Neck Biofidelity Comparison of THOR-AV, THOR and Hybrid III 50th Dummies

Z. Jerry Wang, Brian Loeber, Angela Tesny, George Hu, Yun Seok Kang

Abstract This study evaluated the neck biofidelity of THOR-AV, THOR and Hybrid III 50th dummies in six test conditions. The results showed the neck overall BioRank scores are 1.48, 1.89 and 1.97 for THOR-AV, THOR and Hybrid 50th respectively, all corresponding to "good" biofidelity according to the current NHTSA BioRank method (the lower the score, the better the biofidelity). The THOR-AV neck design has a lordosis curvature, a torsion element and an increased cross section from C1 to C7 in its design. These features in THOR-AV neck design closely reflect human anthropometry and most likely contributed to the improved kinematics and biofidelity.

Keywords Neck, biofidelity, THOR, THOR-AV, HIII 50TH

I. INTRODUCTION

As more postmortem human subject (PMHS) tests are conducted to understand the neck biofidelity responses in the automotive crash environment, the better knowledge we have of human neck responses and the better guidelines for the design and construction of a more biofidelic crash test dummy neck.

Mertz and Patrick (1971) defined neck hyper flexion and hyper extension tolerance in adult human volunteer tests [1]. In this study, static voluntary levels of 23.7 Nm (17.5 ft-lbs) in extension and 35.3 Nm (26 ft-lbs) in flexion were attained. A maximum dynamic load of 47.5 Nm (35 ft-lbs) in extension was reached without injury. In hyperflexion, the chin-chest contact changed the loading condition at the occipital condyle which resulted in a maximum equivalent moment of 88.1 Nm (65 ft-lbs) without injury. Neck response envelopes for the performance of dummy necks were recommended based on the extension and flexion models. Patrick and Chou presented forward flexion, extension, lateral flexion, and oblique flexion responses of the volunteer neck test data in both static and dynamic environments [2]. For dynamic exposures, the maximum neck moments were 46.8 Nm (34.5 ft-lbs) in flexion and 30.5 Nm (22.5 ft-lbs) in extension. These are well within the envelopes of Mertz and Patrick [1]. For lateral flexion, the dynamic value of 45.1 Nm (33.3 ft-lbs) was attained without injury. A preliminary response envelope was proposed based on the limited volunteer tests.

Wismans and Spenny (1983) analyzed the dynamic lateral flexion tests with human volunteers conducted by the Naval Biodynamics Laboratory (NBDL) [3]. The analysis provided head center of gravity (C.G.) trajectory in y- and z-displacements and head rotation in y-direction in coronal plane according to SAE J211 definitions. Thunnissen et al (1995) did similar analysis of the NDBL volunteer data from the frontal flexion tests [4]. Biofidelity corridors for head C.G. trajectory in x- and z-displacements in sagittal plane, head C.G. linear resultant acceleration, head y-rotation, and neck linkage (occipital condyle/thoracic spine vertebra 1, or OC-T1) rotation were established. These two sets of criteria provide a basis for neck kinematic responses in lateral and forward excursion, respectively.

Myers et al (1989) conducted dynamic torsion tests with osteoligamentous cervical spines using a device designed to simulate in vivo conditions [5]. The neck was found to produce near zero moment up to approximately 45° rotation, followed by a nearly linear (slope = 0.472 Nm/deg) increase in moment. A response corridor was established from the PMHS test results. The loading rate of these tests was at approximately 500 degrees/second, which is much lower than the approximately 1500+ degrees/second exhibited by the THOR-50M neck in vehicle crash tests in the NHTSA biomechanics database (test reference nos. b11204 – b11205). In this study it was also shown that the Hybrid III dummy neck does not replicate the initial zero moment response.

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Kang et al (2018) conducted tests with an isolated head and neck system using a mini-sled to produce frontal flexion, lateral flexion and oblique flexion (all 14 km/h) and torsion at 1,800 degrees/second [6]. Biomechanical response corridors were proposed from the frontal flexion tests. Due to a limited number of test samples, there was not enough data to propose corridors for lateral flexion, oblique flexion and torsion impact conditions. However, the data still provides valuable information to evaluate dummy neck responses in dummy development efforts.

Historically, the Hybrid III (HIII) neck was developed based on moment vs. rotation response criteria in forward flexion, extension and oblique flexion as defined in studies [1] and [2]. In automotive crash tests, human neck response is important to replicate in dummies to produce realistic head kinematics so that the head injuries can be predicated properly. The response criteria from [3] and [4], including head CG trajectories, head resultant acceleration, head rotation, neck linkage rotation, provides additional guidelines for neck kinematic responses in addition to the dynamic responses in head accelerations. THOR-50M neck development inherited neck criteria from HIII 50th dummy [1][2], and the kinematics criteria defined in [3][4]. In THOR-5F development [7], response criteria from [3] and [4] were used as primary neck performance requirements, with criteria [1] and [2] used as secondary requirements. Both THOR-50M and THOR-5F were evaluated against the criteria defined in [5]. However, due to its low loading rate, it was considered as a secondary requirement.

In the past two years, Humanetics has been developing THOR-AV 50M (THOR-AV hereafter), which is a modified THOR-50M dummy (THOR hereafter) designed for reclined seat restraint development in automated vehicles (AV). A new neck was developed for the THOR-AV dummy to address torsion biofidelity, handling, and durability in reclined seating scenarios. In this paper, the THOR-AV, THOR, and Hybrid III 50th neck frontal flexion responses are evaluated against both [4] and [6]. Neck lateral flexion responses are evaluated against both [3] and [6]. Neck oblique flexion responses are evaluated against [6]. Neck torsion responses are evaluated against [6].

II. METHODS

Neck tests were conducted with two different devices, a Humanetics mini-sled with the ability to program the sled pulse and the PMHS test rig at Injury Biomechanics Research Center (IBRC) of The Ohio State University (OSU). All sign conventions follow SAE J211 standard.

Comparison of Dummy Neck Designs

The THOR-AV neck design aims to address a few observations from past test experiences with the THOR and HIII 50th percentile necks. First, the HIII 50th neck and THOR necks are both straight in its long axis, while the human neck has lordosis curvature. In a pure forward flexion or lateral bending condition, the HIII neck demonstrated responses that are sufficient to replicate human neck responses. In a more complex loading condition, neck kinematics can be very different between a straight dummy neck and a curved human neck. Secondly, the human head can rotate approximately 45 degrees about the z-axis from its neutral position before it starts to experience noticeable resistance [5][6]. The HIII and THOR necks do not provide such responses. Instead, the dummy necks start to load immediately when the head rotates [5][10]. In an oblique loading condition, this difference in torsion could create a different loading mechanism in the neck that may lead to inaccurate injury prediction. The THOR-AV neck was designed to address these shortcomings in the existing necks. The neck matches the human neck curvature defined in [11]. A torsion element was introduced below the OC joint to produce low resistance until the head reaches 45 degrees of z-axis rotation from neutral position. The neck was also designed with a gradual increase in cross-section from C1 to C7 to mimic human cervical spine anatomy. To reduce the complexity of the neck design, the THOR-AV neck does not have the front and rear cables as in THOR. The upper neck load cell was moved inside the head to eliminate a rigid portion to allow more flexibility in THOR-AV neck design. HIII 50th neck has a center cable, and the cable is torqued to 1.36 ± 0.23 Nm. THOR neck has a front and rear cable that are engaged during the impact test as well. THOR-AV has a center cable designed for safety in case of breakage and the cable is not engaged in normal test as in HIII 50th and THOR necks. The THOR-AV head mass and center of gravity matches THOR-50M's head. The neck designs of the three dummies are shown in Fig. 1.

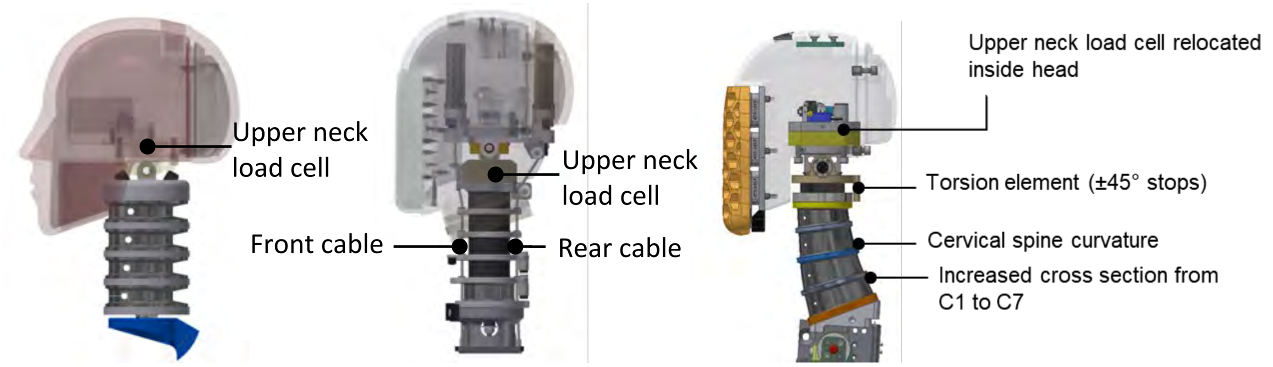

Fig. 1 Neck designs: HIII 50th (left), THOR-50M(center), THOR-AV 50M (right)

Test Sleds

The Humanetics sled (model: E-liner dummy cert sled) uses a computer program to control the sled acceleration of the mounting platform with magnetic force. The acceleration pulse can be pre-programmed and controlled precisely according to the desired input pulse at the first thoracic spine vertebra (T1) for this case. The test setup for frontal impact test is shown in Fig. 2. The mount of the head and neck can be rotated by 90° for lateral impact test, shown in Fig. 3, and 45° for oblique impact test.

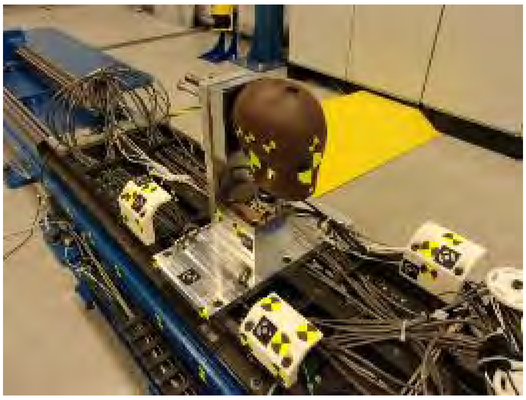

Fig. 2 Humanetics sled setup for frontal tests

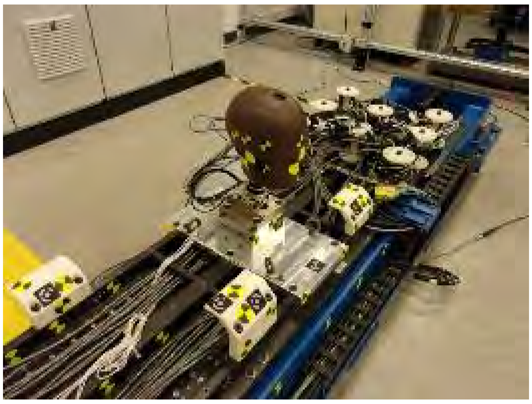

Fig. 3 Humanetics sled setup for lateral tests

The OSU IBRC mini-sled uses a pneumatic impactor to accelerate the base with the head and neck system mounted on it in frontal, oblique, or rear loading configurations [6]. The device can also produce a torsion pulse by impacting a moment arm to the mounting base so that the neck rotates about its center axis, shown in Fig. 4.

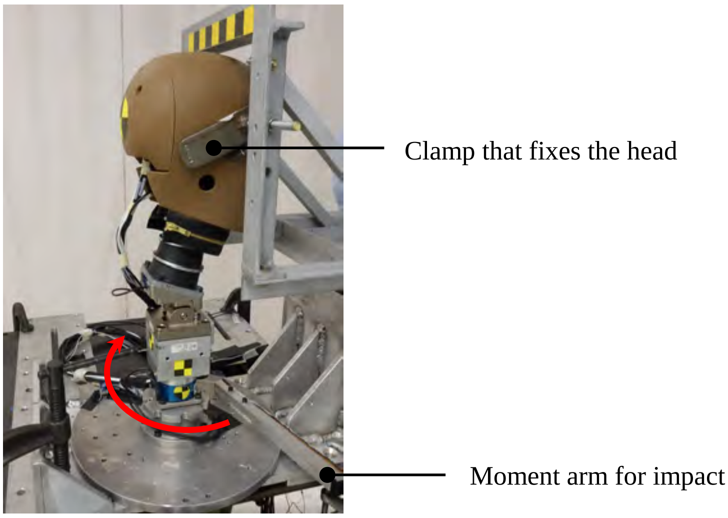

Fig. 4 Torsion test setup of the mini-sled apparatus at OSU IBRC

Test Matrix

THOR-AV, THOR and HIII 50th necks were evaluated for biofidelity. For each neck, a total of 6 different test configurations were conducted to assess the biofidelity in frontal, lateral, torsion and oblique impact test conditions. Unfortunately, due to the coronavirus pandemic situation in the past year, a few tests with THOR and HIII 50th necks could not be conducted due to resource limitations. In these cases, simulations with Humanetics commercial LS-DYNA finite element (FE) models were used in place of these tests. The THOR-AV models were validated in all other test conditions. TABLE I summarizes all tests and FE simulations.

TABLE I
MATRIX OF TESTS AND FE SIMULATIONS

	Frontal		Lateral		Torsion	Oblique
Test Condition	Thunnissen et al (1995)	Kang et al (2018)	Wismans et al (1983)	Kang et al (2018)	Kang et al (2018)	Kang et al (2018)
T1 Peak	29 g	11.3 g	16 g	11.3 g	1800°/sec	11.3 g
THOR-AV	H	H	H	H	H	H
HIII-50th	H	O	H	FE	O	FE
THOR-50M	H	O	H	FE	O	FE

H – tests conducted in Humanetics, O – tests conducted in OSU, FE – simulation results in Humanetics

Time Zero Determination

The sled pulse was used to determine the time zero for each test. The test sled pulse was aligned with the human volunteer or PMHS test pulse. The time corresponding to the human volunteer and PMHS pulse time zero was used as time zero for all data in this test.

Data Processing Method

The instrumentation complies with SAE J211 requirements. The data was filtered with the same filter as its corresponding PMHS tests. For the dummy neck test in [6], the lower neck locations of the dummies do not match the lower neck load cell measurement position in the PMHS test. In this case, the moments in x, y and z directions were corrected to match the position of the corresponding lower neck load cell measurement position of its corresponding PMHS test. Using the head center of gravity (CG) as the reference point, the difference of the lower neck load cell neutral axis between the dummies and PMHS are summarized in TABLE II.

TABLE II
DIFFERENCE OF THE LOWER NECK LOAD CELL NEUTRAL AXIS BETWEEN DUMMY AND PMHS

	ΔX (mm)	ΔY (mm)	ΔZ (mm)
THOR-AV 50M	63	0	-30
THOR-50M	83	0	-59
HIII-50TH	3	0	-73

The following formulae were used to transfer the moments accordingly.

$$Mxp = Mx + Fy*\Delta Z + Fz*\Delta Y$$
$$Myp = My + Fx*\Delta Z + Fz*\Delta X$$
$$Mzp = Mz + Fx*\Delta Y + Fz*\Delta X$$

Where Fx, Fy, Fz, Mx, My, and Mz are measurements from the dummy lower neck load cell. Mxp, Myp, and Mzp are moments corresponding to its PMHS lower neck load cell measurement location.

For the Thunnissen frontal test, the neck linkage rotation could not be obtained from video analysis because the corresponding T1 point in the dummy does not provide a good surface to install a video target. Therefore, technique defined in THOR-5F neck evaluation [7] was used to calculate the neck linkage rotation, using the arctan (ΔY/ ΔX) between the occipital condyle (OC) joint center and the T1 position. The coordinates used in this calculation for the initial position from OC to Thunnissen T1 for 50th percentile male is listed in TABLE III. These coordinates were used to calculate the neck rotation for all three dummies.

TABLE III
OC to Thunnissen et al (1995) T1 coordinates

ΔX (mm)	*ΔY (mm)*	*ΔZ (mm)*
15.9	0	176.9

BioRank Method

Before the biofidelity tests were conducted, each neck was certified according to its corresponding certification corridors. The THOR-AV neck certification corridors are still under development and multiple necks were tested and the data was reviewed to ensure no outliers were included in this study. For biofidelity test, when multiple tests were conducted for a neck, the average BioRank scores of all tests were reported as the BioRank scores for this neck. When multiple necks were tested, the average BioRank scores for all necks were reported as the scores of that dummy neck.

NHTSA BioRank method was used to calculate the BioRank scores to assess neck biofidelity [8]. The method was updated by Kang et al [9]. In this updated method, the dummy data is aligned with the biofidelity corridor mean data by one of the following three methods: the lowest dummy cumulative absolute difference (DCAD), first peak or no shift. The best alignment is chosen for the BioRank score calculation. The BioRank score (B) is defined as DCAD/CCSD (cadaver cumulative standard deviation). The dummy phase shift (DPS), the time shift of the dummy data curve for DCAD calculation, is recorded for reference. The BioRank score was evaluated after the data is filtered. The BioRank of the dummy is defined in TABLE IV.

TABLE IV
Biofidelity ranking based on BioRank Scores

BioRank Score	$B \le 1.0$	$1.0 < B \le 2.0$	$2.0 < B \le 3.0$	$3.0 < B$
Biofidelity	Excellent	Good	Marginal	Poor

Since there is only one PMHS test specimen in the Kang et al 2018 [6] torque test, the PMHS corridor was constructed by using plus 10% of the test data as its upper boundary and minus 10% of the test data as the lower boundary for biofidelity calculation purposes.

III. RESULTS

The B scores and DPS are summarized in this section. Due to limited space, some of dummy phase shifts (DPS) are summarized in the appendix if not found in this section. The unit of the DPS is in second. All test data plots with biofidelity corridors are presented in the appendix.

Biofidelity in Frontal Test Conditions

The neck biofidelity was evaluated in two frontal test conditions, Thunnissen et al (1995) [4] and Kang et al (2018) frontal test condition [6].

For the Thunnissen et al (1995) frontal test condition [4], the BioRank scores are summarized in TABLE V. The neck BioRank score for THOR-AV, THOR and HIII 50th dummies in this test condition are 1.32, 1.33 and 1.68 respectively.

TABLE V

BIORANK B SCORES OF THOR-AV, THOR AND HIII 50TH NECKS IN THUNNISSEN ET AL (1995) TEST CONDITION

	Test ID	Head Resultant Acceleration	Head Y-Rotation	Neck Y-Rotation	Head CG X-Displacement	Head CG X-Displacement	Test
THOR-AV	EN1978-0	1.27	1.60	2.08	0.99	0.35	1.26
	EN1978-1	1.35	1.74	1.99	1.17	0.45	1.34
	EN1978-2	1.42	1.78	1.88	1.17	0.48	1.35
						Average	1.32
	EP2034-1	1.38	1.63	1.95	1.14	0.44	1.31
	EP2034-2	1.40	1.64	1.91	1.16	0.49	1.32
	EP2034-3	1.43	1.69	1.83	1.25	0.55	1.35
							1.33
	EO1786-1	1.25	1.51	2.18	1.07	0.30	1.26
	EO1786-2	1.52	1.57	2.02	1.24	0.39	1.35
	EO1786-3	1.58	1.67	1.93	1.10	0.43	1.34
						Average	1.32
					Average of the averages		1.32
THOR	EO1927-1	1.56	0.78	0.98	2.65	0.49	1.29
	EO1927-2	1.63	0.85	0.88	2.77	0.61	1.35
	EO1927-3	1.63	0.88	0.85	2.78	0.63	1.35
							1.33
H350	EL8550-1	1.40	0.60	3.55	1.20	1.52	1.65
	EL8550-2	1.64	0.62	3.52	1.24	1.47	1.70
	EL8550-3	1.52	0.63	3.49	1.30	1.48	1.68
						Average	1.68

See appendix for DPS values.

For Kang et al (2018) frontal test condition [6], the BioRank scores are summarized in TABLE VI. The BioRank scores for THOR-AV, THOR and HIII 50th in this test condition are 1.28, 1.80 and 2.13 respectively.

TABLE VI

BIORANK B SCORES OF THOR-AV, THOR AND HIII 50TH NECKS IN KANG ET AL (2018) FRONTAL TEST CONDITION

	Test ID	Head X-Acceleration	Head Z-Acceleration	Head Y-Rotation	Lower Neck Fx	Lower Neck Fz	Lower Neck My	Test
THOR-AV	EO1786-1	0.90	0.84	2.16	1.37	1.28	1.11	1.28
	EO1786-2	0.89	0.86	2.17	1.37	1.28	1.10	1.28
	EO1786-3	0.89	0.88	2.19	1.36	1.26	1.09	1.28
							Average	1.28
THOR	THOR-01	1.23	0.96	2.14	1.81	2.79	1.89	1.80
	THOR-02	1.24	0.94	2.11	1.81	2.81	1.88	1.80
	THOR-03	1.21	1.01	2.35	1.78	2.60	1.88	1.81
							Average	1.80
H350	HIII50-02	2.07	1.20	3.41	1.57	1.91	2.63	2.13
	HIII50-03	2.13	1.21	3.39	1.57	1.90	2.56	2.13
	HIII50-04	2.16	1.21	3.32	1.57	1.91	2.62	2.13
							Average	2.13

See appendix for DPS values.

Biofidelity in Lateral Test Conditions

The neck biofidelity were evaluated in two lateral test conditions, Wismans et al (1983) [3] and Kang et al (2018) lateral test condition [6].

For Wismans et al (1983) lateral test condition [3], the BioRank scores are summarized in TABLE VII. The neck BioRank scores for THOR-AV, THOR and HIII 50th are 2.19, 1.14 and 2.09 respectively.

TABLE VII

BIORANK B SCORES AND DPS OF THOR-AV, THOR, HIII 50TH NECKS IN WISMANS ET AL (1983) LATERAL TEST CONDITION

		Head Y-Rotation		Head CG X-Displ.		Head CG X-Displ.		Test
	Test ID	B	DPS (s)	B	DPS (s)	B	DPS (s)	B
THOR-AV	EO1786-2	1.25	0.0104	3.84	0.0069	1.03	-0.0068	2.04
	EO1786-3	1.41	0.0105	3.90	0.0065	1.22	-0.0058	2.17
	EO1786-4	1.07	0.0108	3.94	0.0066	1.26	-0.0058	2.09
								2.10
	EN1978-0	1.61	0.0111	3.93	0.0084	1.84	-0.0083	2.46
	EN1978-1	1.37	0.0147	3.89	0.012	1.22	-0.0056	2.16
	EN1978-2	1.45	0.0111	3.73	0.0074	1.50	-0.0085	2.23
							Average	2.28
							Average of the averages	2.19
THOR	EO1927-1	0.64	0.0101	0.98	0.0006	2.11	-0.0036	1.24
	EO1927-2	0.55	0.0117	0.77	0.0036	1.99	-0.0028	1.10
	EO1927-4	0.54	0.0095	0.74	0.0011	1.99	-0.0054	1.09
							Average	1.14
H350	EL8550-1	1.50	0.0116	1.98	0.0109	3.06	0.0422	2.18
	EL8550-2	1.41	0.0116	1.76	0.0086	3.08	0.0425	2.09
	EL8550-3	1.29	0.011	1.67	0.013	3.04	0.0408	2.00
							Average	2.09

For Kang et al (2018) lateral test condition [6], the BioRank scores are summarized in TABLE VIII. The BioRank scores for THOR-AV, THOR and HIII 50th are 0.87, 1.00 and 1.26 respectively.

TABLE VIII

BIORANK B SCORES OF THOR-AV, THOR AND HIII 50TH NECKS IN KANG ET AL (2018) LATERAL TEST CONDITION

	Test ID	Head Y-Acceleration	Head Z-Acceleration	Head X-Rotation	Lower Neck Fy	Lower Neck Fz	Lower Neck Mx	Test
THOR-AV	EO1786-1	0.58	0.66	0.74	2.04	0.66	0.50	0.86
	EO1786-2	0.57	0.65	0.82	2.04	0.65	0.50	0.87
	EO1786-3	0.55	0.65	0.82	2.03	0.65	0.51	0.87
							Average	0.87
THOR	FE	0.63	0.68	1.01	2.46	0.52	0.70	1.00
H350	FE	0.66	0.76	1.42	2.82	0.84	1.06	1.26

See appendix for DPS values.

Biofidelity in oblique test condition

For Kang et al 2018 oblique test condition [6], the BioRank scores are summarized in the TABLE IX. The neck BioRank scores are 2.06, 2.94 and 3.14 for THOR-AV, THOR and HIII 50th respectively.

TABLE IX

BIORANK B SCORES OF THOR-AV THOR-50M AND HIII-50TH NECKS IN KANG ET AL 2018 OBLIQUE TEST CONDITION

		Head Acceleration			Head Rotation			Lower Neck						Test
	Test ID	X	Y	Z	X	Y	Z	Fx	Fy	Fz	Mx	My	Mz	
THOR-AV	EO1786-1	2.08	0.95	1.15	0.49	3.05	2.61	1.94	1.90	1.45	0.61	6.52	2.27	2.08
	EO1786-2	2.11	0.95	1.12	0.49	2.94	2.64	1.91	1.92	1.43	0.60	6.38	2.27	2.06
	EO1786-3	2.02	0.92	1.15	0.47	2.82	2.75	1.90	1.93	1.43	0.60	6.35	2.27	2.05
												Average		2.06
THOR	FE	1.97	0.81	1.33	0.74	4.02	1.99	2.37	2.78	3.47	0.71	8.75	6.32	2.94
H350	FE	2.58	1.00	1.31	0.89	4.47	1.38	2.28	2.83	1.75	1.04	11.15	7.05	3.14

See appendix for DPS values.

Biofidelity in torsion test condition

For Kang et al 2018 torsion test condition along neck z-axis [6], the BioRank scores are summarized in TABLE X. The BioRank scores are 1.11, 3.08 and 1.46 for THOR-AV, THOR and HIII 50th respectively.

TABLE X

BIORANK SCORES FOR THOR-AV, THOR AND HIII 50TH NECKS IN KANG ET AL 2018 TORSION TEST CONDITION

		Head Z- Rotation		Lower Neck Mz		Test
	Test ID	B	DPS (s)	B	DPS (s)	B
THOR-AV	THORAVNCKS8	1.19	0.0001	1.65	-0.0019	1.42
	THORAVNCKS9	0.78	0.0003	1.01	0.0015	0.90
	THORAVNCKS10	0.77	0.0004	1.27	-0.0013	1.02
						1.11
THOR	test1	0.05	-0.0016	6.11	0.0125	3.08
H350	test1	0.10	-0.0009	2.81	0.0152	1.46

The neck z-moment vs z rotation relationship is shown in Fig. 5.

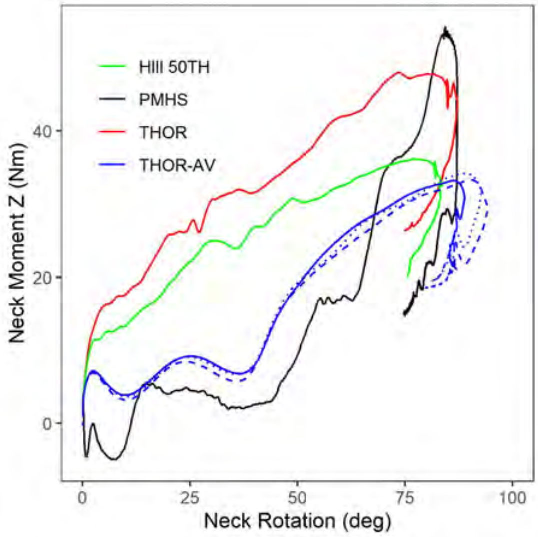

Fig. 5 Neck torsion responses for THOR-AV, THOR, and HIII 50th in Kang et al (2018) condition

Overall BioRank scores

The overall BioRank scores are summarized in TABLE XI. The overall BioRank scores for THOR-AV, THOR and HIII 50th necks are 1.47, 1.88 and 1.96 respectively.

TABLE XI

SUMMARY OF NECK OVERALL B SCORES

Test	Reference	THOR-AV	THOR	H350
Frontal	Thunnissen et al (1995)	1.32	1.33	1.68
	Kang et al (2018)	1.28	1.80	2.13
Lateral	Wismans et al (1983)	2.19	1.14	2.09
	Kang et al (2018)	0.87	1.00	1.26
Oblique	Kang et al (2018)	2.06	2.94	3.14
Torsion	Kang et al (2018)	1.11	3.08	1.46
	Average	1.47	1.88	1.96

IV. DISCUSSION

The study provides an objective way to evaluate the neck biofidelity of THOR-AV, THOR and HIII 50th dummies in six test conditions.

In Thunnissen [4] frontal test conditions, the neck BioRank score for THOR-AV, THOR and HIII 50th are 1.32, 1.33 and 1.68 respectively, all corresponding to “good” biofidelity. Thunnissen biofidelity criteria mainly focus on head and neck kinematics, including head CG acceleration, head CG trajectories, head rotation and neck linkage (OC-T1) rotation. The THOR-AV and THOR have similar biofidelity scores, and both are better than HIII 50th. In this test condition, all three necks demonstrated similar response in head resultant acceleration. The THOR-AV head has higher y-rotation than both THOR and HIII 50th. The THOR has slightly better neck linkage rotation (OC-T1) than THOR-AV, while HIII 50th neck linkage rotation is poor. Since the head rotation is an accumulation of the neck linkage rotation and the OC rotation, the THOR neck has the best rotation distribution between neck linkage rotation and head OC rotation. THOR-AV OC joint buffer stiffness can be increased to future improve its biofidelity. For head CG x-displacement, THOR neck demonstrated much higher forward excursion than the THOR-AV 50M and HIII 50th necks. This could be due to the higher neck linkage rotation for THOR-AV. For head CG z-displacement, THOR-AV and THOR showed similar peak magnitudes. The HIII 50th neck is lacking in head CG z-displacement, with about two thirds of the biofidelity corridor peak value. The HIII 50th neck has a steel central cable, which limits the neck extension. The THOR neck front and rear cables constrain the cable, but the spring in the cable systems allows the neck to extend.

In the Kang frontal test condition [6], the neck BioRank scores for THOR-AV, THOR and HIII-50th are 1.28, 1.80 and 2.13 respectively. The Kang frontal biofidelity criteria focus on head x- and z-accelerations, head y-rotation, the lower neck x- and y-force, and y-moment. The THOR-AV neck has the best biofidelity rating, followed by THOR and HIII 50th. The BioRank scores places the biofidelity of THOR-AV and THOR in the “good” biofidelity category, and HIII 50th in “marginal”. For the head CG acceleration in x- and z-direction, there is small difference among the three dummy necks. For head y-rotation, THOR-AV and THOR necks have similar responses, while HIII 50th head y-rotation is poor, less than half of the biofidelity corridor peak value. The y-rotation (lower than the biofidelity corridor) is opposite to Thunnissen frontal flexion test results (higher than the biofidelity corridor). It is unknow what caused the difference between the two different biofidelity criteria. For lower neck force in x-direction, THOR-AV and HIII 50th neck has similar peak magnitude, both close to the mean of the first peak of the biofidelity corridor, while THOR neck is near the upper boundary. The lower neck force in x-direction could be due to the front and rear cable loads that are not measured by the lower neck load cell. For the neck z-force, the THOR showed a much higher value in rebound, which most likely was caused by the front and rear cables. The cables limited the neck rubber extension and reduced the energy absorption by the neck rubber. For the lower neck y-moment, THOR-AV neck response is well within the biofidelity corridor, and THOR neck response is slightly out of biofidelity upper boundary for the first peak. HIII 50th neck y-moment is poor, nearly twice as high as the biofidelity corridor peak value.

In the Wismans lateral test conditions [3], the neck BioRank scores for THOR-AV, THOR and HIII 50th are 2.19, 1.14 and 2.09 respectively. THOR neck has the best rating among the three dummies, followed by HIII 50th and THOR-AV necks. Wismans biofidelity criteria focus on kinetics by specifying the head CG y- and z-displacement, and head y-rotation. THOR-AV showed much higher head CG y-displacement while THOR and HIII 50th showed similar head CG y-displacement near the corridors. For head CG z-displacement, THOR-AV neck is slightly over the biofidelity upper boundary, while both THOR and HIII 50th failed to reach the z-displacement biofidelity lower boundary. This high CG z-displacement of THOR-AV neck could be caused by absence of steel neck cables. HIII has a center cable, and THOR has a front and rear cable, both of which would limit the neck extension in those two necks. It seems the THOR-AV neck lateral stiffness could be increased to improves its biofidelity in this test condition.

In the Kang lateral test condition [6], the neck BioRank scores for THOR-AV, THOR and HIII 50th are 0.87, 1.00 and 1.26 respectively. THOR-AV neck has the best biofidelity among the three dummies, corresponding to “excellent”. The THOR and HIII 50th necks are in “good” category as well. For the head CG y- and z-accelerations, head x-rotation, and neck z-force, all three dummy necks have similar responses. For neck y-force and x-moment, THOR-50M and HIII 50th necks have similar responses, while THOR-AV neck has higher magnitude.

It was noticed the THOR-AV and HIII 50th necks ranked “marginal” in Wismans lateral test condition [3], but in contrary ranked “excellent” and “good” respectively in Kang lateral test condition [6]. The Wismans criteria emphasize kinematics by specifying head CG resultant accelerations, head CG y- and z-displacement and head x-rotation. Kang lateral criteria specify head CG y- and z- acceleration, head rotation and lower neck loads. The only overlap between the two sets of criteria is the head acceleration and head x-rotation. The three necks showed a similar trend in head x-rotation in both test conditions with THOR-AV 50M neck having the highest magnitude, and HIII 50th neck having the lowest magnitude. THOR-AV head x-rotation is above the Wismans corridor, and the magnitude of x-rotation for all three necks are lower than the Kang lateral corridors. It is not clear what the root cause of the large discrepancy in BioRank scores is due to limited common parameters between the two test conditions. If more PMHS tests will be conducted in the Kang test condition, it is suggested to include the head CG trajectory data to establish equivalent biofidelity criteria as in Wismans test condition for additional comparison.

In the Kang oblique test condition [6], the neck BioRank scores are 2.06, 2.94 and 3.14 for THOR-AV, THOR and HIII 50th dummies respectively. THOR-AV neck has the best biofidelity, but still in the “marginal” category. THOR and HIII 50th necks are slightly below and above 3.0, corresponding to “marginal” and “poor” respectively. The three dummy necks have similar responses in head x-, y- and z-acceleration. For head x-rotation, THOR-AV neck is within the corridor, while THOR and HIII 50th necks only reached half of the peak value of the corridor. For head y-rotation, all three necks failed to reach the biofidelity corridor, which is inconsistent with the high head y-rotations observed in Thunnissen test condition. For head z-rotation, THOR-AV neck has much higher rotation than THOR and HIII 50th necks. The high rotation is caused by the rotational element introduced in THOR-AV neck design. For neck x- and y-force, all three necks reached above the first peak of the biofidelity corridor but failed to match the second peak of the corridor. For the neck z-force, all three necks responses are poor, only reached less than half the first peak of the corridor. THOR-AV and HIII 50th necks match the second peak of the corridor better than THOR neck. For x-moment, THOR-AV neck matches the peak of the corridor better than THOR and HIII 50th necks. For y-moment, THOR-AV neck matches the biofidelity much closer, though they are all above the corridors. For the z-moment, all three necks showed much higher moment than the biofidelity corridors. In general, the three necks in oblique test condition do not perform as good as in frontal and lateral test conditions. One of the reasons could be the OC joint design. All three necks have only one degree of freedom in y-rotation, while human neck OC joint has six degrees of freedom. The limited degree of freedom may have caused different kinematic responses.

In Kang torsion test condition [6], the neck BioRank scores are 1.11, 3.08 and 1.46 for THOR-AV, THOR and HIII 50th respectively. THOR-AV neck has the best biofidelity rating, followed by HIII 50th neck, both corresponding to “good”. The poor BioRank score of THOR neck was most likely caused by its front and rear cables that are offset from the neck centerline and limited the neck torsion motion. In the meantime, these cables in THOR most likely caused the higher peak torsion moment, but closer to the PMHS peak magnitude. Reducing the free rotation stop angle of the 45° in THOR-AV design, which means earlier stop, may help to increase its peak torsion moment. However, the limited PMHS test may not be sufficient to determine a dummy neck design target.

The neck overall BioRank scores are 1.47, 1.88 and 1.96 for THOR-AV, THOR and HIII 50th respectively. The biofidelity for all three necks are “good”. THOR-AV has the best overall biofidelity among the three necks. While some of the biofidelity improvements can be directly related to the design differences among the three dummy necks, others are too complex to explain clearly.

There are limitations in this study. There are limited samples in some test conditions in [6], two PMHS in both lateral and oblique impact test, one PMHS in torsion tests. More PMHS samples are desired to generate more representative biofidelity corridors. Humanetics commercial FE dummy models were used to substitute the tests that were not accomplished due to the restrictions and limited resources during the COVID-19 pandemic. Though these FE models were extensively validated in other test conditions, they were not validated for the biofidelity tests they substituted for in this paper.

V. CONCLUSIONS

The THOR-AV neck was designed to address a few shortcomings observed from existing 50th percentile necks, including neck curvature, torsion responses, handling, front and rear cable durability. This new neck design has a humanlike lordotic curvature, a torsion element, and an increased cross section to represent human C1 to C7 anatomy. The humanlike neck curvature and torsion element provide a better approach to mimic human neck kinematics in complex loading conditions.

The biofidelity evaluation in six test conditions, i.e., two in frontal, two in lateral, one in oblique and one in torsion test, showed THOR-AV neck has the best biofidelity overall with a BioRank score of 1.48. Except for the Wismans lateral test condition, THOR-AV neck demonstrated better biofidelity than THOR and HIII 50th necks in each of the other five test conditions. The comparison showed that good biofidelity in both frontal and lateral test conditions does not necessarily guarantee good biofidelity in oblique test condition. More PMHS test samples are desired to generate representative biofidelity corridors. It was observed different biofidelity criteria can provide opposite BioRank results, which is worthy of investigating in the future to determine a priority preference for neck development.

VI. ACKNOWLEDGEMENT

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VIII. APPENDIX

The test data plots with biofidelity corridors and the neck BioRank scores B and dummy phase shift DPS, if not fully presented in the tables in the context, are presented in this appendix.

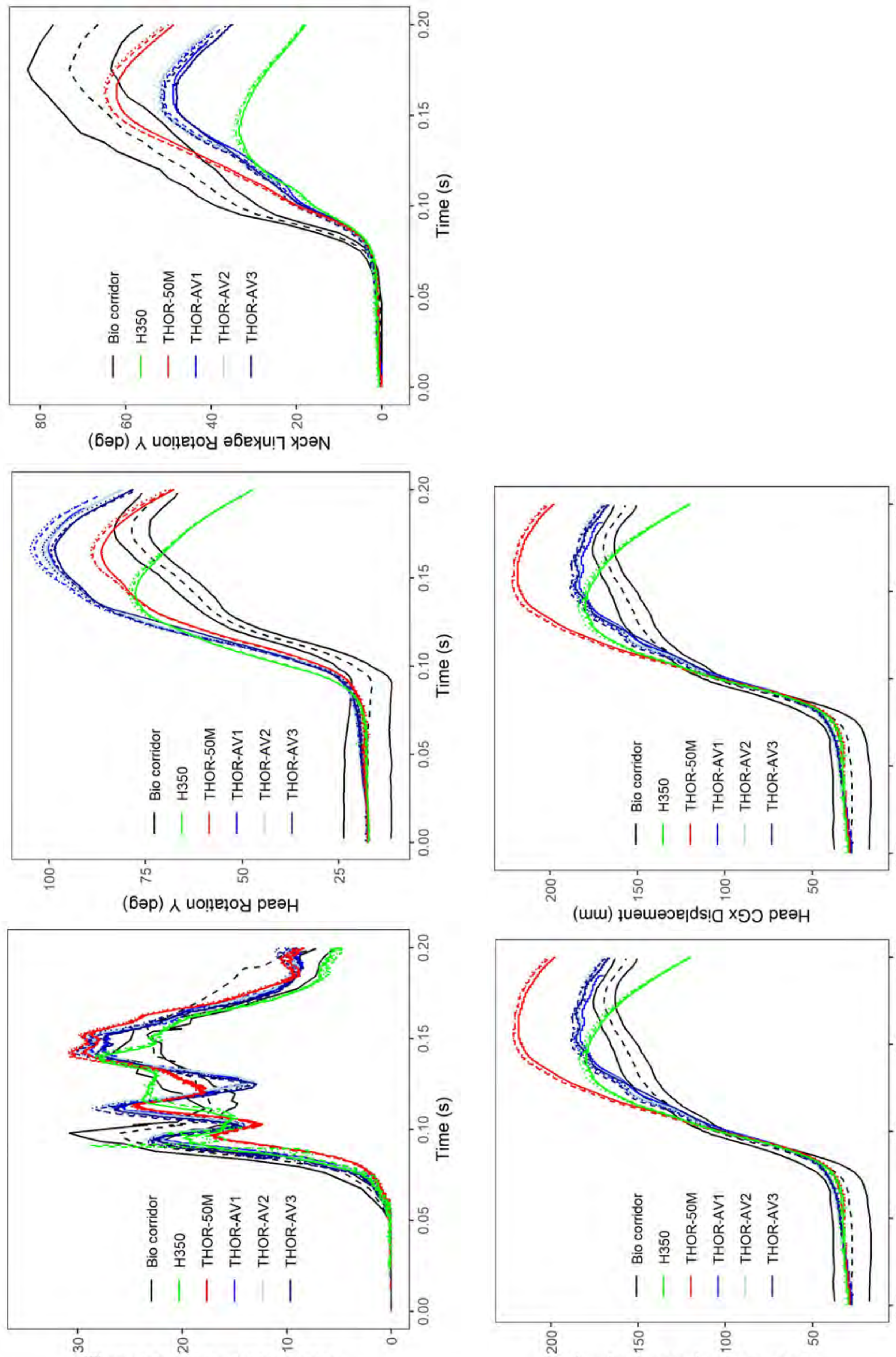


Figure A1, Neck responses in frontal flexion test condition of Thunnissen et al 1995

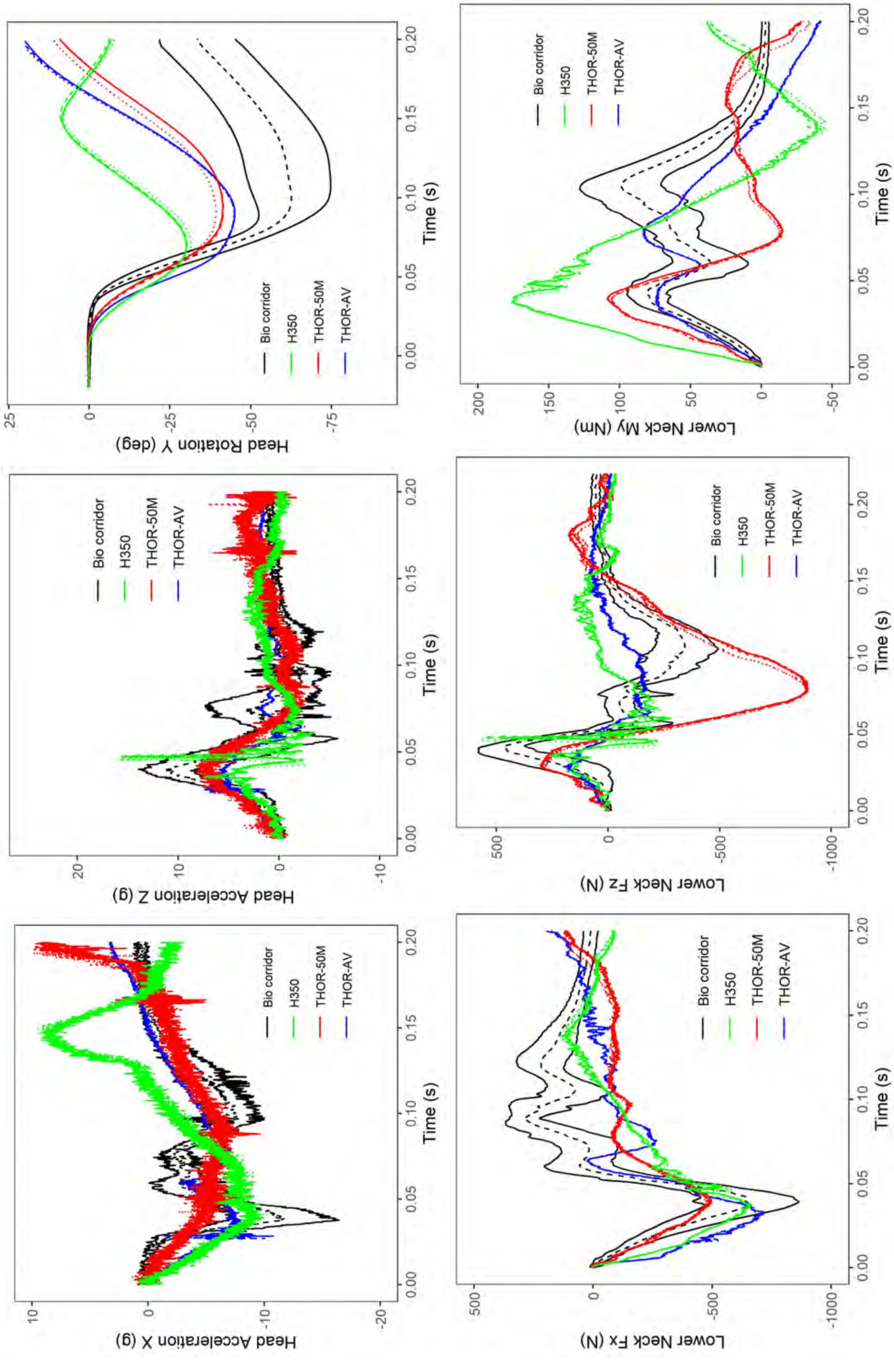


Figure A2, Neck responses in frontal flexion test condition of Kang et al 2018

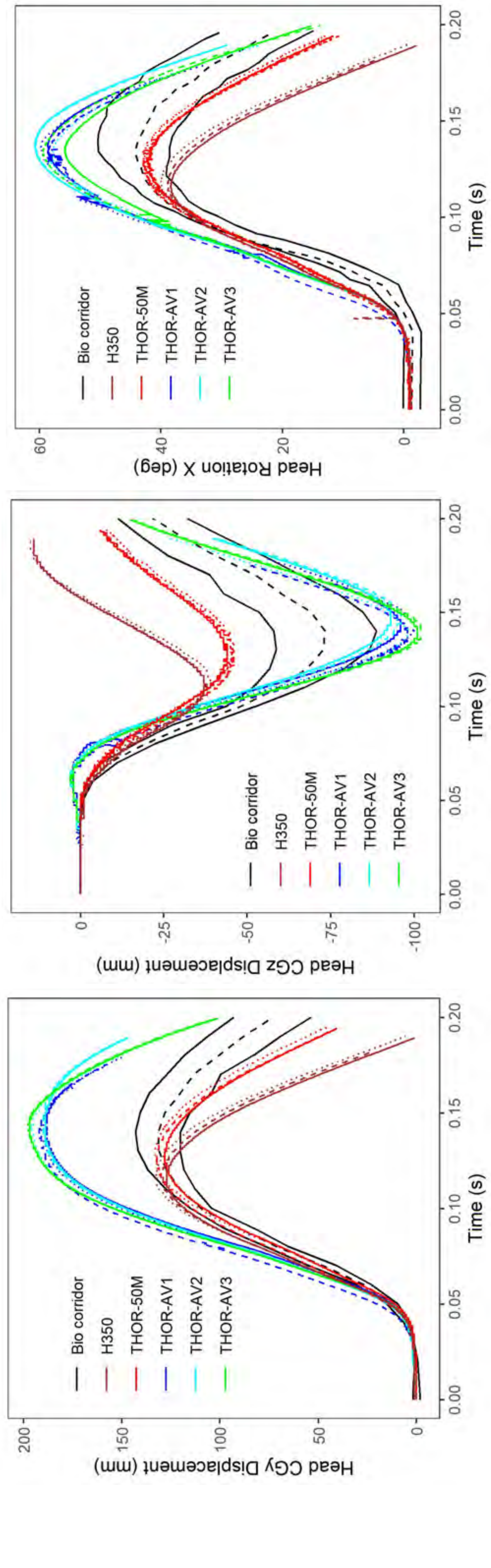


Figure A3, Neck responses in lateral test condition of Wismans et al 1983

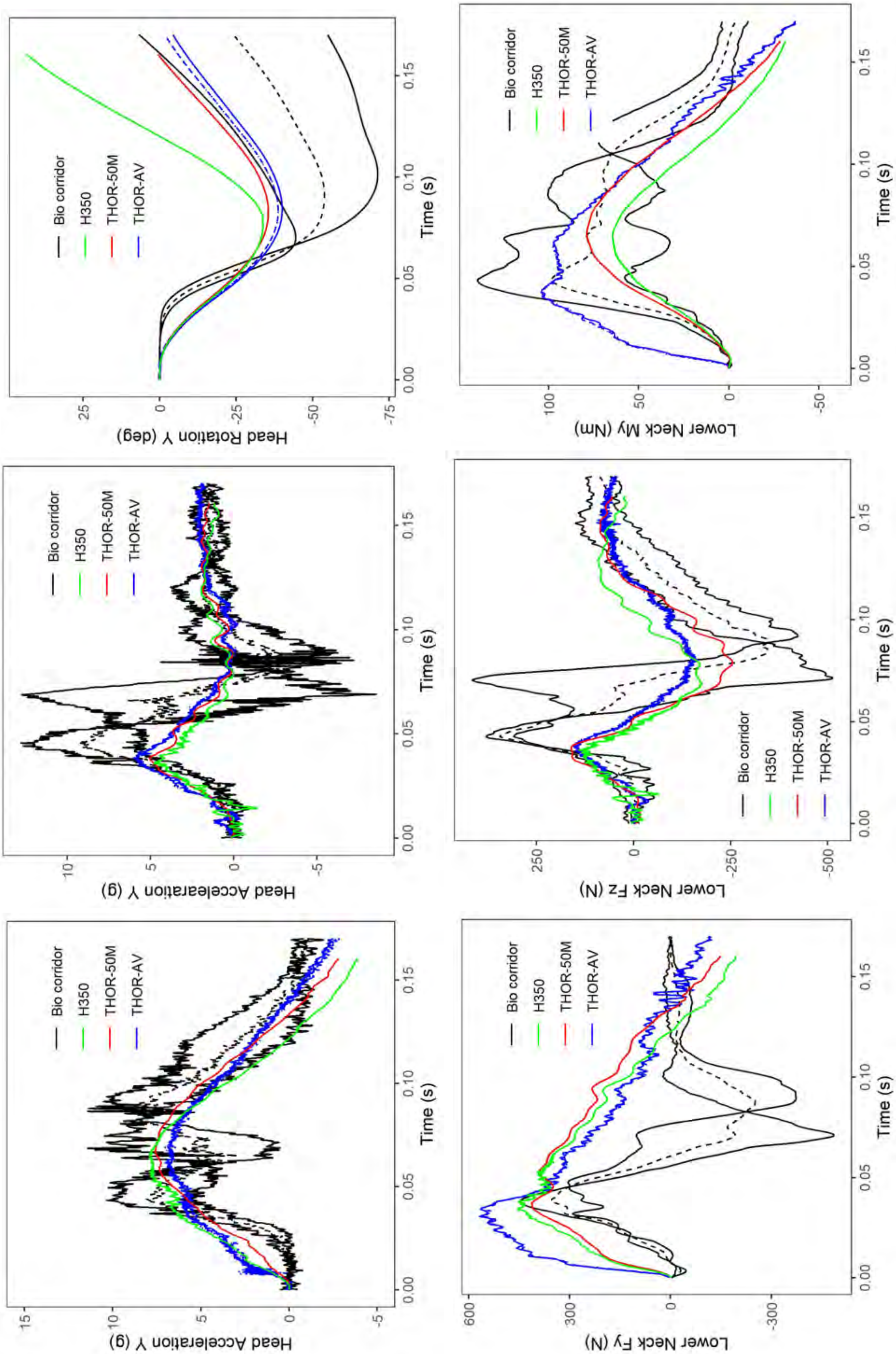


Figure A4 Neck responses in lateral flexion test condition of Kang et al 2018

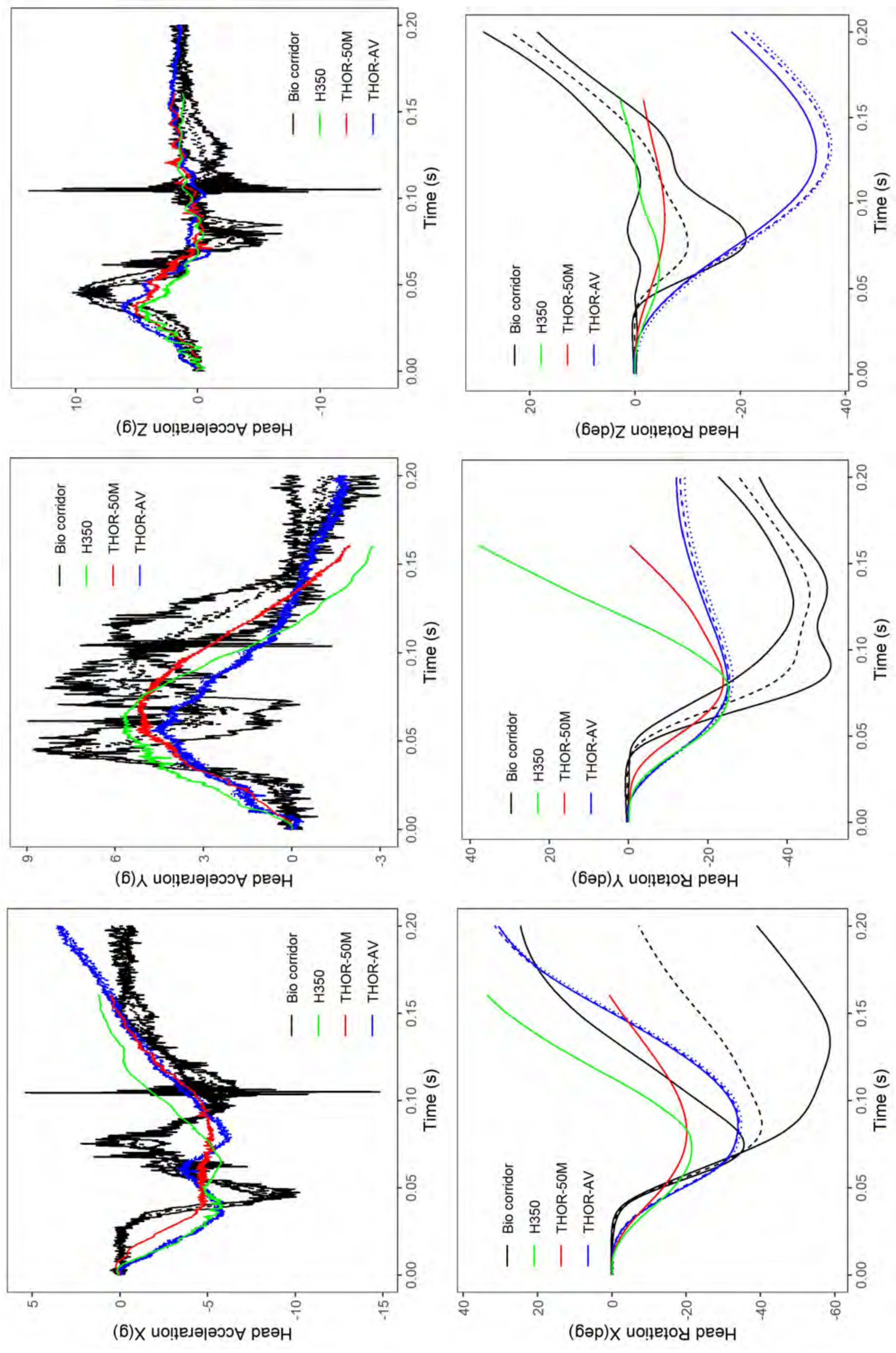
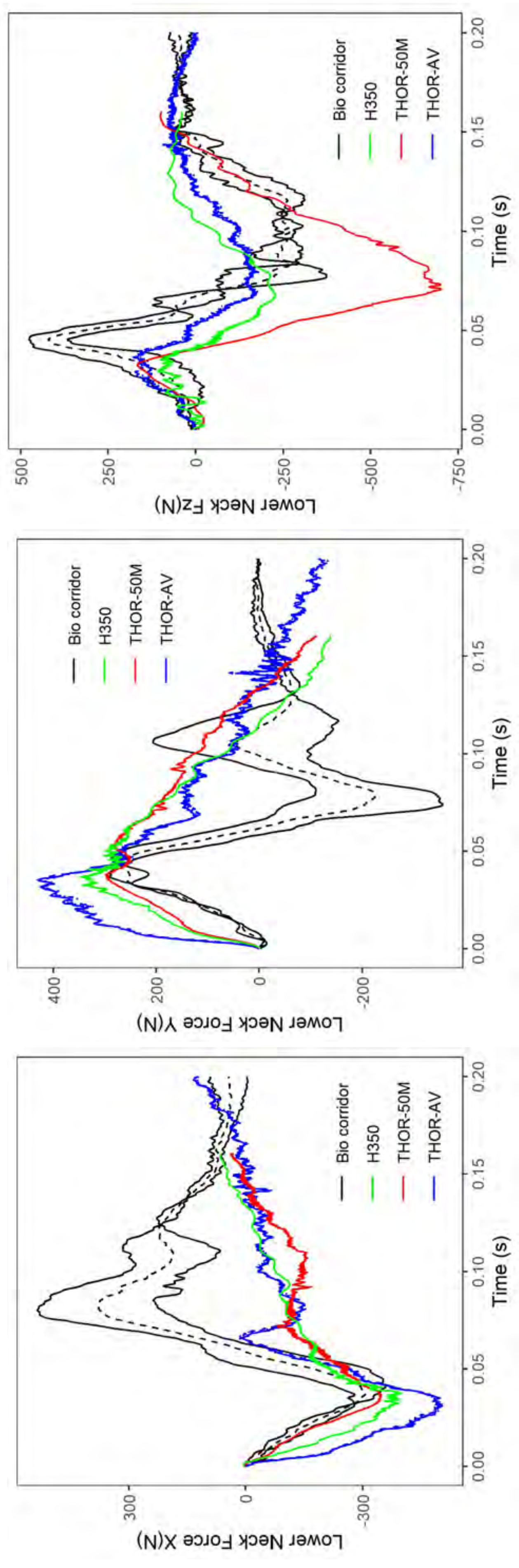


Figure A5 Neck responses in oblique test condition of Kang et al 2018


Lower Neck Force X(N)
300
0
-300
0.00
0.05
0.10
0.15
0.20
Time (s)
Bio corridor
H350
THOR-50M
THOR-AV
Lower Neck Force Y(N)
400
200
0
-200
0.00
0.05
0.10
0.15
0.20
Time (s)
Bio corridor
H350
THOR-50M
THOR-AV
Lower Neck Fz(N)
500
250
0
-250
-500
-750
0.00
0.05
0.10
0.15
0.20
Time (s)
Bio corridor
H350
THOR-50M
THOR-AV

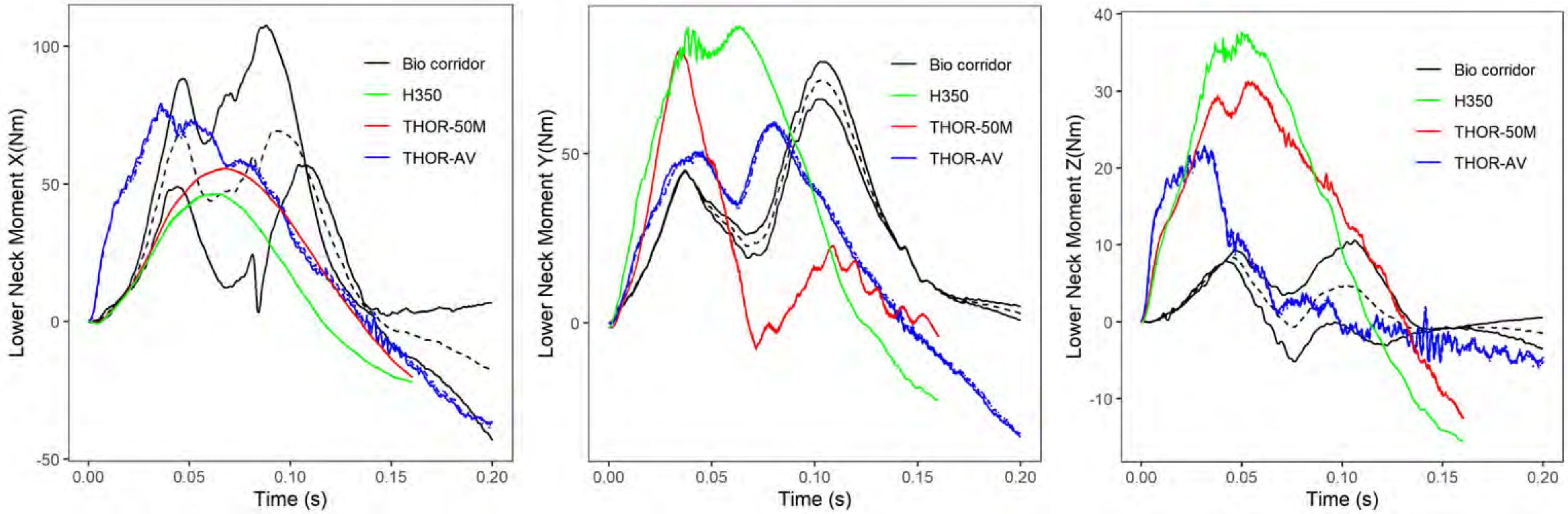


Figure A6 Neck responses in oblique flexion test condition of Kang et al 2018 (continued)

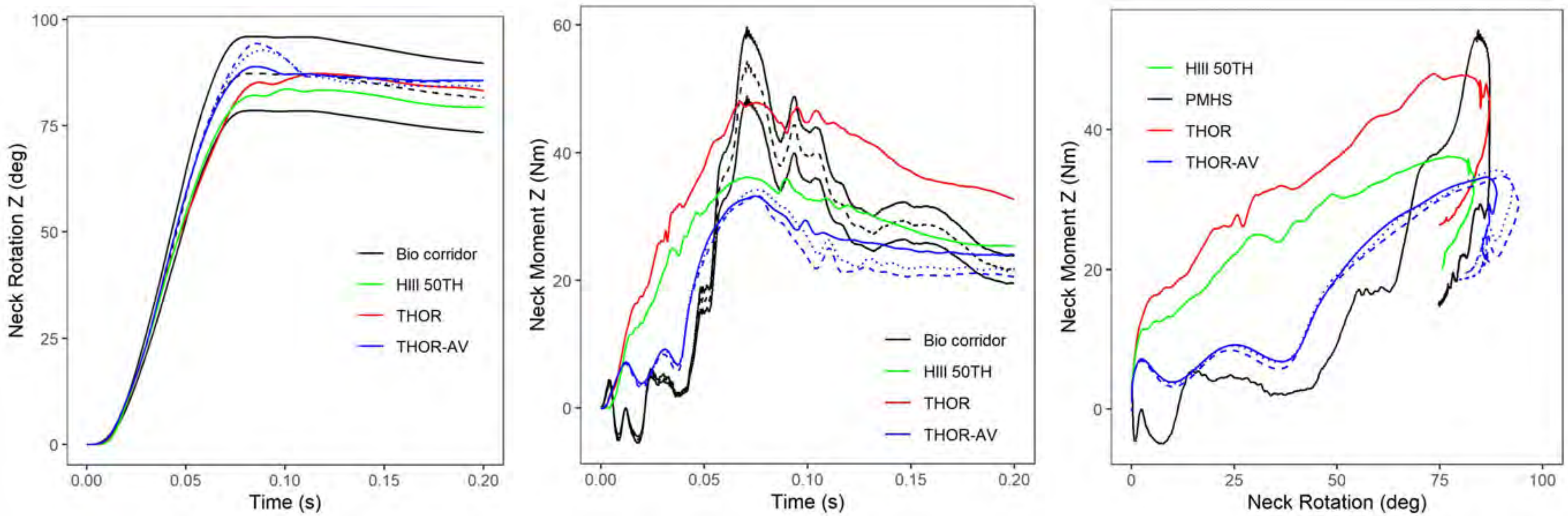


Figure A7 Neck responses in torsion test condition of Kang et al 2018

The full BioRank B score and DPS are shown in the following tables if DPS was not shown in the main context of this paper.

TABLE XII

B SCORES OF THOR-AV, THOR AND HIII 50TH NECKS IN THUNNISSEN ET AL (1995) TEST CONDITION

		Head Resultant Acceleration		Head Y-Rotation		Neck Y-Rotation		Head CG X-Displacement		Head CG X-Displacement		Test
	Test ID	B	DPS (s)	B	DPS (s)	B	DPS(s)	B	DPS	B	DPS(s)	B
THOR-AV	EN1978-0	1.27	-0.0038	1.60	0.0230	2.08	-0.0148	0.99	-0.0007	0.35	0.0034	1.26
	EN1978-1	1.35	-0.0039	1.74	0.0246	1.99	-0.0123	1.17	0.0007	0.45	0.0036	1.34
	EN1978-2	1.42	-0.0032	1.78	0.0250	1.88	-0.0128	1.17	0.0005	0.48	0.0034	1.35
											Average	1.32
	EP2034-1	1.38	-0.0035	1.63	0.0205	1.95	-0.0104	1.14	0.0003	0.44	0.0044	1.31
	EP2034-2	1.40	-0.0031	1.64	0.0231	1.91	-0.0101	1.16	0.0012	0.49	0.0052	1.32
	EP2034-3	1.43	-0.0033	1.69	0.0236	1.83	-0.0104	1.25	0.0014	0.55	0.0045	1.35
											Average	1.33
	EO1786-1	1.25	-0.0026	1.51	0.0174	2.18	-0.0107	1.07	-0.0007	0.30	0.0054	1.26
	EO1786-2	1.52	-0.0014	1.57	0.0190	2.02	-0.0090	1.24	0.0019	0.39	0.0058	1.35
	EO1786-3	1.58	-0.0019	1.67	0.0212	1.93	-0.0101	1.10	0.0007	0.43	0.0050	1.34
											Average	1.32
											Average of the averages	1.32
THOR	EO1927-1	1.56	-0.0070	0.78	0.0093	0.98	-0.0094	2.65	0.0042	0.49	0.0019	1.29
	EO1927-2	1.63	-0.0067	0.85	0.0098	0.88	-0.0074	2.77	0.0048	0.61	0.0018	1.35
	EO1927-3	1.63	-0.0069	0.88	0.0096	0.85	-0.0080	2.78	0.0038	0.63	0.0010	1.35
											Average	1.33
H350	EL8550-1	1.40	0.0011	0.60	0.0176	3.55	-0.0085	1.20	0.0042	1.52	0.0001	1.65
	EL8550-2	1.64	0.0007	0.62	0.0180	3.52	-0.0086	1.24	0.0042	1.47	-0.0001	1.70
	EL8550-3	1.52	0	0.63	0.0185	3.49	-0.0081	1.30	0.0051	1.48	-0.0003	1.68
											Average	1.68

TABLE XIII

NECK BIORANK B SCORE AND DPS FOR THOR-AV, THOR, HIII 50TH IN KANG ET AL 2018 FRONTAL TEST CONDITION

		Head Ax		Head Ax		Head Ry		Lower Neck Fx		Lower Neck Fz		Lower Neck My		Test
	Test ID	B	DPS (s)	B	DPS (s)	B	DPS (s)	B	DPS (s)	B	DPS (s)	B	DPS (s)	B
THOR-AV	EO1786-1	0.90	0.0157	0.84	0.0004	2.16	0.0346	1.37	-0.1086	1.28	0.0133	1.11	0.0159	1.28
	EO1786-2	0.89	0.0154	0.86	-0.0005	2.17	0.0351	1.37	-0.1091	1.28	0.0117	1.10	0.0155	1.28
	EO1786-3	0.89	0.0144	0.88	0.0005	2.19	0.0357	1.36	-0.1087	1.26	0.0123	1.09	0.0154	1.28
													Average	1.28
THOR	THOR-01	1.23	0.0085	0.96	0.0037	2.14	0.0173	1.81	-0.0012	2.79	0.0059	1.89	0.0654	1.80
	THOR-02	1.24	0.0089	0.94	0.0038	2.11	0.0174	1.81	-0.0007	2.81	0.0065	1.88	0.0667	1.80
	THOR-03	1.21	0.0121	1.01	0.0054	2.35	0.0224	1.78	-0.0008	2.60	0.0070	1.88	0.0665	1.81
													Average	1.80
H350	HIII50-02	2.07	0.0619	1.20	0.0114	3.41	0.0722	1.57	0.0035	1.91	0.0121	2.63	0.0323	2.13
	HIII50-03	2.13	0.0591	1.21	-0.0772	3.39	0.0714	1.57	0.0028	1.90	0.0500	2.56	0.0318	2.13
	HIII50-04	2.16	0.0621	1.21	0.0127	3.32	0.0700	1.57	0.0038	1.91	0.0495	2.62	0.0308	2.13
													Average	2.13

TABLE XIV

NECK BIORANK B SCORES AND DPS FOR THOR-AV, THOR, HIII 50TH KANG ET AL 2018 LATERAL TEST CONDITION

		Head Ay		Head Az		Head X-Rotation		Lower Neck Fy		Lower Neck Fz		Lower Neck Mx		Test
	Test ID	B	DPS (s)	B	DPS (s)	B	DPS (s)	B	DPS (s)	B	DPS (s)	B	DPS (s)	B
THOR-AV	EO1786-1	0.58	0.012	0.66	0.0071	0.74	0.016	2.04	-0.095	0.66	0.0117	0.50	0.0138	0.86
	EO1786-2	0.57	0.0117	0.65	0.0070	0.82	0.0152	2.04	-0.095	0.65	0.0123	0.50	0.0143	0.87
	EO1786-3	0.55	0.0128	0.65	0.0074	0.82	0.0154	2.03	-0.095	0.65	0.0125	0.51	0.0144	0.87
													Average	0.87
THOR	FE	0.63	0.0093	0.68	0.0058	1.01	0.0166	2.46	-0.0836	0.52	0.0123	0.70	0.0119	1.00
H350	FE	0.66	0.0183	0.76	0.0078	1.42	0.0501	2.82	-0.0794	0.84	0.0177	1.06	0.0259	1.26

TABLE XV

NECK BIORANK B SCORES AND DPS FOR THOR-AV, THOR AND HIII 50TH IN KANG ET AL 2018 OBLIQUE TEST CONDITION

		Head Acceleration						*Head Rotation*					
		X		Y		Z		X		Y		Z	
	Test ID	B	DPS (s)	B	DPS (s)	B	DPS (s)	B	DPS (s)	B	DPS (s)	B	DPS (s)
THOR-AV	EO1786-1	2.08	0.0172	0.95	0.0238	1.15	0.0084	0.49	0.0298	3.05	0.0214	2.61	0.0104
	EO1786-2	2.11	0.0167	0.95	0.0239	1.12	0.0073	0.49	0.0288	2.94	0.0202	2.64	0.0106
	EO1786-3	2.02	0.0169	0.92	0.0232	1.15	0.0078	0.47	0.0271	2.82	0.0209	2.75	0.0090
THOR	FE	1.97	0.0116	0.81	0.0133	1.33	0.0026	0.74	0.0418	4.02	0.0287	1.99	-0.0170
H350	FE	2.58	0.0296	1.00	0.0260	1.31	0.0063	0.89	0.0773	4.47	0.0820	1.38	0.0396

TABLE XV (continued)

		Lower Neck												Test
		Fx		Fy		Fz		Mx		My		Mz		
	Test ID	B	DPS (s)	B	DPS (s)	B	DPS (s)	B	DPS (s)	B	DPS (s)	B	DPS (s)	B
THOR-AV	EO1786-1	1.94	-0.1072	1.90	-0.1100	1.45	0.0144	0.61	0.0189	6.52	0.0248	2.27	0.0278	2.08
	EO1786-2	1.91	-0.1072	1.92	-0.1100	1.43	0.0133	0.60	0.0177	6.38	0.0233	2.27	0.0229	2.06
	EO1786-3	1.90	-0.1072	1.93	-0.1100	1.43	0.0137	0.60	0.0179	6.35	0.0233	2.27	0.0271	2.05
													Average	2.06
THOR	FE	2.37	-0.0778	2.78	0.0047	3.47	0.0187	0.71	0.0111	8.75	0.0673	6.32	0.1099	2.94
H350	FE	2.28	-0.0763	2.83	0.0047	1.75	0.0255	1.04	0.0272	11.15	0.0322	7.05	0.0785	3.14