarized in Table VIII.

TABLE VIII
BIOFIDELITY DEFINITION BASED ON THE BIORANK SCORE

Biofidelity	BioRank Score	Statistics Meaning
Excellent	BioRank ≤ 1.0	Within mean ± 1 SD
Good	1.0 < BioRank ≤ 2.0	Between mean ±1 SD and mean ±2 SD
Marginal	2.0 < BioRank ≤ 3.0	between mean ±2 SD and mean ±3 SD
Poor	BioRank > 3.0	outside mean ±3 SD

III. RESULTS

The test results and the biofidelity results are presented by body regions. The overall dummy and each body region showed good biofidelity according to their BioRank scores. In the legend of all plots, the "mean" is the mean of the corridor, "upper" is the upper boundary of the corridor, "lower" is the lower boundary of the corridor. The test numbers of Humanetics, OSU and TRC are referenced in the plots for each tests; the tests will be later assigned NHTSA test numbers when added to the Biomechanics Database.

Head BioRank

The head has a body region BioRank of 0.55, corresponding to "excellent" biofidelity. The time history responses of the three tests are shown in Fig. 15, Fig. 16 and Fig. 17 respectively.

For the head impact test, the peak probe force was aligned with the middle of the corridor, then the time coincident with the corridor time zero was defined as the time zero of the test data. Different methods of defining time zero were experimented and discussed later in this paper and no significant different were found among the

methods. To find the time zero for the facial bar and facial disk impact test, the test data was first aligned with the corridor mean at 200N, then the time coincident with the corridor time zero was defined as the time zero of the test data.

For the facial bar and facial disk impact tests, the corridors are straight lines. The mean was calculated from the upper and lower boundary of the corridor. To calculate the BioRank, the beginning of the corridor mean was padded with zero between the time zero and the first data point of the corridor mean.
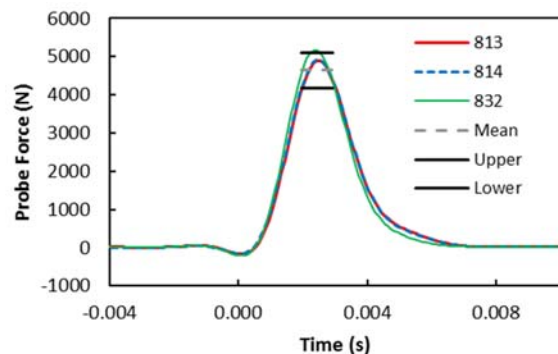
Fig. 15. Probe force time history of head impact.
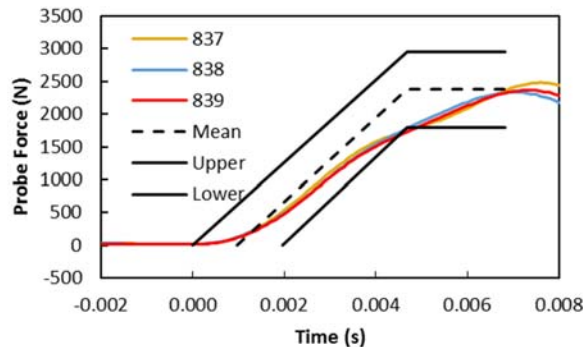
Fig. 16. Probe force time history of facial bar impact.
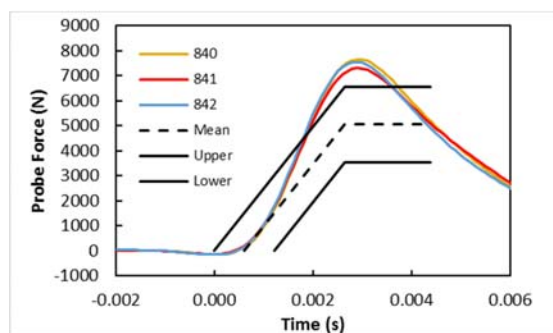
Fig. 17. Probe force time history of facial disk impact

The head BioRank scores are summarized in Table IX.

Table IX
HEAD BIOFIDELITY SUMMARY

Test Condition	SM	P	RMS
Head Impact	0.50	NA	0.50
Facial Bar Impact	0.33	0.11	0.35
Facial Disk Impact	0.78	0.18	0.79
Head Overall			**0.55**

Neck BioRank

The neck has a body region BioRank of 1.77, which corresponds to "good" biofidelity.

For the neck frontal sled tests, the resultant acceleration of head center of gravity (CG), head linkage angle (rigid connection between head CG and occipital condyle (OC)), neck linkage angle (rigid connection between the OC and C7/T1 joint), and CG displacement in both x and z directions were evaluated. A headrest was used to stabilize the head before T1 pulse was applied. However, the head rebound contacted the headrest and generated spike in the head acceleration data, which skewed the BioRank score. To address this issue, the BioRank score for the head acceleration was only calculated up to 0.22 second. The BioRank for this test condition is 1.38, corresponding to "good" biofidelity. The input acceleration at T1 and the responses of these evaluated parameters are shown in Fig. 18 through Fig. 23. The neck was also used to study the variation of the rubber tube/spring assembly, and unfortunately it was found out later that only two repeat tests were conducted on the final selected design.
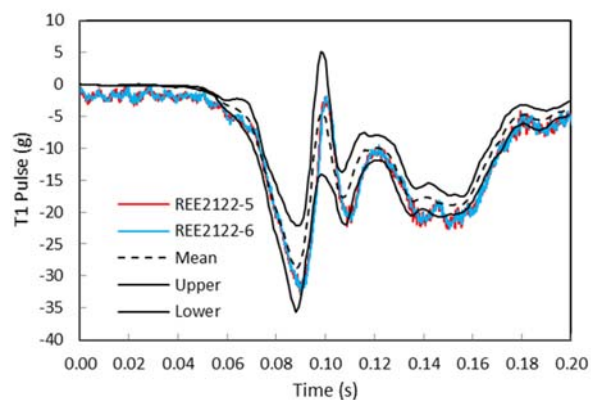
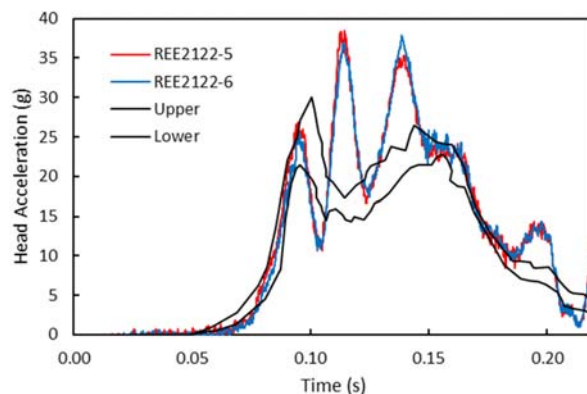Fig. 18. T1 acceleration in x direction (sled)
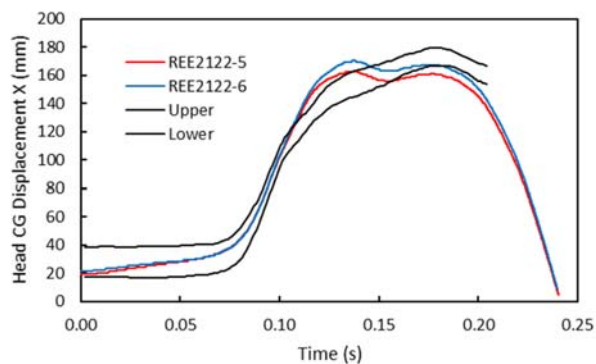

Fig. 19. Head CG resultant acceleration

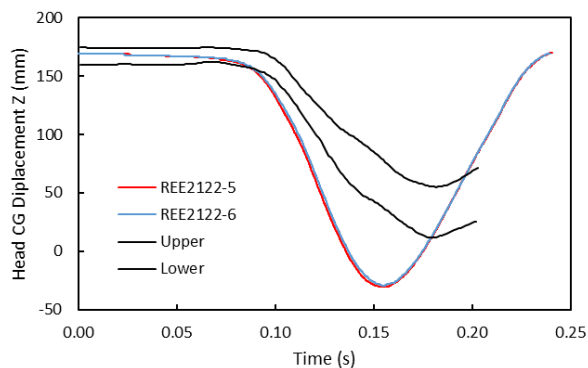Fig. 20. Head CG displacement in x direction
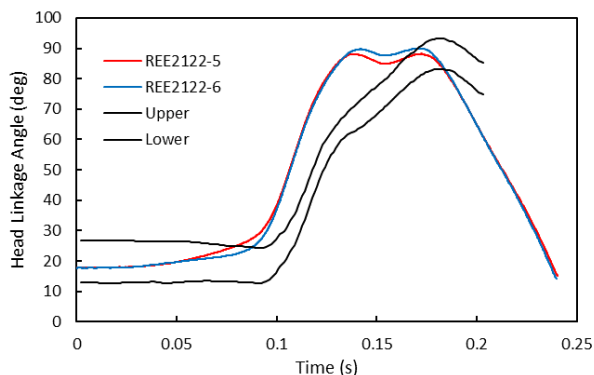

Fig. 21. Head CG displacement in z direction

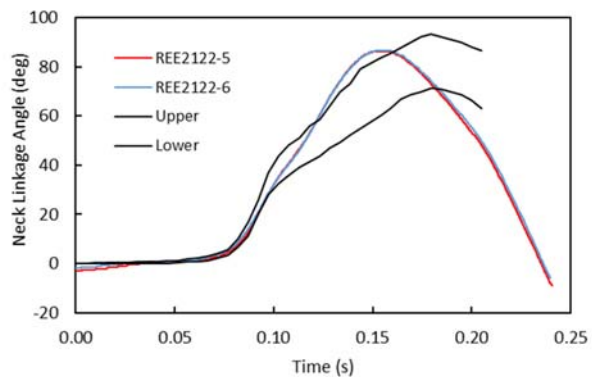Fig. 22. Neck linkage angle (OC-C7/T1 joint)

Fig. 23. Head linkage rotation (Head CG to OC joint)

For the neck lateral sled test, head CG displacements in y and z directions, and head linkage angle were evaluated. The BioRank of this test condition is 2.15, corresponding to "marginal" biofidelity. The input pulse at T1 and the responses of the evaluated parameters are shown in Fig. 24 through Fig. 27.
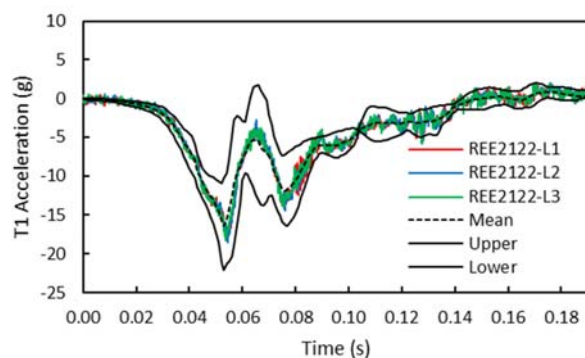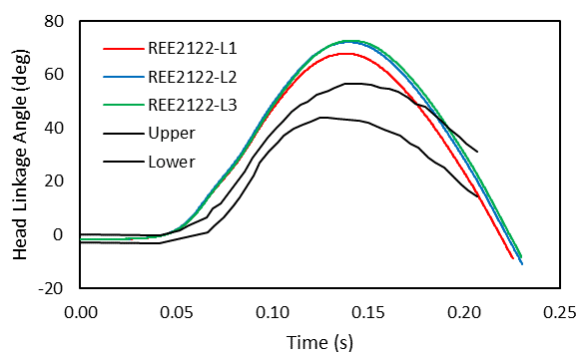
Fig. 24. T1 acceleration (sled pulse)
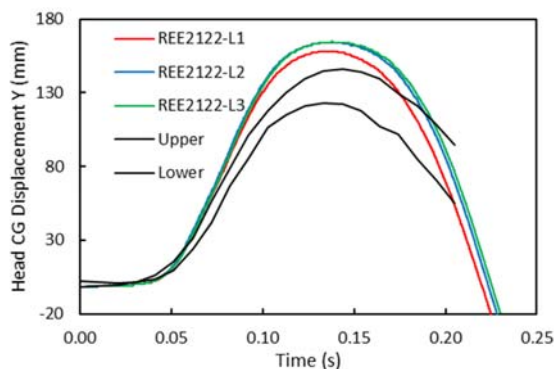

Fig. 25. Head linkage angle

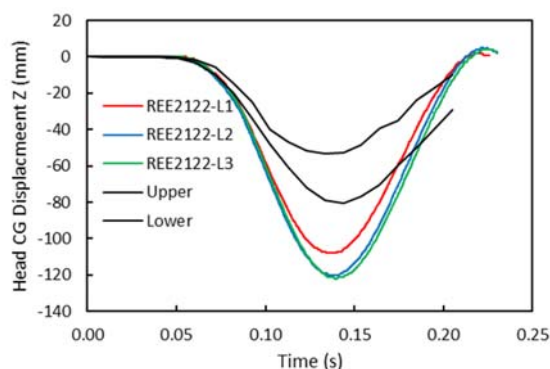Fig. 26. Head CG displacement in y direction

Fig. 27. Head CG displacement in z direction

The BioRank scores for the neck test are summarized in Table X.

Table X

NECK SLED TEST BIOFIDELITY SUMMARY

	SM	P	RMS
Neck frontal sled test			**1.38**
Head resultant acceleration	2.36	0.04	2.37
Head CG displacement X	0.70	0.09	0.71
Head CG displacement Z	1.50	0.66	1.64
Head linkage angle	0.82	0.78	1.13
Neck linkage angle	1.07	0.17	1.08
Neck lateral sled test			**2.15**
Head linkage angle	1.91	0.63	2.02
Head CG displacement Y	1.84	0.30	1.87
Head CG displacement Z	2.56	0.25	2.57
Neck Overall			**1.77**

Neck torsion and pendulum tests responses were evaluated, but given lack of a suitable corridor for BioRank analysis, their scores were not included in the overall neck BioRank calculation. The torsion response is shown in Fig. 28. Test RT10CMLFAIL4, RT11CMLFAIL4 and RT12CMLFAIL4 were the tests with the head rotating toward the left and the test RT10CMRFAIL4, RT11CMRFAIL4 and RT12CMRFAIL4 were the tests with head rotating toward the right. The upper portion of the test data is the loading curve, which did not pass through the corridor, and was considered stiffer than the torsion biofidelity requirement.
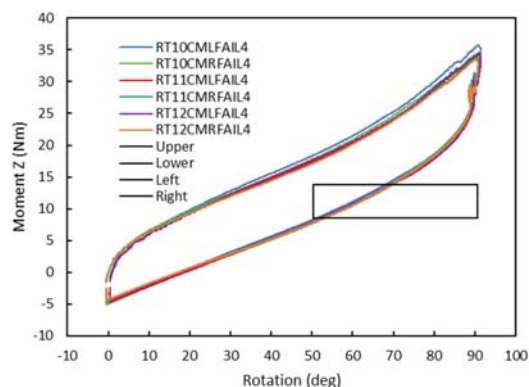
Fig. 28. Neck torsion moment Z vs rotation.

The neck pendulum test moment vs. rotation responses for frontal flexion and lateral bending are shown in Fig. 29 and Fig. 30. The lower boundary was padded with zero values between zero rotation and the first data point of the lower boundary. The corridor mean consist of a starting point at zero and the points of the mean calculated at each turning point of the upper and lower boundaries.
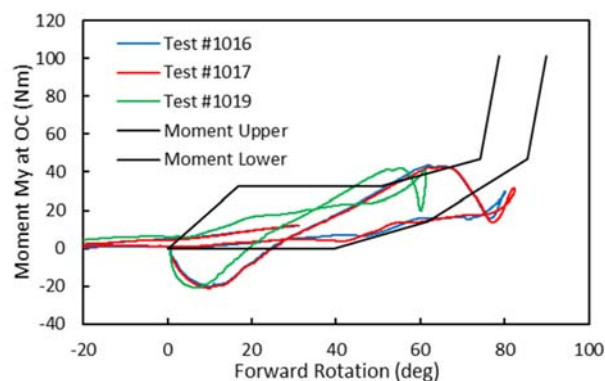

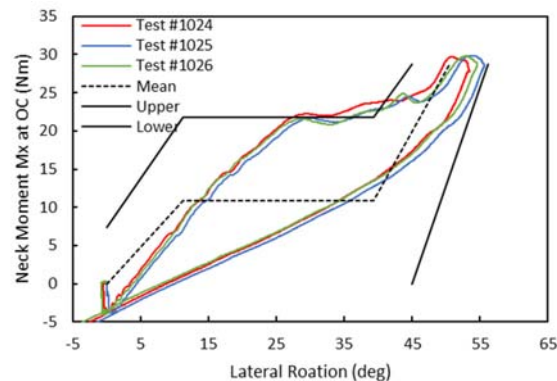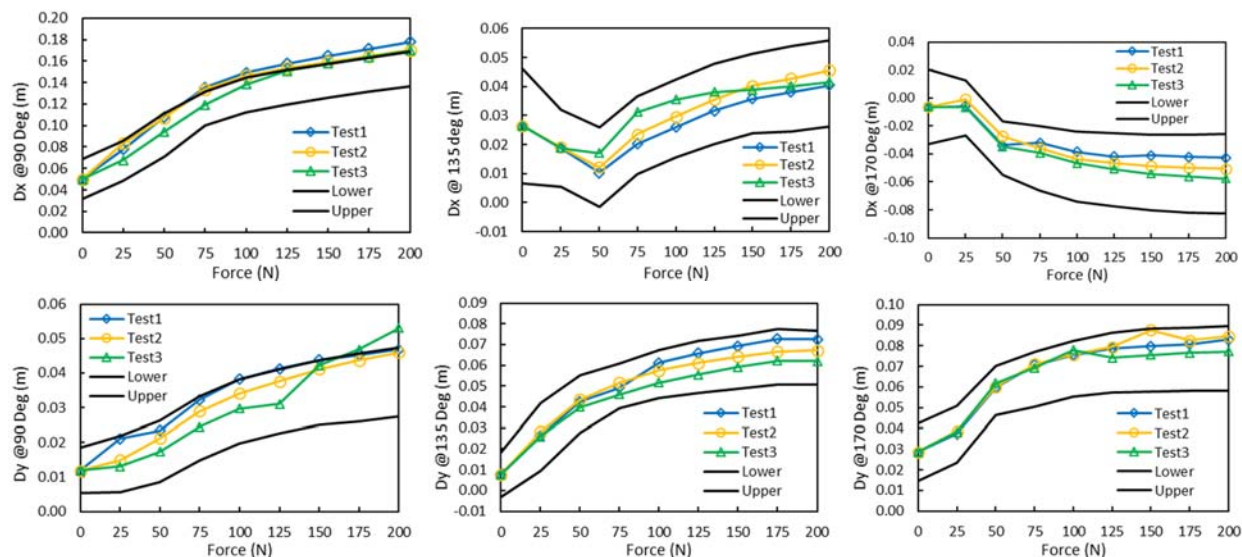Fig. 29. Moment Y at OC vs head rotation Y of neck pendulum impact test frontal flexion

Fig. 30. Moment X at the OC vs. the head rotation X of neck pendulum lateral flexion

Shoulder Biofidelity

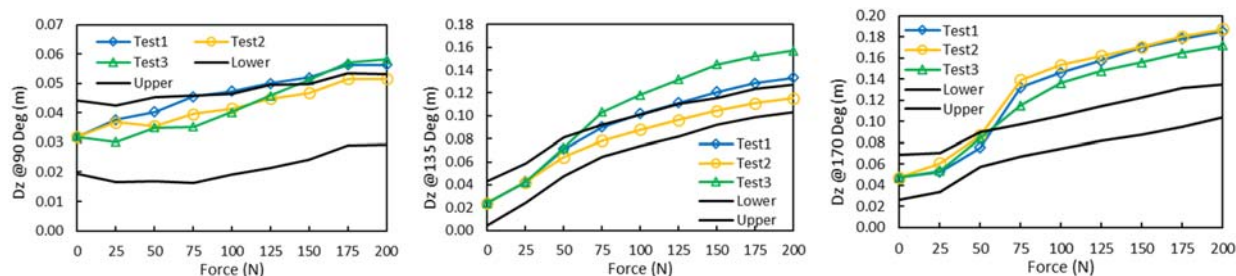Shoulder biofidelity responses are shown in Fig. 31.

Fig. 31. Shoulder range of motion pull test results

The shoulder BioRank scores are summarized in Table XI. Since this is a force vs. displacement type of corridor, as mentioned in the biofidelity calculation, the P was not calculated. The SM was calculated without applying the repetitive shifting method. The RMS and SM scores are identical. To make it sample, only RMS scores are shown. The shoulder body region BioRank is 0.81, corresponding to "excellent" biofidelity. The 90° and 145° degree arm positions scores are 0.97 and 0.42 respectively, corresponding to "excellent" biofidelity and the 170° arm position score is 1.04, corresponding to "good" biofidelity.

Table XI
SUMMARY OF THE BIOFIDELITY RANK OF THOR-5F SHOULDER RESPONSES

	Dx	Dy	Dz	Test Condition
90° Arm Position	1.10	0.88	0.92	0.97
145° Arm Position	0.12	0.33	0.80	0.42
170° Arm Position	0.32	0.36	2.43	1.04
Shoulder Overall				**0.81**

Thorax Biofidelity

The overall thorax BioRank is 1.18, corresponding to "good" biofidelity. The upper thorax responses of tests are shown in Fig. 32 , Fig. 33 and Fig. 34. Unfortunately, the internal deflection time history biofidelity corridor was not available. Instead the external force vs internal deflection corridor was used as an alternative for the evaluation.
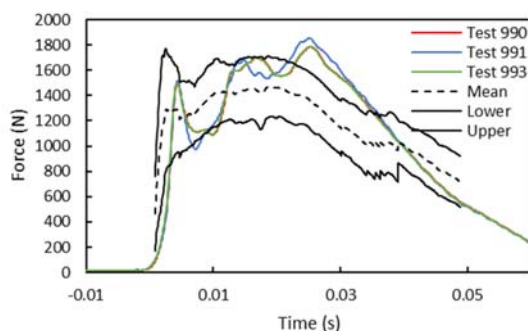

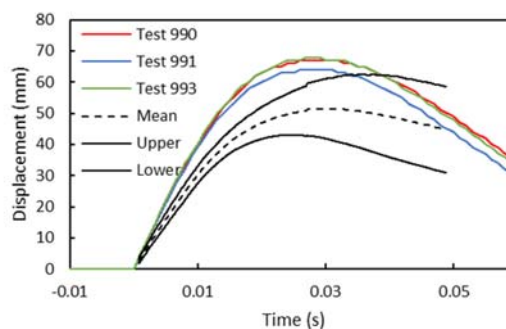Fig. 32. Thorax impact test probe force time history   Fig. 33. Thorax impact external deflection time history
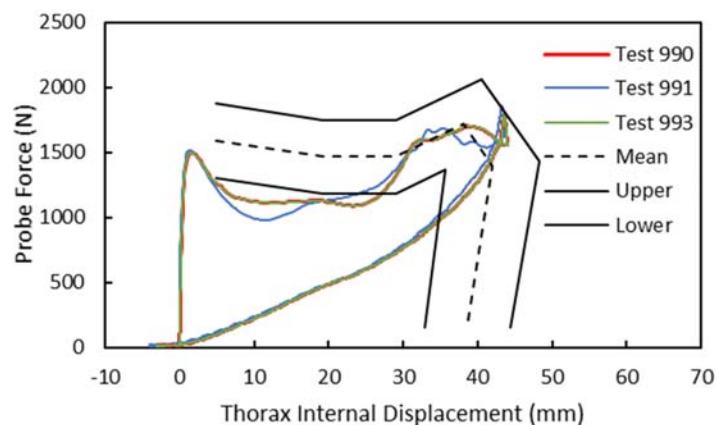

Fig. 34. Thorax impact test force vs internal deflection

The lower thorax oblique impact test was conducted at 4.3 m/s at 15° with the dummy rotated toward its right side. Certification were conducted later on both side to ensure the left and right side have equivalent responses. The test condition BioRank is 1.10, corresponding to "good" biofidelity. The responses are shown in Fig. 35 and Fig. 36.
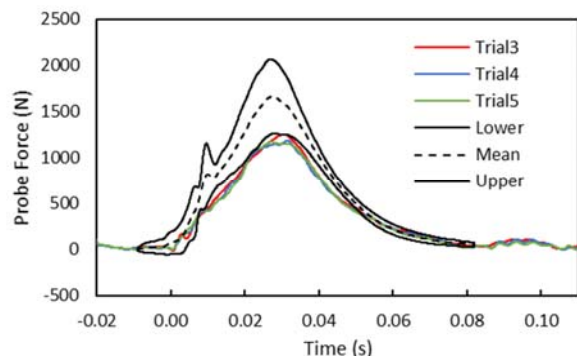

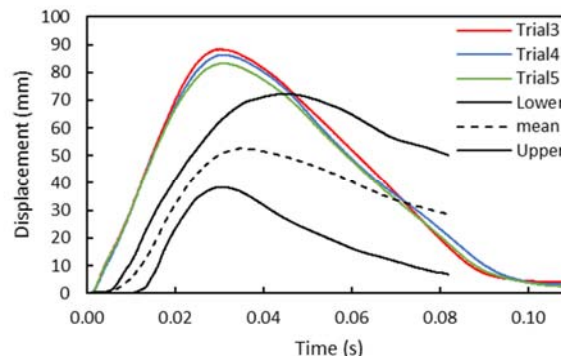Fig. 35. Probe force of lower thorax oblique impact test

Fig. 36. External deflection of lower thorax oblique impact test

The thorax BioRank scores are summarized in Table XII. In addition, three pendulum tests were conducted for the upper thorax at 6.7 m/s for durability evaluation. It was observed the metal inserts in the sternum/breast that connect the ribs to the sternum popped out in the first test. Also there is contact between the sternum and the front of the spine. To address these problems, the flange of the inserts were enlarged and the front of the spine were machined to increase additional 8.3 mm clearance. No damages were observed in testing with this updated design and the contact was eliminated as well.

Table XII

THORAX BIOFIDELITY SUMMARY

	SM	P	RMS
Thorax Upper			**1.25**
External deflection	1.70	0.33	1.73
Force	0.99	0.39	1.06
Force vs internal deflection	0.95	NA	0.95
Oblique Thorax			**1.10**
Force	1.11	0.04	1.11
External deflection (chestband)	1.04	0.34	1.09
Thorax Overall			**1.18**

Abdomen Biofidelity

The overall BioRank for the abdomen is 1.79, corresponding to "good" biofidelity. The upper abdomen steering wheel test has a BioRank of 1.55, corresponding to "good" biofidelity. The test results are shown in Fig. 37 and Fig. 38
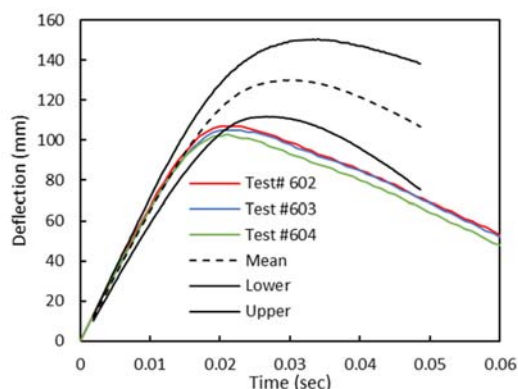

Fig. 37. Deflection of upper abdomen steering wheel impact test.
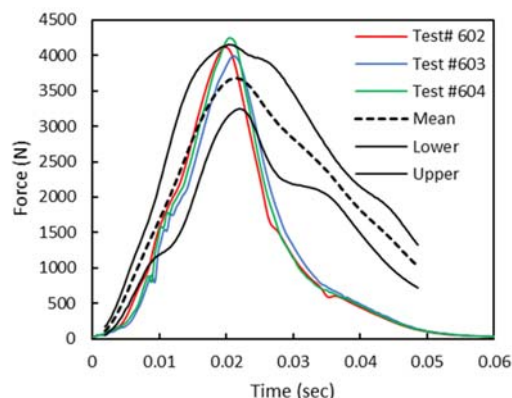

Fig. 38. Pendulum force of upper abdomen steering wheel impact test.

The lower abdomen rigid bar test has a BioRank score of 2.36, corresponding to "marginal" biofidelity. The test results are shown in Fig. 39 and Fig. 40.
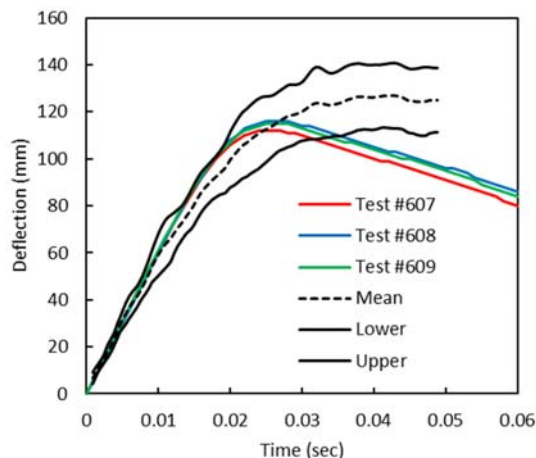

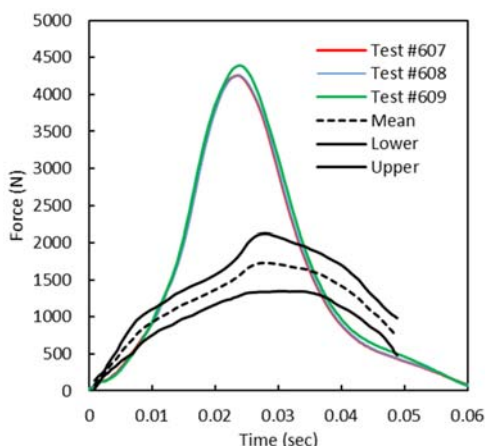Fig. 39. Deflection of lower abdomen rigid bar test.   Fig. 40. Probe force of lower abdomen rigid bar test.

In the abdomen belt test, the force vs deflection was evaluated and the BioRank score is 1.46, corresponding to "good" biofidelity. The belt penetration velocity and the force vs deflection are shown in Fig. 8 and Fig. 41 respectively.
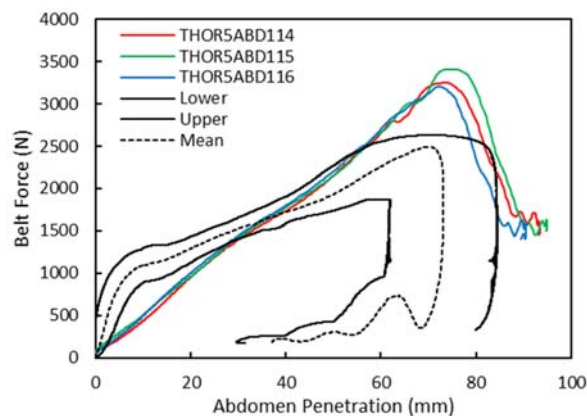

Fig. 41. Force vs deflection of belt test with fixed seatback overlay with corridor defined in [13].

The abdomen BioRank scores are summarized in Table XIII.

Table XIII
ABDOMEN BIORANK SUMMARY

	SM	P	RMS
Upper Abdomen			**1.55**
Force	1.85	0.16	1.86
External displacement	1.24	0.05	1.24
Lower Abdomen			**2.36**
Force	3.72	0.53	3.76
External displacement	0.94	0.09	0.95
Abdomen Belt Test			**1.46**
Force vs Deflection	1.46	NA	1.46
Abdomen Overall			**1.79**

Knee-Thigh-Hip

The overall BioRank for the KTH is 1.18, corresponding to "good" biofidelity. The knee slider impact has a BioRank score of 0.53, corresponding to "excellent" biofidelity. The ATD knee slider impact test response at 2.15 m/s is shown in Fig. 42.
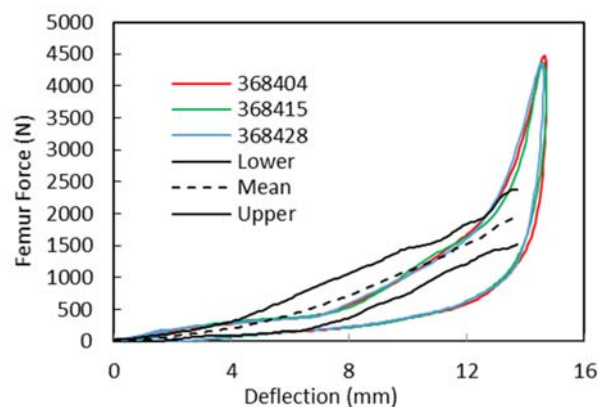
Fig. 42. Response of knee slider impact at 2.15 m/s

The response of the KTH full-body impact has BioRank score 1.93, corresponding to "good" biofidelity. The responses evaluated for BioRank were acetabulum Fx, pelvis acceleration and the impactor plate force. The test results are shown in Fig. 43 through Fig. 45. The 4.9 m/s impact test was unsuccessful and caused major damages to the test apparatus. Due to the safety concern, the tests were conducted with the impact speed at 3.5 m/s. These tests were successful though minor repairs were necessary after each test.
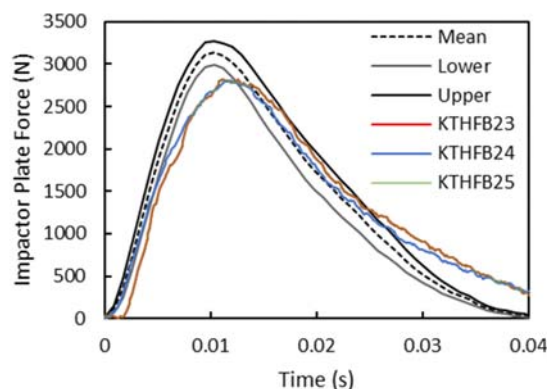
Fig. 43. Impactor force of the KTH full body test.
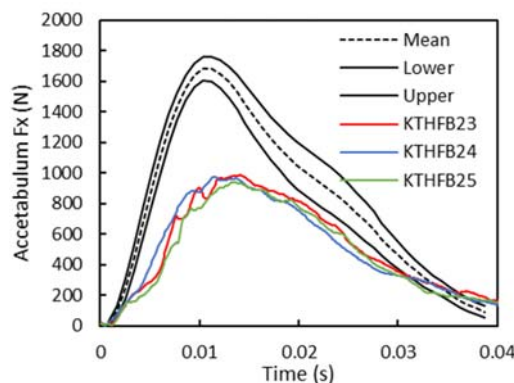
Fig. 44 Acetabulum force Fx of KTH full body impact.
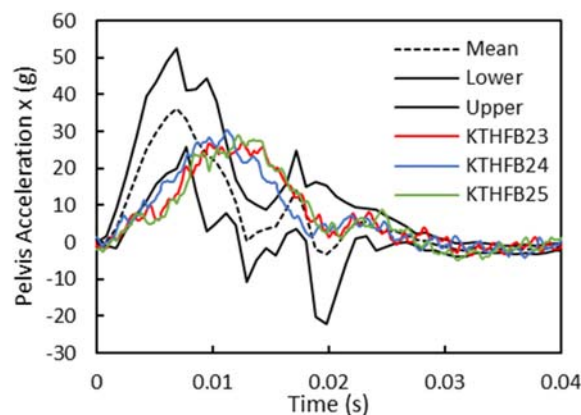
Fig. 45. Pelvis acceleration x of KTH full body impact test.

To determine the time zero of the KTH isolated test, the force of the test data was aligned with initial value of the corridor mean (81.9 N), the time coincident with the corridor time zero was the time zero for the test data. The KTH isolated test has a BioRank score of 1.08, corresponding to "good" biofidelity. The test results are shown in Fig. 46 and Fig. 47.

Fig. 46. Deflection of the KTH isolated test.
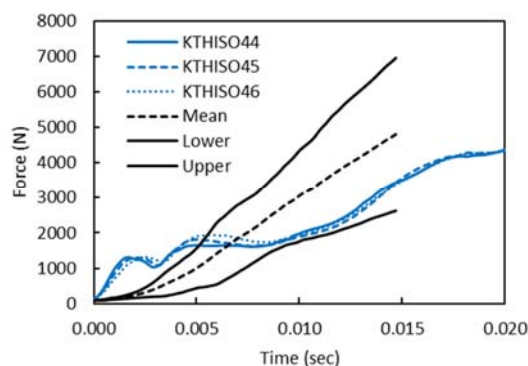
Fig. 47. Force of the KTH isolated test.

The KTH complex BioRank is summarized in Table XIV.

Table XIV
BIORANK SUMMARY OF THE KNEE–THIGH–HIP COMPLEX

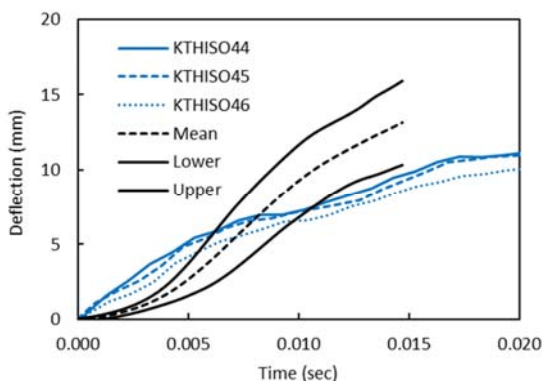|	SM	P	RMS
Knee Slider			**0.53**
Force vs Deflection	0.53	NA	0.53
KTH Full-body			**1.93**
Impactor Force	1.38	0.70	1.58
Acetabulum Fx	3.37	0.24	3.38
Pelvis Acceleration X	0.81	0.21	0.84
KTH Isolated			**1.08**
Deflection	1.23	0.21	0.91
Force	0.87	0.21	0.91
KTH Overall BioRank			**1.18**

Lower Extremity

The body region BioRank of the lower extremity is 1.36, which corresponds to "good" biofidelity. The ball of foot impact has a BioRank score 0.71, corresponding to "excellent" biofidelity. The moment vs. rotation response at 5 m/s impact speed is shown in Fig. 48.
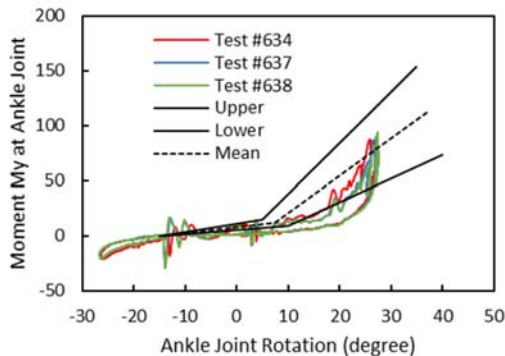
Fig. 48. Moment vs. rotation response of the ball of foot impact test

The dynamic impact test of ankle eversion has a BioRank score of 1.15, corresponding to "good" biofidelity. The test results are shown in Fig. 49 and Fig. 50.
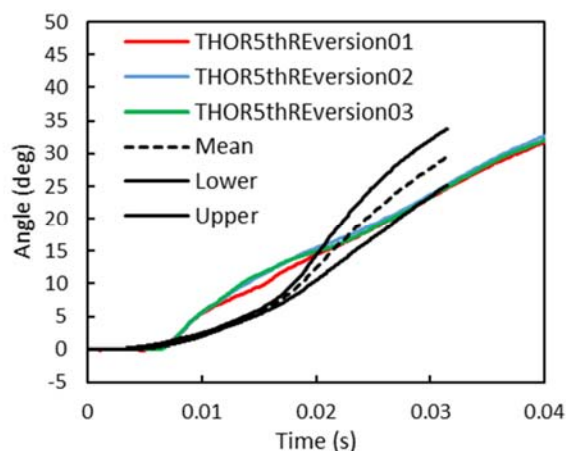
Fig. 49. Rotation of dynamic impact test of ankle eversion
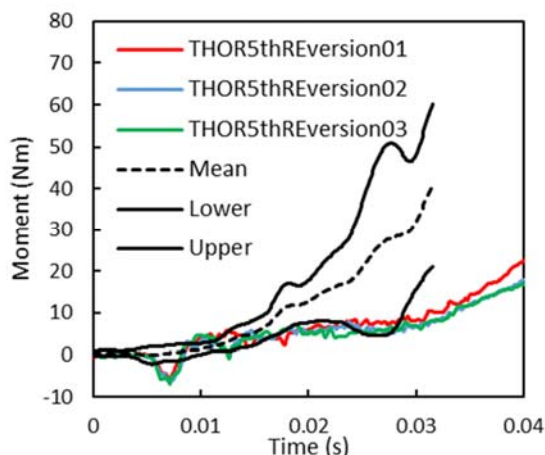
Fig. 50. Moment of dynamic impact test of ankle eversion

The dynamic inversion test has a BioRank score of 1.57, corresponding to "good" biofidelity. The test results are shown in Fig. 51 and Fig. 52.
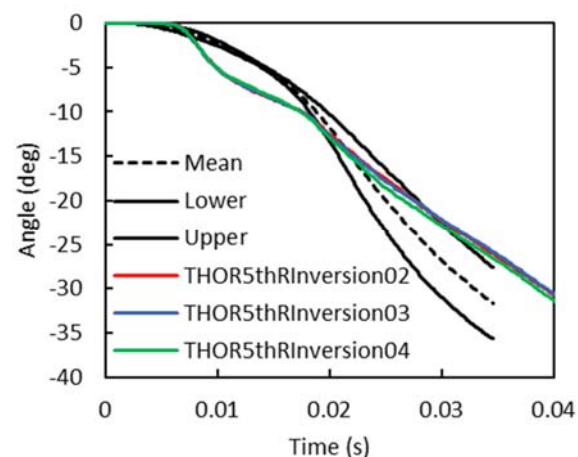
Fig. 51. Rotation of dynamic impact test of ankle inversion
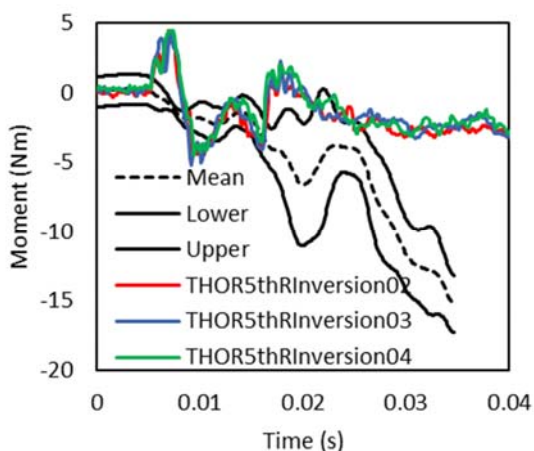
Fig. 52. Moment of dynamic impact test of ankle inversion

The tibia axial impact test has a BioRank score of 1.72, corresponding to "good" biofidelity. The plate displacement, lower tibia force and the plate force are shown in Fig. 53, Fig. 54 and Fig. 55 respectively.

Fig. 53. Plate displacement of tibia axial impact test

Fig. 54. Sum of tibia and fibula force of tibia axial impact test
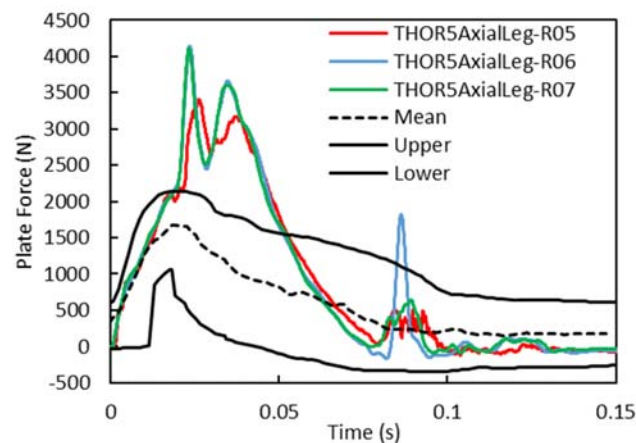
Fig. 55. Plate force of tibia axial impact test

The BioRank scores of the lower extremity are summarized in Table XV.

Table XV
BIORANK SCORE SUMMARY OF LOWER EXTREMITY
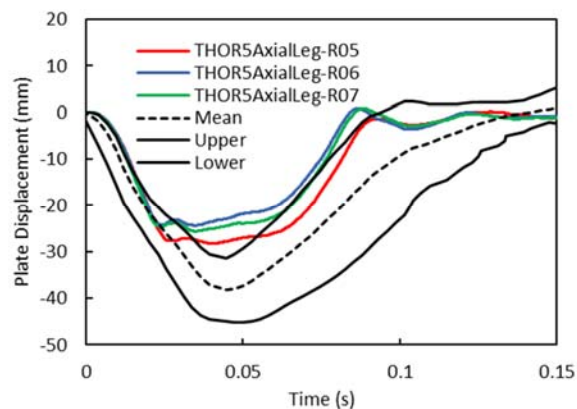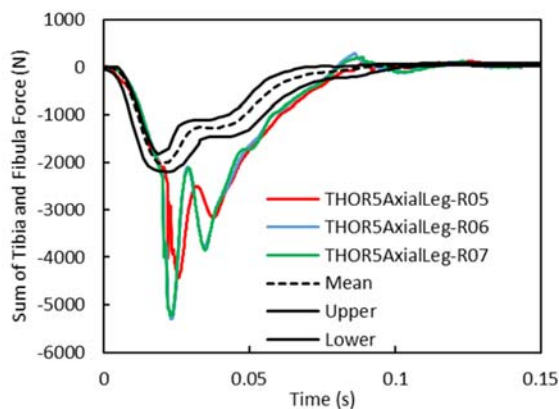
	SM	P	RMS
Ball of Foot			**0.71**
Moment Y vs Rotation Y	0.71	NA	0.71
Dynamic Inversion			**1.57**
Rotation X	1.27	0.04	1.27
Moment X	1.86	0.12	1.86
Dynamic Eversion			**1.45**
Rotation X	1.58	0.25	1.60
Moment X	1.25	0.29	1.29
Tibia Axial Impact Test with Shod			**1.72**
Sum of Tibia and Fibula Force Z	3.40	0.33	3.42
Impact Plate Force	0.81	0.00	0.81
Impact Plate Displacement	0.92	0.01	0.93
Lower Extremity Overall BioRank			**1.36**

The overall ATD BioRank is summarized in Table XVI. The overall dummy BioRank score of 1.23 corresponds to "good" biofidelity. The head and shoulder BioRank are both less than 1.0, which corresponds to "excellent" biofidelity. The neck, thorax, abdomen, KTH, and lower extremity BioRank are between 1.0 and 2.0, which corresponds to "good" biofidelity.

Table XVI
SUMMARY OF BODY REGION BIORANK

Body Region	BioRank
Head	0.55
Neck	1.77
Shoulder	0.81
Thorax	1.18
Abdomen	1.79
Knee-Thigh-Hip	1.18
Lower Extremity	1.36
Overall	**1.23**

IV. DISCUSSION

The THOR-5F prototype dummy was tested under twenty-three test conditions. All body regions showed "good" to "excellent" biofidelity according their BioRank scores. In general, the ATD demonstrated good durability and repeatability, for the limited number of tests conducted. Three repeated tests were conducted for each test condition to the final ATD design though many more tests were conducted to tune the ATD responses. In addition,

three full body sled tests were conducted at 30 kmph, using a seat belt restraint that was force-limited to 2 kN according to [17]. No major damage was observed except for a few instances of normal wears and tears on the dummy.

The repeatability varied from test to test. The majority of the tests provided excellent repeatability with coefficient of variation (CV) less than 5%, while a few tests with more complex setup, such as the full body sled test, provided CV more than 10%.

BioRank was used as an objective measure to quantify ATD biofidelity in this study. An averaging scheme was used, in which parameters subject to BioRank calculation for each test were averaged to create a test condition BioRank score, the test condition BioRank scores were averaged to create a body region BioRank score, and the body region BioRank scores were averaged to create an overall BioRank score. However, each test condition did not contain the same number of parameters. For example, the head impact test condition only required one parameter, the impactor force, which is much easier to tune the ATD to meet the requirement. The neck frontal sled test had performance requirements for five parameters, i.e. head CG acceleration, head CG displacement in X and Z, the head linkage angle, and the neck linkage angle, which made it more complicated and challenging to balance them to achieve the best biofidelity for this test condition. In general, the test conditions with fewer required parameters achieved better biofidelity. Similarly, some body regions had different numbers of test conditions. For example, the thorax had two test conditions, i.e. upper thorax and oblique lower thorax impact tests, while there were four tests in the lower extremity, i.e. tibia axial impact, dorsiflexion impact, inversion and eversion impact tests. Thus, this averaging scheme contributed to the final BioRank scores presented.

For the head impact test, the time zero, which was defined as the contact time between the impactor and the head, could not be determined precisely. The filtered data near time zero was distorted with a small amount and made it impossible to determine the time zero. A few techniques were explored in the data processing. One is to set the 1g probe acceleration as time zero. However due to the short duration, the rising time to 1g was relatively long and made the time zero inaccurate. The second method was to align the probe force peak with the middle of the time of the corridor, which yielded a reasonable time zero. The third method was to use unfiltered data to manually determine the time zero from the data plot. The second and third methods did not yield significant difference. Considering the second method is simpler for programming, the second method was used for the data process in this paper. To meet the biofidelity requirements, two skins with different stiffness, and three facial inserts with different stiffness were made for experiment. The combination with the best biofidelity was selected for the final design. No damage was observed in testing.

As the neck design has the most parameters required for biofidelity evaluation (five for frontal, three for lateral), the biofidelity tuning process was complex. It was found that the flexion biofidelity was less sensitive to the rubber stiffness change in frontal than in lateral sled tests, because the rear neck cable limited the head rotation in frontal tests while the cable did not contribute to the neck response in lateral sled tests. In frontal and lateral flexion, the neck generally needs to be stiffer to improve the overall biofidelity, whereas in torsion, the neck was stiffner than desired. Reducing the torsional stiffness had an adverse effect on the neck response in lateral flexion. Significant effort was made to tune the response to maximize the biofidelity in frontal and lateral flexion. However, a stiffer rubber posed higher risk of damage in testing due to increased fragility and reduced toughness. Therefore, effort was made in manufacturing and testing to determine the highest rubber stiffness without breakage in testing. Despite these challenges, the overall neck biofidelity was "good" according to the BioRank scores.

In the thorax, the upper thoracic spine, rib damping and breast stiffness all contributed to its response. The upper thoracic spine was made from the same rubber material as THOR-50M ATD. The damping material is tunable by increasing or reducing its thickness. Two sternum/breasts were made for experimenting, one with breast made of solid polyurethane, and one with the breast made of polyurethane skin with a foam insert. The damping material with a thickness of 6.6 mm and the breast with foam insert provided the best biofidelity among different combinations. The external deflection of THOR-5F in the thorax impact test was higher than the scaled 5th female biofidelity corridor (Fig. 33) while the internal deflection was well within the corridor (Fig. 34). These corridors were, as noted, scaled primarily from male data [2], wherein breast tissue influence was not considered. Despite this limitation in the corridor, and given lack of original small female to create a new corridor, the overall biofidelity in the thorax was "good". During the validation test, signal noise from the Y potentiometer of the upper thoracic spine was observed. Further investigation showed it was caused by the contact of the Y

potentiometer housing with the damping material of the fourth rib. A possible future solution is to move the IR-TRACC mounting position forward, however this would reduce the maximum chest compression before the IR-TRACC bottoms out. Another solution is to reduce the damping material within the potential contact zone from 6.6 mm to 2.0 millimeter. The remaining 2.0 millimeter was intended to prevent metal to metal contact. This solution was tested in the 4.3 m/s central thorax impact test and no contact was observed for the rib with the local damping material removed. Contact switch was used to detect the contact in testing.

In the abdomen, the original design involved separate upper and lower sections [1]. During testing, it was observed that the upper and lower abdomen separated while the impactor was in contact with the abdomen. Concern over the non-biofidelic separation between the upper and lower abdomens prompted investigation into a design change to a single piece abdomen. The biofidelity testing referenced here was conducted on the final design, i.e. the one piece abdomen. In addition, it was noticed that upward slippage of the abdomen impactors (steering wheel, rigid bar, and belt) occurred during impact. This could be attributed to the geometry difference between the ATD and the PMHS, the material difference between the human tissue and the ATD polyurethane skin/foam, and the curved shape of the ATD abdomen that resulted in the impactors not being perpendicular to the impact surface. The results of the abdomen testing suggest that a softer abdomen could further reduce the magnitude of the force to improve the biofidelity. However, a lower stiffness abdomen would likely be less durable. Changing the location of the abdomen pressure sensor [18] further rearward was another possible solution to reduce the abdomen stiffness. However, it was believed that this would reduce the sensitivity of the pressure measurement in testing and therefore this was not implemented.

In the knee slider design, a solid bumper was replaced with an "E" shape design to meet the biofidelity requirement. Instead of rubber, the thermoset plastic material was used to improve the durability. The knee slider test condition biofidelity is "excellent".

In the KTH isolated test, the rubber element were made of two stiffness, one was called base material, another was one and half stiffer under quasi-static test condition. The base material, which was made the same as THOR-50M material provide better biofidelity responses in testing and was selected as the final design.

The KTH full-body test has a high energy input with 255 kg at 3.5 and 4.9 m/s impact speeds. Although the ATD survived the 4.9 m/s tests without any damage, the test apparatus was damaged. Instead, the test with 3.5 m/s was conducted, though minor repairs were necessary after each test. The rubber element of the two different stiffness were tested in KTH full-body test and the no significant difference were observed between the parts with different stiffness. Pelvis acceleration and the acetabulum force appeared to be insensitive to the rubber stiffness of the femur compliance element under this test condition.

In the tibia axial impact test, the BioRank score suggests "good" biofidelity for this test condition. However, the time history data of the tibia and fibula forces sum and the plate force were much higher than their biofidelity corridor (Fig. 54 and Fig. 55). This good BioRank score was mainly caused by the wide biofidelity corridor. Further investigation showed that the tibia and fibula force sum vs. plate displacement and plate force vs. plate displacement are reasonable comparing to the corridor, see Fig. 56 and Fig. 57 respectively. Although the force vs displacement is a key indicator of the ATD response, the force vs displacement responses were not included in the BioRank calculation because of the concern of the redundant calculation in addition to their time history ranking. It was noticed that the force vs displacement corridor only covers the loading portion of the test, while the time history included both loading and unloading data of the test. Both the sum of tibia and fibula forces and the plate force rose fast near the end of the loading curves. Further investigation showed the Achilles spring tube might have contacted the cable clamp block at the rear side of the upper tibia load cell though a 17.8 mm clearance was made to mitigate the potential contact. In additional the plunger design limits the rubber compression to 20 mm maximum. An investigation is in process to explore the possibility to clear the load cell connector from the Achilles assembly travel path and increase the plunger design travel range.
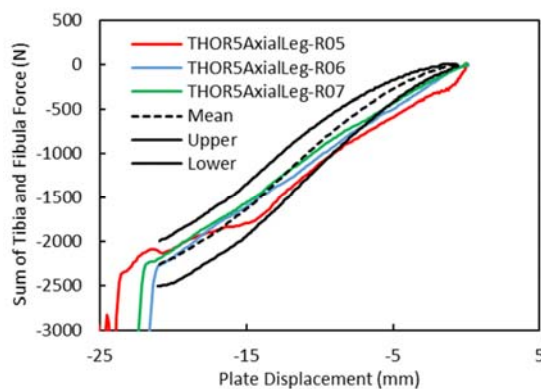
Fig. 56. Sum of tibia and fibula forces vs plate displacement of tibia axial impact test
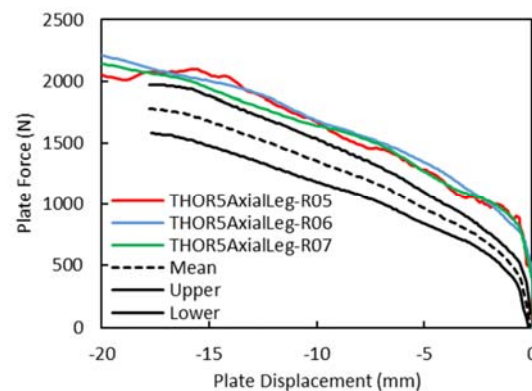
Fig. 57. Plate force vs. plate displacement of tibia axial impact

In the dynamic dorsiflexion impact test, a wave spring replaced the foam tube in the Achilles spring damper assembly to provide better reproducibility. However, the wave spring was not durable and damaged after each test. Further investigation found a coil spring provided good biofidelity and durability and therefore was implemented in the final design.

Only one of the three dummies went through all the biofidelity tests and changes were made when necessary to meet the biofidelity requirements. The other two dummies were built to the same level of the final design of the first dummy with satisfactory biofidelity. Qualification tests were conducted to all three dummies to ensure the responses of the second and third dummy were similar to the first dummy.

There are limitations in this research. The intent of the biofidelity evaluation was to exactly match PMHS test conditions when testing the ATD. However, this was not always possible. When the original apparatus used to test PMHS was not available, such as for the abdomen belt, KTH isolated and full-body, tibia axial impact, and inversion/eversion impact tests, new apparatus were built according to the information documented in the original papers. These original papers often did not provide enough details to allow for exact replication of the test and therefore interpretation by the authors using their best engineering judgement was necessary. There were also a few test conditions in which the ATD test did not exactly match the original PMHS test condition. In the knee slider test, the original study involved forced translation of the tibia relative to the femur, whereas the ATD was simplified by using a pendulum impact. To confirm a comparable test condition, the compression rate of the 2.15 m/s ATD pendulum test was compared to the original study. For the abdomen belt pull, as noted above, the belt velocity input did not match the original PMHS test condition. PMHS tests using the same input as the ATD test are planned at OSU, and the biofidelity will be reevaluated at that time. The neck sled test conducted on the ATD was a simplification of the NBDL full body volunteer/PMHS tests. Given lack of detail on the body restraints used in the original paper, and the use of the volunteer T1 acceleration pulse as input to the sled for the ATD head/neck subsystem tests, this simplification appears reasonable. Finally, as noted, the majority of biofidelity corridors were scaled from male data, due to paucity of data on fifth female specimens. The scaling approach assumes that material properties are equal, irrespective of size or sex, and that impact response is directly related to body size. This approach has been used in the development of previous small female ATDs, including Hybrid III [19], SID-IIs [20][21], and WorldSID [22].

V. CONCLUSIONS

THOR-5F biofidelity was evaluated under twenty-three different test conditions. One dummy went through twenty-three biofidelity tests. The other two dummies were built to the final version of the first dummy after achieving satisfactory biofidelity. All three dummies were certified to ensure the later built two dummies had equivalent response to the first dummy in these test conditions. The overall ATD BioRank score 1.28 represents "good" biofidelity of the dummy. The head and shoulder biofidelity are in "excellent" range, while the neck, thorax, abdomen, KTH and lower extremity are in "good" range. The ATD withstood minimum three tests in each biofidelity test condition without damage, which showed satisfactory durability as prototype. The repeatability of the ATD was reasonable for the limited tests conducted to date. The THOR-5F ATD is ready for full scale testing evaluation, such as sled and vehicle crash tests, understanding there are always new biofidelity requirements from current and future research that can be used to further improve the ATD biofidelity.

VI. Acknowledgement

VII. References

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VIII. APPENDIX

Neck Sled Test Data Processing Procedure

The anthropometry differs between the volunteer/PMHS head and the THOR-5F. The THOR-5F was designed according to the UMTRI AMVO 1983 5th percentile female anthropometry specification [1]. The coordinates of Thunnnissen et al 1995 [23] and the UMTRI AMVO 1983 are shown in the following table. Since it is reasonable to assume there is no motion before the pulse is applied, the initial position are used to locate the head CG in the Thunnissen T1 coordinate system. The T1 and head CG coordinates are summarized in Table A1.

Table A1

COORDINATES OF THE LANDMARKS IN HEAD AND NECK

UMTRI Coordinate System	X	Y	Z
OC	-189	0	519
Head CG	-184	0	578
T1	-183	0	429
UMTRI T1 to UMTRI CG	1	0	-149
UMTRI OC to UMTRI CG	-5	0	-59
Thunnissen T1 to Thunnissen CG	-27.9	0	-166.9
Coordinates After Align Thunnissen Head CG with UMTRI Head CG			
UMTRI T1 to Thunnissen T1	28.9	0	17.9
UMTRI OC to Thunnissen T1	22.9	0	107.9
CG to Thunnissen T1	27.9	0	166.9

After aligning the two datasets at the head CG, the Thunnissen T1 location in the UMTRI AMVO coordinate system is shown in Fig. A1.
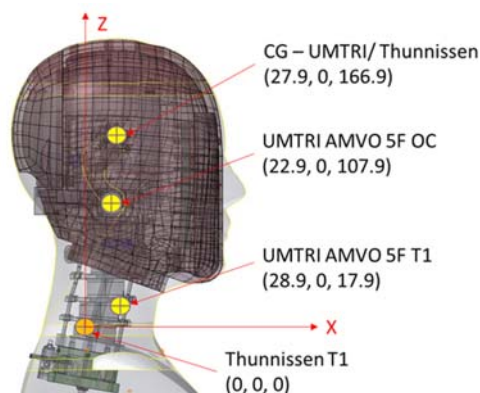

Fig. A1. Landmarks overlay of scaled Thunnissen et al 1995 and UMTRI AMVO 5F with CG aligned

Due to the difficulty of physically attaching a target on the T1 location, the neck linkage angle could not be measured from the video analysis. Instead, the OC coordinates are calculated in reference to the Thunnisen T1 coordinate system. The rotation angle is calculated with the following formula.

$$\theta_y = \arctan(z/x)$$