Head Trajectories of Post Mortem Human Surrogates in Moderate-Speed Rear Impacts

Yun-Seok Kang, Kevin Moorhouse, John H. Bolte IV

Abstract One potential non-standard seating configuration for vehicles with automated driving systems is to have seating that faces the centre of the vehicle. This would result in the rear-facing seats experiencing rear-impact crash dynamics when the vehicle is in a frontal collision. Because rear crashes often occur at low speeds, there are limited biomechanical data in this seating configuration in moderate speed rear impacts. The objective of this study was to investigate head trajectories of post-mortem human surrogates (PMHS) with respect to seats that have different seat back rotations, so that human body models and anthropomorphic test devices can be evaluated and potentially modified to better reflect head trajectories. Twenty-one rear impact sled tests using fifteen PMHS were conducted with ΔVs ranging from 17 to 24 km/h. The PMHS were placed in both experimental and production seats that exhibited seat back rotations ranging from 5 to 35 degrees. The head average downward displacements were 48.7 mm (17 km/h) and 140.3 mm (24 km/h) in the experimental seats, while the average upward displacements were 47.9 mm (17 km/h) and 83.6 mm (24 km/h) in the production seats. This directional difference in the z direction is likely due to the higher rotation of the seat back in the experimental seat than in the production seat and different subject interaction with the seat back from different seat back properties.

Keywords automated vehicle, head trajectories, rear impact, rear-facing, seat back rotation

I. INTRODUCTION

Non-standard seating configurations for vehicles with automated driving systems (ADS) are currently being evaluated by many researchers using computational models to assess the crashworthiness safety of ADS vehicles [1-2]. One potential seating configuration of focus is rear facing seats. However, there are very limited data for biomechanical responses from post mortem human surrogates (PMHS) in the rear facing configuration at moderate speeds that can be used to evaluate human body models (HBMs) and anthropomorphic test devices (ATDs). In particular, head trajectories should be considered as an important design parameter for safety since head contact to the interior structures within the compartment is highly possible [26]. Biomechanical responses of volunteers and PMHS in rear impacts have been studied extensively with a wide range of ΔV (e.g., 4 to 25 km/h) and seat configurations, i.e., rigid seats to production seats [3 - 19]. However, most of the previous studies have focused on low-speed rear impacts below a ΔV of 17 km/h. Even though a few studies have tested human subjects to generate biomechanical responses in moderate-speed rear impacts [3-4][9-10], they did not use production seats nor experimental seats with a yielding seat back and typical padding/cushion from a production seat.

Many studies have generated biomechanical responses using PMHS and human volunteers in rear impact conditions using head local kinematics (e.g. head linear acceleration in body fixed coordinate system, such as Frankfort plane) or relative head kinematics to first thoracic vertebra (T1) [3-8,11,12,24]. Few studies reported head displacements in the global coordinate system [9,12], and none of the studies used either an experimental seat that mimics a yielding seat back or production seats in moderate-speed rear impacts. A previous study investigated biomechanical responses of PMHS (4 females and 1 male) in moderate speed rear impacts (24 km/h) [9]. A rigid seat with no head restraint was used such that hyperextension was observed with the head rotation ranging from 123 to 149 degrees in their study [9]. While head CG displacements and trajectories have been investigated [9,12], they have not also considered different head sizes of the subjects.

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In 2012 and 2013, biomechanical data from moderate-speed rear impacts (17 km/h and 24 km/h pulses) were generated using eight PMHS that were seated in an experimental seat with a yielding seat back and padding/cushion from a production seat [16-17]. The biomechanical targets generated were acceleration, rotation, force, and moment from various body regions to evaluate biofidelity of the rear impact ATDs [16][20]. In 2014, seven additional PMHS were tested using two production seats and three different sled pulses, such as 17 km/h, 24 km/h, and Japan New Car Assessment Program (JNCAP) pulses [18-19]. Biomechanical responses created from this study were acceleration and rotation from the head and T1. While several studies have been published using this combined data set of 21 tests of 15 PMHS in moderate-speed rear impact to generate biomechanical responses used for evaluating biofidelity of rear impact ATDs [16-20], none have included head trajectories. Therefore, the objective of this study is to investigate head trajectories of PMHS in moderate-speed rear impacts. Such information could be used by safety designers to understand how to design interior compartments to best protect against head contacts likely to cause head and neck injuries.

II. METHODS

PMHS Information

The 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 Institutional Review Board (IRB) protocol, were reviewed and followed. PMHS were scanned using Computed Tomography (CT) to exclude subjects who exhibited severely degenerative discs, osteophytes, or previously documented spinal surgery. In order to exclude osteoporotic PMHS, the PMHS were scanned using Dual Energy X-ray Absorptiometry (DXA). The average age of the PMHS was 73 ± 11. Average weight (79 ± 6 kg) and height (179 ± 6 cm) were similar to the 50th percentile male (77 kg and 175 cm) [25] as shown in Table 1. Detailed anthropometric information and selection criteria of the PMHS were reported in previous studies (PMHS01 through 08 in [16] and PMHS09 through 15 in [18])

TABLE I
PMHS INFORMATION AND TEST MATRIX

	Age	Weight (kg)	Height (cm)	Sled Pulse	Seat Type
PMHS01	80	87.3	182	24 km/h	Exp
PMHS02	71	68.6	175	17 km/h	Exp
PMHS03	87	87.3	178	17/24 km/h	Exp
PMHS04	82	79.8	182	17/24 km/h	Exp
PMHS05	62	69.0	165	17/24 km/h	Exp
PMHS06	42	76.2	174	17/24 km/h	Exp
PMHS07	76	74.0	167	17/24 km/h	Exp
PMHS08	75	84.8	183	17/24 km/h	Exp
PMHS09	67	83.0	177	17 km/h	Prod A
PMHS10	82	78.5	183	JNCAP	Prod A
PMHS11	66	81.6	184	JNCAP	Prod B
PMHS12	65	75.3	184	24 km/h	Prod B
PMHS13	78	78.5	188	JNCAP	Prod B
PMHS14	81	84.8	180	24 km/h	Prod A
PMHS15	80	71.2	178	24 km/h	Prod B
Mean (SD)	73 (11)	79 (6)	179 (6)	--	--

Rear Impact Sled Tests

Rear impact sled tests using PMHS on a Hydraulic-controlled, Gas-Energised (HyGE) sled were conducted using three different pulses (17 km/h [21], JNCAP [22] and 24 km/h [16][20]), as shown in Figure A1. General set-up and initial positioning of the PMHS are shown in Figure 1. Twenty-one rear impact sled tests using fifteen PMHS were conducted using both experimental and production seats that exhibited peak seat back rotations ranging from 5 to 35 degrees (Table AI and AII). For PMHS03 through 08, the PMHS were tested at two speeds: 17 km/h (always first) and 24 km/h (second). Three different types of seats (Exp: experimental seat, Prod A: 2012 Chevrolet Cruze, Prod B: 2011 Toyota Camry) were used in moderate-speed rear impact conditions (Table I). Since 2012-2013 studies [16,17] focused on evaluating biofidelity of rear impact dummies, an experimental seat that was capable of measuring external forces (e.g., reaction forces from the seat pan, seat back and head restraint) was built and used. The detailed information for the experimental seat can be found in Appendix B. Since 2014-2015 studies [18,19] focused on cervical spine injury in moderate-speed rear impacts, the production seats were selected based on IIHS head restraint rating (Prod A was good, while Prod B was marginal). The seating procedures for the PMHS were also reported in previous studies [16-19]. Desired backset, i.e., horizontal distance between the head and the head restraint, and topset, i.e., vertical distance from the centre of gravity (CG) 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 was provided in previous studies [16][18]. A three-point belt with no pretenioner and load limiter was used to restrain the PMHS on the seats, with initial belt tensions of 17.8 N (4 lb) for the lap-belt and 26.7 N (6 lb) for the shoulder-belt. The initial seat-back angle was approximately 25 degrees from the vertical based on SAEJ826. The production seats (Prod A and B) were replaced following each sled test, while the seat cushion and cover of the experimental seat were replaced each test.

(a) Experimental seat (Exp) (b) Production seat A (Prod A) (c) Production seat B (Prod B)

Fig.1. General set-up for the sled test

Instrumentation

Six accelerometers and three angular rate sensors were installed on a tetrahedron fixture, which was rigidly attached to the skull to quantify head kinematics. High speed videos were recorded and analysed to determine peak seat back rotations. Although more instrumentation was used on the PMHS, the focus of this study is only on the head, i.e., head trajectories. More information for the PMHS instrumentation was reported in the previous studies [16-19].

Data Processing

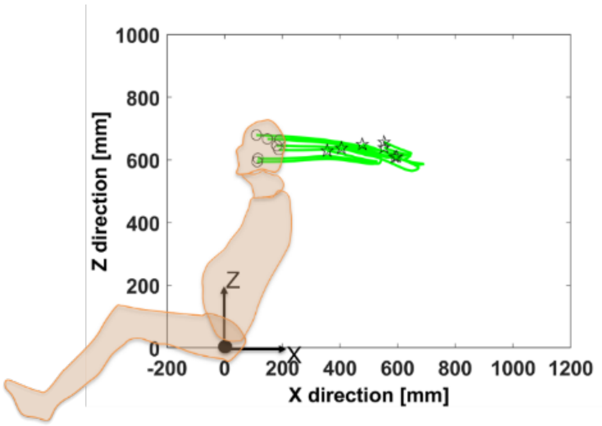
The sampling frequency used in all sled tests was 12,500 Hz. Prior to calculating and transforming raw data, data were zeroed and filtered according to SAE J211 (e.g., CFC1000 for the head data). In order to create local coordinate systems on the head and the tetrahedron fixture, points on the head (e.g., infraorbital notches and tragions) and tetrahedron fixture (vertex and each corner) were digitized. By using these digitized points and the local coordinate system, data measured at the tetrahedron were transformed to the CG of the head to obtain head kinematics from the sled tests. The influence of gravity on the accelerometers was compensated for and thus removed from the traces [23]. For plotting purposes, a custom coordinate system was used (X: rearward, Z: upward in the global coordinate system) as shown in Figure 2, with the origin of the coordinate system defined at the greater trochanter (GT) of the femur. This origin remained fixed at the initial GT position like a global coordinate system or ground fixed coordinate system. Subject-specific head models were built using CT images and were used to visualise and estimate allowable compartment space to avoid direct head contact with the vehicle interior for given seats. A commercial statistical software (Minitab LLC, State College, PA, USA) was used to perform correlation analyses, such as peak seat back rotation vs. head displacement and body size vs. head displacement.

III. RESULTS

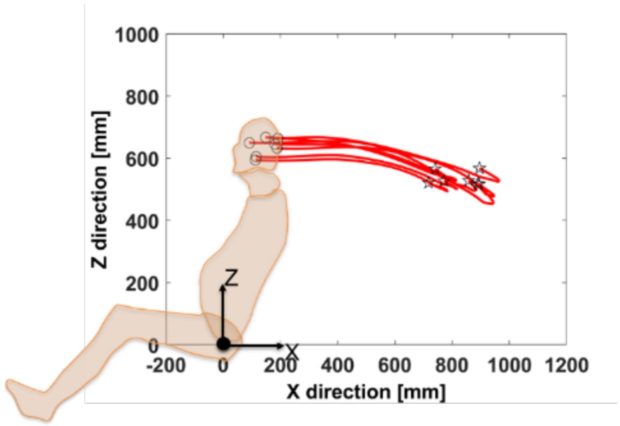
For the experimental seat, the head moved rearward with average peak displacements in the x direction of 466.8 ± 51.7 mm for the 17 km/h test and 732.2 ± 69.3 mm for the 24 km/h test as shown in Table II. The head stayed close to the initial position at first then moved downward in the z direction 48.7 ± 27.3 mm (17 km/h test) and 140.3 ± 31.5 mm (24 km/h test). Head excursion that was measured at the CG locations with respect to the GTs in the defined coordinate system can be found in Figure 2 and Table II. For the experimental seat, the average peak seat back rotation for the 17 km/h test was 22.0 ± 2.0 degrees, while that for the 24 km/h test was 33.4 ± 1.2 degrees (Table AI). General kinematics of the PMHS tested in the experimental seat can be seen in Figure A2.

TABLE II
PEAK DISPLACEMENTS AND EXCURSION AT CG IN THE EXPERIMENTAL SEAT (UNIT: MM)

	Peak displacements				Peak excursion			
	17 km/h test		24 km/h test		17 km/h test		24 km/h test	
	X	Z	X	Z	X	Z	X	Z
PMHS01	--	--	792.7	-153.2	--	--	883.6	654.9
PMHS02	536.7	-67.1	--	--	646.3	679.4	--	--
PMHS03	495.6	-66.0	815.4	-141.9	643.5	667.0	963.2	667.0
PMHS04	491.4	-80.1	762.9	-191.4	671.9	645.1	943.3	645.3
PMHS05	414.1	-6.7	671.5	-100.2	526.3	628.9	783.8	596.4
PMHS06	400.9	-56.3	622.8	-137.7	591.6	664.2	813.5	664.1
PMHS07	428.4	-16.5	701.7	-103.5	543.2	637.1	816.5	609.7
PMHS08	500.5	-47.9	758.3	-154.3	688.2	634.2	946.1	635.7
Mean	466.8	-48.7	732.2	-140.3	615.9	650.8	878.6	639.0
SD	51.7	27.3	69.3	31.5	63.2	19.3	74.2	27.0



(a) 17 km/h test



(b) 24 km/h test

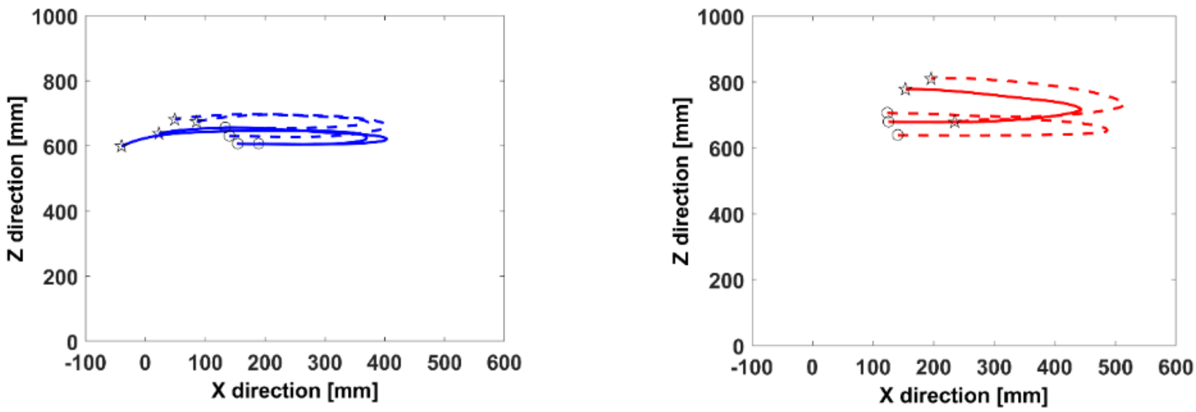
Fig. 2. Head trajectories in the experimental seat. Circle represents head CG initial position. Star represents head CG end position.

For the production seats, PMHS09 tested in the 17 km/h test was grouped with PMHS tested in JNCAP, since the ΔV for the JNCAP was also 17 km/h. Similar kinematics were observed as in the experimental seat prior to head contact with the head restraint, but in contrast the head moved upward during and after contact with the head restraint. Average peak rearward head displacements in the x direction were 232.4 ± 22.8 mm (17 km/h test) and 351.7 ± 37.7 mm (24 km/h test) while the upward displacements in the z direction were 47.9 ± 12.8 (17 km/h test) and 83.5 ± 31.3 mm (24 km/h test). Head excursion which was measured at the CG locations with respect to the GTs in the defined coordinate system can be found in Figure 3 and Table III. For the production seats, the average peak seat back rotation for the 17 km/h test was 6.6 ± 1.2 degrees, while that for the 24 km/h test was 11.1 ± 0.3 degrees (Table AII). General kinematics of the PMHS tested in the production seats are shown in Figure A3 and A4.

TABLE III
PEAK DISPLACEMENTS AND EXCURSION AT CG IN THE PRODUCTION SEATS (UNIT: MM)

	Peak displacements				Peak excursion			
	17 km/h test*		24 km/h test		17 km/h test*		24 km/h test	
	X	Z	X	Z	X	Z	X	Z
PMHS09	213.8	48.3	--	--	402.9	655.6	--	--
PMHS10	215.5	38.9	--	--	369.9	646.1	--	--
PMHS11	262.3	65.9	--	--	402.7	697.0	--	--
PMHS12	--	--	392.0	104.8	--	--	515.4	811.1
PMHS13	238.0	38.6	--	--	371.5	695.8	--	--
PMHS14	--	--	317.4	98.0	--	--	442.9	777.4
PMHS15	--	--	345.6	47.6	--	--	486.4	687.0
Mean	232.4	47.9	351.7	83.5	386.8	673.6	481.6	758.5
SD	22.8	12.8	37.7	31.3	18.5	26.6	36.5	64.2

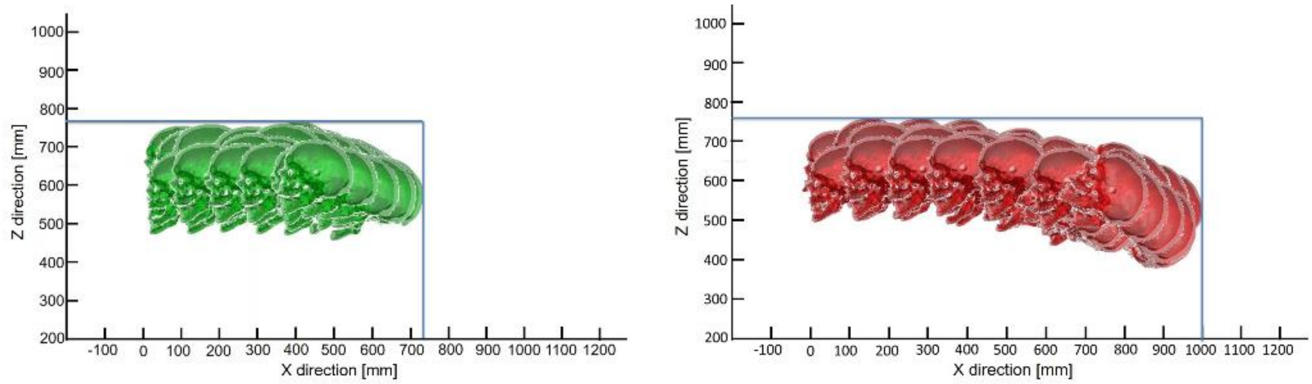
* JNCAP tests (PMHS10, 11, and 13) were combined with 17 km/h test (PMHS09) for the production seat tests



(a) 17 km/h test (combine with JNCAP) (b) 24 km/h test

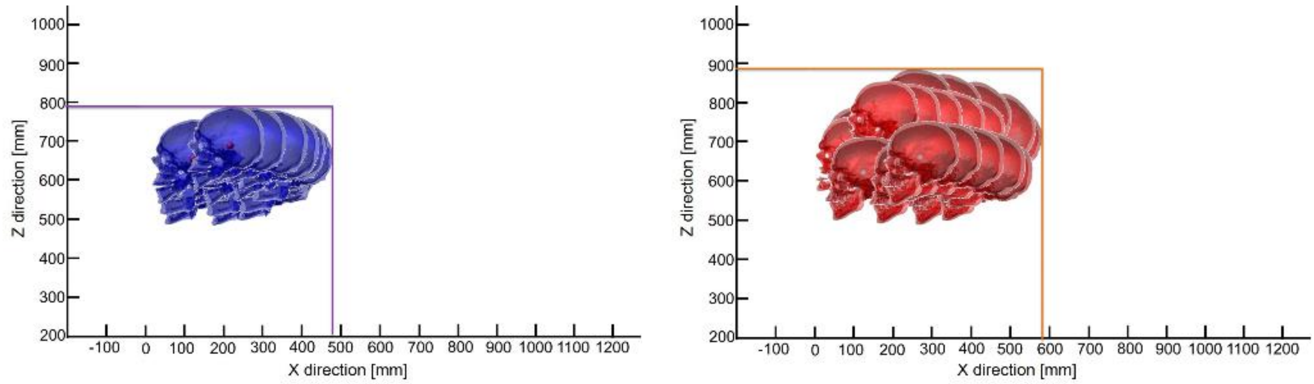
Fig. 3. Head trajectories in the production seats (solid lines: Prod A and dotted lines: Prod B). Circle represents head CG initial position. Star represents head CG end position.

In order to consider head sizes of each PMHS for estimating allowable compartment space to avoid direct head contact with the vehicle interior for given experimental and production seats, subject-specific head models were built using CT images of each PMHS. The head kinematic data were applied to the subject-specific head models and superimposed over time as shown in Figure 4 for the experimental seat and Figure 5 for the production seats. For the experimental seat, the compartment design space where the heads can move without contacting the vehicle interior was defined as 733 mm in the X direction and 766 mm in the Z direction for 17 km/h test and 1000 mm in the X direction and 759 mm in the Z direction for 24 km/h test (Fig. 4). For the production seat, the design space can be defined as 480 mm in the X direction and 789 mm in the Z direction for 17 km/h test and 581 mm in the X direction and 886 mm in the Z direction for 24 km/h test (Fig. 5).



(a) 17 km/h (b) 24 km/h

Fig. 4. Superimposed subject-dependent head trajectories in the experimental seat. Sequential head motions were created every 10 ms for all PMHS in each group. Solid horizontal and vertical lines represent design space (overall maximum excursion - X: 733 mm and Z: 766 mm for 17 km/h and X: 1000 mm and Z: 759 mm for 24 km/h)



(a) 17 km/h (combined with JNCAP) (b) 24 km/h

Fig. 5. Superimposed subject-dependent head trajectories in the production seats. Sequential head motions were created every 10 ms for all PMHS in each group. Solid horizontal and vertical lines represent design space (overall maximum excursion - X: 480 mm and Z: 789 mm for 17 km/h and X: 581 mm and Z: 886 mm for 24 km/h)

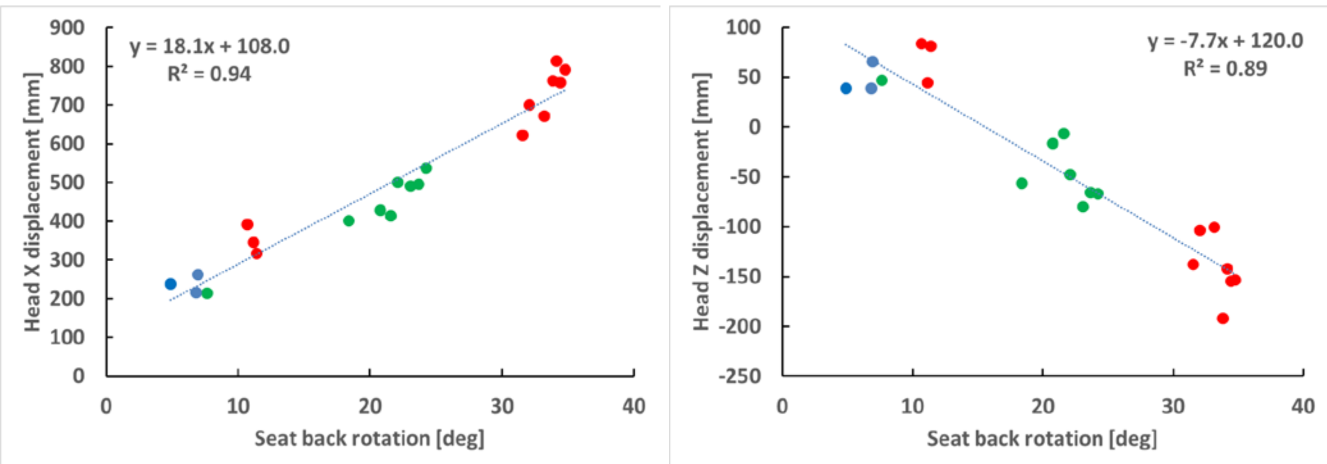
IV. Discussion

One potential non-standard seating configuration for vehicles with automated driving systems (ADS) is rear-facing seats for first row occupants, who would experience rear-impact crash dynamics when the vehicle is in a frontal collision. There are very limited biomechanical data in moderate speed rear impacts that can be used for designing interior space for vehicles with ADS. Head trajectories, especially, should be regarded as a crucial design parameter for safety since head contact to the interior structures within the compartment is highly possible. This study investigated head displacement and trajectories measured from twenty-one moderate-speed rear impact tests using 15 PMHS.

Generally, the peak head excursions presented herein were much larger than previously-published data sets. For example, Yoganandan et al. [9] presented head CG displacements ranging from 80 mm to 160 mm in the x direction, which may have resulted from the use of a rigid seat. The head translated rearward more in the experimental seat with a yielding seat back and production seats as compared to the rigid seat because the whole body moved into the seat back due to yielding of and pocketing within the seat back due to seat pads and cushions with seat back rotation. The upward z displacements (i.e., ramping up motion) were observed from 10 to 30 mm in the rigid seat [9], which were smaller than the displacements (47.6 to 104.8 mm) exhibited in the current study using the production seats in the 24 km/h test. It should be noted that head upward motion was observed during the head restraint contact in the current study, while the rigid seat study did not use a head restraint. The downward z displacement ranged from 40 to 100 mm in the rigid seat testing [9], which was induced from hyperextension due to absence of the head restraint. In the current study, the downward z displacements ranged from 100.2 to 191.4 mm in the experimental seat in the 24 km/h test, which were higher than those from the rigid seat tests, likely due to the yielding seatback with seat back rotation (31.5 to 34.8 degrees).

In the current study, the head moved downward in the experimental seat, while the head moved upward in the production seats. This directional difference in the z direction is likely due to the higher rotation of the seat back in the experimental seat than in the production seat (Table AI and AII) and different subject interaction with the seat back from different seat back properties. Since seat back rotations seem to be one of the factors that determine head displacement and trajectories, the relationship between head displacements and seat back rotations for all 21 rear impact sled tests were investigated (Fig. 6). Figure 6a shows the head global X displacements with respect to the seat back rotations for 17 km/h, JNCAP and 24 km/h rear impacts, while Figure 6b shows head global Z displacements with respect to the seat back rotations. For the X displacement, a positive relationship can be seen between the head displacements and the seat back rotations with R^2 of 0.94 (p-value < 0.001), while a negative relationship was found for the Z displacement with R^2 of 0.89 (p-value < 0.001). Based on these, there may be an optimal seat back rotation that may keep the head in the best place for a given vehicle compartment since differing amounts of vertical and/or horizontal motion may be allowable for different vehicle compartments to avoid head contacts. The other factor that could influence head displacement and trajectories is body size, such as stature, weight, seated height, and BMI. The relationship between body size and head movement for all 21 tests were also investigated for the experimental seat study (Table CI), the production seat study (Table CII), and combined data from both experimental and production seat studies (Table CIII) in Appendix C. For the experimental seat, only seated height exhibited a positive relationship with the peak head Z excursion (R^2 of 0.42, p-value of 0.013) shown in Table CI. For the production seat, the seated height also showed positive relationships with peak head displacements and excursions in both X and Z directions (R^2 ranged from 0.58 to 0.64, p-value from 0.031 to 0.048). However, when both experimental and production seat data were combined in Table CIII, no relationships were found between the seated height and peak head displacements and excursions, while a positive relationship was found between the stature and peak Z excursion (R^2 of 0.24, p-value of 0.025) shown in Table CIII. The statistical significances in Table CI, CII and CIII were weak (lowest p-value of 0.013), likely due to limited sample size and number of tests. In addition, 50th percentile male PMHS were collected for both experimental and production seat studies so that the body size was somewhat controlled. Therefore, the variations of the PMHS body size may not be large enough to produce a strong linear relationship between the body size and peak head displacements and excursions. In future rear impact studies, different body sizes could be considered.

The seat back properties (e.g., foam properties, seat back frame properties) must be accounted for since the seat back properties could also affect the head trajectories in moderate speed rear impacts. In addition to optimising all of these based on head trajectories, other potential injuries have to also be considered such as head, neck and thorax injuries that could occur in high speed rear facing ADS scenarios.



(a) displacement in X direction (b) displacement in Z direction

Fig. 6. Relationship between head displacement and seat back rotation (green dots: 17 km/h, blue dots: JNCAP, and red dots: 24 km/h pulse).

By using PMHS CT images, subject-specific PMHS head trajectories were used to determine the overall excursion of the head in tests of experimental and production seats in moderate-speed rear impacts. Previously-published kinematic corridors considered only the CG of the head, which does not account for different head sizes or head rotations. In coupling the head CG with the subject-specific CT images, this study allowed for the definition of a compartment space to avoid head contact for given seats for a range of relevant crash pulses (Fig. 4 and 5).

Limitations

First, in this study, PMHS were used as test specimens, not human volunteers, since our target speeds were more severe than low speed tests that may be used in human volunteer tests without inducing any injuries. PMHS could not account for neck muscle activation so some caution needs to be taken when the data are applied to the real world. However, for the speeds used in this study, it has been reported that the effect of the lack of muscle activation is minimal, particularly because the data for rear impacts are intended to be applicable to a live unaware occupant [20]. Even though PMHS were screened with extra caution, it is possible that age-related differences in the properties of the spine had an influence on the head displacement and trajectories.

The seat back rotation from the experimental seat is more uniform than production seats. Due to the instrumentation installed in the seat, the seat back frame of the experimental seat was more rigid than production seats so that the seat back frame was minimally deformed during the moderate-speed rear impacts. Due to this rigidity of the seat frame, deformation of the seat induced by PMHS weight and gravity was minimal when the PMHS was seated in the experimental seat. This made seated height of the PMHS tall relative to the seat back height. Even though the seat back height was relatively short, the head restraint had to move up to make consistent topset for each PMHS, which created an unexpected gap between the head restraint and top of the seat back. This gap possibly affected head and neck responses in the experimental seat. The experimental seat was designed for biofidelity evaluation of the ATDs so repeatability and durability were prioritised along with the capability to measure occupant loading and allow for seat back rotation [16][20]. Only two production seats were used in this study. Differences in seat back and head restraint characteristics might have influenced PMHS kinematics if other seats had been used. Biomechanical responses with respect to the seat back and head restraint properties in moderate-to-high speed rear impacts should be investigated more in the future. A standard three-point belt with no pretensioner was used in this study. A pretensioner that could potentially reduce ramping up motion of the PMHS could affect head kinematics. Future studies would be required to investigate effectiveness of the pretensioners on occupants in moderate-speed rear impacts.

V. CONCLUSIONS

A total of 21 sled tests using 15 PMHS were analyzed to quantify head responses in moderate speed rear impacts. Since head displacements and trajectories for the given speeds are limited in the literature, this study should help to better understand head trajectories not only for rear impacts but also for the rear-facing seats in frontal impacts, both of which are likely seating configurations in vehicles with ADS. Based on the results from this study, seat back rotational properties are very important to consider when optimising seats and interior compartments to ensure proper head protection, though this is just one of many considerations necessary to ensure occupant safety.

VI. ACKNOWLEDGEMENT

We would like to thank Kyle Icke, Rakshit Ramachandra, Julie Mansfield, Amanda Agnew and all IBRC members of The Ohio State University, USA, and Jim Stricklin, Brian Suntay, Jason Jenkins and Duey Thomas from the Transportation Research Center, Inc., USA, and Jason Stammen from the NHTSA/VRTC, USA, for their considerable support for the study.

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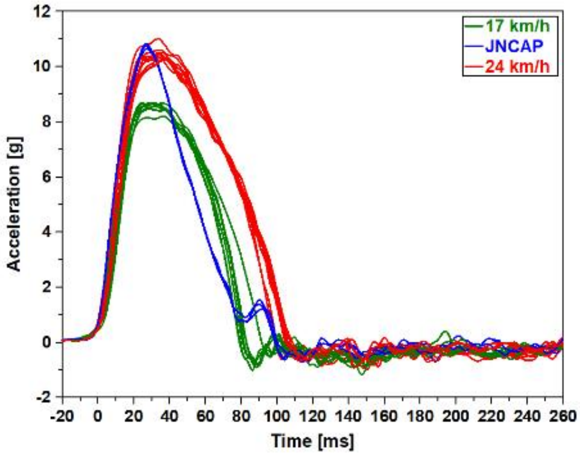
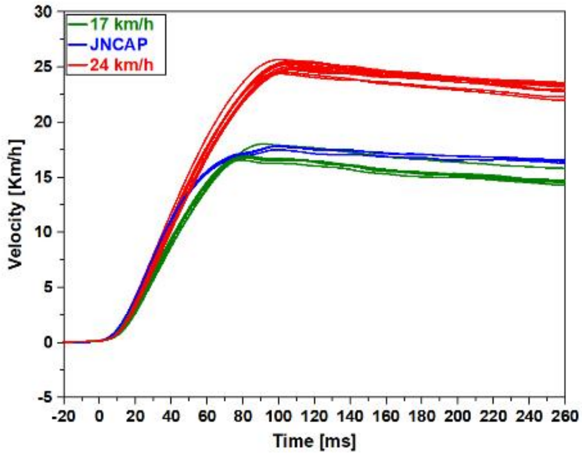
Appendix A



(a) Sled acceleration



(b) Sled velocity

Fig. A1. Sled pulses

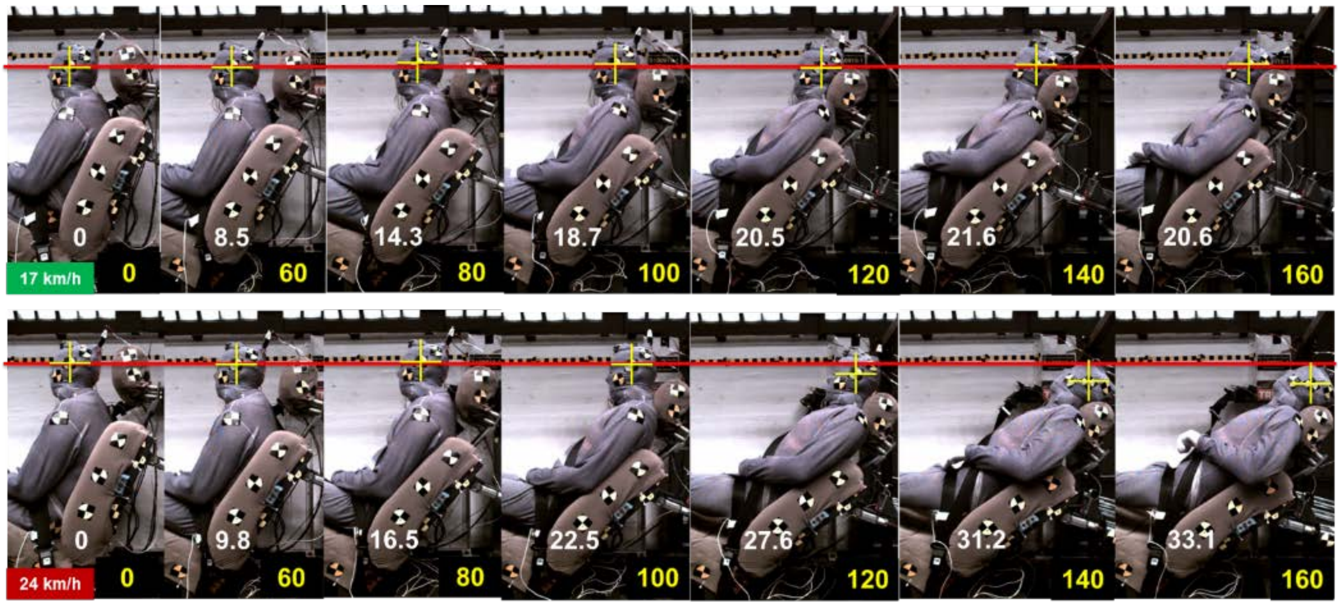


Fig. A2. General kinematics in the experimental seat. Yellow crosshair shows CG location. Red line represents initial CG location in the z axis. Yellow numbers are time, while white numbers represent seat back rotation at each time frame.

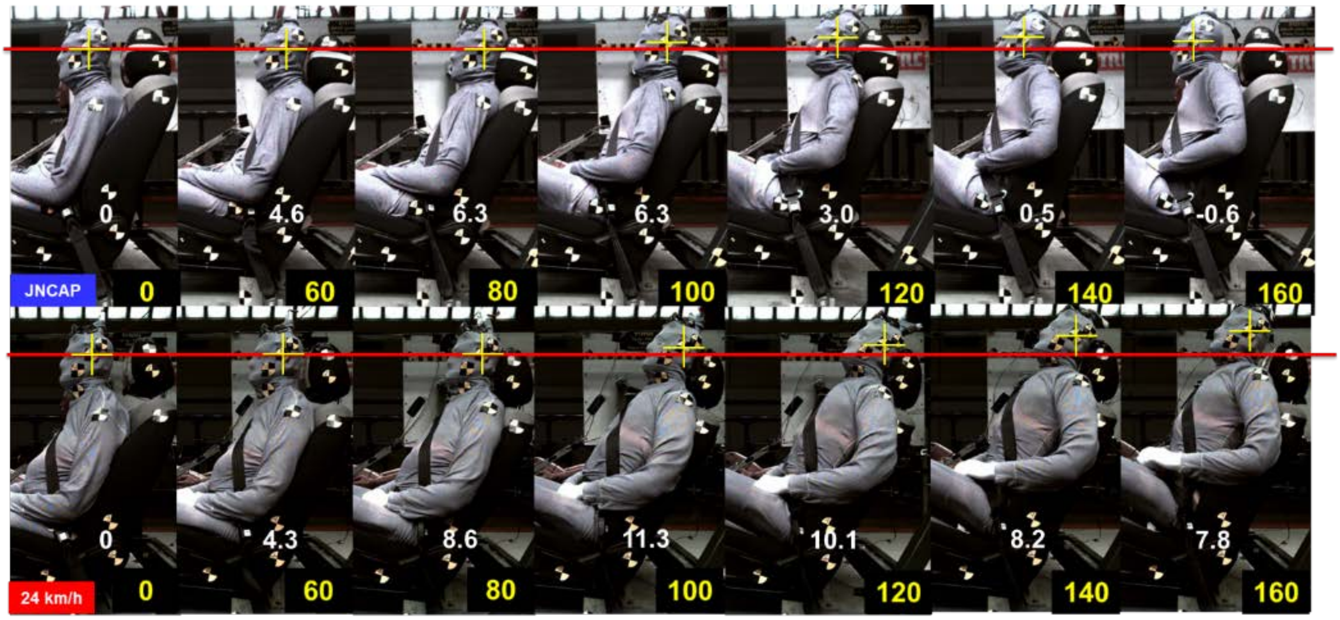


Fig. A3. General kinematics in the production seat A. Yellow crosshair shows CG location. Red line represents initial CG location in the z axis. Yellow numbers are time, while white numbers represent seat back rotation at each time frame.

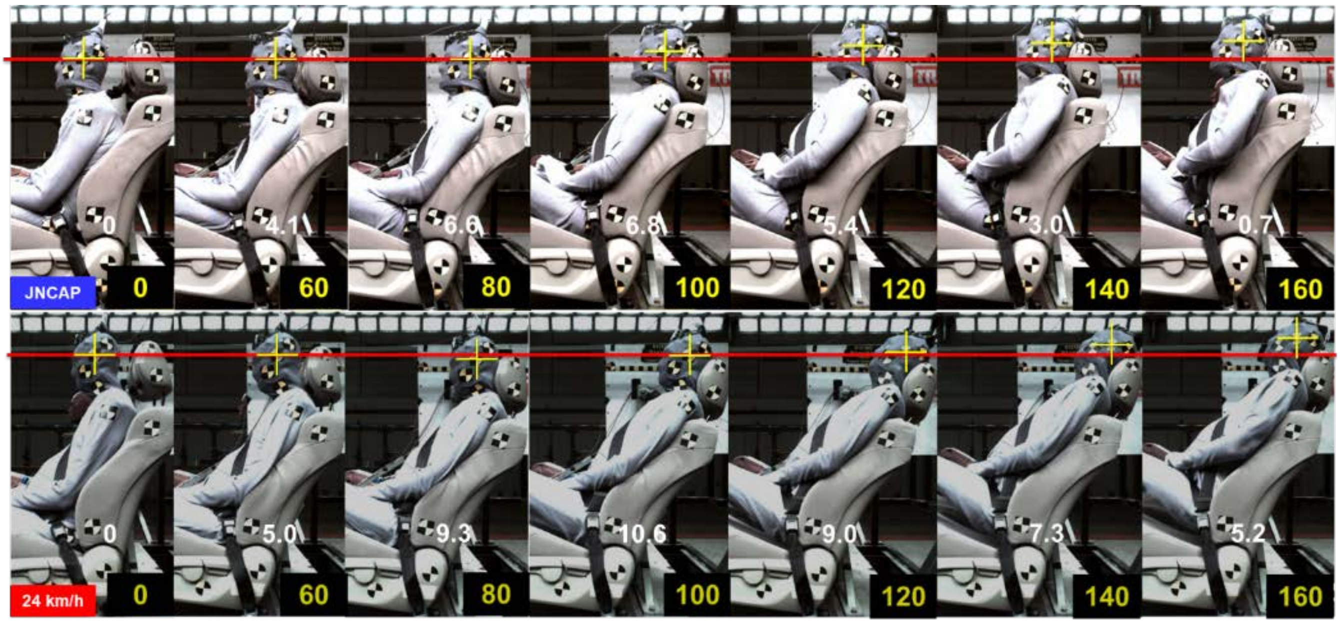


Fig. A4. General kinematics in the production seat B. Yellow crosshair shows CG location. Red line represents initial CG location in the z axis. Yellow numbers are time, while white numbers represent seat back rotation at each time frame.

TABLE AI
PEAK SEATBACK ROTATION IN EXPERIMENTAL SEAT (UNIT: DEG)

	17 Km/h	24 Km/h
PMHS01	--	34.8
PMHS02	24.2	--
PMHS03	23.7	34.1
PMHS04	23.1	33.8
PMHS05	21.6	33.2
PMHS06	18.4	31.5
PMHS07	20.8	32.1
PMHS08	22.1	34.4
Mean	22.0	33.4
SD	2.0	1.2

TABLE AII
PEAK SEATBACK ROTATION IN PRODUCTION SEATS (UNIT: DEG)

	17 Km/h	24 Km/h
PMHS09	7.6	--
PMHS10	6.9	--
PMHS11	7.0	--
PMHS12	--	10.8
PMHS13	4.9	--
PMHS14	--	11.4
PMHS15	--	11.1
Mean	6.6	11.1
SD	1.2	0.3

VIII. APPENDIX B

Experimental seat design

An experimental seat was built and instrumented with uni-axial load cells to measure the PMHS loading on the seat during impact (Fig. B1). The seat instrumentation includes four load cells in the head restraint, six load cells in the seat back, and four load cells in the seat pan. The uni-axial load cells were connected to load cell plates intended to interact with the subject through the seat cushions during impact in order to record the subject loading on the seat.

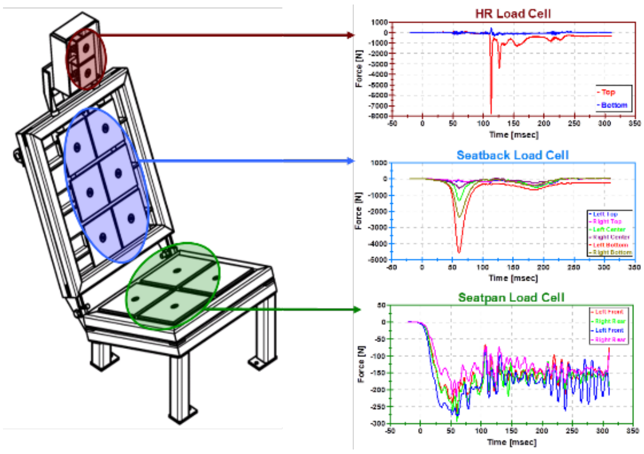


Fig. B1: Seat instrumentation for measuring subject loading during impact

In order to determine the seat back rotational characteristics of the experimental seat, the average rotational stiffness of various production seats was obtained from the literature shown in Table BI [B1].

TABLE BI
ROTATIONAL STIFFNESS OF VARIOUS OEM SEATS (1994 – 1996) [B1]

Year/Make/Model	Recliner / Structure	Rot. Stiffness (N-m/deg)	Avg Rot. Stiffness (N-m/deg)
1996 Chevrolet Astro Van	Single / Tubular	24.4	24.4
1996 Chevrolet Suburban	Single / Tubular	44.9, 25.2	35.1
1995 Hyundai Sonata	Single / Tubular	76.9, 71.4	74.2
1996 Hyundai Accent	Single / Tubular	58.9, 69.6	64.3
1995 Honda Passport	Single / Tubular	61.9, 66.7, 62.5, 66.2	64.4
1994 Dodge Neon	Single / Tubular	36.9, 51.7	44.3
1996 Dodge Intrepid	Single / Tubular	56.6, 40.3	48.5
1996 Isuzu Rodeo	Single / Tubular	63.4, 59.2	61.3
1996 Ford Taurus	Single / Tubular	58.5, 50.2	54.4
1996 Pontiac Sunfire	Single / Tubular	38.5, 41.9	40.2
1995 Chevrolet Blazer	Single / Tubular	41.1, 51.9	46.5
1995 Mazda Protege	Single / Tubular	49.3, 59.1	54.2
1996 Chevrolet T-600	Single / Tubular	28.9, 33.9	31.4
1995 Ford Windstar	Single / Formed	54.7, 48.8	51.8
1996 Ford Explorer	Single / Formed	44.5, 36.3	40.4
1996 Dodge B250 Van	Dual / Tubular	53.2, 52.9	53.1
1996 Chrysler Cirrus	Dual / Tubular	40.4, 42.1	41.3
1996 Saab 900S	Dual / Formed	97.4, 117.5	107.5
1995 Ford Contour	Dual / Formed	77.2, 88.4	82.8
1995 Nissan Quest	Dual / Hybrid	83.0, 79.3	80.0
1996 Nissan Sentra	Dual / Hybrid	103.2	103.2
1996 Toyota 4-Runner	Dual / Hybrid	105.6, 94.2	99.9
1995 Nissan Maxima	Dual / Hybrid	100.2	100.2
1995 Mazda Millenia	Dual / Hybrid	87.7, 134.6	111.2
Average All Seats			**65.1**

The average seat back rotational stiffness for all of the seats included in the study was 65 N-m/deg (Table BI). An analytical model of a target production seat was created to analyze the expected dynamic rotational response of the experimental seat back for both the 17 km/h and 24 km/h pulses. The target rotational stiffness of 65 N-m/deg was applied at the seat back pivot, the mass and dimensions of a Hybrid III 50th percentile male dummy were used, and the two pulses were applied to the model. The geometry of the seat was similar to that of a 1999 Toyota Camry seat, along with the seat pan angle (20 degrees) and seat back angle (25 degrees). Seat back mass used for the analytical model was 5.1 kg based on a 1999 Toyota Camry seat. The corresponding target seat back rotations calculated from the analytical model were determined to be 18 degrees and 32 degrees, respectively. These target rotations were compared to maximum rotation reported in previous studies [B2, B3] at similar severities and were found to be consistent as shown in Fig. B2 for the 24-kph pulse.

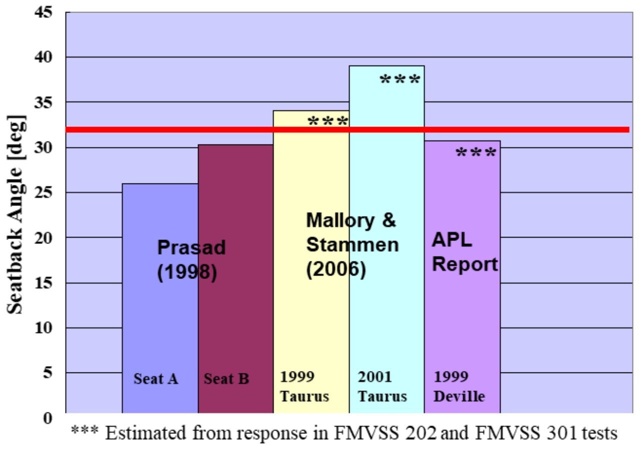


Fig. B2: Average maximum seat back rotation from the literature

In order to simplify the design as well as ensure a repeatable seat back rotational response for the experimental seat, it was decided to implement a translational spring-damper system to mimic the seat back recliner mechanism of an average production seat as reported by Molino (1998) [B1]. Rebound motion of the experimental seat was eliminated because the focus of this study is to evaluate the response of the PMHS during the rearward kinematics of rear impact.

The dimensions of the seat are given in Figure B3. The padding, cushions and seat cover are also from a 1999 Toyota Camry [B4]. The head restraint height could be adjusted using set screws to position the subjects identically in the vertical direction relative to the head restraint. The head restraint was also covered by the padding, cushion and cover of a 1999 Toyota Camry head restraint.

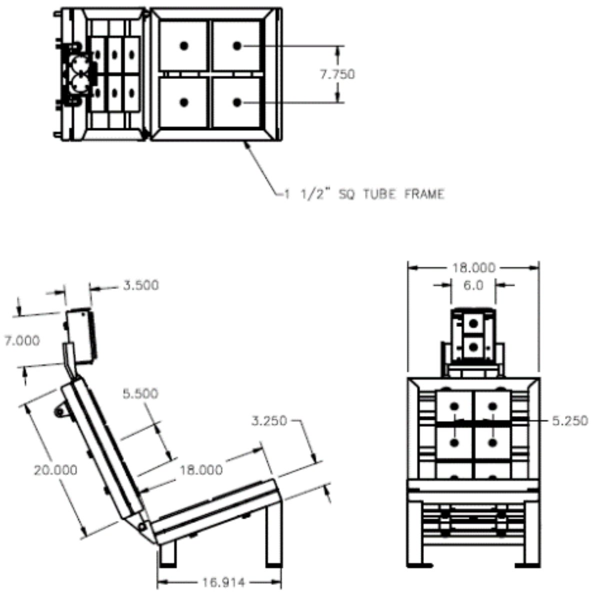


Fig. B3: Experimental seat dimensions (shown without cushions/covers)

The two seats were placed side-by-side so that each sled test would produce a match-paired PMHS and ATD test (Fig. B4).

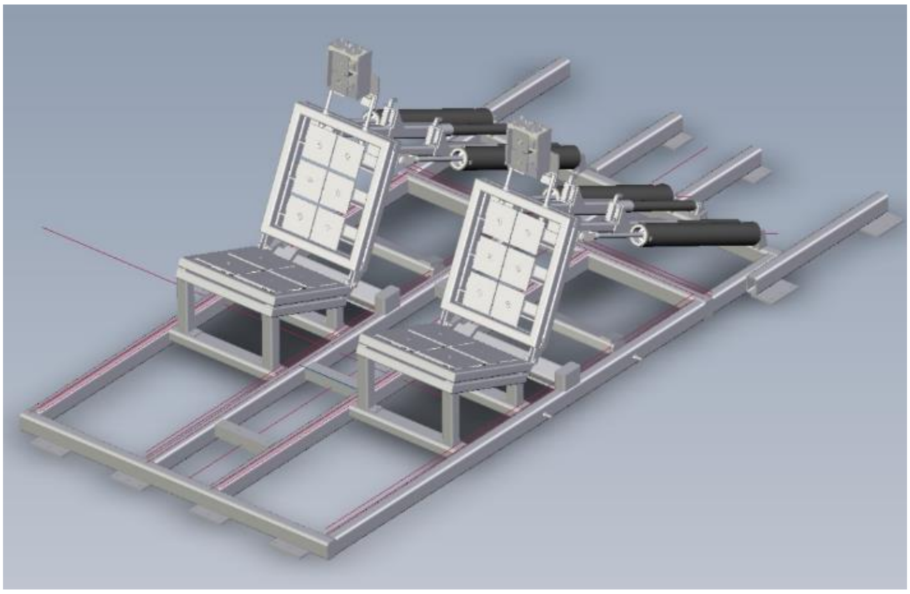


Fig. B4: Sled buck configuration of the experimental seats (shown without cushions/covers)

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IX. APPENDIX C

Head movement vs. body size

TABLE CI
RELATIONSHIP BETWEEN HEAD MOVEMENT AND BODY SIZE FOR EXPERIMENTAL SEAT
HIGHLIGHTED IN GREY IF P-VALUE < 0.05

N = 14	Peak displacement				Peak excursion			
	X		Z		X		Z	
	R^2	p-value	R^2	p-value	R^2	p-value	R^2	p-value
Stature	0.108	0.252	0.256	0.065	0.212	0.098	0.226	0.086
Weight	0.164	0.151	0.193	0.116	0.239	0.489	0.116	0.234
Seated Height	0.001	0.918	0.111	0.245	0.023	0.604	0.417	0.013
BMI	0.035	0.523	0.000	0.987	0.020	0.633	0.015	0.673

TABLE CII
RELATIONSHIP BETWEEN HEAD MOVEMENT AND BODY SIZE FOR PRODUCTION SEATS
HIGHLIGHTED IN GREY IF P-VALUE < 0.05

N = 7	Peak displacement				Peak excursion			
	X		Z		X		Z	
	R^2	p-value	R^2	p-value	R^2	p-value	R^2	p-value
Stature	0.004	0.894	0.000	0.990	0.085	0.524	0.041	0.663
Weight	0.247	0.257	0.033	0.696	0.256	-0.506	0.000	0.984
Seated Height	0.576	0.048	0.627	0.034	0.640	0.031	0.602	0.040
BMI	0.135	0.416	0.021	0.755	0.060	0.597	0.014	0.798

TABLE CIII
RELATIONSHIP BETWEEN HEAD MOVEMENT AND BODY SIZE FOR BOTH EXPERIMENTAL AND PRODUCTION SEATS
HIGHLIGHTED IN GREY IF P-VALUE < 0.05

N = 21	Peak displacement				Peak excursion			
	X		Z		X		Z	
	R^2	p-value	R^2	p-value	R^2	p-value	R^2	p-value
Stature	0.040	0.383	0.036	0.407	0.021	0.528	0.238	0.025
Weight	0.023	0.509	0.023	0.516	0.043	0.208	0.020	0.540
Seated Height	0.084	0.202	0.160	0.072	0.148	0.085	0.024	0.502
BMI	0.148	0.084	0.138	0.097	0.151	0.082	0.135	0.102