Head-to-T1 Relative Rotation of the BioRID-II, Hybrid III, and Post Mortem Human Subjects with Increased Backsets in Moderate-Speed Rear Impacts

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Abstract In rear impact tests using OEM seats, neck extension of the Hybrid III, defined as rearward head-to-T1 relative rotation (HTTRR), has been shown to correlate to backsets that were related to whiplash injury. However, it is unknown whether rearward HTTRR in an ATD designed specifically for rear-impacts, e.g., the BioRID-II, also correlates to increasing backsets. As a first step towards developing appropriate neck extension-based injury criteria for the BioRID-II, increased backsets are explored. A series of ATD sled tests was first conducted using the BioRID-II and Hybrid III with increased backsets in moderate-speed rear impacts. Next, another sled test series was conducted using mid-size male PMHS and both ATDs using a head restraint that was modified to provide an excessive backset intended to guarantee extension of the neck. In the first series, the rearward HTTRR from the Hybrid III increased in the tests with increased backsets. However, when the Hybrid III had rearward HTTRR, the BioRID-II exhibited forward HTTRR, and never exhibited rearward HTTRR throughout the entire event regardless of backset. In the second series, the Hybrid III exhibited rearward HTTRR much earlier in the event and ultimately with much higher magnitude than the BioRID-II or any of the PMHS.
Keywords BioRID-II, extension injury, head-to-T1 rotation, Hybrid III, rear-ended impact

I. INTRODUCTION

Cervical spine injuries in rear-end impacts continue to be a substantial problem and have yet to be fully understood. Numerous studies have investigated occupant biomechanical responses and cervical spine injury mechanisms in simulated rear impacts utilizing human volunteers [1-5] and/or post mortem human subjects (PMHS) [1][3][6-13]. Among these studies, many focused on low speed (< 17kph) rear impact tests [2-5][7-8][10][14], even though the frequency of cervical spine injuries (e.g., MAIS 1 and 2+ injuries) that occurred at moderate speeds (≥ 17kph) was similar to the frequency of the injuries that occurred at low speeds [11]. Due to the bulk of the research studies being conducted at low speeds, current safety tools, such as anthropomorphic test devices (ATD) and finite element (FE) human body models (HBM), have been designed, built, and validated against biomechanical data generated from low-speed rear-impact conditions [14-16]. However, it is also important to evaluate the safety tools at other severities (e.g., low-to-moderate speeds) that occur in real world crashes in order to assess the combined system of seat and head restraint [9].

Despite the fact that rear impact events and whiplash-type injuries have been studied extensively, there are still many questions remaining regarding the exact injury mechanisms and injury tolerance levels. Proposed soft tissue injury sites vary and include muscles, facet joints, capsular ligaments, and intervertebral discs [17]. Based on the information about the injury sites and biomechanical responses of the head and neck in rear impact conditions, various neck injury criteria have been hypothesized: Neck Injury Criterion (NIC) [18], Nij [19], Nkm [20], lower neck extension moment [21], Lower Neck Load (LNL) [22], Inter-Vertebral Neck Injury Criterion (IVNIC) [23], and Neck Displacement Criterion (NDC) [24]. Although, the biomechanical relationship between the proposed injury criteria and cervical spine injuries is still conjectural, minimizing head motion relative to T1 (i.e., limiting neck deformation) is commonly assumed to have the potential for reducing injury risk as well as justifying the validity of the injury criteria in rear impacts [9-10][24-27]. Moreover, it has been reported that seat design parameters, such as seat stiffness, backset (horizontal distance between the back of the head and the front of

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the head restraint) and topset (vertical distance between the head center of gravity and the top of the head restraint) substantially affected head motion relative to T1 [27-28]. Kuppa (2004) investigated the probability of whiplash injury as a function of head motion relative to T1 using whiplash insurance claim data of certain original equipment manufacturer (OEM) seats and data from sled tests using the same OEM seats [29]. In this study head-to-T1 relative rotation (HTTRR) was highly correlated with the head-to-T1 relative translation (R^2 of 0.98), and this has been shown to correlate to backsets and corresponding whiplash injury risk. Therefore, the HTTRR of the Hybrid III was used to develop the whiplash injury risk curve. As a result, the proposed kinematic based injury measure, HTTRR, and the corresponding whiplash injury risk curve was adopted in the FMVSS 202a standard as an optional criterion that allowed for the continued development of active head restraints. In this optional requirement, a limit of 12 degrees of rearward HTTRR was proposed for the Hybrid III to ensure that head restraints could effectively reduce neck extension injuries in rear impacts [30-31].

A few studies have focused on the sensitivity of the biomechanical responses with respect to backsets, and it was found that backset is one of the most critical seat design variables that can affect the potential for neck injury risk in rear impact conditions [10][27][32]. Sundararajan et al. (2004) explored the influence of head and neck positions (e.g., normal, zero clearance, and body forward) with respect to the head restraint on the cervical facet stretch of the PMHS during low speed rear impacts (ΔVs of 12.8 and 15.3kph) [10]. They demonstrated that the body forward position (i.e., large backset) resulted in maximum facet stretch when the head contacted the head restraint, implying that the increased backset might increase the risk of potential whiplash injury. However, the increased backset was achieved by changing the PMHS head, neck and thoracic spine position and orientation rather than changing the backset by adjusting the head restraint. Kim et al. (2005) conducted a series of sled tests using Hybrid III, RID2 and BioRID-II with two different backset levels (57mm and 83mm) at three different speeds (16, 24, and 27kph) [32]. The study quantified response differences of the ATDs in resultant head acceleration, T1 x-acceleration, upper neck tensile force, external head impact force, and NIC between the two different backsets. Based on the BioRID-II backset sensitivity outcomes, 83mm backset increased the measured responses from 20% to 83% when compared to responses from the 57mm backset. However, similar to the Sundararajan study [10], the backsets were varied by adjusting the ATDs, not by adjusting the head restraints, so that the increased responses and differences could be a result of the adjusted ATD postures and positions, and not entirely due to the increased backset. Moreover, biofidelity of the ATDs and the head-to-T1 motions (e.g., HTTRR) were not evaluated. Unlike the other two studies, Kleinberger et al. (2007) used a modified head restraint that allowed for adjusting backset without altering ATD posture and position [27]. A series of sled tests using Hybrid III, RID3D, BioRID-II and THOR was conducted to evaluate performance of the ATDs in a FMVSS 202a sled condition (ΔV of 17kph). An experimental seat equipped with a spring-damper mechanism was utilized to control seatback stiffness. Three important seat design parameters, rotational stiffness, backset, and topset were changed to quantify the sensitivity of the ATD responses to the parameters. It was found that the Hybrid III was more sensitive to the backset changes than the BioRID-II, when the HTTRR were evaluated. However, biofidelity of the ATDs was not evaluated, and the experimental seat might not represent performance of OEM seats due to the modification made for seatback stiffness using the spring-damper system.

In order to assess the biofidelity of ATDs used for rear impact tests, a series of sled tests using PMHS and ATDs (BioRID-II, RID3D, and Hybrid III) were conducted at a ΔV of 17 and 24kph [11-12][33]. It was found that the two rear impact ATDs (BioRID-II and RID3D), in particular the BioRID-II, were more biofidelic than the others when kinematics, kinetic and external loads (seat reaction forces) were evaluated [33]. They also found that PMHS and BioRID-II intervertebral rotation as well as HTTRR were mainly forward rotation or neck flexion during the entire events (i.e., before, during and after head restraint contact) [12]. However, they used an experimental seat that mimicked yielding seatback characteristics based on seats produced in 1994-1996 but may not represent performance of modern OEM seats. Thus, it was unclear if the intervertebral flexion and injuries reported in the studies were specific to the experimental seat. Therefore, another series of PMHS and match-paired BioRID-II tests (BioRID-II was chosen since it was found to be the most biofidelic from the previous studies [11-12]) were conducted using two OEM seats in 17 – 24kph rear impacts [13]. It was found that both intervertebral rotations and HTTRR measured from the PMHS and BioRID-II were still primarily flexion even in the test using the OEM seats at a ΔV of 24kph, while the PMHS sustained ligamentous injury due to the intervertebral flexion. Based on the results from the previous studies [12-13], it was unclear whether the BioRID-II (which was shown to have responses similar to the PMHS) would ever show rearward HTTRR for modern OEM seats, even as the Hybrid III clearly exhibited rearward HTTRR. Since the BioRID-II did not exhibit rearward HTTRR in the tests using modern OEM seats, it is likely not appropriate to use the extension limits developed for the Hybrid III when evaluating seat and head restraint performance with the BioRID-II. However, it is postulated that some criterion for the BioRID needs to be implemented to prevent hyperextension of the neck to avoid potential injury. In order to investigate extension-based injury criteria for the BioRID-II, biomechanical data for neck extension kinematics, i.e., rearward HTTRR, in modern OEM seats should be generated in both PMHS and BioRID-II in low-to-moderate rear impacts. Due to a lack of biomechanical data in the literature, an alternative approach could be exploring the development of a transfer function from the 12 degrees of rearward HTTRR for the Hybrid III in FMVSS 202a to rearward HTTRR for the BioRID-II by conducting a series of ATD tests under identical conditions with varying backsets.

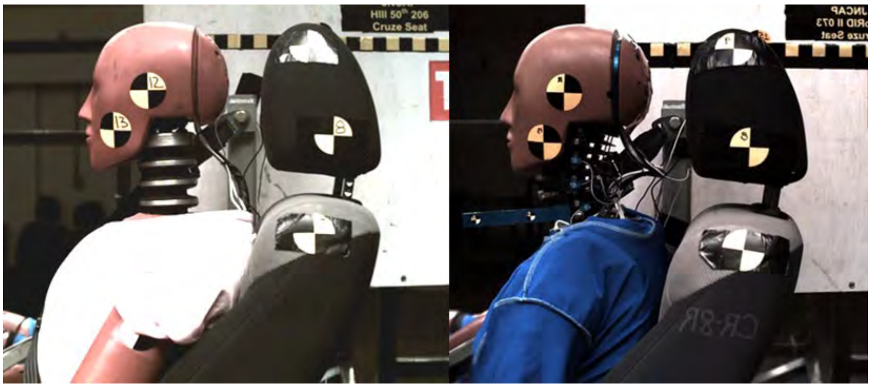
No previous studies have investigated HTTRR of the Hybrid III, BioRID-II and PMHS under identical moderate-speed rear impacts in an OEM seat with various backsets while also investigating the feasibility of developing a transfer function from the 12 degrees of rearward HTTRR limit for the Hybrid III to rearward HTTRR for the BioRID-II. In addition to this, no previous studies explored what backsets might be required for the BioRID-II to demonstrate rearward HTTRR in practice. Therefore, the main objectives of this study were 1) to investigate the sensitivity of the rearward HTTRR limit to increasing backset for both the Hybrid III and BioRID-II in an OEM seat where backset is controlled by adjusting the head restraint without altering the ATD position/posture; and 2) to evaluate the biofidelity of the HTTRR of the Hybrid III and BioRID-II relative to a 50th percentile male PMHS in moderate-speed rear impacts (ΔV of 18 - 25kph) in which neck extension would be ensured.

II. METHODS

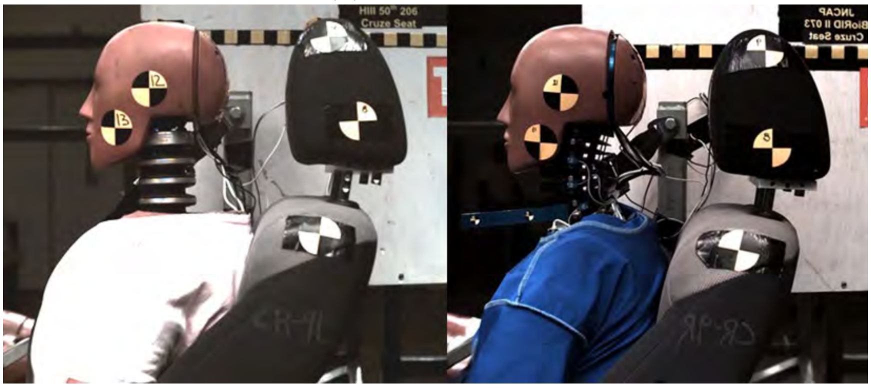
First Sled Series: ATD Sled Tests with Various Backsets

A first sled series was conducted using the Hybrid III and BioRID-II with varying backsets in a moderate-speed rear impact (10.8g and ΔV of 18.2kph, hereafter referred to as JNCAP [34], shown in Fig. A1 in Appendix A). These sled inputs were consistent with a previous PMHS rear impact study [13]. The main purpose of this test series was to explore sensitivity of the HTTRR measures from both Hybrid III and BioRID-II ATDs to various backsets. This testing utilized an OEM driver seat (2011 Chevy Cruze, General Motors, Detroit, MI, USA) fitted with a three-point belt, which was the same seat used in the previous PMHS study [13]. The seat had a good rating for rear impact performance based on data from the Insurance Institute for Highway Safety (IIHS) and European New Car Assessment Program (EuroNCAP). Prior to the ATD tests, the H-point of the seat was determined using an OSCAR H-point device to be used in the seating procedures. The FMVSS 202a seating procedure [31] was used for the Hybrid III, while the seating procedure that was previously developed based on the BioRID-II user manual was applied to the BioRID-II [33]. Backsets used in this test series were three different levels: 50mm, 90mm, and 130mm (Fig. A2). The 50mm backset condition was achieved with no modification of the head restraint and used as a baseline condition. The 90mm and 130mm backsets were determined to locate the front of the head restraint at approximately 25% and 50% of the seatback depth, respectively. Custom brackets that allowed for increasing the backsets to 90mm and 130mm were utilized for both ATD tests (Fig. A2). General sled set-ups including a coordinate system used for both ATDs are also shown in Fig. A3. ATD head and neck positions with respect to the head restraint locations to achieve the target backsets are shown in Fig. 1. The seat was replaced following each test.

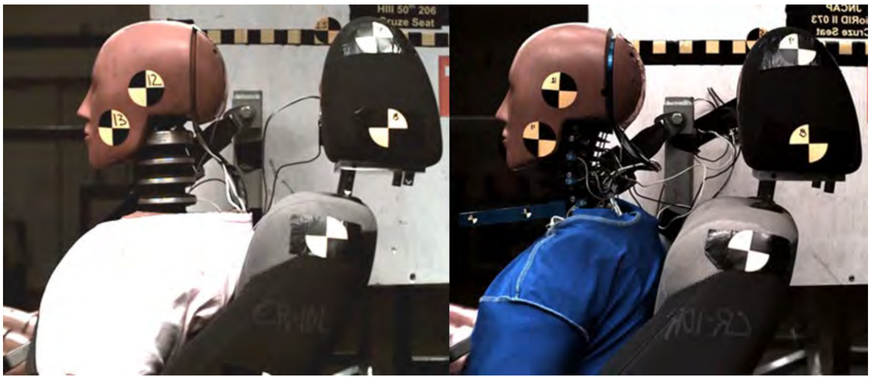
In order to measure angular kinematics at the head and T1, angular rate sensors (ARS) (18K Pro, Diversified Technical System, Inc., Seal Beach, CA) were installed at the center of gravity (CG) of both ATD heads and the instrumentation location at T1 for the BioRID-II and the spine box for the Hybrid III. It should be noted that angular kinematics at T1 for the Hybrid III should be the same as those measured at the spine box, since the Hybrid III has a rigid thoracic spine. The ARS data were then numerically integrated to calculate the head and T1 rotations. HTTRR was then calculated by subtracting the T1 rotation from the head rotation.



(a) 50mm backset



(b) 90mm backset



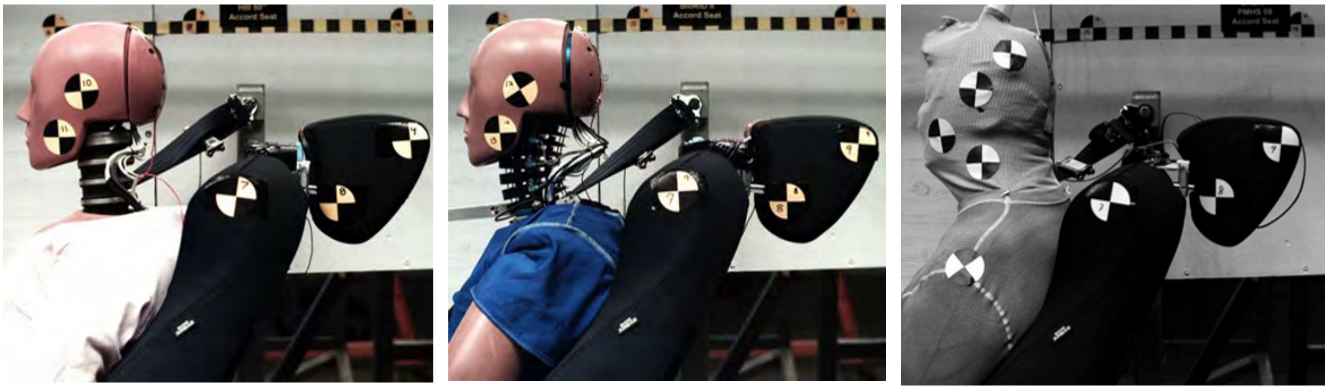
(c) 130mm backset

Fig. 1. Hybrid III (left) and BioRID-II (right) with various backsets used in the first sled series.

Second Sled Series: ATD and PMHS Sled Tests with Excessive Backset

Next, another sled test series (hereafter referred to as second sled series) was conducted using a modified head restraint shown in Figs. A4 and A5. This modified head restraint condition shown in Fig. 2 was employed to provide an excessive backset intended to guarantee large global head rotations and extension of the neck while preventing catastrophic injuries due to excessive head motions. The general sled set-up, including a coordinate system used for the second sled series, is presented in Fig. A5. The seat used was an OEM seat (2018 Honda Accord, TS Tech Americas, INC., Reynoldsburg, OH, USA), which differed from the seat used in first series, but also had a good rating for rear impact performance based on data from IIHS. This seat was also a front driver seat with dual recliners and a standard three-point seat belt. In this series, PMHS and match-paired Hybrid III and BioRID-II ATD tests were conducted in identical conditions to further understand HTTRR responses and assess biofidelity of the ATDs in the condition with excessive backset where it was believed that neck extension was sure to occur. A test matrix is provided in Table I. In this test series, the ATDs and PMHS were also tested in the JNCAP pulse along with two additional sled pulses (FMVSS 202a [31], and 24kph [11] hereafter referred to as 202a and 24kph) as shown in Fig. A1. Seating procedures for the Hybrid III and BioRID-II ATDs were consistent with those used in the first series but with no requirement of target backsets. The Hybrid III and BioRID-II were tested at least twice at each condition (Table I).

A total of nine mid-size male PMHS were tested: three PMHS at each sled pulse to generate biomechanical corridors for each condition (Table I). The PMHS utilized for this study were available through Ohio State University's body donor program and all applicable National Highway Traffic Safety Administration (NHTSA) and University guidelines were reviewed and followed. Nine fresh frozen male PMHS (age ranging from 24 to 65-year-old with mean ± standard deviation of 53 ± 14-year-old shown in Table AI) were scanned using computerized tomography (CT) to ensure there were no severely degenerated discs, osteophytes, or any hardware due to previous spinal surgery on the cervical and/or upper thoracic spine. Dual Energy X-ray Absorptiometry (DXA) was used to assess areal bone mineral density (aBMD) of the PMHS, in order to screen for osteoporotic PMHS (Table AI). Average PMHS weight was 75.2 ± 8.5kg (ranging from 61.2 to 88.5kg), while average PMHS height was 179.5 ± 5.7cm (ranging from 168.5 to 185.4cm). Anthropometric data for each PMHS head and neck are also provided in Table AI. PMHS were dressed in shirts/pants made of cotton as used in previous studies [11-13]. The PMHS lumbar spine region was placed against the seatback of the production seat, while the center of the mid-sagittal plane of the PMHS was aligned with that of the seatback. Initial head angles for each PMHS were set to be 0 ± 3 degrees, i.e. the Frankfort plane was set to be horizontal. A harness that supported each PMHS head was attached to a release system using a cable (~2mm diameter). This cable passed through a pyrotechnic cutter device (Model G2, Roberts research laboratory, Torrance, CA, USA). Each PMHS head was released by cutting the cable at time zero, which was defined as 0.5g of sled acceleration. The head release mechanism was not required for the ATD heads. A three-point belt was used to restrain the PMHS and ATDs. Initial belt tensions were adjusted to 26.7N (6.0lb) for the shoulder belt and 17.8N (4.0lb) for the lap belt [11][13]. Prior to each test, instrumentation and featured bony landmarks were digitized using a FARO device (Edge FaroArm, Faro Arm Technologies, Lake Mary, FL, USA). The seat was replaced following each test.



(a) Hybrid III (b) BioRID-II (c) PMHS

Fig.2. Hybrid III, BioRID-II, and PMHS with excessive backset used in the second sled series.

TABLE I
TEST SEVERITY AND TEST MATRIX

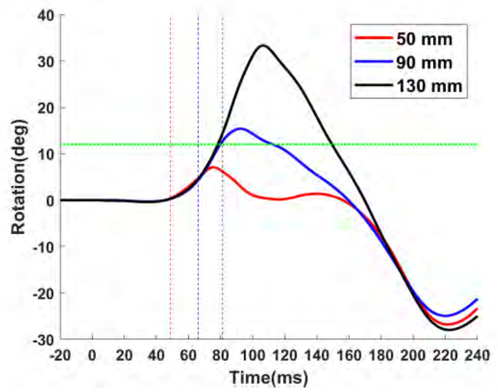
PMHS	ATDs	Sled pulse name
PMHS1	Hybrid III & BioRID-II	24kph
PMHS2	Hybrid III & BioRID-II	202a
PMHS3	Hybrid III & BioRID-II	JNCAP
PMHS4	Hybrid III & BioRID-II	24kph
PMHS5	Hybrid III & BioRID-II	202a
PMHS6	Hybrid III & BioRID-II	JNCAP
PMHS7	Hybrid III & BioRID-II	24kph
PMHS8	BioRID-II	202a
PMHS9	BioRID-II	JNCAP

For the ATDs, the same instrumentation for quantifying angular kinematics of the head and T1 employed in the first sled series was also used in the second sled series. For the PMHS, the head was instrumented using an array of six accelerometers and three ARS (6aω), while three accelerometers and three ARS (3aω) were installed at T1 to determine HTTRR [11-13]. Anatomical and instrumentation coordinate systems are shown in Fig. B1. Detailed information regarding data transformation to anatomical origins for the head and T1 is provided in Appendix B.

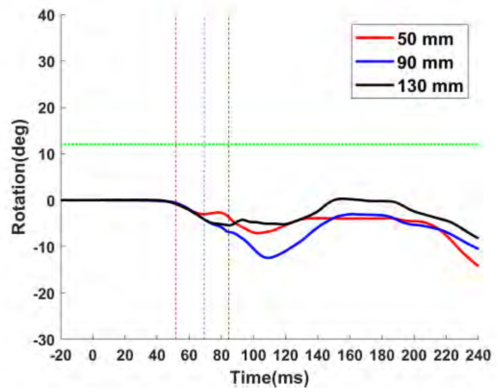
For PMHS biomechanical corridors, a corridor generation technique proposed in previous studies [11][35] was applied to the PMHS data. PMHS phase shifts when developing corridors were also quantified. The most updated NHTSA BioRank System (BRS) was utilized to quantify the biofidelity scores for HTTRR for each of the ATDs [35]. In this study, BRS was calculated using BRS = Dummy Cumulative Absolute Difference/Cadaver Cumulative Standard Deviation and Dummy Minimizing Phase Shift (DMPS) proposed in the 2020 version of the BRS are reported to evaluate biofidelity of the ATDs.

III. RESULTS

In the first series, the Hybrid III exhibited increasingly rearward HTTRR (+7.1 to +33.3deg) with increasing backset as shown in Fig. 3(a), while the BioRID-II exhibited only forward HTTRR (-5.4 to -12.5deg) at all backset levels including 130mm as shown in Fig. 3(b) and Table II. Head contact time to the head restraint and peak HTTRR as well as corresponding times are provided in Table II. Peak HTTRR for both ATDs occurred after head contact (Table II). The FMVSS 202a neck extension limit of 12 degrees HTTRR for the Hybrid III was exceeded in the tests with 90mm and 130mm backset (Fig. 3a). However, at the points in time that the Hybrid III exceeded that 12 degrees of rearward HTTRR limit (79.7ms for 90mm backset and 78.3ms for 130mm backset), the BioRID exhibited forward HTTRR (-5.8deg at 79.7ms for 90mm backset and -5.1deg at 78.3ms for 130mm backset), and never exhibited rearward HTTRR throughout the entire event regardless of backset (Fig. 3b).



(a) Hybrid III



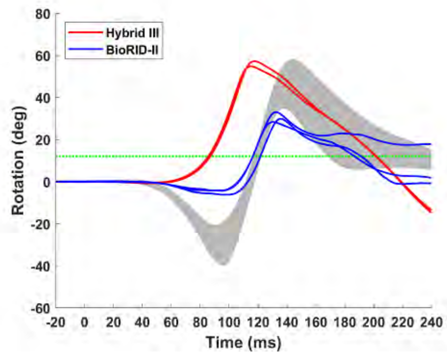
(b) BioRID-II

Fig. 3. ATD HTTRR responses from the first series.
Vertical dashed lines: times when head contacted HR.
Horizontal green line: 12 degrees of rearward HTTRR limit.

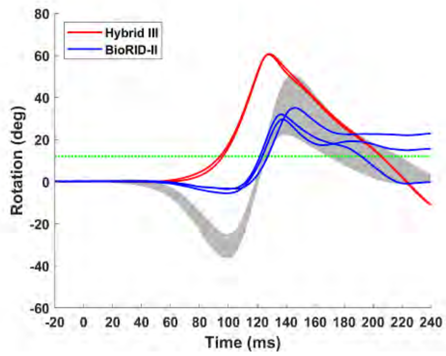
TABLE II HEAD CONTACT TIMING AND PEAK HTTRR

	Backset (mm)	Hybrid III	BioRID-II
Head Contact Timing (ms)	50	48.6	51.6
	90	65.9	69.3
	130	81.2	84.6
Peak HTTRR Timing (ms)	50	75.4	102.3
	90	92.5	108.8
	130	106.5	85.0
Peak HTTRR (deg)	50	7.1	-7.1
	90	15.4	-12.5
	130	33.3	-5.4

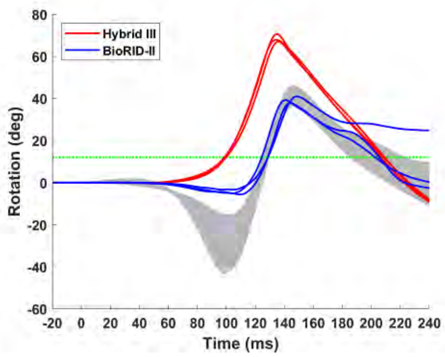
For the results from the second series, the Hybrid III and BioRID-II HTTRR responses along with PMHS biomechanical corridors are shown in Fig. 4. The BRS scores are provided in Table III. General kinematics of the PMHS and ATDs can be seen in Fig. B2. The BioRID-II demonstrated better HTTRR BRS scores (1.2 for JNCAP, 1.3 for 202a, 1.1 for 24kph) than the Hybrid III (1.4 for JNCAP, 2.3 for 202a, 2.5 for 24kph) shown in Table III. In addition, the Hybrid III exhibited rearward HTTRR much earlier in the event (Fig. 4), resulting in large DMPS ranging from 13.0 to 28.1ms shown in Table III. PMHS phase shift values for developing corridors are also provided in Table III. This finding is supported by the timing information when HTTRR changed the polarity from negative (forward rotation) to positive (rearward rotation) in Fig. C1. The Hybrid III also showed higher magnitude of the rearward HTTRR (56.0deg for JNCAP, 60.5deg for 202a, 68.5deg for 24kph) than the BioRID-II (30.4deg for JNCAP, 32.2deg for 202a, 39.3deg for 24kph) or any of the PMHS (46.3deg for JNCAP, 37.0deg for 202a, 41.3deg for 24kph) shown in Fig. 4 and Fig. C2. Interestingly, the PMHS exhibited large forward HTTRR (-30.2deg for JNCAP, -30.9deg for 202a, -29.3deg for 24kph) prior to the neck extension (i.e., rearward HTTRR) shown in Fig. 4 and Fig. C2, while the Hybrid III had nearly zero forward HTTRR (-0.1 to -0.6deg). The BioRID-II also showed small forward HTTRR (-5.0deg for JNCAP, -4.2deg for 202a, and -4.7deg for 24kph) shown in Fig 4 and Fig. C3. It should be noted that the PMHS and BioRID showed forward HTTRR when the Hybrid III exceeded that 12 degrees of rearward HTTRR limit shown in Fig. 4.



(a) JNCAP



(b) 202a



(c) 24kph

Fig. 4. ATD HTTRR responses and PMHS corridors from the second series.
PMHS corridors vs. Hybrid III and BioRID-II.
Horizontal dotted line: 12 degrees of rearward HTTRR limit.

TABLE III
BIORANK SCORES

	Test Condition	Hybrid III	BioRID-II	PMHS average phase shift	PMHS maximum phase shift
	JNCAP	1.4	1.2	N/A	N/A
BRS	202a	2.3	1.3	N/A	N/A
	24kph	2.5	1.1	N/A	N/A
	JNCAP	28.1	4.1	1.6	2.4
DMPS (ms)	202a	13.0	2.7	3.8	4.4
	24kph	17.2	2.2	1.6	2.4

IV. DISCUSSION

The first rear-impact sled series was conducted using the Hybrid III and BioRID-II under identical test conditions to explore HTTRR sensitivity with various backsets and to investigate a transfer function approach for neck extension values of the BioRID-II as the Hybrid III exceeds the 12 degrees of rearward HTTRR limit in FMVSS 202a [31]. The second sled series was performed using the same ATDs and nine PMHS to further understand HTTRR with excessive backsets in which extension was likely to occur. These tests were conducted so that the biofidelity of the Hybrid III and BioRID-II could be assessed in these conditions. Since the BioRID-II exhibited better biofidelity scores, the tests with excessive backsets would help in understanding extension kinematics in the PMHS and BioRID-II relative to the injuries observed in the PMHS so that extension-based injury criteria for HTTRR or intervertebral rotation could be developed for the PMHS and corresponding IARVs for the BioRID-II (detailed in a separate publication).

First Sled Series: HTTRR sensitivity with respect to increased backsets

The HTTRR indicates what the neck experiences dynamically during rear impacts, e.g., negative rotation: neck flexion; positive rotation: neck extension, and has been considered relevant to the likelihood of whiplash-type neck injuries that FMVSS 202a is designed to mitigate [26]. Consequently, the Hybrid III extension limit of 12 degrees of rearward HTTRR, has been used to evaluate head restraint effectiveness in occupant neck injury prevention [29-31]. Based on the results from the first sled series in this study, the Hybrid III HTTRR was sensitive to the increased backsets; that is, the rearward HTTRR of the Hybrid III became larger with the increased backsets. However, the BioRID-II showed only forward HTTRR, even though the Hybrid III exceeded the 12 degrees of rearward HTTRR limit in the test conditions with 90 and 130mm backsets. A similar trend was found in a previous study at ∆V of 17kph [27], in which the Hybrid III rearward HTTRR exceeded 12 degrees when the backset increased from 50mm to 75mm with a head restraint height of 800mm, while the BioRID HTTRR was close to zero or forward rotation in both backsets. Since the HTTRR of the BioRID-II was mainly forward and did not exhibit rearward rotation (Fig. 3b), a transfer function between the extension limit of the Hybrid III and the rearward HTTRR of the BioRID-II could not be made in this study.

For the Hybrid III kinematics, the Hybrid III head rotation increased with increasing backsets and was larger than the T1 rotations, explaining the rearward HTTRR of the Hybrid III regardless of the backsets. The peak T1 rearward rotations (10.0deg for 50mm, 9.7deg for 90mm, 9.0deg for 130mm) were consistent with one another regardless of backset, and consistently lower than the peak head rotations (14.6deg for 50mm, 24.0deg for 90mm, 41.9deg for 130mm) in all backset conditions as shown in Fig. C4 (a) and (b). The Hybrid III T1 rotations were not sensitive to increasing the backset (Fig. C4). The relatively small and consistent T1 rotations across backset conditions for the Hybrid III are likely due to its rigid thoracic spine. The influence of the rigid thoracic spine on the biofidelity of the Hybrid III has been discussed in previous rear impact studies [14-15][33][36]. The rigid thoracic spine and non-segmented neck of the Hybrid III also can explain why it does not exhibit the head lag effect, i.e., the head stays close to its initial position while T1 moves forward and rotates rearward, commonly seen in volunteers, PMHS, and biofidelic rear impact dummies in rear impact. Given that the rigid spine of the Hybrid III does not absorb energy through deformation, all the energy is transferred into the head and neck. Consequently, these combinations, e.g., minimal head lag, consistent and small T1 rotation, and increased head rotations with increasing backset, result in the rearward HTTRR responses of the Hybrid III.

Unlike the Hybrid III, the BioRID-II has a flexible thoracic spine. The T1 rotations for the BioRID-II were larger than the head rotation in the BioRID-II tests (Fig. C4), which results in forward HTTRR. Due to the flexibility of the thoracic spine of the BioRID-II, T1 rotations increased with increasing backsets serving to dissipate energy and reduce rotations in the head/neck. Both head and T1 rotations for the BioRID-II increased with the increased backsets but the head rotations were always smaller than the T1 rotations (Fig. C4 c and d), resulting in the forward HTTRR, and allowing for the biofidelic head lag response as observed in previous studies [8][10-13].

Despite the fact that biofidelity of the BioRID-II should be better than the Hybrid III due to the thoracic spine flexibility and head lag effect, it was still not fully known if the forward (BioRID-II) HTTRR was more biofidelic than the rearward (Hybrid III) HTTRR observed in the first test series. Kang et al. (2014) tested seven PMHS using two production seats at three moderate speeds (202a, JNCAP, and 24kph) [13]. One PMHS (referred to PMHS2 in their study) was tested in the identical condition as the first sled series in this study, i.e., the same OEM seat with 50mm backset at the JNCAP sled pulse. They found that the peak HTTRR of the PMHS was -27.9 degrees (forward rotation). It is important to note that the PMHS did not experience rearward HTTRR throughout the entire event [13]. In the current study, peak HTTRR of the Hybrid III and BioRID-II tested with the 50mm backset were +7.1 degrees and -7.1 degrees, respectively. Both PMHS from the previous study [13] and BioRID-II tested in the current study experienced forward HTTRR. However, the HTTRR magnitude of the BioRID-II was smaller than the PMHS, which is due to the limited range of motion (ROM) and stiff neck bumpers in intervertebral flexion as well as neck cable spring properties of the BioRID-II cervical spine, because it was designed and tuned specifically to neck extension which has been discussed in the literature [12][37]. In contrast to the BioRID-II and PMHS, the Hybrid III showed rearward HTTRR, demonstrating the lack of biofidelity in the given 50mm backset condition. Since the HTTRR of the BioRID-II was forward rotation when the Hybrid III exceeded the rearward HTTRR limit (+12deg) shown in Fig. 3, developing a simple transfer function from the Hybrid III to the BioRID-II will not be feasible using the results from the first sled series nor is the current Hybrid III rearward HTTRR applicable to the BioRID-II. Therefore, an extension limit for the BioRID-II could not be explored from the first sled series. Besides, the biofidelity of both ATDs in the increased backset conditions (e.g., 90 and 130mm) was unknown given there were no PMHS data available to be compared to the ATD HTTRR. For this reason, the second sled series was conducted using both ATDs and PMHS.

Second Sled Series: HTTRR Biofidelity of ATD with excessive backset

In order to further understand HTTRR sensitivity with respect to the 12 degrees of rearward HTTRR limit, and get a more conclusive look at biofidelity of both Hybrid III and BioRID-II in the moderate-speed rear impacts where neck extension should occur, the second sled series was conducted with excessive backset. Even with the excessive backset, the BioRID-II and PMHS exhibited forward HTTRR at the point in time where the Hybrid III exceeded 12 degrees of rearward HTTRR, regardless of the sled pulse (Fig. 4). Unlike the outcomes from the increased backsets used in the first sled series, the excessive backset in this series did allow for both the BioRID-II and PMHS to exhibit rearward HTTRR eventually (Fig. 4). However, the rearward HTTRR of the BioRID-II and PMHS occurred much later than the Hybrid III (Fig B1), which is associated with head lag as well as large T1 rotations occurring at the initial phase of the event (< 100ms). Interestingly, at the points in time when the HTTRR of the BioRID-II and PMHS exceeded the 12 degrees of rearward HTTRR limit for each of the three pulses, the Hybrid III was near its peak and showed similar HTTRR (~55.4deg for JNCAP, ~58.6deg for 202a, and ~57.4deg for 24kph) as shown in Fig. 4 and Fig. C1. Both BioRID-II and PMHS exhibited the forward HTTRR in the initial phase of the rear impact and then sequentially rearward HTTRR regardless of sled pulse (Fig. 4), which was also observed in the previous PMHS study where OEM seats were used [3][10]. In contrast, the Hybrid III did not show forward HTTRR in the initial phase nor at any point in the event. The BRS scores of the head global rotations about the y-axis for the Hybrid III were within two standard deviations of the PMHS head global rotations (BRS ranged from 1.3 to 1.7) as shown in Fig. C5. Again, it was believed that the main reason that the Hybrid III never exhibited forward HTTRR was due to the rigid thoracic spine. T1 global rotations of the Hybrid III were much smaller than that of the BioRID-II and PMHS shown in Fig. C6, resulting in the BRS scores ranging from 3.6 to 9.2. The rigid thoracic spine of the Hybrid III resulted in rearward HTTRR in both sled series regardless of using different seats and sled pulses, which was found in a previous study [33]. Given the PMHS did not show early rearward HTTRR, the rearward HTTRR of the Hybrid III that occurred in the early phase of the rear impact events displays a response that is less biofidelic than the BioRID-II. Thus, the 12 degrees of rearward HTTRR limit for the Hybrid III used in FMVSS 202a could not be directly transformed to the BioRID-II. Further investigation should be made to develop an extension limit, injury risk curve, and ultimately an injury criterion for the BioRID-II. The forward HTTRR of the BioRID-II observed in the initial phase (-5.0deg for JNCAP, -4.2deg for 202a, -4.7deg for 24kph) was much smaller than the PMHS (-30.2deg for JNCAP, -30.9deg for 202a, -29.3deg for 24kph) shown in Fig. C3. Similarly, small forward HTTRR of the BioRID-II was observed in the first sled series with the increased backsets shown in Table II. The differences in the forward HTTRR between the BioRID-II and PMHS are likely due to design constraints within the BioRID-II's neck that limit forward flexion and result in less biofidelic T1 global rotations (BRS ranged from 1.7 to 3.7 shown in Fig. C6), due to the ATD being designed primarily for neck extension. In spite of the lack of neck biofidelity in flexion, the rearward HTTRR of the BioRID-II that occurred later in the event were in the corridors at all three moderate-speeds (Fig. 4), resulting in BRS scores for overall HTTRR ranging from 1.1 to 1.3, shown in Table III. It should also be noted that the DMPS for the BioRID-II were less than 5ms, indicating the phase difference of the rearward HTTRR between BioRID-II and PMHS were small (Table III). The BRS scores for the Hybrid III ranged from 1.4 to 2.5 due to the absence of the forward HTTRR and higher rearward HTTRR, and the Hybrid III also exhibited a large DMPS (13.0 to 28.1ms) as compared to the typical phase difference observed in the PMHS. Given the BioRID-II had better BRS scores for the HTTRR, the BioRID-II may offer advancements in assessing head restraints in dynamic conditions, but further investigation is required to confirm whether the HTTRR is a potential injury predictor for the PMHS and BioRID-II. This should be done by analyzing injuries sustained in PMHS and corresponding kinematics and kinetics measured from the PMHS and BioRID-II. Since the Hybrid III did not exhibit early forward HTTRR, developing appropriate extension-based injury criteria for the BioRID-II is not possible using a transfer function approach from the Hybrid III HTTRR to the BioRID-II. Therefore, results from this study should help to further investigate the extension limit for the BioRID-II. Since a transfer function approach between the Hybrid III extension limit and the BioRID-II could not be achieved in this study, future work should be carried out to explore extension criteria for the BioRID-II by using the data from this study and potentially additional data from different conditions, i.e., no head restraint condition and lower topsets.

Limitations

Small sample size is one of the limitations in this study. A total of nine rear impact sled tests were conducted using nine PMHS in three different sled pulses (three PMHS for each sled pulse). However, since HTTRR responses in moderate-speed rear impacts are limited in the literature, this study should help to better understand the HTTRR responses in moderate-speed rear impacts and to evaluate and potentially improve current safety tools, such as ATDs and FE HBMs.

Due to high severity of the sled pulses, human volunteers could not be tested so that PMHS had to be chosen and used as test specimens in this study. Studies using human volunteers found that bracing of the neck muscles affected head and neck responses in low-speed rear impacts [2], however, similar to other rear impact PMHS studies, the results from this study are intended to be applicable to a live unware occupant. Moreover, at the given moderate-speeds used in this study, the influence of the lack of muscle activation on HTTRR could be minimal [33]. However, caution should still be used when the data from this study are applied since PMHS cannot simulate active neck musculatures during rear impact events.

Although the head position was adjusted to set up a zero degree initial head angle in this study, the initial relative head position to the T1 might not be consistent across the PMHS tests. The initial relative head position to the T1 was not controlled as one of the positioning criteria since it might change cervical spine curvature to be more extension or flexion. Therefore, the head position was adjusted so as not to apply unnecessary loads to the neck while maintaining the zero degree head angle.

Only backset was evaluated in this study. The backsets used in this study were not designed to replicate a realistic production seat but to investigate influence of the increased backsets to the HTTRR. Other seat design parameters, such as topsets, seat structural stiffness, seat foam properties and different head restraint types, e.g., active head restraint, could affect HTTRR differently. Moreover, only two OEM seats were used in this study. Different seat properties and dynamic characteristics might influence PMHS head and neck responses in moderate-speed rear impacts. Dynamic characteristics of the seatback, seat pan, recliner, and seat frames can affect lower extremity, pelvis, torso, neck and head kinematics. If the torso moves more rearward into the seatback, i.e., pocketing into the seatback, than the head, due to seat properties, the neck is more prone to be in flexion due to the head lag. If seatback properties are too stiff so that the torso cannot move into the seatback but is coupled to the seatback, then the neck is more prone to be in extension. Therefore, future work should be carried out to investigate the influence of the seat properties on the head and cervical spine responses. This could be done after safety tools (ATDs and HBMs) are improved by using the biomechanical responses from this study.

V. CONCLUSIONS

A series of rear impact sled tests using the BioRID-II and Hybrid III was conducted with increased backsets. Opposite polarity trends of the HTTRR between the two ATDs were observed, and the BioRID-II never demonstrated rearward HTTRR. Therefore, another test series was conducted with PMHS, BioRID-II, and Hybrid III using excessive backset intended to ensure rearward HTTRR. The BioRID-II exhibited more biofidelic HTTRR than the Hybrid III based on the BRS method that evaluated ATD time-history HTTRR. Future work should account for other neck injury metrics to develop extension-based PMHS injury criteria and ATD injury assessment reference values. For a more biofidelic ATD like the BioRID-II, this is a necessary step in order to develop extension-based injury criteria to ensure vehicles have a sufficiently protective head restraint that prevents hyperextension.

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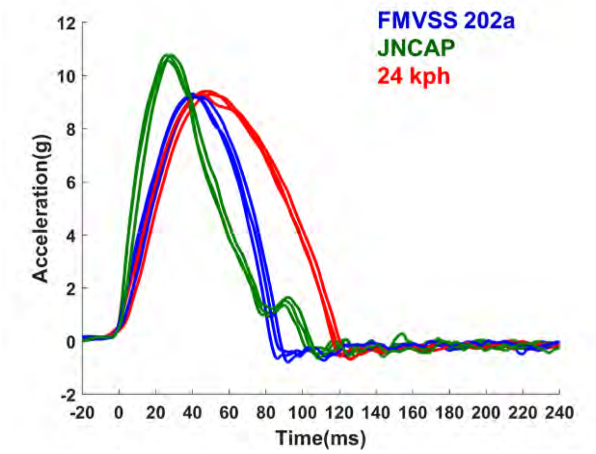
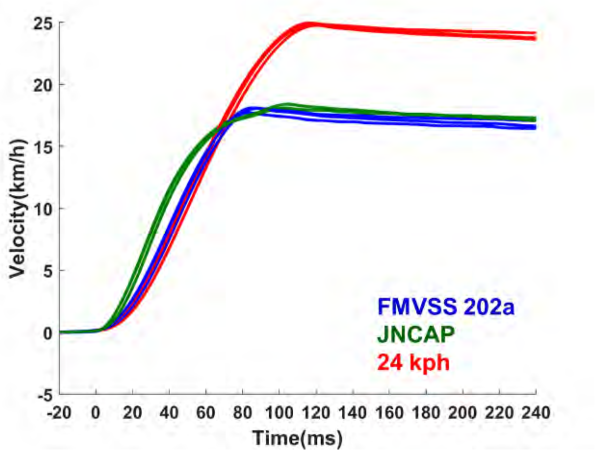
VIII. APPENDIX

Appendix A

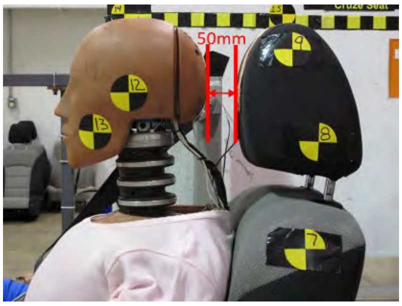


(a) Acceleration

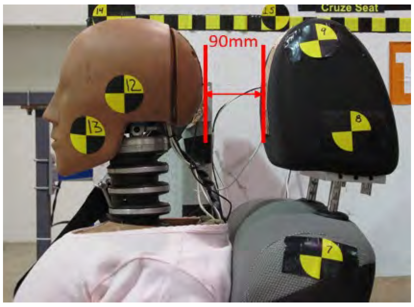


(b) Velocity

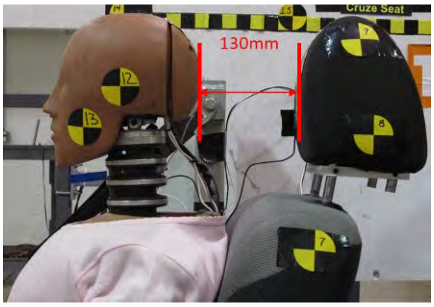
Fig. A1. Sled pulses.



(a) 50mm backset with no bracket



(b) 90mm backset bracket



(c) 130mm backset bracket

Fig. A2. Adjustable backsets used in the first sled series. To achieve the 90mm and 130mm backset conditions, the ATD was initially seated with 50mm of backset (which is considered to be the baseline configuration), and then the head restraint was adjusted to achieve the target backset.

(a) Hybrid III

(b) BioRID-II

Fig. A3. General test set-up for the first sled series.

Fig. A4. Excessive backset used in the second sled series.

(a) PMHS (b) BioRID-II

Fig. A5. General test set-up for the second sled series.

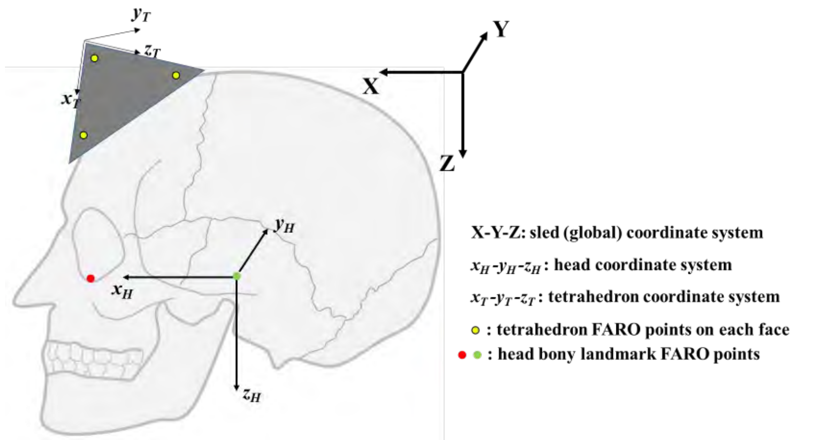
TABLE AI
PMHS INFORMATION (ANTHROPOMETRY UNIT: CM AND KG)
BD: BREADTH, HT: HEIGHT, DP: DEPTH, CR: CIRCUMFERENCE

	Age	aBMD T-Score	Weight	Height	Seated Height	Head BD	Head HT	Head DP	Head CR	Neck BD	Neck DP	Neck CR
PMHS1	65	+1.7	78.5	185.0	85.0	15.1	23.7	17.1	60.4	10.5	11.1	41.4
PMHS2	34	-1.5	85.7	185.4	83.0	14.7	23.2	19.8	60.5	10.9	10.9	35.0
PMHS3	56	-1.4	66.7	175.3	80.2	14.7	21.9	18.5	56.8	10.0	11.9	36.2
PMHS4	63	+0.5	88.5	181.5	85.0	14.7	22.7	19.7	59.1	11.3	11.8	37.6
PMHS5	24	+0.7	75.3	168.5	80.0	14.1	24.2	18.1	56.6	11.4	12.3	43.2
PMHS6	58	+3.9	72.6	182.2	89.0	14.5	21.4	19.2	58.3	9.7	11.7	37.4
PMHS7	59	+1.2	72.1	177.0	83.3	13.6	21.5	19.1	58.3	11.5	11.7	41.5
PMHS8	57	+1.2	61.2	184.5	89.0	14.7	21.4	19.0	58.9	9.1	11.9	33.3
PMHS9	64	+2.8	75.2	175.3	84.0	14.6	22.9	18.3	57.5	13.7	13.1	47.3
Mean	53	1.0	75.2	179.4	84.3	14.5	22.5	18.8	58.5	10.9	11.8	39.2
(SD)	(14)	(1.8)	(8.5)	(5.7)	(3.2)	(0.4)	(1.0)	(0.9)	(1.4)	(1.3)	(0.6)	(4.5)

Appendix B

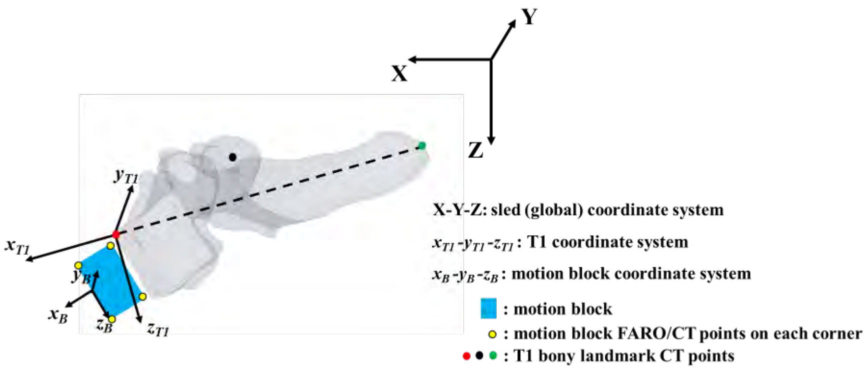
Head and T1 transformation

For the head instrumentation, the 6aω was installed on a tetrahedron fixture that was rigidly attached to the PMHS skull. In order to create a body-fixed local coordinate system on the tetrahedron fixture three points on each face of the fixture were digitized using a FARO arm device in each PMHS test (Fig. B1a). Head bony landmarks (e.g., tragions and infraorbital notches) were also digitized to define a head anatomical coordinate system with the same orientation of the Frankfort plane (Fig. B1a). After each PMHS test, the head CG was measured using a moment table method proposed in a previous study [38]. The tragions and infraorbital notches of the head placed on the moment table were also digitized so the head CG position could be determined in the head local coordinate system. Using these digitized points, the head kinematic data directly measured from the tetrahedron fixture could be transformed to the head anatomical coordinate system as well as to the sled (global) coordinate system using the Euler angle approach (e.g., 2-1-3 sequence) to determine head rotation about global Y-axis. For the T1 instrumentation, the T1 3aω motion block was digitized in each PMHS test to quantify an initial orientation of the block (Fig. B1b). From the 3D CT images, both bony landmarks and the 3aω motion block at T1 were digitized so a transformation matrix from the 3aω motion block coordinate system to the anatomical coordinate system could be defined (Fig. B1b). The T1 local kinematics at the anatomical origin (antero-superior edge of the T1 vertebral body) were transformed to the sled coordinate system.



(a) Head, instrumentation, and global coordinate systems

FARO points: three points on each face in the tetrahedron fixture, right and left tragions and infraorbital notches



(b) T1, instrumentation, and global coordinate systems

FARO points: four points on each corner on the motion block;

CT points: four points on each corner on the motion block, right and left transverse processes, antero-superior edge of the vertebral body, and spinous process

Fig. B1. Anatomical, instrumentation, and global coordinate systems.

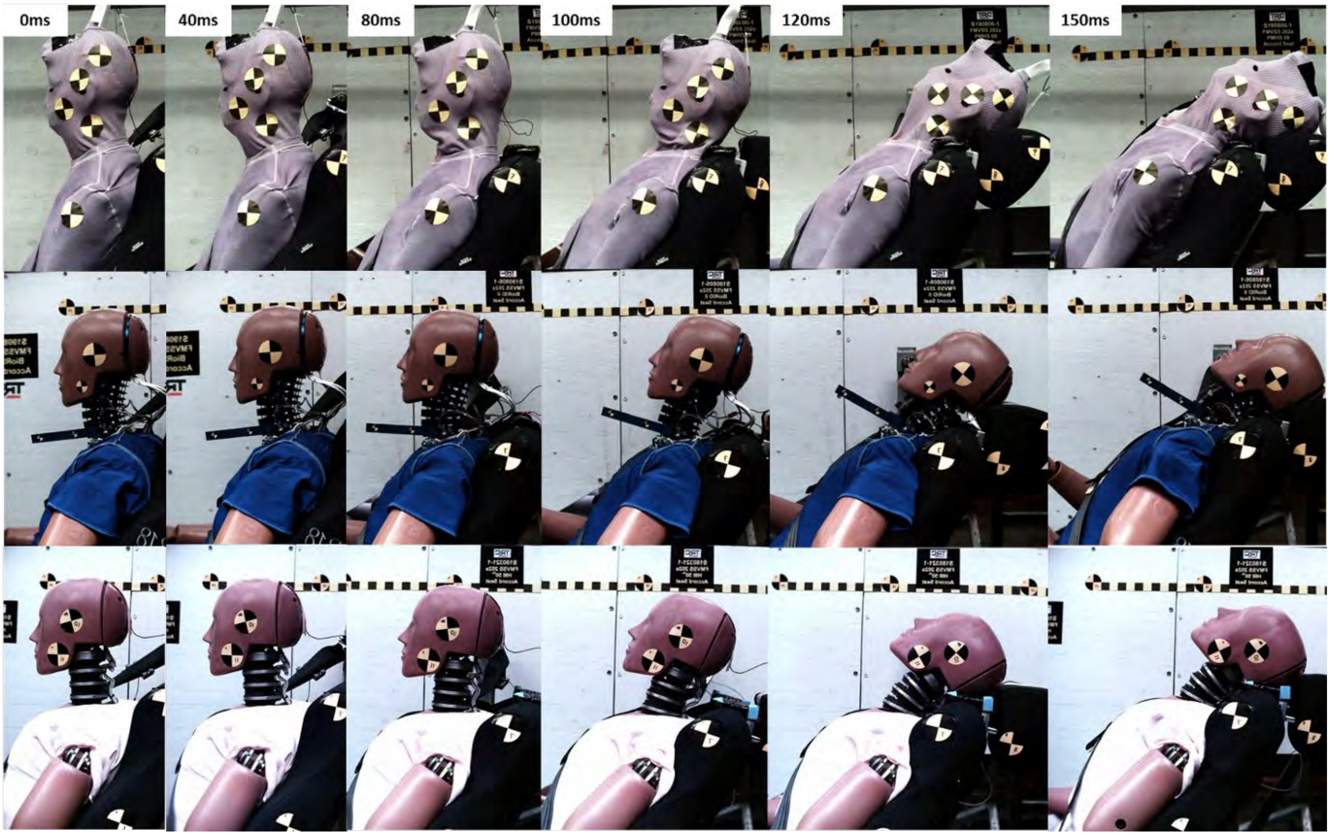


Fig. B2. General kinematics of the PMHS, BioRID-II, and Hybrid III in the second series.

Appendix C

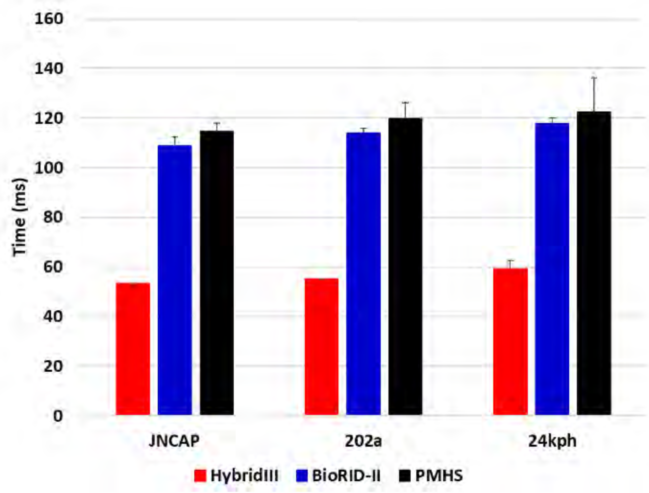


Fig. C1. Timing when HTTRR changed polarity from negative (forward rotation) to positive (rearward rotation).

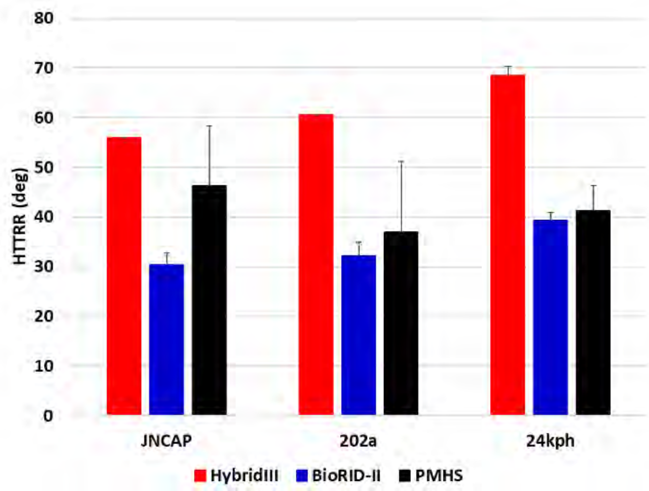


Fig. C2. Rearward HTTRR.

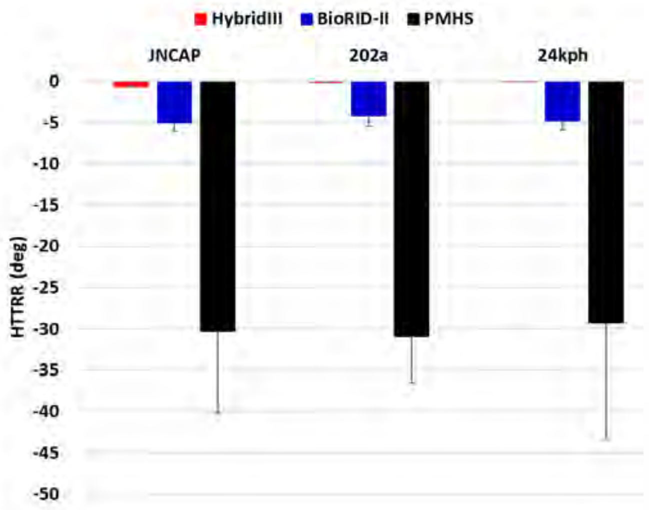
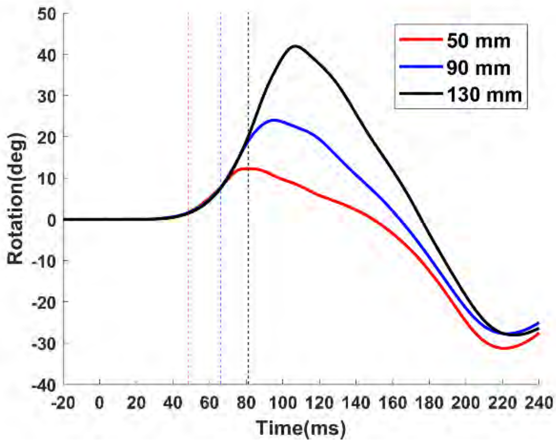
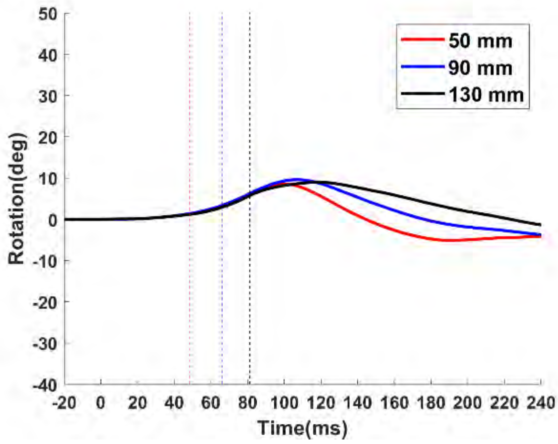


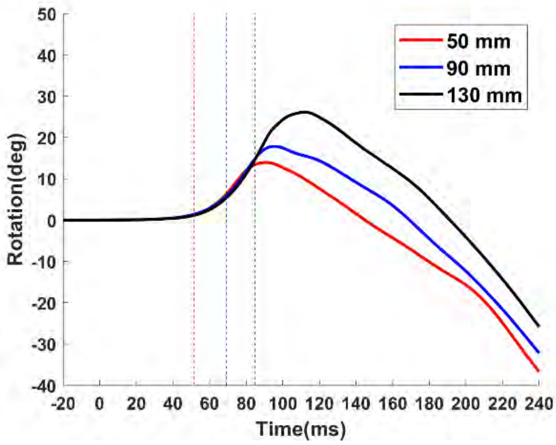
Fig. C3. Forward HTTRR.



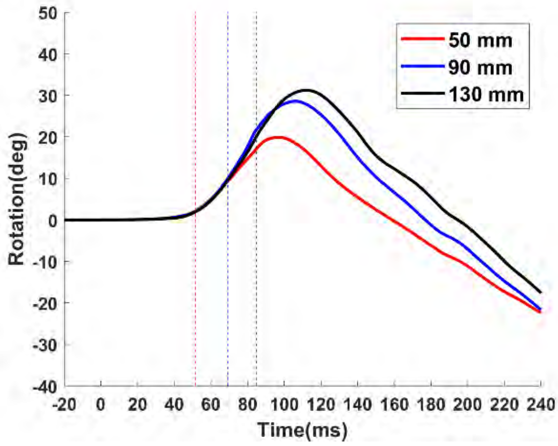
(a) Hybrid III head rotation



(b) Hybrid III T1 rotation

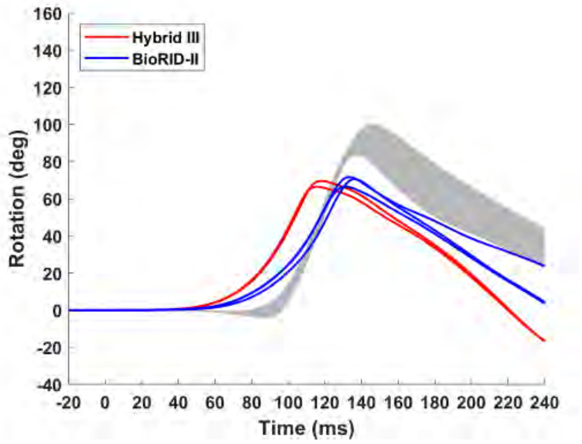


(c) BioRID-II head rotation

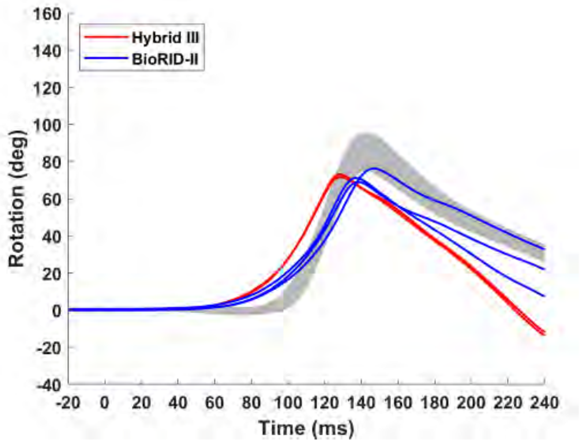


(d) BioRID-II T1 rotation

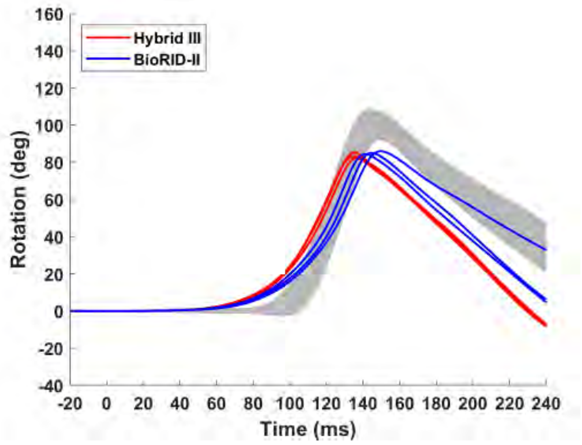
Fig. C4. Head and T1 global rotation of the Hybrid III and BioRID-II in the first sled series.



(a) JNCAP
Hybrid III: BRS of 1.66 & DMPS of 32.6ms
BioRID-II: BRS of 1.61 & DMPS of 17.7ms
PMHS Ave. Shift of 0.50ms
PMHS Max Shift of 0.70ms

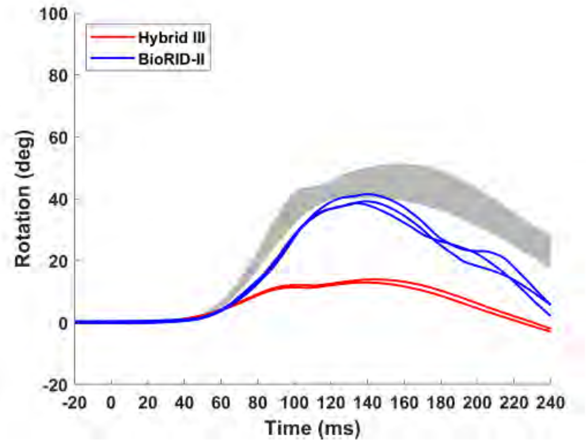


(b) 202a
Hybrid III: BRS of 1.48 & DMPS of 27.4ms
BioRID-II: BRS of 1.17 & DMPS of 11.6ms
PMHS Ave. Shift of 1.20ms
PMHS Max Shift of 1.75ms

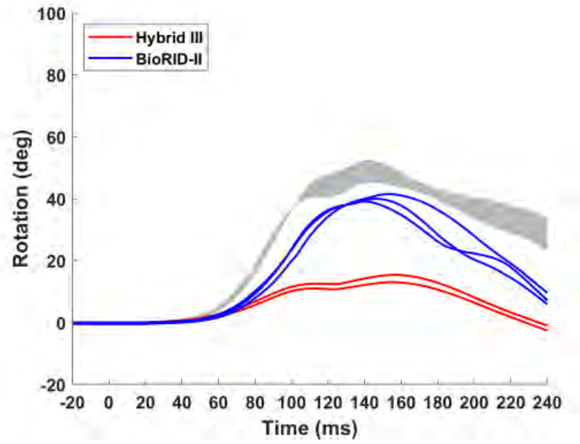


(c) 24kph
Hybrid III: BRS of 1.30 & DMPS of 23.6ms
BioRID-II: BRS of 1.02 & DMPS of 12.6ms
PMHS Ave. Shift of 3.65ms
PMHS Max Shift of 5.45ms

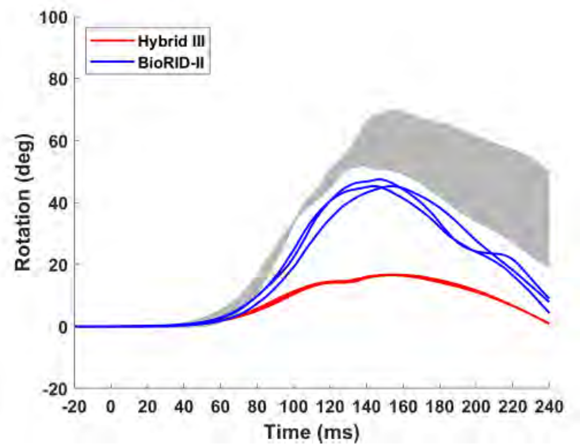
Fig. C5. Head global rotation of the Hybrid III and BioRID-II in the second sled series.



(a) JNCAP
Hybrid III: BRS of 5.27 & DMPS of 15.0ms
BioRID-II: BRS of 2.14 & DMPS of 3.5ms
PMHS Ave. Shift of 0.10ms
PMHS Max Shift of 0.15ms



(b) 202a
Hybrid III: BRS of 9.20 & DMPS of 9.7ms
BioRID-II: BRS of 3.74 & DMPS of 9.3ms
PMHS Ave. Shift of 0.15ms
PMHS Max Shift of 0.25ms



(c) 24kph
Hybrid III: BRS of 3.58 & DMPS of 0.4ms
BioRID-II: BRS of 1.70 & DMPS of 4.7ms
PMHS Ave. Shift of 0.55ms
PMHS Max Shift of 0.80ms

Fig. C6. T1 global rotation of the Hybrid III and BioRID-II in the second sled series.