Rear Impact Head and Cervical Spine Kinematics of BioRID II and PMHS in Production Seats

Yun-Seok Kang, Kevin Moorhouse, Kyle Icke, Jim Stricklin, Rod Herriott, John Bolte IV

Abstract In a previous study, a comparison of cervical spine kinematics between a current rear impact dummy, BioRID II, and post mortem human subjects (PMHS) was made by subjecting them to moderate speed rear impacts while positioned in an experimental seat. The objective of this study is to make a similar comparison of head and cervical spine kinematics in more realistic production seat conditions. A total of seven sled tests using seven PMHS (males 181.9 ± 3.9 cm of stature and 79.0 ± 4.7 kg of weight) were conducted in several moderate speed rear impact test conditions. The BioRID II was also tested under the same conditions, with each cervical vertebra instrumented with one angular rate sensor so that rotational kinematics of the cervical spine of BioRID II could be compared to those measured from the PMHS. Results show that the BioRID II exhibited generally comparable results to the PMHS, although the biofidelity of the BioRID spine in flexion could be improved. As seen previously in the experimental seat, the intervertebral rotations for both PMHS and the BioRID II in the production seats were primarily relative forward rotations (i.e. intervertebral flexion) even though the cervical vertebrae rotated rearward with respect to the global coordinate system. Contrary to the experimental seat, a transition to relative rearward rotation (i.e. intervertebral extension) occurs in the lower spine of the BioRID in the two production seats in this study.

Keywords Anthropomorphic Test Device (ATD), BioRID, cervical spine injury, intervertebral kinematics, whiplash.

I. INTRODUCTION

Claims of cervical spine injuries (e.g. whiplash) in rear impact collisions are very common and result in enormous societal cost, with estimates on the order of $2.7 billion annually [1]. Cervical spine injuries have also been identified as a serious problem in Europe and Asia [2-3]. Societal cost in Europe resulting from this type of injury is approximated to be between €5 and €10 billion per year [3]. It is reported that 50% of vehicle collisions resulted in cervical injuries in Japan [2]. Cervical spine injuries can result from frontal and rear impact crashes, but their risk in rear impact crashes is twice that of frontal impact crashes [4].

In order to reduce the possibility of cervical spine injuries, car manufacturers have been developing seats that include improved restraint systems, seat properties (e.g. stiffness of seat-backs, dynamic behavior of recliners and properties of seat foam) and head restraint design as a result of FMVSS No. 202a. For this development process, anthropomorphic test devices (ATDs) have been used to improve safety of seats and restraint systems in rear impacts [5-7]. There are two ATDs designed specifically for rear impact: BioRID II [8] and RID3D [9]. The biofidelity of these ATDs has been evaluated extensively [8-20], but these studies have focused on comparison of global measures (e.g. head and T1 kinematics) obtained from human volunteers and/or PMHS with those obtained from the rear impact ATDs, rather than comparing detailed intervertebral kinematics of the entire cervical spine. In 2012, eight unembalmed PMHS and rear impact ATDs were tested under an identical test condition in two moderate speeds (8.5 g and 17 km/h; 10.5 g and 24 km/h) using an experimental seat [19]. Additionally, an instrumentation technique for measuring the kinematics of each vertebra in the PMHS cervical spine was developed, validated and used to assess the cervical kinematics of the PMHS in that test series [21]. An angular rate sensor was installed on each of the cervical vertebrae of the

Y. Kang, Ph.D. is a research scientist at Injury Biomechanics Research Center at the Ohio State University in Columbus, OH, USA (e-mail: yunseok.kang@osumc.edu, tel: 1.614.366.7584, fax: 1.614.292.7659). K. Moorhouse, Ph.D. is at National Highway Traffic Safety Administration (NHTSA), J. Stricklin, R. Herriott are at Transportation Research Center Inc. K. Icke, Ph.D. and J. Bolte, Ph.D. are at the Ohio State University.

BioRID II so that rotations of the cervical spine of the BioRID II could be compared to those measured from the PMHS [21]. They found that the BioRID II exhibited comparable results to the PMHS in the 17 km/h test. For the 24 km/h test, the cervical spine of the BioRID II exhibited less extension than the PMHS at all levels (C2–C7) [21]. It is also reported that the intervertebral rotations for both the PMHS and the BioRID II were primarily relative flexion rotations, even though the cervical vertebrae rotated rearward with respect to the global coordinate system [21]. No previous studies have evaluated rotations measured from the cervical vertebrae of the BioRID II compared to those measured from PMHS in identical sled test conditions using production seats. Therefore, the objective of this study is to make a similar comparison of head and cervical spine kinematics in more realistic production seat conditions.

II. METHODS

Rear Impact Sled Tests Using PMHS and BioRID II

The post mortem human subjects (PMHS) used for this study were available through the Ohio State University's Body Donor Program and all applicable National Highway Traffic Safety Administration (NHTSA) and University guidelines, as well as IRB protocol, were reviewed and followed. Rear impact sled tests using PMHS on a Hydraulic-controlled, Gas-Energized (HyGE) sled were conducted using three different pulses (FMVSS 202a [1], JNCAP [22] and 10.5 g, 24 km/h [23]), as shown in Table I. A total of seven rear impact sled tests were conducted with seven different PMHS using two different types of production seats (seat A and seat B) in the three speeds (Table I). The production seats used in this study do not have any advanced features (e.g. active head restraints). Model years for Seat A and B were 2011 and 2010, respectively, so the head restraints of both seats were presumed compliant with FMVSS 202a. The BioRID II was also tested under identical test conditions such that a direct comparison can be made. Only five matched BioRID II tests were conducted in this study, as two of the PMHS tests were repeated test conditions (Table I).

TABLE I

TEST SEVERITY AND TEST MATRIX

Test#	PMHS	ATD	Pulse name	Max. sled acceleration (g)	ΔV (km/h)	Seat type
Test1	PMHS1	BioRID II	202a	8.1	16.0	Seat A
Test2	PMHS2	BioRID II	JNCAP	10.6	17.5	Seat A
Test3	PMHS3	Not tested	JNCAP	10.8	17.8	Seat B
Test4	PMHS4	Not tested	24kph	10.3	24.8	Seat B
Test5	PMHS5	BioRID II	JNCAP	10.7	17.8	Seat B
Test6	PMHS6	BioRID II	24kph	10.3	24.7	Seat A
Test7	PMHS7	BioRID II	24kph	10.3	24.9	Seat B

Detailed anthropometric information and selection criteria of the PMHS were reported in the previous study [24]. Seven unembalmed male subjects (74 ± 8 year old) were used, and their average size was comparable to a 50th percentile male with an average weight of 79.0 ± 4.7 kg and height of 181.9 ± 3.9 cm. The BioRID II has similar weight (78.2 kg) as the average PMHS weight (79.0 kg), while its head mass and seated height were heavier and taller than those average values obtained from the PMHS (Table II). The seating procedure for the BioRID II was based on guidelines found in the user manual [27]. Before seating the BioRID II, the H-point of each production seat was determined using an OSCAR H-point device as required for the seating procedure of the BioRID II. The seat back angle was set up as 25 degrees based on SAE J826 for all tests. The detailed seating procedures for the BioRID II and PMHS were reported in previous studies [19][23]. Target backset (i.e. horizontal distance between the head and the head restraint) and topset (i.e. vertical distance from the center of gravity of the head to the top surface of the head restraint) were 50 ± 5 mm and 80 ± 5 mm, respectively. The backset and topset information for both PMHS and BioRID II is provided in Table III. However, some PMHS used in this study could not satisfy topset tolerances due to the nature of the PMHS spine curvature and limited adjustability of the head restraint (HR) of the production seats. Therefore, the topset for the BioRID II were set up similar to those measured from matched PMHS, while the backset was within the tolerance range (i.e. 50 ± 5 mm). Photographs of the general set-up and initial positioning for the sled tests are shown in Fig. 1. Strips of conductive tape were placed on both the posterior aspect of the head and the anterior surface of the HR to record head-to-HR contact times. A three-point belt was used to restrain the PMHS and the BioRID II on the seats, with initial belt tensions of 17.8 N (4lb) for the lap-belt and 26.7 N (6lb) for the shoulder-belt. The initial seat-back angle was approximately 25 degrees from the vertical (Z-axis according to SAE J211). The seat was replaced following each sled test.

TABLE II
AGE, SEATED HEIGHT, WEIGHT AND HEAD MASS FOR BOTH PMHS AND BIORID II
unit: mm and kg

	Age	Seated Height	Weight	Head Mass
PMHS1	67	80.0	83.0	4.2
PMHS2	82	75.0	78.5	4.1
PMHS3	66	80.0	81.6	4.0
PMHS4	65	83.0	75.3	3.8
PMHS5	78	78.0	78.5	3.8
PMHS6	86	81.0	84.8	3.8
PMHS7	71	80.0	71.2	4.0
Mean (SD)	N/A	79.6 (2.5)	79.0 (4.7)	4.0 (0.2)
BioRID II	NA	88	78.2	4.5

TABLE III
BACKSET AND TOPSET INFORMATION
unit: mm

	Backset		Topset	
Test#	PMHS	BioRID II	PMHS	BioRID II
Test1	55	53	112	106
Test2	50	51	97	93
Test3	75	N/A	78	N/A
Test4	50	N/A	65	N/A
Test5	55	53	79	82
Test6	55	54	81	83
Test7	52	55	79	74
Mean (SD)	56.0 (8.7)	53.2 (1.5)	84.4 (15.3)	87.6 (12.3)

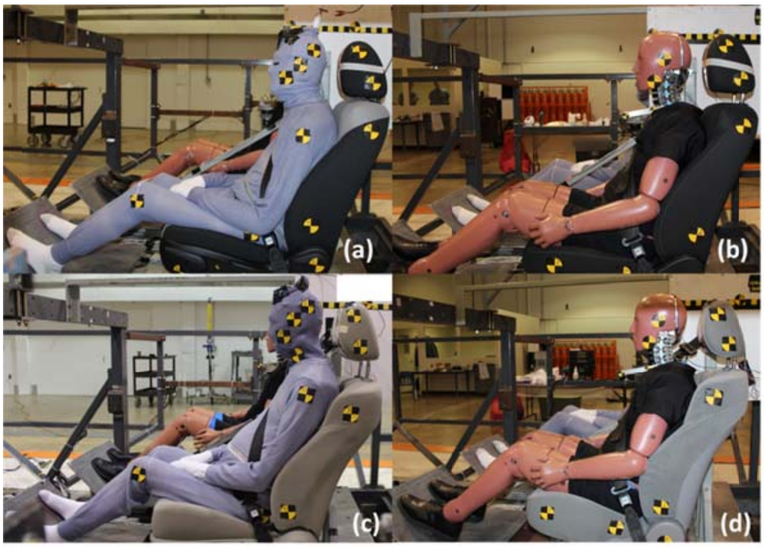


Fig. 1. General set-up for the sled tests: (a) PMHS seated in seat A; (b) BioRID II seated in seat A; (c) PMHS seated in seat B; (d) BioRID II seated in seat B

Head and neck instrumentation

For the PMHS instrumentation, head kinematics were measured using six accelerometers and three angular rate sensors (6aw) installed on an aluminum tetrahedron fixture, while cervical kinematics were recorded using three accelerometers and three angular rate sensors (3aw) installed on the anterior aspect of the cervical vertebral bodies (C2–C7), as described in the previous study [24]. For the BioRID II instrumentation, a 3aw block was installed at the center of gravity (CG) of the head. Threaded holes for installing angular rate sensors on the lateral aspect of the cervical vertebrae (C2–C7) of the BioRID II were created by the manufacturer (Humanetics, Inc.) so that the BioRID II had the capability of measuring neck angular kinematics. The angular rate sensors (ARS) were attached to each cervical vertebra in alternating fashion (C3, C5 and C7 on the right side, and C2, C4 and C6 on the left side), as shown in Fig. 2. Due to limited space between each cervical vertebra, accelerometers for linear kinematics cannot be installed on the BioRID II cervical spine. Although the instrumentation on the PMHS cervical spine is capable of measuring linear kinematics, the pinned vertebral joints of the BioRID II neck do not allow for relative translation, so only angular kinematics measured from the BioRID II are reported in this study. For the T1 instrumentation of the BioRID II, two accelerometers and one ARS were installed on the left side of the T1. One redundant ARS was installed on the right side of the T1, but results from this redundant ARS were similar to the one on the left side with a maximum 0.2 degree error for all tests, so only kinematics from the left side are reported in this paper. Although more instrumentation was installed on both PMHS and BioRID II, the focus of this study is only on the head, cervical spine and T1 kinematics.

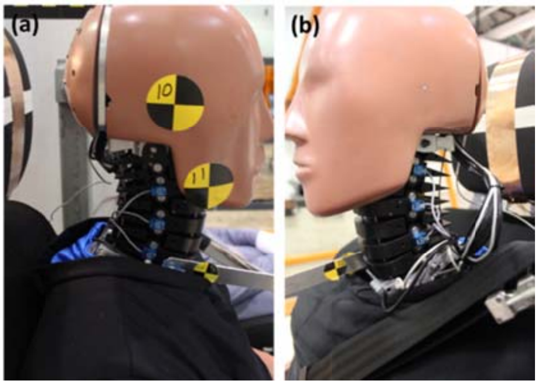


Fig. 2. Angular rate sensors installed on each cervical vertebra of the BioRID II: (a) right view; (b) left view.

Data processing

The sampling frequency used in all sled tests was 12,500 Hz and all data obtained from the tests were filtered according to SAE J211. SAE J211 coordinate system and sign conventions were used for the head, cervical and T1 kinematics. The influence of gravity on the accelerometers was compensated for [25]. Data measured from the PMHS head instrumentation were transformed to the center of gravity (CG) in the body-fixed coordinate system, such that a direct comparison of head kinematics at the PMHS CG with those measured at the BioRID II CG can be made. The instrumentation blocks installed on the PMHS cervical vertebrae were digitized to transform the data measured from the blocks to the antero-superior edge of each cervical vertebral body. Angular velocity recorded from the ARS installed on the BioRID II cervical vertebrae was numerically integrated to determine cervical rotations. In order to quantify comparison of kinematics measured from both PMHS and BioRID II over time, the normalized root mean squared deviation (NRMSD), shown in Equation (1), was used. The NRMSD provided an average percent error over time between the PMHS data and BioRID II data. Before the NRMSD calculation, phase differences between PMHS and BioRID II kinematics were first removed. It should be noted that this phase shift was only for NRMSD calculation purposes. All time history plots presented in this study kept original phasing (i.e. no time shift) to qualitatively provide magnitude, shape and phase differences between PMHS and BioRID II. The relevant time window used for the NRMSD calculation was from 0 ms (when the sled begins moving) to 150 ms (approximately when the head leaves the head restraint).

$$NRMSD = \frac{\sqrt{\frac{1}{n}\sum_{i=0}^{n}(Y_i - Y_i')^2}}{Y'_{\max} - Y'_{\min}} \quad (1)$$

Where n is the total number of data points, $Y'max$ and $Y'min$ represent the maximum and minimum values of the PMHS data, Yi and $Y'i$ are the ith data point obtained from the response being evaluated (e.g. BioRID II data) and the ith data point obtained from the response being compared to (PMHS data), respectively.

III. RESULTS

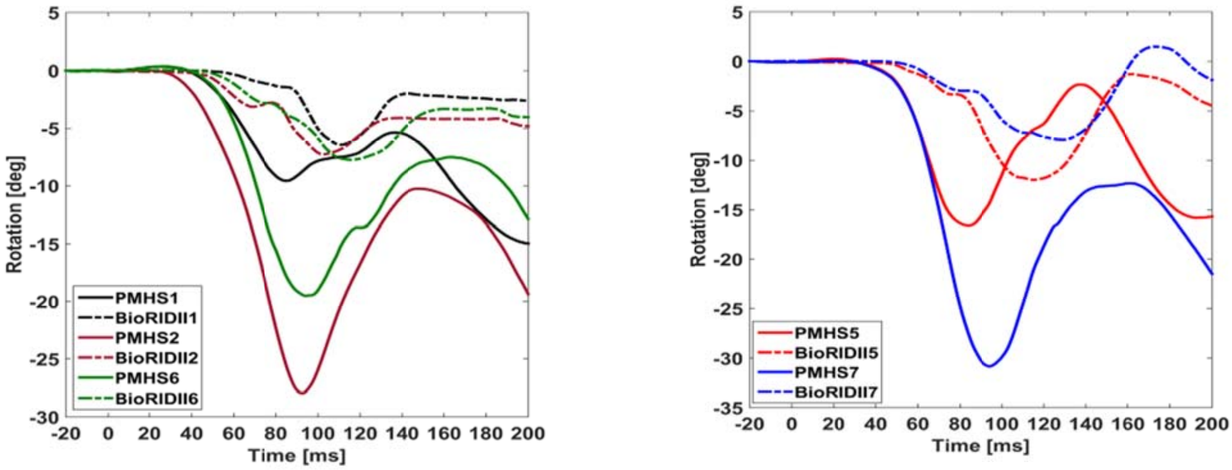
For all comparison plots in this paper, the PMHS is plotted with solid lines, and the BioRID II with dotted lines. Kinematic data were plotted by each seat (e.g. seat A: Test1, 2, and 6; seat B: Test5 and 7). PMHS numbers, sled inputs, NRMSD and seats used in each test are shown in the caption of each Figure.

Head and T1 kinematics

Both PMHS and BioRID II responses for the acceleration of the head and T1 in the x- and z-direction and rotation of the head and T1 about the y-axis are shown in Fig. A1 and Fig. A2, respectively. The NRMSD values ranged from 8% to 41% for the head kinematics (Fig. A1), while those from the T1 kinematics ranged from 10% to 34% (Fig. A2).

Head rotation relative to T1

Figure 3 shows the head rotation with respect to T1 about the y-axis. The PMHS exhibited a large head forward rotation relative to T1 (i.e. neck flexion) for most of the event, and the magnitude of the relative rotation increased with increasing test severity, as shown in Fig. 3. (a) and (b). The BioRID II showed this general behavior but with relative forward rotations of much less magnitude. NRMSD for comparison of the PMHS with the BioRID II were over 34% for all tests, with an average of 37.7 ± 3.2%).



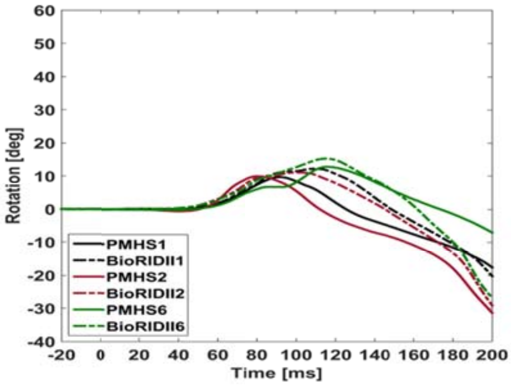
(a) Seat A.
PMHS1 vs. BioRIDII1 (FMVSS202a): NRMSD = 36.44%
PMHS2 vs. BioRIDII2 (JNCAP): NRMSD = 40.10%
PMHS6 vs. BioRIDII6 (24 km/h): NRMSD = 35.60%

(b) Seat B.
PMHS5 vs. BioRIDII5 (JNCAP): NRMSD = 34.50%
PMHS7 vs. BioRIDII7 (24 km/h): NRMSD = 42.01%

Fig. 3. Head rotation relative to T1 rotation (average NRMSD of 37.7 ± 3.2%)

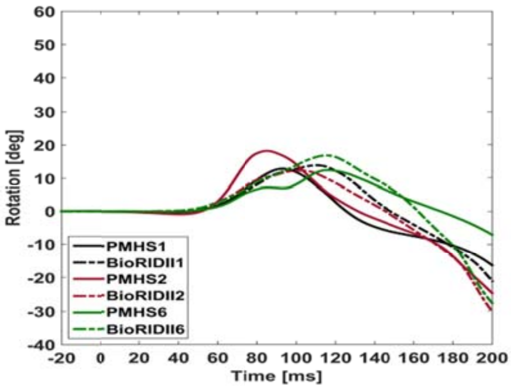
Cervical rotations

Cervical rotations (e.g. C2–C7) for both PMHS and BioRID II were plotted in the global y-axis, as shown in Fig. 4 (Seat A) and Fig. 5 (Seat B). The NRMSD values ranged from 7% to 34% for Seat A (Fig. 4) and 16% to 36% for Seat B (Fig. 5).



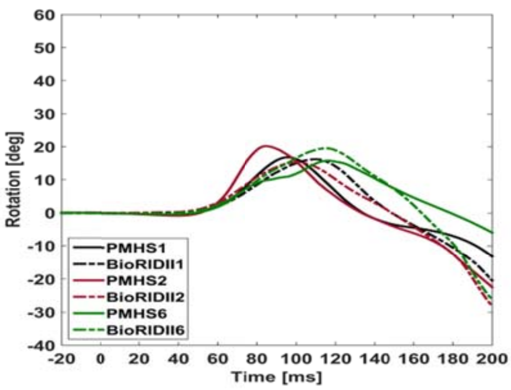
(a) C2.

PMHS1 vs BioRIDII1: NRMSD = 28.42%
PMHS2 vs BioRIDII2: NRMSD = 29.65%
PMHS6 vs BioRIDII6: NRMSD = 15.43%
Average NRMSD = 24.5 ± 7.9%



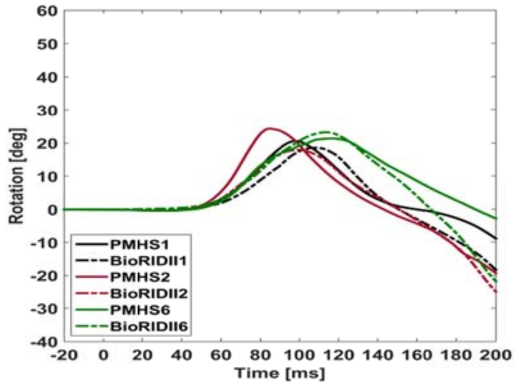
(b) C3.

PMHS1 vs BioRIDII1: NRMSD = 24.32%
PMHS2 vs BioRIDII2: NRMSD = 17.07%
PMHS6 vs BioRIDII6: NRMSD = 21.23%
Average NRMSD = 20.9 ± 3.6%



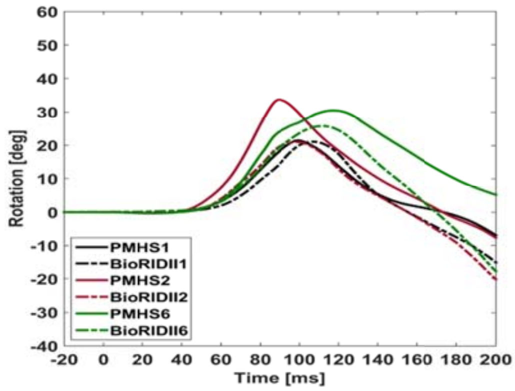
(c) C4.

PMHS1 vs BioRIDII1: NRMSD = 17.95%
PMHS2 vs BioRIDII2: NRMSD = 16.57%
PMHS6 vs BioRIDII6: NRMSD = 12.38%
Average NRMSD = 15.6 ± 2.9%



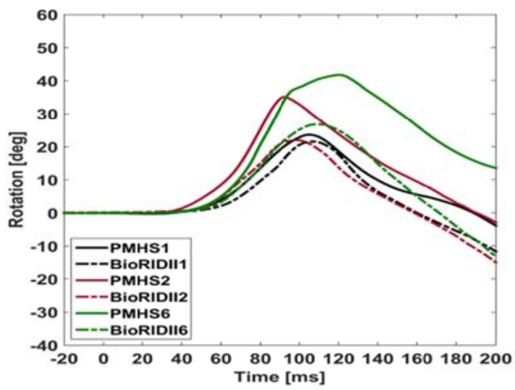
(d) C5.

PMHS1 vs BioRIDII1: NRMSD = 12.32%
PMHS2 vs BioRIDII2: NRMSD = 16.17%
PMHS6 vs BioRIDII6: NRMSD = 7.05%
Average NRMSD = 11.8 ± 4.6%



(e) C6.

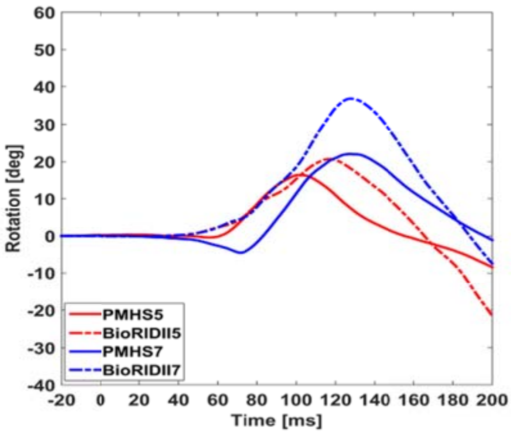
PMHS1 vs BioRIDII1: NRMSD = 9.64%
PMHS2 vs BioRIDII2: NRMSD = 19.57%
PMHS6 vs BioRIDII6: NRMSD = 20.81%
Average NRMSD = 16.7 ± 6.1%



(f) C7.

PMHS1 vs BioRIDII1: NRMSD = 10.05%
PMHS2 vs BioRIDII2: NRMSD = 23.63%
PMHS6 vs BioRIDII6: NRMSD = 33.71%
Average NRMSD = 22.5 ± 11.9%

Fig. 4. Cervical rotation about y-axis using Seat A (Test1: FMVSS202a; Test2: JNCAP; Test6: 24 km/h).

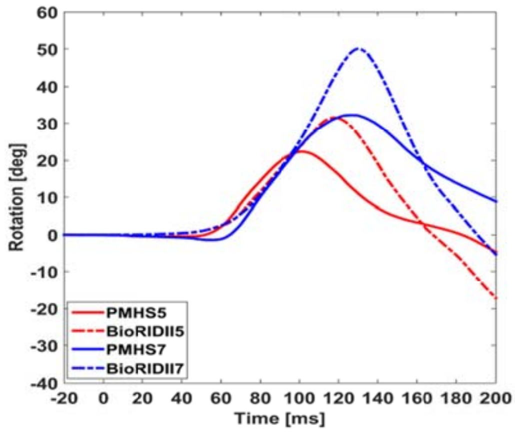


(a) C2.

PMHS5 vs BioRIDII5: NRMSD = 29.89%

PMHS7 vs BioRIDII7: NRMSD = 31.35%

Average NRMSD = 30.6 ± 1.0%

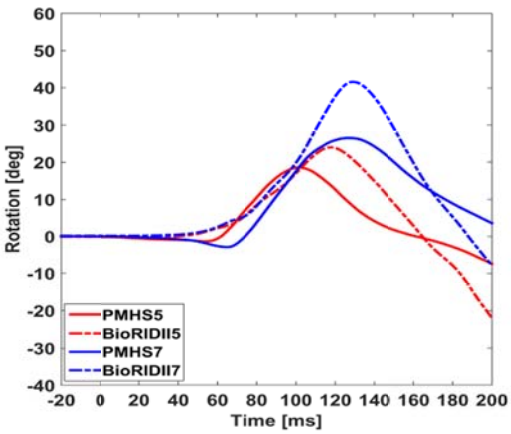


(d) C5.

PMHS5 vs BioRIDII5: NRMSD = 31.11%

PMHS7 vs BioRIDII7: NRMSD = 22.05%

Average NRMSD = 26.6 ± 6.4%

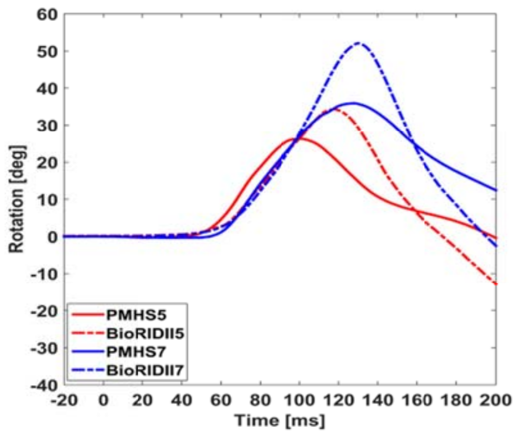


(b) C3.

PMHS5 vs BioRIDII5: NRMSD = 29.04%

PMHS7 vs BioRIDII7: NRMSD = 23.87%

Average NRMSD = 26.5 ± 3.7%

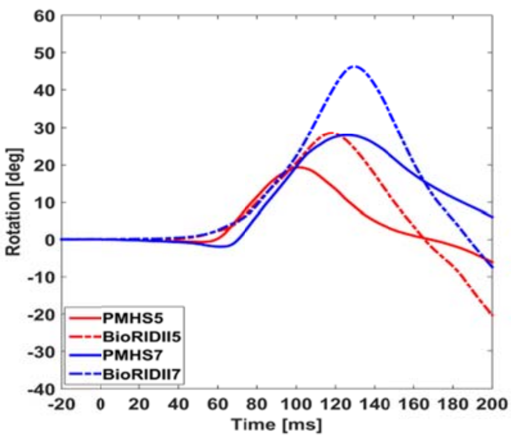


(e) C6.

PMHS5 vs BioRIDII5: NRMSD = 24.83%

PMHS7 vs BioRIDII7: NRMSD = 18.76%

Average NRMSD = 21.8 ± 4.3%

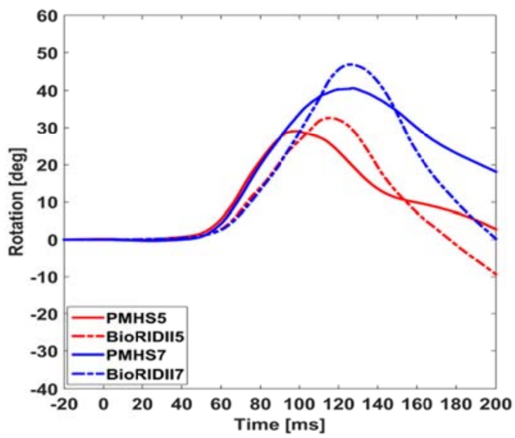


(c) C4.

PMHS5 vs BioRIDII5: NRMSD = 35.56%

PMHS7 vs BioRIDII7: NRMSD = 26.91%

Average NRMSD = 31.2 ± 6.1%



(f) C7.

PMHS5 vs BioRIDII5: NRMSD = 17.00%

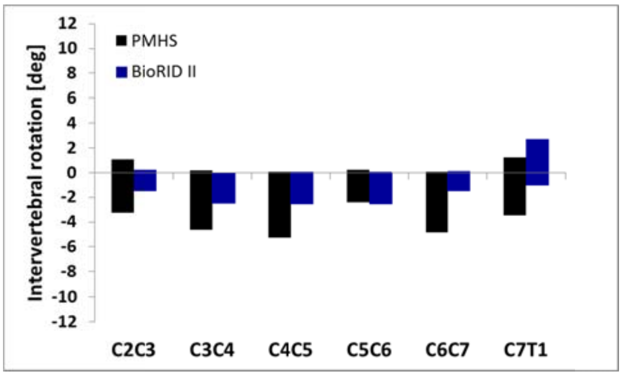
PMHS7 vs BioRIDII7: NRMSD = 16.06%

Average NRMSD = 16.5 ± 0.7%

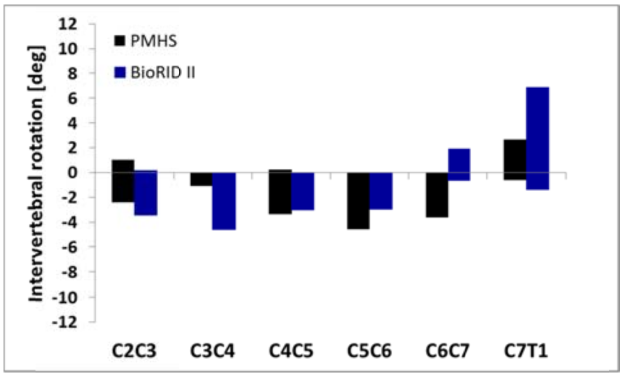
Fig. 5. Cervical rotation about y-axis using Seat B (Test5: JNCAP; Test7: 24 km/h).

Intervertebral rotation

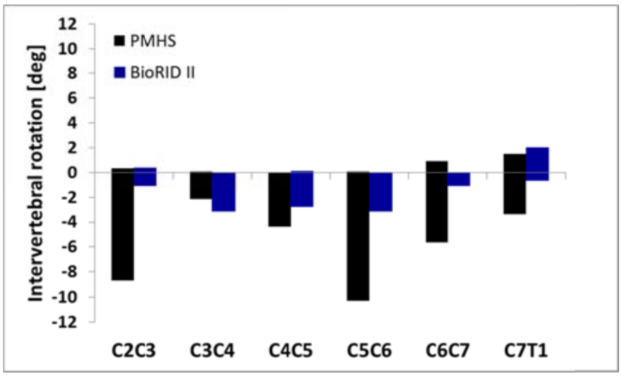
The relative intervertebral rotations for C2–T1 were determined for both the PMHS and BioRID II, as shown in Fig. 6. Negative values represented relative forward rotations (e.g. upper cervical vertebra rotated forward relative to the lower vertebra). The majority of peak intervertebral rotations (93% of PMHS and 77% of BioRID II) were relative forward rotation (i.e. flexion), as shown in Fig. 6. Relative rearward rotations (greater than 5 deg) of the BioRID II cervical vertebrae were identified only in the Seat B tests at C7/T1 (6.9 deg) in Test5 (Fig. 6 (d)), and at C6/C7 (5.6 deg) and C7/T1 (10.5 deg) in Test7 (Fig. 6 (e)). Statistical analysis was not performed due to the comparison of a single paired matched test per each configuration.



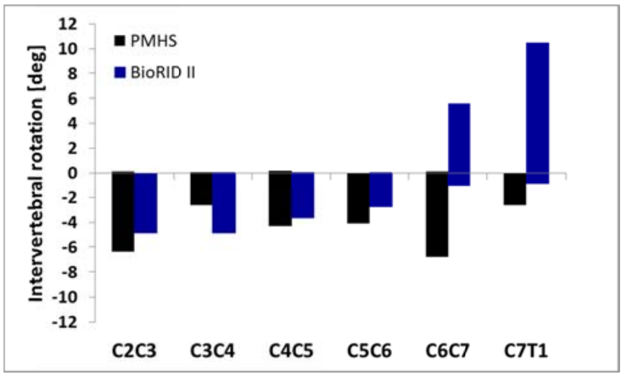
(a)



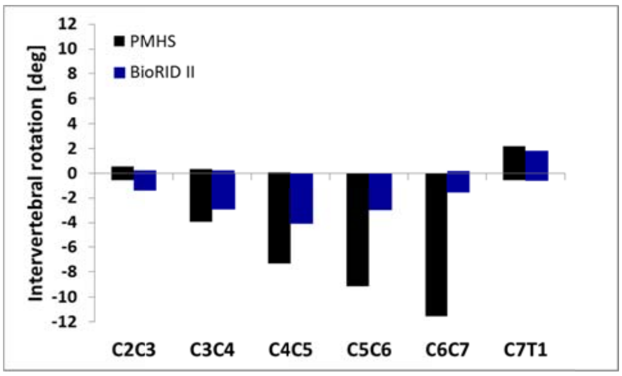
(d)



(b)



(e)



(c)

Fig. 6. Intervertebral rotations.
(a) Test1 in FMVSS202a and seat A; (b) Test2 in JNCAP and seat A; and (c) Test6 in 24 km/h and seat A.
(d) Test5 in JNCAP and seat B; and (e) Test7 in 24 km/h and seat B.

IV. DISCUSSION

Head and T1 kinematics

The biofidelity studies using BioRID II and human subjects have been conducted in many different seat configurations (e.g. rigid bench seats, various production seats, with/without head restraints, etc.) [8][10][14][16][19-20]. Most studies used rigid seat configurations without head restraints at low speeds [8][10][14][16][20]. The Kim study [16] and the Moorhouse study [19] evaluated biofidelity of the BioRID II at moderate-speeds (ΔV greater than 24 km/h), but the Kim study used a rigid seat without a head restraint, in order to compare rear impact ATDs to PMHS and volunteer data recorded from Mertz and Patrick [26]. The Moorhouse study used an experimental seat that is capable of simulating the dynamic seat-back rotation of modern vehicle seat-backs by considering the moment-rotation properties of a typical passenger vehicle seat [19]. The only study that has investigated the detailed cervical spine biofidelity of the BioRID II, was performed by Kang et al. (2013) [21].

Kinematics measured at the head and T1 have been commonly evaluated in previous rear impact studies [8-10][15-16][27]. In the current study, the head linear acceleration in both x- and z-directions of the BioRID II exhibited similar shape and magnitude as the PMHS head linear acceleration (Fig. A1), with average NRMSD values for x- and z- directions of 13.4 ± 6.3% and 15.4 ± 3.5%, respectively. In the Moorhouse study [19] in which an experimental seat was used, the biofidelity was poor and magnitudes of the peak head linear acceleration of the BioRID II were much higher than the current study (ranging from 96 g to 104 g), due to the nature of the experimental seat. The experimental seat was designed for assessing both external and internal biofidelity, so load cells were installed on the seat and head restraint resulting in a much more rigid head restraint than the production seats used in this study. They also reported that the less flexible neck and spine and less compliant skull of the BioRID II likely caused higher peaks in the head acceleration, resulting in poor biofidelity. However, it appears that those results may have been an artifact of the experimental seat since this study shows that head linear acceleration of the BioRID II was comparable to that measured from PMHS when tested in two different production seats (Fig. A1).

With regard to head rotation, however, the NRMSD values were greater than those observed in the linear acceleration (average NRMSD of 26.2 ± 10.2%). The PMHS head stayed close to the initial head angle (~0 degrees), with a small amount of forward rotation, while the BioRID II did not exhibit any forward rotation and began rotating rearward earlier than the PMHS, as shown in Fig. A1. This difference in head lag response was also observed in the previous study [19]. In their study, the BioRID II head rotation was comparable to PMHS in the 17 km/h test (e.g. FMVSS 202a), but the PMHS exhibited a larger amount of head rotation than BioRID II in the 24 km/h test [19]. Both the current study and the Moorhouse study showed that PMHS head rotations were greater than the BioRID II for all tests, with the interesting exception of Test2 in this current study, in which peak head rotation of the BioRID II (13.9 degrees) was greater than that obtained from the PMHS (10.7 degrees).

The BioRID II exhibited slightly better biofidelity for T1 linear acceleration than for head linear acceleration, with average NRMSD values for x- and z- directions of 12.4 ± 2.4% and 13.4 ± 2.5%, respectively. The Moorhouse study reported that T1 acceleration of the BioRID II in the x-direction was very similar in magnitude to the PMHS in 17 km/h, but they observed a high spike in the T1 acceleration in the z-direction after head restraint contact [19]. For the 24 km/h test, this high spike was observed in both x- and z-directions [19]. In this current study, similar high spike signals from the BioRID II were not observed in the T1 acceleration traces (Fig. A2). For T1 rotation, the PMHS showed larger T1 rotation than the BioRID II for all tests, with average NRMSD values of 22.2 ± 9.4% for all tests (Fig. A2), which is similar to that from the head rotations (26.2 ± 10.2%). The Moorhouse study reported that the T1 rotation obtained from the BioRID II in the 17 km/h was comparable to that from the PMHS, while the T1 rotation of the BioRID II in 24 km/h was close to the lower bound of the biomechanical target (i.e. minus one standard deviation) [19]. Similarly, the T1 rotation of the BioRID II in the current study showed more deviation from the PMHS curve in the 24 km/h test (Fig. A2).

Head rotation relative to T1

Head rotation relative to T1 has been considered as an important component of rear impact ATD biofidelity due to its relevance to injuries related to rear impacts [1]. In this study, the PMHS showed a large amount of relative forward rotation of the head with respect to T1 and did not exhibit any relative rearward rotation (Fig. 3). This large relative forward head rotation to T1 was also observed in Kang's previous study [23]. The BioRID II exhibited this general behavior, but with relative forward rotations of much less magnitude (Fig. 3), resulting in a large average NRMSD value of 37.7 ± 3.2%. Similarly, Moorhouse's study also showed that head rotation relative to T1 of the BioRID II was much less than that of the PMHS [19]. This forward head rotation relative to T1 implies that the T1 rotated rearward more than the head, which can be explained by the head lag effect (i.e. head stayed close to zero degrees or rotated slightly forward while upper torso rotated rearward). It should be noted that this relative forward rotation creates neck flexion while the neck rotated rearward in the global y-axis. This was supported by the intervertebral relative forward rotations C2/C3–C7/T1, shown in Fig. 6.

Cervical rotations in global y-axis

Gross kinematics of the head and T1 of the BioRID II have been studied extensively [8][14][16][18], but no previous studies actually measured individual cervical kinematics of the BioRID II, with the exception of one study performed by Kang et al. (2013) [21]. This previous Kang study found that in an experimental seat the cervical spine of the BioRID II exhibited good biofidelity in the 17 km/h test, but not in the 24 km/h [21]. This supported the fact that the BioRID II cervical spine was designed to model low-speed rear impacts on the order of 10 km/h [8]. The rotations of the cervical spine determined from the current study were lower than the previous Kang study [21], likely due to differences in seat-back rotations and in different seat types (i.e. an experimental seat vs. production seats).

In the current study, the responses of the cervical spine of the BioRID II differed in the two different production seats. For seat A, the upper cervical spine (C2–C3) of the BioRID II generally rotated rearward more than the PMHS (except C3 in Test2), while the lower cervical spine (C6–C7) of the PMHS rotated rearward more than the BioRID II (Fig. 4). There was no clear trend like this in the mid-cervical area (C4 and C5), but the BioRID II exhibited better biofidelity in the mid-cervical area with an average NRMSD value of 13.7 ± 4.0%, as compared to 22.7 ± 5.8% in the upper spine and 19.6 ± 9.0% in the lower spine. For seat B, however, the cervical spine of the BioRID II always rotated rearward more than the PMHS, as shown in Fig. 5. With respect to biofidelity, the lower cervical spine of the BioRID II (NRMSD of 19.2 ± 3.9) was better than the upper (NRMSD of 28.5 ± 3.3) or mid-cervical spine (NRMSD of 28.9 ± 5.8). These differences in responses from seat A to seat B are likely due to the differing head restraint and seat designs. The cervical spine responses are affected by the interaction of each region of the spine (e.g. cervical, thoracic, lumbar, sacral and coccygeal) with the seat backs and head restraints. Different seat designs likely produce different interactions of the lower spine with the seat back, which then affects the kinematics of the cervical spine. However, more investigation is needed to better understand this spine-seat interaction.

Intervertebral rotation

Since shape and magnitude of the intervertebral rotations measured from the BioRID II were not similar to those from the PMHS, time history evaluation did not provide any valuable information (average NRMSD values ranged from 18% to 204% for all tests). Therefore, peak intervertebral rotations were provided in Fig. 6 instead. The only study for comparison that measured individual cervical kinematics of the BioRID II by installing sensors on each cervical vertebra was performed by Kang et al. (2013) [21] using an experimental seat. They reported peak intervertebral rotations of the BioRID II for C2–C7, and found that all peak intervertebral rotations occurred in flexion (i.e. forward rotation of upper vertebra relative to lower vertebra), with average values ranging from 1.2 to 5.6 degrees (Table IV). In contrast to the experimental seat, although the peak intervertebral rotations throughout most of the spine were in flexion in the production seats from this study, the BioRID demonstrated some peak intervertebral extension values as well, particularly in the lower spine (Fig. 6). Furthermore, the transition from intervertebral flexion to intervertebral extension occurred at different locations of the spine for the two seats (C7/T1 for seat A and C6/C7 for seat B), further illustrating how dependent cervical kinematics are on the seat design (experimental versus seat A versus seat B). The higher propensity to develop intervertebral extension rotations in seat B likely explains why the BioRID II showed more rearward global rotation in the tests using seat B (Fig. 5).

It should be noted that intervertebral forward rotation of the BioRID II measured from both current and previous studies did not exceed 6 degrees, likely due to the initial design targets of the range of motion between two adjacent cervical vertebrae of the BioRID II (i.e. 11.5 degrees for rearward rotation and 4.5 degrees for forward rotation) [28]. The intervertebral range of motion (ROM) of the cervical spine of the BioRID II may need to be expanded in forward rotation (e.g. neck flexion), in order to improve biofidelity and overall head-neck kinematics.

TABLE IV
COMPARISON OF INTERVERTEBRAL FORWARD ROTATIONS OF BIORID II WITH PREVIOUS STUDY
unit: deg

Test severity	Study	Test ID	Seat type	BioRID II intervertebral kinematics C2/C3 mean (SD)	C3/C4 mean (SD)	C4/C5 mean (SD)	C5/C6 mean (SD)	C6/C7 mean (SD)
FMVSS202a	Kang 2013	N/A	Experimental seat	-1.8 (0.5)	-4.8 (0.6)	-4.4 (0.2)	-5.6 (1.2)	-4.3 (0.5)
24 km/h	Kang 2013	N/A	Experimental seat	-1.2 (1.5)	-3.0 (1.0)	-3.7 (0.9)	-4.9 (0.9)	-5.4 (0.6)
FMVSS202a	Current study	Test1	Production Seat A	-1.5	-2.5	-2.6	-2.5	-1.5
JNCAP	Current study	Test2	Production Seat A	-1.1	-3.1	-2.8	-3.1	-1.1
JNCAP	Current study	Test5	Production Seat B	-3.4	-4.6	-3.0	-3.0	-0.7
24 km/s	Current study	Test6	Production Seat A	-1.4	-2.9	-4.1	-3.0	-1.6
24 km/s	Current study	Test7	Production Seat B	-4.9	-4.9	-3.7	-2.8	-1.0

Limitations

Seven PMHS were tested in three different input sled pulses and two different seats. The main reason for having different combinations of the seats with pulses was to investigate injury reference assessment values (IARVs) for the BioRID II using a direct correlation approach of paired tests, which will be the subject of a future manuscript. For this approach, PMHS injury criteria will be evaluated and investigated first to find predictive variables to PMHS injuries. After determining the best injury predictive variables for the PMHS, the relationship between PMHS predictive variables and BioRID II measures will be investigated to determine the BioRID II injury measures (and injury assessment reference values) that are most correlated with the PMHS injuries. Since different seats and pulses were used in this study, the test matrix did not allow enough repeat PMHS tests to generate biomechanical targets, so a quantitative evaluation using NHTSA's Biofidelity Ranking System could not be performed. Therefore, an estimate of biofidelity was obtained by comparing five individual PMHS curves to five individual BioRID II curves in paired test conditions by calculating NRMSD values.

This study is somewhat limited by a small sample size of PMHS. A total of 7 rear impact sled tests were conducted using 7 PMHS [24], but only 5 test conditions were chosen and tested using the BioRID II. However, due to the lack of biomechanical data in the literature comparing PMHS and the BioRID II in rear impacts, this study should help to better understand head and cervical kinematics of both PMHS and BioRID II in rear impacts.

V. CONCLUSIONS

The BioRID II generally exhibited better biofidelity for the head and T1 linear accelerations than for the head and T1 rotations. Although the BioRID II exhibited generally comparable results to the PMHS, it appears that the biofidelity/ROM of the BioRID II in flexion could be improved in order to obtain more accurate head-neck kinematics. All cervical vertebrae for the PMHS and BioRID II rotated rearward in the global coordinate system. However, the intervertebral rotations for the cervical vertebrae were relative forward rotations (i.e. intervertebral flexion) in all cervical levels of the PMHS and for the upper and mid-cervical spine of the BioRID II. The intervertebral rotations at the lower cervical spine of the BioRID began to transition to relative rearward rotations at C7/T1 for seat A and at C6/C7 for seat B, as opposed to relative forward rotations at the other cervical levels. This transition was not observed in similar tests/severities using an experimental seat. This illustrates that different seat designs have a large effect on the resulting cervical kinematics in rear impacts.

VI. ACKNOWLEDGEMENTS

We would like to thank Rakshit Ramachandra, Julie Bing, Amanda Agnew and all IBRC members of the Ohio State University, and Jason Jenkins and Duey Thomas from Transportation Research Center, Inc., for their considerable support during test days.

VII. REFERENCES

[1] NHTSA. Federal Motor Vehicle Safety Standards; Head Restraints (FMVSS 202), Federal Register 49 CFR Part 571, Docket no. NHTSA-2004-19807, December 14 2004.

[2] Ono, K., Kanno, M. Influence of the Physical Parameters on The Risk to Neck Injuries in Low Impact Speed Rear-End Collisions. *Accident Analysis & Prevention*, 28:493–9.

[3] EEVC. Dummy Requirements and Injury Criteria for a Low-speed Rear Impact Whiplash Dummy. Working group 12 report, 2007.

[4] Kuppa, S. Injury Criteria and Anthropomorphic Test Devices for Cervical Spine Injury Assessment. NHTSA Docket No. 19807, 2004.

[5] Ishikawa, T., Okano, N., Ishikura, K., Ono, K. An evaluation of prototype seats using BioRID-P3 and Hybrid III with TRID neck. *Proceedings of the IRCOBI Conference*, 2000, Montpellier (France), pp. 379–91.

[6] Sano, K., Dokko, Y., Negishi, H., Goto, T., Ono, K., Warren, J. Development of a cervical spine injury reducing seat system using BioRID II dummy. *17th International Technical Conference on the Enhanced Safety of Vehicles*, 2001, Amsterdam (The Netherlands), Paper No. 370.

[7] Zellmer, H., Stamm, M., Seidenschwang, A., Brunner, A. Enhancement of seat performance in low-speed rear impact. *17th International Technical Conference of the Enhanced Safety of Vehicles*, 2001, Amsterdam (The Netherlands), Paper No. 231.

[8] Davidsson, J., Flogard, A., Lovsund, P., Svensson, M. Y. BioRID P3- Design and performance compared to Hybrid III and volunteers in rear impacts at ΔV=7 km/h. *Stapp Car Crash J*., 1999a; 43: SAE Paper No. 99SC16.

[9] Cappon, H., Philippens, M., van Ratingen, M., Wismans, J. Development and evaluation of a new rear-impact crash dummy: The RID 2. *Stapp Car Crash J*., 2001, 45:225–38.

[10] Davidsson, J., Lovsund, P., Ono, K., Svensson, M. Y., Inami, S. A comparison between volunteer, BioRID P3 and Hybrid III performance in rear impacts. *Proceedings of the IRCOBI Conference*, 1999b, Sitges (Spain), pp. 165–78.

[11] Cappon, H. J., Philippens, M. M. G. M., van Ratingen, M. R., Wismans, J. S. W. M. Evaluation of dummy behaviour during low severity rear impact. *Proceedings of the IRCOBI Conference*, 2000, Montpellier (France), pp. 53–66.

[12] Gotou, T., Ono, K., Ito, M., Matuoka, F. A comparison between BioRID AND Hybrid III head/neck/torso response in middle speed sled rear impact tests. *17th International Technical Conference on the Enhanced Safety of Vehicles*, 2001, Amsterdam (The Netherlands). Paper No. 116.

[13] Siegmund, G. P., Heinrichs, B. E., Lawrence, J. M. Kinetic and Kinematic Responses of the RID 2a, Hybrid III and Human Volunteers in Low-Speed Rear-End Collisions. *Stapp Car Crash J*., 2001, 45. SAE Paper No. 2001-22-0011.

[14] Philippens, M., Cappon, H., et al. Comparison of the rear impact biofidelity of BioRID II and RID2. *Stapp Car Crash J*., 2002, 46: 461–76.,

[15] Bortenschlager, K., Kramberger, D., et al. Comparison tests of BioRID II and RID2 with regard to repeatability, reproducibility and sensitivity for assessment of car seat protection potential in rear-end impacts. *Stapp Car Crash J*., 2003, 47:473–88.

[16] Kim, A., Anderson, K. F., et al. A biofidelity evaluation of the BioRID II, Hybrid III and RID2 for use in rear impacts. *Stapp Car Crash J*., 2003, 47:489–523.

[17] Croft, A., Philippens, M. The RID2 Biofidelic Rear Impact Dummy: A Pilot Study Using Human Subjects in Low-Speed Rear Impact Full Scale Crash Tests. *Accident Analysis & Prevention*, 2007, 39:340–46.

[18] Mallory, A., Stammen, J. Comparative evaluation of rear impact ATDs static seat interaction and dynamic testing. NHTSA Docket No. 2007-27986-19.

[19] Moorhouse, K., Kang, Y., Donnelly, B., Herriott, R., Bolte, J. H. Evaluation of the internal and external biofidelity of current rear impact ATDs to response targets developed from moderate-speed rear impacts of PMHS. *Stapp Car Crash J*., 2012, 56:171–229.

[20] Willis, C., Carroll, J., Roberts, A. An evaluation of a current rear impact dummy against human response corridors in both pure and oblique rear impact. *19th International Technical Conference of the Enhanced Safety of Vehicles*, 2005, Washington D.C. (USA). Paper No. 05-0061.

[21] Kang, Y., Moorhouse, K., Herriott, R., Bolte, J. H. Comparison of Cervical Vertebrae Rotations for PMHS and BioRID II in Rear Impacts. *Traffic Injury Prevention J*., 2013, 14(sup1):S136–S147.

[22] Ikari, T., Kaito, K., Nakajima, T., Yamazaki, K., Ono, K. Japan New Car Assessment Program for Minor Neck Injury Protection in Rear-end collisions. *22nd International Technical Conference on the Enhanced Safety of Vehicle*, 2009, Stuttgart (Germany).

[23] Kang, Y., Moorhouse, K., Donnelly, B., Herriott, R., Mallory, A., Bolte, J. H. Biomechanical responses of PMHS in moderate-speed impacts and development of response targets for evaluating the internal and external biofidelity of ATDs. *Stapp Car Crash J*., 2012, 56:105–70.

[24] Kang, Y., Moorhouse, K., Icke, K., Herriott, R., Bolte, J. H. Head and Cervical Spine Responses of Post Mortem Human Subjects in Moderate Speed Rear Impacts. *Proceedings of the IRCOBI Conference*, 2014, Berlin (Germany), pp. 268–85.

[25] Wu, J., Shi, Y., Kang, J., Nusholtz, G. S. Using Trial-Axial Angular Rate Sensor and Accelerometer to Determine Spatial Orientation and Position in Impact Tests. SAE Paper 2009-01-0055, 2009, *Society of Automotive Engineers*, Warrendale, PA.

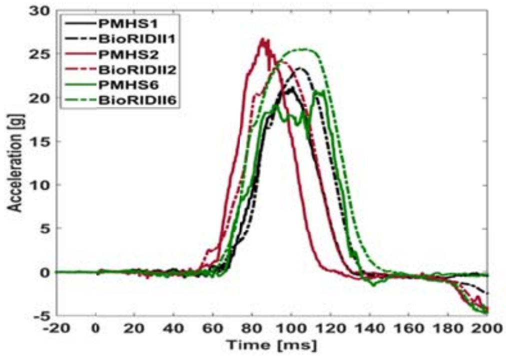
[26] Mertz, H. J., Patrick, L. M. Investigation of the Kinematics and Kinetics of Cervical Spine. *Stapp Car Crash J*., 1967, 11. SAE Paper No. 670919.

[27] Kim, A., Sutterfield, A., et al. A Comparison of the BioRID II, Hybrid III, and RID2 in Low-Severity Rear Impacts. *19th International Technical Conference of the Enhanced Safety of Vehicles*, 2005, Washington D.C. (USA). Paper No. 05-0225.

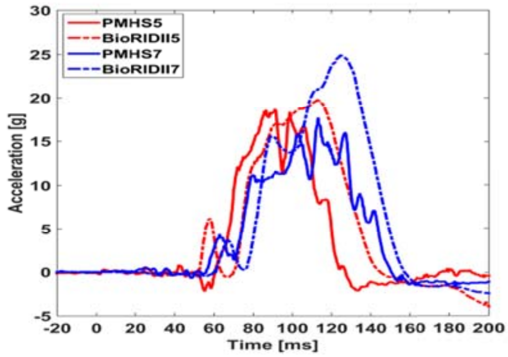
[28] Davidsson, J., Svensson, M. Y., et al. BioRID I – A new biofidelic rear impact dummy. *Proceedings of the IRCOBI Conference*, 1998, Göteborg (Sweden): 377–90.

[29] Humanetics, Inc. BioRID II user manual, 2001/2009.

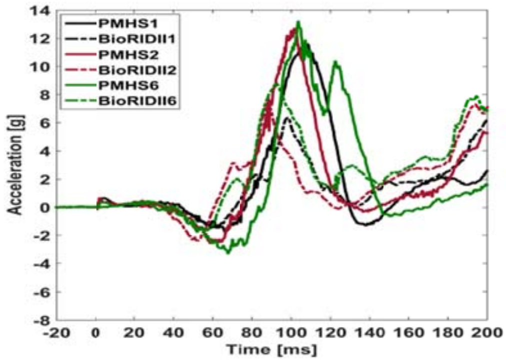
VIII. APPENDIX



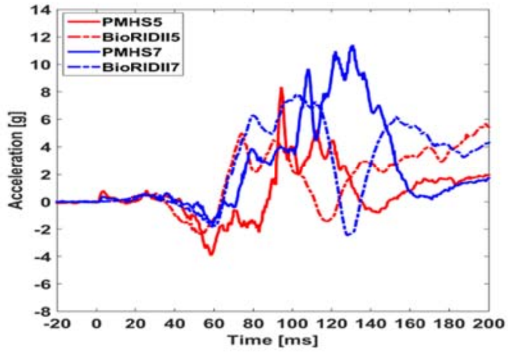
(a) acceleration in x-axis
PMHS1 vs BioRIDII1: NRMSD = 8.46%
PMHS2 vs BioRIDII2: NRMSD = 7.58%
PMHS6 vs BioRIDII6: NRMSD = 15.19%



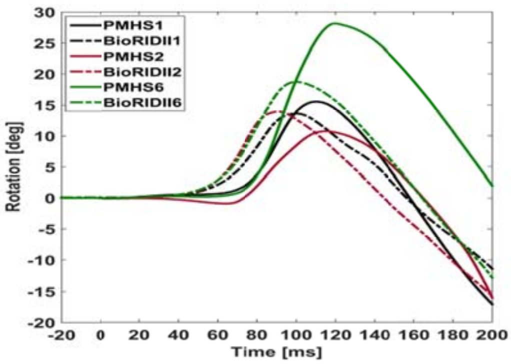
(d) acceleration in x-axis
PMHS5 vs BioRIDII5: NRMSD = 12.68%
PMHS7 vs BioRIDII7: NRMSD = 23.22%



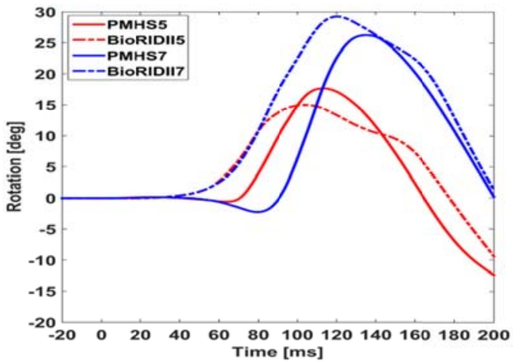
(b) acceleration in z-axis
PMHS1 vs BioRIDII1: NRMSD = 19.25%
PMHS2 vs BioRIDII2: NRMSD = 14.16%
PMHS6 vs BioRIDII6: NRMSD = 16.27%



(e) acceleration in z-axis
PMHS5 vs BioRIDII5: NRMSD = 10.05%
PMHS7 vs BioRIDII7: NRMSD = 17.45%

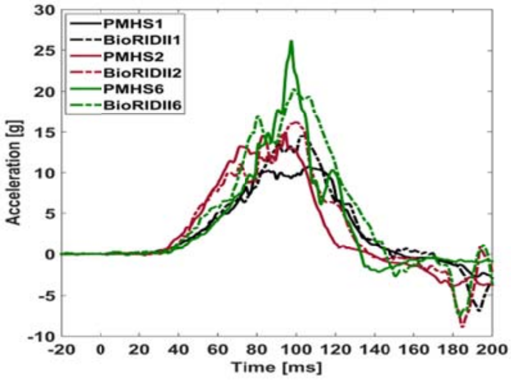


(c) rotation in y-rotation
PMHS1 vs BioRIDII1: NRMSD = 16.03%
PMHS2 vs BioRIDII2: NRMSD = 41.14%
PMHS6 vs BioRIDII6: NRMSD = 28.18%

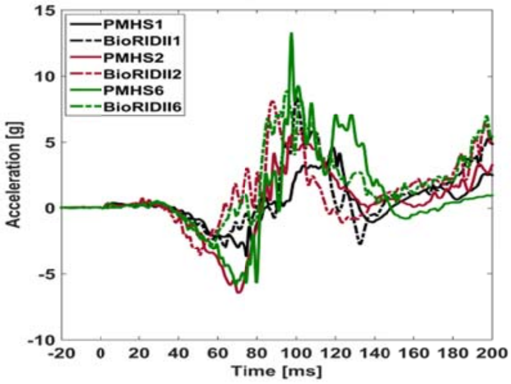


(f) rotation in y-rotation
PMHS5 vs BioRIDII5: NRMSD = 17.11%
PMHS7 vs BioRIDII7: NRMSD = 28.33%

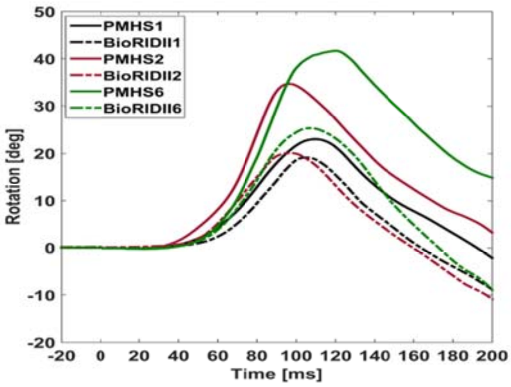
Fig. A1. Head kinematics for both PMHS and BioRID II
Seat A: (a), (b) and (c) vs. Seat B: (d), (e) and (f)
FMVSS202a:Test1; JNCAP: Test2 and 5; and 24 km/h: Test6 and 7
Average NRMSD for linear acceleration in x- direction: 13.4 ± 6.3 %
Average NRMSD for linear acceleration in x- direction: 15.4 ± 3.5 %
Average NRMSD for rotation in y- direction: 26.2 ± 10.2 %



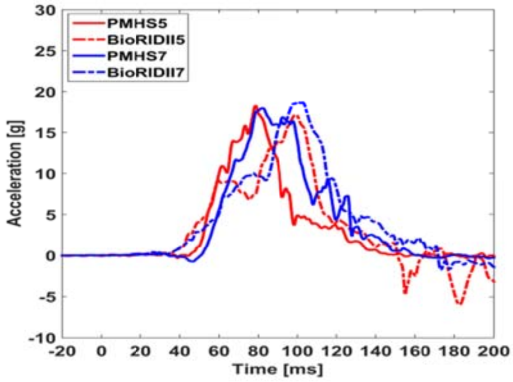
(a) acceleration x
PMHS1 vs BioRIDII1: NRMSD = 13.32%
PMHS2 vs BioRIDII2: NRMSD = 10.06%
PMHS6 vs BioRIDII6: NRMSD = 10.17%



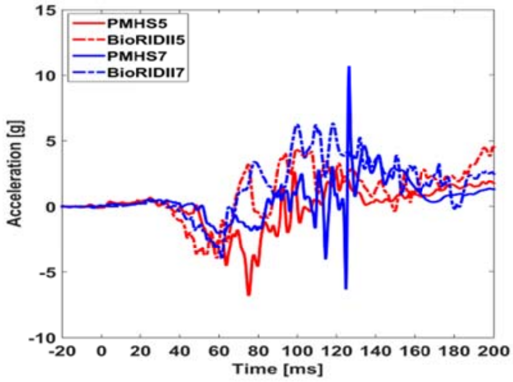
(b) acceleration z
PMHS1 vs BioRIDII1: NRMSD = 13.29%
PMHS2 vs BioRIDII2: NRMSD = 14.21%
PMHS6 vs BioRIDII6: NRMSD = 10.63%



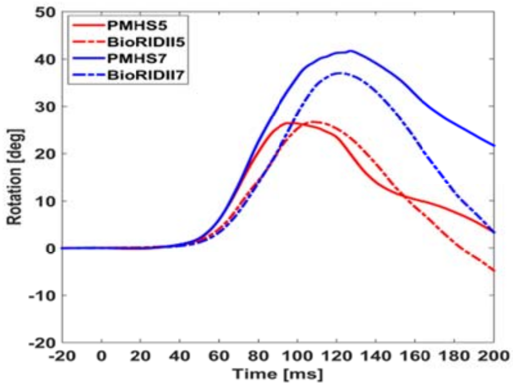
(c) rotation y
PMHS1 vs BioRIDII1: NRMSD = 15.44%
PMHS2 vs BioRIDII2: NRMSD = 28.74%
PMHS6 vs BioRIDII6: NRMSD = 34.20%



(d) acceleration x
PMHS5 vs BioRIDII5: NRMSD = 15.81%
PMHS7 vs BioRIDII7: NRMSD = 12.73%



(e) acceleration z
PMHS5 vs BioRIDII5: NRMSD = 17.20%
PMHS7 vs BioRIDII7: NRMSD = 11.80%



(f) rotation in y axis
PMHS5 vs BioRIDII5: NRMSD = 11.10%
PMHS7 vs BioRIDII7: NRMSD = 21.33%

Fig. A2. T1 kinematics for both PMHS and BioRID II
Seat A: (a), (b) and (c) vs. Seat B: (d), (e) and (f)
FMVSS202a: Test1; JNCAP: Test2 and 5; and 24 km/h: Test6 and 7
Average NRMSD for linear acceleration in x- direction: 12.4 ± 2.4 %
Average NRMSD for linear acceleration in x- direction: 13.4 ± 2.5 %
Average NRMSD for rotation in y- direction: 22.2 ± 9.4 %