Influence of Initial Belt Torso Contact on the Kinematics and Kinetics of Booster-Seated ATDs in Frontal Impacts

Gretchen H. Baker, Julie A. Mansfield, John. H Bolte IV

Abstract This study sought to evaluate the influence of initial belt torso contact (belt gap) and belt fit provided by belt-positioning booster seats on various kinematic and kinetic outcomes. Frontal crash tests (n=18) were conducted at a peak deceleration of 22.5±1.0 g using the Q-Series 6-year-old (Q6), Q-Series 10-year-old (Q10), and Large Omni Directional Child (LODC10) anthropomorphic test devices (ATDs). Each ATD was evaluated on two highback (HB), three low-back (LB), and one low-profile (Low) booster seat, which provided varying initial belt fit and gap conditions. Resultant head, chest, and pelvis accelerations, and HIC15 were similar across boosters. Larger gap boosters produced greater peak lumbar MZ (HB: -28.3 Nm, LB: -24.7 Nm) compared to smaller gap boosters (HB: -13.1 Nm, LB/Low: -3.5 Nm) for the LODC10 and Q10 on average. Larger gap LB/Low boosters also produced greater axial shoulder rotation (43.3°) compared to smaller gap LB/Low boosters (30.1°). This suggests ATDs on larger gap boosters experienced greater torso rotation and lumbar moment due to lack of initial contact between the belt and inferior torso. While no shoulder belt slip-off occurred, larger shoulder rotations may indicate propensity for slip-off in more severe crashes, oblique manoeuvres, or with variations in initial occupant posture.

Keywords Belt Fit, Belt-Positioning Boosters, Paediatric ATDs, Restraint Interaction.

I. INTRODUCTION

While important strides have been made in improving the safety of children restrained by belt-positioning booster seats in motor vehicle crashes, further efforts are required to continue to reduce the number of injuries and fatalities for children restrained by booster seats. Motor vehicle crashes remain the global leading cause of death for young people aged 5–29 years, the leading cause of injury death for children aged 5–14 years in the United States, and the secondary leading cause of injury death for children aged 1–4 years in the United States [1-2]. Additionally, motor vehicle crashes contributed to over 98,000 children aged 4–12 years receiving treatment in emergency departments in the US in 2017 [3]. In particular, children appropriately restrained by booster seats may still sustain head injuries, often due to contact with the vehicle interior structures, such as the side-door panel or back of the front vehicle seats [4-5]. Booster-seated children may contact the vehicle interior in part due to suboptimal pre-crash restraint scenarios [4]. For example, if the shoulder belt is placed on the lateral edge of the shoulder or has slipped off the shoulder completely, the child will experience less direct restraint of the torso and may display increased head excursions. Previous evaluation of booster-seated paediatric ATDs, specifically the Hybrid III 6-year-old (HIII06) and Hybrid III 10-year-old (HIII10), have identified that cases of shoulder belt slip-off can be associated with extreme flexion of the torso, head strikes, elevated belt loads, and greater sternum deflections [6]. These conditions indicate the potential for increased injury risk due to shoulder belt slip-off. Thus, understanding conditions which may influence the likelihood of shoulder belt slip-off are important to continue to improve the safety of children restrained by booster seats, particularly by preventing head injury due to contact with the vehicle interior.

Previous studies have identified that anthropometry, initial belt fit on the shoulder, and contact between the shoulder belt and torso (i.e. belt gap) may influence the likelihood of shoulder belt slip-off during low-speed evasive vehicle manoeuvres for children restrained by booster seats [7-9]. In particular, an initial lack of contact between the shoulder belt and the inferior torso contributed to less engagement between the shoulder belt and torso and more cases of belt slip-off compared to cases where full contact was maintained between the shoulder

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belt and torso [7-9]. These results suggest that initial belt fit and belt-to-torso contact influence child kinematics and restraint interaction under low-speed conditions and may also influence the likelihood of belt slip-off during full-scale crashes.

Previous work has investigated the interaction between the shoulder belt and torso and slip-off potential for children and paediatric ATDs during full-scale crash conditions; however, many have not included booster seats or quantified initial belt fit or belt gap conditions. In particular, crash direction has been shown to influence shoulder belt slip-off, beginning at 15° offset from the frontal crash direction for the HIII06 and at 30° offset for the Hybrid III 5th percentile female (HIII5F) [10]; however, neither ATD was restrained by a booster seat. Lateral impacts have also been shown to result in shoulder belt slip-off and large lateral excursions for the HIII06 restrained by a booster seat, but the study evaluated only two boosters and did not quantify initial belt fit [11]. Variations in initial shoulder belt placement have been shown to influence kinematic and injury outcomes for the HIII06, HIII10, and Q Series 10-year-old (Q10) during frontal impacts [11-14]. Generally, boosters which provided more inboard initial shoulder belt fit were shown to produce good torso kinematics for the HIII10 [14]. Similarly, initial "close to neck" shoulder belt placement for the Q10 displayed less instances of slip-off compared to initial shoulder belt placement that was "far out on the shoulder" on the same booster seat [12]. However, more recent sled tests of the HIII06 and HIII10 restrained by 14 different boosters during frontal impacts have identified that booster seats which provide similar initial shoulder and lap belt fit conditions do not necessarily provide similar kinematic and injury outcomes [13]. These results suggest initial shoulder and lap belt placement may influence kinematic and kinetic outcomes, but that other factors may also influence dynamic outcomes.

These studies suggest that slip-off potential may be influenced by a combination of initial belt fit, the amount of belt-to-torso contact, booster design features, seatbelt technologies, and crash characteristics. Further efforts are required to develop deeper understanding of the relationships between initial belt fit and belt gap on the resulting kinematics in a variety of crash directions. Previous work has developed novel methodology to evaluate initial belt-to-torso contact for booster-seated children and ATDs and identified differences between booster seat designs in terms of initial belt gap metrics [15-16]; however, children and ATDs were only evaluated under static conditions. This study builds upon the results from the static belt fit studies by evaluating the sensitivity of dynamic outcomes for ATDs restrained by booster seats which provided varying initial static belt fit. Specifically, the goal of this study was to assess differences in the kinematic and kinetic metrics of the Q6, Q10, and LODC10 ATDs in frontal impacts while restrained by booster which provided varying initial belt fit and belt gap conditions.

II. METHODS

Frontal sled tests (n=18) were conducted to evaluate the influence of initial belt fit and belt gap conditions provided by six booster seats on the kinematic and kinetic outcomes for three paediatric ATDs. Each ATD was tested for one repetition on each booster seat (Appendix, Table A.I). Sled tests were conducted using a HYGE sled system with a target pulse defined by FMVSS 213 [17]. The peak deceleration was 22.5 ± 0.1 g at 12.8 ± 0.2 ms (Fig. 1).

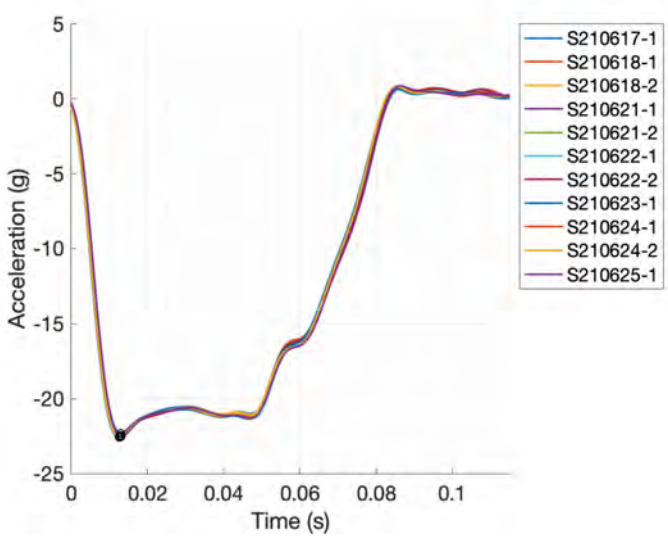

Fig. 1. Sled X Acceleration.

Test Set-Up

Mid-row, left-side captain's chairs (stand-alone second row seats) from a recent model year minivan were fixed onto the sled buck. Use of captain's chairs enabled evaluation of two seats per sled fire while maintaining the same belt routing for each occupant. Thus, two captain's chairs were installed on the sled buck, and tests were run two at a time (Appendix, Fig. A.1). Captain's chairs were set at the most forward track position, and the seatback was set to the fourth most upright setting, corresponding to a vehicle seatback angle of 23.8 ± 1.0°.

An externally mounted seatbelt system was installed onto a custom fixture mounted to the sled buck and included a production retractor assembly. No pre-tensioners or load limiters were included. In an attempt to enable more direct comparison of initial belt fit occupant conditions with previous volunteer belt fit studies [15-16], seatbelt anchorage positions of the sled testing and volunteer setups were compared. The volunteer seat set-up was a recent model year sedan rear bench seat, which replicated the true upper belt anchorage position of the vehicle and allowed for a range of lower seatbelt anchorage positions that contained the true vehicle's position, in addition to wider and more fore positions representative of the vehicle fleet. The locations, with respect to centreline of the seat bight, of the upper and lower seatbelt anchorage positions for both the sled testing and volunteer seats can be found in Appendix, Table A.I. The location of the upper seatbelt anchorage location used in the sled testing setup was 17.5 mm rear, 4.2 mm medial, and 26.1 mm superior compared to the position of the upper belt anchorage utilized in the volunteer belt fit [15-16] (Appendix, Table A.II). However, due to the mounting requirements for the external belt system, the lower seatbelt anchorage positions for the sled testing fixture were wider than those investigated in the laboratory volunteer vehicle seat set-up and wider than the original anchorage positions for the vehicle seat used in sled testing. Vehicle seats were utilized for a maximum of three tests, and most seats were utilized for a maximum of two tests. Vehicle seats were inspected for damage after each test. Seatbelt assemblies were replaced after each test.

Booster seats were selected from previous volunteer belt fit studies [15-16] to represent various initial belt fit and belt gap conditions (Table I). Belt fit and gap metrics included: shoulder belt score (SBS), lap belt score (LBS), maximum gap size (max gap), and gap length. These metrics have been developed and described in depth previously but are briefly summarized here. SBS represents the lateral distance between the suprasternale landmark and the inboard edge of the shoulder belt, with smaller and negative values representing more inboard shoulder belt position and larger positive values indicating more outboard positioning [18-19]. LBS represents the sagittal distance from the ASIS landmark to the superior edge of the lap belt, along a spline fit to the contour of the inferior abdomen and proximal thigh of the occupant [18-19]. Larger positive LBS indicate the lap belt placed more inferiorly on the pelvis or forward on the thighs. Smaller and negative LBS indicate the lap belt placed more superiorly on the pelvis. Maximum gap size represents the largest 3D distance between the shoulder belt and the inferior torso [15]. Gap length represents the length along the shoulder belt where no contact was present between the belt and the torso [15]. Booster seats included two high-back (HB), three low-back (LB), and one low-profile (Low) design. No booster seats were installed using the Lower Anchors and Tethers for Children (LATCH) or ISOFIX systems. Booster seats were replaced after each test.

The Q-Series 6-year-old (Q6), Q-Series 10-year-old (Q10), and Large Omni Directional Child (LODC10) ATDs were positioned following the FMVSS 213 guidelines [17], with a few modifications. The fore/aft position with respect to the seat bight of a representative ATD ASIS landmarks were positioned such that they fell within the volunteer mean ± one standard deviation measured previously, where volunteers were instructed to maintain upright, seated positions (Appendix, Table A.III) [15]. As the Q Series ATDs lack a true biofidelic ASIS landmark, representative positions of the ASIS landmarks were visually identified, labelled, and utilized for all measurements and comparisons. For the Q6, the representative ASIS landmarks were approximately 7.2 cm lateral of the torso centreline and 27.4 cm from the top of the torso. For the Q10, the representative ASIS landmarks were 9.5 cm lateral of the torso centreline and 35.2 cm from the top of the torso. For the LODC10, the representative ASIS landmark was identified 8.5 cm lateral of the torso centreline and 30 cm inferior of the top of the torso. After positioning, a certified child passenger safety technician routed the seat belt through appropriate belt guides and placed the belt to fall within the volunteer mean ± one standard deviation of the SBS and LBS recorded from previous volunteer measurements [15]. Slack was removed from the seat belt such that the lap belt tension was approximately 4 lbf and shoulder belt tension was approximately 2–4 lbf, as measured by a hand-held tension gauge.

TABLE I
BOOSTER SEATS INCLUDED IN SLED TESTING

Booster Seat		Image	Booster Type	SBS* (mm)	LBS* (mm)	Max. Gap* Size (mm)	Gap Length* (mm)	Exemplary Child Belt Fit*
1	Baby Trend, PROtect Yumi		HB	38.9	27.0	28.8	111.8	
2	Cosco, Topside		LB	2.3	54.0	16.5	16.5	
3	Diono, Solana 2		LB	44.0	51.8	26.6	156.9	
4	Graco, RightGuide		Low	26.0	27.7	13.2	25.1	
5	Peg Perego Viaggio, Flex 120		HB	30.3	8.7	14.0	4.9	
6	Osann, Junior ISOFIX		LB	†	†	†	†	†

**Average value or exemplary image of child belt fit and belt gap for each booster seat from previous volunteer study [15].*
†Booster seat not included in previous volunteer study [15].

Data Collection and Analysis

A 3D coordinate measurement device (FARO Edge Arm, Lake Mary, Florida) was utilized to measure the initial position of the ATDs, booster seats, seatbelts, and vehicle seats. Initial belt fit and belt gap metrics were quantified as described in previous studies [15][19-20]. Based on initial belt gap outcomes from child volunteers evaluated previously [15], booster seats were categorized as “smaller gap” or “larger gap” for comparison in the current study. The position, belt fit and belt gap of the LODC10, Q6, and Q10 were compared to the average ± one standard deviation of the child outcomes collected previously [15].

A VICON 3D Motion Capture system was utilized to quantify ATD kinematics, which are presented the SAE-

J211 Standard [22], where X points forward, Y points to the occupant's right, and Z points upward. Fourteen VICON Vantage V5 cameras (Oxford Metrics, Oxford, United Kingdom) were placed surrounding the sled buck, and positional data from photo-reflective markers placed on the ATDs, booster seats, seat belts and vehicle seats were captured using the Vicon Nexus Version 2.11 software at 1,000 Hz. Excursion was defined as the position of the markers with respect to the point on the sled floor defined by the X position of the seat bight and the Y position of seat centreline. Knee–Head excursion has also been utilized to identify differences in kinematics for booster-seated occupants and was defined by subtracting the maximum forward head excursion from the maximum forward knee excursion [13][21]. Displacements were defined by subtracting the initial position of each marker from the maximum forward position of each marker. ATD sensor data (Appendix, Table A.IV), upper and lower shoulder belt loads, and sled acceleration were acquired at a sampling rate of 20,000 Hz and were filtered according to the SAE-J211 Standard [22], using channel filter classes (CFC) between CFC 60 and CFC 1,000. All ATD sensors are presented in the coordinate system defined by the SAE-J211 Standard [22], where X points forward, Y points to the occupant's right, and Z points upward. The main measures of interest included: resultant head acceleration, head injury criterion (HIC), upper neck force along the Z axis (FZ), upper neck moment about the Y axis (MY), resultant chest acceleration, upper chest deflection, lumbar force along the Y axis (FY), lumbar moment about the Z axis (MZ), and resultant pelvis acceleration. ATD kinematic and kinetic measures were compared to previously published thresholds and certification standards (Appendix, Table A.V).

III. RESULTS

Initial Position, Belt Fit, and Belt Gap

The ATDs were positioned such that the representative ASIS position fell within the child mean ± one standard deviation of the child volunteer data [15], where available. Generally, ATDs fell within the volunteer ranges (Appendix, Table A.VI). The Q6 did not fall within the child range on booster seats 3–LB and 5–HB, and the Q10 did not fall within the child range on boosters 2–LB and 5–HB. Initial ATD SBS (Appendix, Table A.VII) and LBS (Appendix, Table A.VIII) generally fell within the child mean ± one standard deviation, with the exception of the LODC10 LBS, which was more inferior on all booster seats. The ATDs generally produced larger initial maximum gap size than the child mean ± one standard deviation (Appendix, Table A.IX). The initial gap length fell within the child mean ± one standard deviation on approximately half of the boosters (Appendix, Table A.X). However, ATD initial torso contact fell within the child mean ± one standard deviation on a majority of boosters (Appendix, Table A.XI). Based on average gap size and length outcomes and results from the child volunteer study [15], booster seats were categorized into "smaller gap" and "larger gap" boosters for comparisons. Smaller gap boosters included 2–LB, 4–Low, and 5–HB. Larger gap boosters included 1–HB, 3–LB, and 6–LB.

Summary of Dynamic Outcomes

Overall, ATDs displaced forward and displayed varying amounts of rotation about the spine in the positive Z direction, as the shoulder belt was routed over the right shoulder. Interaction between the shoulder belt and torso was generally favourable, as no instances of shoulder belt slip-off were observed. Images of the initial and maximum forward position of the ATDs during the tests can be found in the Appendix (Appendix, Table A.XXII, Table A.XXIII, Table A.XXIV, Table A.XXV, Table, A.XXVI, Table A.XXVII).

Kinetic Metrics

ATD kinetic metrics during frontal tests are summarized below (Table II). Some trends were observed between smaller gap and larger gap booster seats for chest deflection, Lumbar MZ, and Lumbar FY. Generally, chest deflections (Appendix, Table A.XII) were greater for the LODC10 and Q10 compared to the Q6. For the LODC10 and Q6, the HB boosters (1–HB, 5–HB) provided the greatest peak chest deflection. However, when comparing backless boosters, the larger gap boosters (3–LB and 6–LB) produced greater chest deflection compared to the smaller gap boosters (2–LB, 4–Low). For the Q10, larger chest deflections were observed for larger gap boosters (1–HB, 3–LB, and 6–LB) compared to smaller gap boosters (2–LB, 4–Low, and 5–HB).

TABLE II

KINETIC METRICS, PEAK VALUES

ATD	Booster Seat	Head ACC (g)		HIC		Upper Neck			Chest ACC (g)		Up. Chest DX (mm)	Lumbar		Pelvis ACC (g)	
		Res.	Res. 3ms	15ms	36ms	FZ (N)	-MY (Nm)	+MY (Nm)	Res.	Res. 3ms		FY (N)	MZ (Nm)	Res.	Res. 3ms
LODC10	1–HB (large)	60.7	55.4	282.3	342.8	1932.1	-36.3	0.3	39.0	37.8	57.0♥	1105.7	-40.0	54.1	53.5
	2–LB (small)	64.3	59.5	399.2	631.1	1877.2	-42.8♥	-7.1	64.6	47.4	37.9♥	201.2	12.1	54.0	52.8
	3–LB (large)	63.3	61.9	337.1	438.3	1428.2	-38.7	2.2	47.1	40.1	47.9♥	908.3	-34.1	57.0	54.5
	4–Low (small)	64.2	61.6	389.1	596.4	1612.2	-50.1♥	-9.8	66.7	49.0	43.0♥	561.3	-15.0	44.8	42.6
	5–HB (small)	49.7	47.7	221.0	370.4	1389.4	-42.1♥	-7.9	56.3	42.5	54.9♥	299.7	-18.1	47.1	46.5
	6–LB (large)	59.5	55.8	286.9	465.5	1952.3	-37.0	-11.6	58.7	38.8	51.5♥	686.6	-31.8	48.8	42.5
Q6	1–HB (large)	75.9	71.1♠ ♠	498.4	638.4	2277.5♠	-15.0	41.2♠	47.0	45.8	23.4	†	†	51.0	48.8
	2–LB (small)	63.9	62.0♠ ♠	387.6	626.3	1859.5♠	-16.6	40.8♠	55.4	52.3	17.9	†	†	53.1	51.9
	3–LB (large)	110.3	72.1♠ ♠	714.2	880.8	3532.6♠	-21.5	15.9	50.1	47.7	20.6	†	†	54.4	53.6
	4–Low (small)	58.1	56.9	333.0	620.9	1705.5♠	-18.8	22.9	57.7	54.4	17.8	†	†	55.0	52.4
	5–HB (small)	69.6	68.6♠ ♠	474.2	838.3	2149.1♠	-25.7	18.5	54.5	52.6	23.6	†	†	50.5	49.5
	6–LB (large)	69.6	66.9♠ ♠	437.9	727.2	2006.4♠	-20.4	44.8♠	45.8	44.6	19.1	†	†	48.1	47.2
Q10	1–HB (large)	70.0	67.9♠ ♠	488.6	582.7	2325.8♠	-20.5	36.9	44.0	41.5♠ ♠	57.9♠ ♥	581.4	-16.5	*	*
	2–LB (small)	56.5	55.6	307.5	586.7	1855.5♠	-20.7	32.1	45.1	43.1♠ ♠	46.0♥	-333.1	3.1	*	*
	3–LB (large)	70.8	67.1♠ ♠	474.4	621.9	2354.6♠	-16.5	36.3	42.3	39.4	60.5♠ ♥	739.9	-18.3	*	*
	4–Low (small)	73.9	71.2♠ ♠	594.7♠	893.3	2383.4♠	-24.5	39.0	45.7	43.6♠ ♠	53.0♥	503.7	-14.3	*	*
	5–HB (small)	58.3	57.9	354.5	681.1	2026.5♠	-24.4	35.7	58.2	48.8♠ ♠	45.4♥	-299.4	-8.2	*	*
	6–LB (large)	63.5	61.1♠ ♠	415.1	717.6	2054.9♠	-20.2	33.8	51.6	47.1♠ ♠	57.3♠	423.1	-14.4	*	*

**Data not collected due to sensor error.*

† Sensor not included on ATD.

♠ *Exceeds threshold in Appendix, Table A.V. If two values present, exceeds "higher rating" threshold in Appendix, Table A.V.*

♠ ♠ *Exceeds "lower rating" threshold in Appendix, Table A.V.*

♥ *Exceeds threshold in Appendix, Table A.V.*

On all booster seats, the LODC10 displayed positive Lumbar FY peaks (Fig. 2), while the Q10 displayed negative peaks on boosters 2–LB and 5–HB. Generally, larger gap boosters (1–HB, 3–LB, and 6–LB) provided greater positive peak Lumbar FY for both the LODC10 and Q10 compared to smaller gap boosters (2–LB, 4–Low, and 5–HB). However, booster 4–Low (categorized as smaller gap) displayed peak Lumbar FY more similar to the larger gap boosters. Lumbar FY was not available for the Q6.

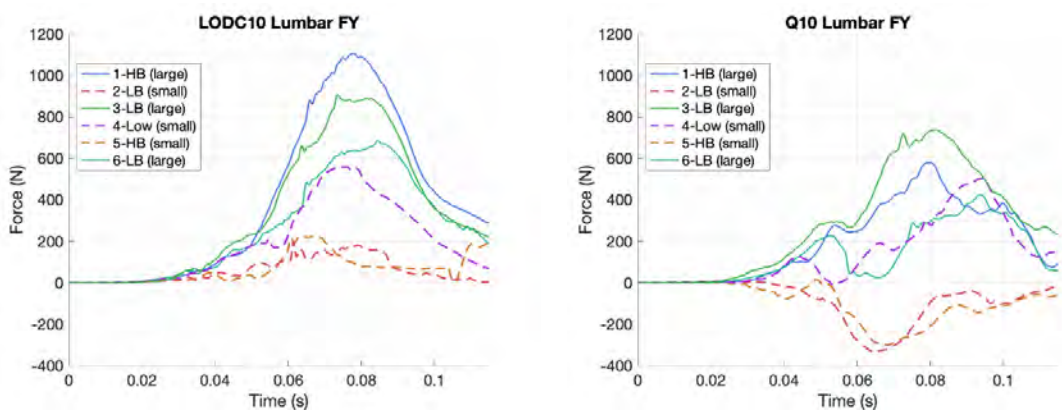

Fig. 2. Frontal Lumbar FY, with larger gap boosters represented by solid lines and smaller gap boosters represented by dashed lines.

Most booster seats displayed negative Lumbar MZ peaks (Fig. 3), indicating that the LODC10 and Q10 were rotating in the "out of the shoulder belt" direction, which was routed over the occupant's right shoulder. However, booster 2–LB displayed generally positive Lumbar MZ, suggesting that the LODC10 and Q10 experienced lumbar rotation consistent with rotating into the shoulder belt. Larger gap boosters (1–HB, 3–LB, and 6–LB) tended to provide greater negative peak Lumbar MZ compared to smaller gap boosters (2–LB, 4–Low, and 5–HB) for the LODC10 and Q10. Lumbar MZ was not available for the Q6.

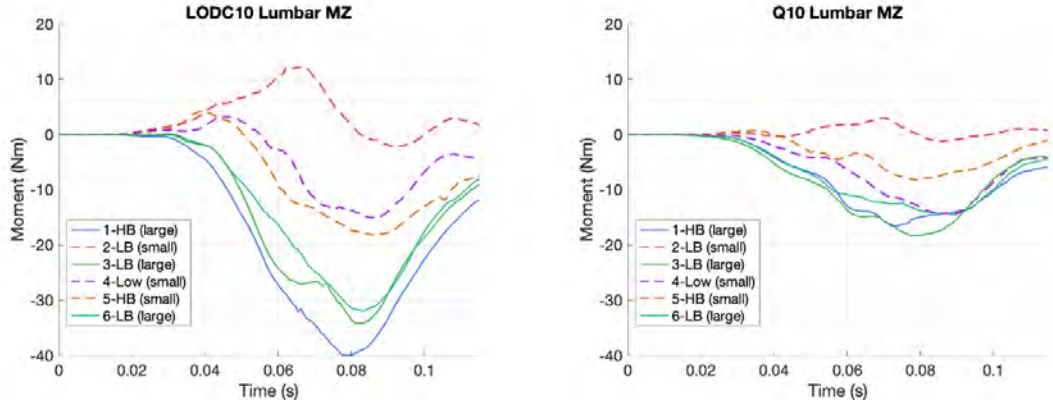

Fig. 3. Frontal Lumbar MZ, with larger gap boosters represented by solid lines and smaller gap boosters represented by dashed lines.

In terms of resultant head acceleration, HIC15 and HIC36 trends between smaller and larger gap boosters were not consistent across ATDs (Table II). The largest difference between smaller and larger gap boosters was observed for the peak head acceleration and HIC15 for the Q10, where the larger gap boosters (1–HB, 3–LB, and 6–LB) and booster 4–Low displayed higher compared to the backless smaller gap boosters (2–LB and 5–HB). No dramatic differences were observed between smaller and larger gap boosters in terms of upper neck FZ, upper neck MY, chest resultant acceleration, pelvis resultant acceleration, or shoulder or lap belt loads (Table II and Appendix, Table A.XII).

The LODC10 had additional sensors available for analysis (Appendix, Table A.XIII, Table A.XIV, Table A.XV). The shoulder belt was routed over the inferior left abdomen for all ATDs. In terms of left abdominal pressure, both HB boosters (1–HB and 5–HB) displayed greater pressure than the backless boosters. Considering only backless designs, the smaller gap boosters (2–LB and 4–Low) displayed lower peak left abdominal pressures than the larger gap designs (3–LB and 6–LB). Peak right abdominal pressures were similar for HB boosters (1–HB and 5–HB) and larger gap backless designs (3–LB and 6–LB) and were larger than smaller gap backless boosters (2–LB and 4–Low).

The LODC10 displayed greater peak T1, T6, and T12 Z angular rate (Fig. 4) for larger gap boosters (1–HB, 3–LB, and 6–LB) compared to smaller gap boosters (2–LB, 4–Low, and 5–HB). Left peak upper ASIS forces tended to be greater than the right, while the lower peak ASIS forces fell within a similar range for each booster seat. Lower ASIS forces were generally greater than upper ASIS forces on both the left and right sides. Upper and lower ASIS forces did not show obvious trends between smaller and larger gap boosters. The pelvis Y angular rate sensor in the LODC10 was integrated to obtain pelvis rotation about the Y axis. No trends were observed between smaller and larger gap boosters; however, greater peak negative pelvis rotations were observed for boosters 1–HB, 2–LB, and 4–Low (Appendix, Fig. A.2).

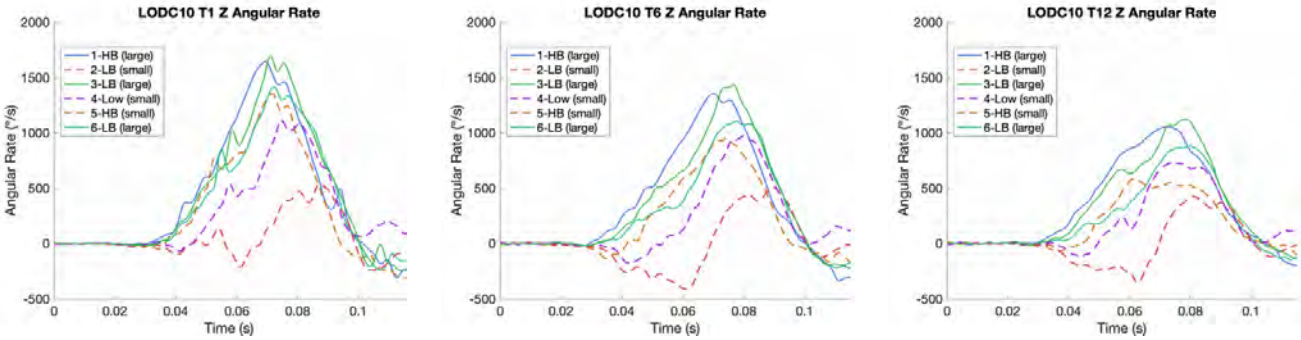

Fig. 4. Frontal Test LODC10 Thoracic Spine Z Angular Rate, with larger gap boosters represented by solid lines and smaller gap boosters represented by dashed lines.

Upper shoulder belt loads were similar between boosters for each ATD (Appendix, Table A.XVI); however, for

the LODC10, larger gap boosters (1–HB, 3–LB, and 6–LB) displayed greater peak loads than smaller gap boosters (2–LB and 5–HB). Lower lap belt loads did not display trends between smaller and larger gap boosters (Appendix, Table A.XVI).

Kinematic Metrics

ATD kinematics displayed some differences between boosters (Appendix, Table A.XVII, Table A.XVIII, Table A.XIX, Table A.XX). Considering forward head excursion, HB boosters (1–HB, 5–HB) displayed the largest positive X (forward) excursion compared to LB (2–LB, 3–LB, 6–LB) and 4–Low boosters. The 4–Low booster displayed the most positive Z (downward) head excursion for all ATDs. In terms of head X (forward) displacement, larger gap boosters (1–HB, 3–LB, and 6–LB) and booster 4–Low tended to provide greater displacement compared to smaller gap boosters (2–LB, 5–HB). The 5–HB displayed the largest positive Z (downward) head displacement for all ATDs.

For all ATDs, HB boosters (1–HB, 5–HB) tended to produce the most forward left acromion excursion compared to LB (2–LB, 3–LB, 6–LB) and 4–Low boosters. The LODC10 and Q10 displayed greater forward left acromion X displacement for larger gap (1–HB, 3–LB, and 6–LB) and 4–Low boosters compared to smaller gap boosters (2–LB, 5–HB); however, the Q6 showed similar forward left acromion displacement for all booster seats. Right acromion forward excursions and displacements were less than those of the left acromion but did not display similar trends between smaller and larger gap boosters.

For all ATDs, the HB boosters (1–HB, 5–HB) produced less forward right acromion displacement compared to the backless boosters in most cases. For some ATDs, peak transverse shoulder rotation (Fig. 5) was not captured due to the acromion markers becoming obscured from view by the booster side wings or head restraints on the HB designs during peak forward flexion. However, for the LODC10 and Q10, the boosters with larger gap (3–LB, and 6–LB) and the 4–Low booster produced greater shoulder rotation than the smaller gap 2–LB booster.

Boosters 1–HB and 6–LB tended to produce the most forward knee excursion for all ATDs. In terms of knee displacement, LB boosters generally produced greater forward displacement. For the LODC10, boosters 5–LB and 6–LB produced the greatest forward knee displacement. For the Q10, the greatest forward knee displacement occurred for the LB boosters 2–LB, 5–LB, and 6–LB. The greatest forward knee displacement for the Q6 was on the boosters 2–LB and 6–LB. Peak knee-head excursion was smallest for the Q6 and largest for the Q10 overall and varied by booster seat (Appendix, Table A.XXI). Generally, the LB boosters provided the greatest knee-head excursion while the HB boosters provided the smallest.

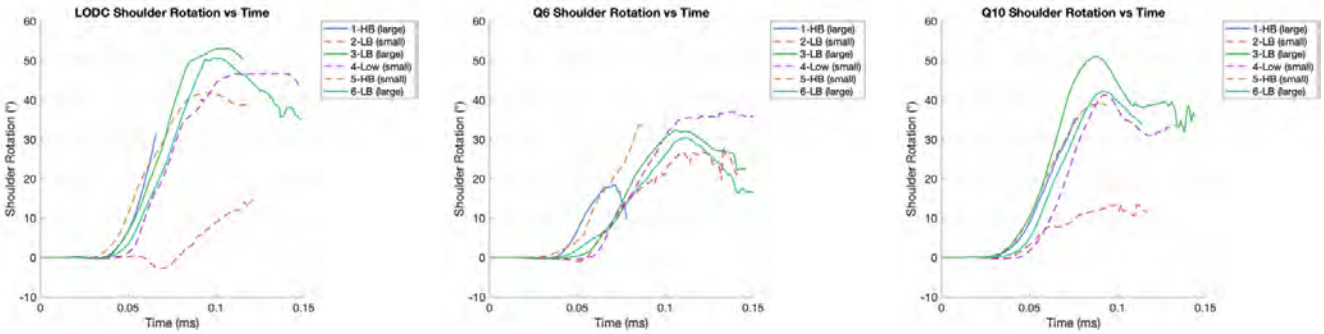

Fig. 5. Frontal Tests Transverse Shoulder Rotation vs Time, with larger gap boosters represented by solid lines and smaller gap boosters represented by dashed lines.

IV. Discussion

Initial Position and Belt Fit

The ATD initial ASIS position, belt fit, and belt gap conditions were compared to the previously published child volunteer data [15-16] to evaluate the ability of the Q6, Q10 and LODC10 to represent realistic differences in initial belt fit and gap conditions across booster seats. This comparison was especially important for the Q6 and Q10 ATDs which were not included in the initial static belt fit evaluation [16] and given the use of a different vehicle seat and seatbelt anchorage positions compared to the initial studies. ATDs were generally able to represent realistic child ASIS positions (Appendix, Table A.VI), initial belt fit, and belt gap conditions for the

evaluated booster seats (Appendix, Table A.VII, Table A.VIII). SBS maintained similar differences across booster seats to those observed for child volunteers evaluated on the same boosters [15-16], with booster 2–LB providing the most inboard SBS for all ATDs (Appendix, Table A.VII). Booster 4–Low also provided more inboard SBS for the LODC10 and Q6, similar to results of the children volunteers [15-16]. However, the Q10 provided more outboard SBS compared to children on all boosters and provided a particularly more outboard SBS on booster 4–Low compared to the other ATDs and children. Differences in child LBS across boosters were generally represented by the ATDs, with boosters 2–LB, 3–LB, and 6–LB providing more inferior LBS compared to boosters 1–HB, 4–Low, and 5–HB (Appendix, Table A.VIII). However, the LBS for the Q6 on booster 1–HB was more inferior compared to booster 3–LB, which did not follow the trend from the average child results [15-16]. While there were some specific differences in SBS and LBS for some ATDs compared to children, then ATDs generally represented the child differences in belt fit across booster seats.

Similar to previous work, the ATDs generally overestimated maximum gap size and length compared to children evaluated on the same booster seats [15-16]; however, differences between "smaller gap" (2–LB, 4–Low, 5–HB) and "larger gap" (1–HB, 3–LB, 6–LB) boosters were still represented with the selected ATDs (Appendix, Table A.IX, Table A.X). For the ATDs in this study, the larger gap boosters provided 12.5–15.2 mm larger gap size and 13.1–68.9 mm longer gap length compared to the smaller gap boosters, on average, suggesting that boosters did provide different initial belt gap conditions for the ATDs utilized here. However, the Q6 belt gap outcomes differed from child results [15][16] for boosters 1–HB and 4–Low. The Q6 provided similar gap size on these boosters and longer gap length on booster 4–Low, which was the opposite of the trend observed for the child volunteers [15-16]. Overall, the larger initial belt gap conditions provided by ATDs compared to children suggest that the ATDs may represent a more extreme initial belt gap than might be expected for the average child; however, differences in belt gap across booster seats were maintained.

Dynamic Outcomes

ATD outcomes were similar for many metrics comparing smaller and larger gap booster seats. Generally, metrics fell below previously published injury thresholds [23] and certification standard requirements [17][24-25]; however, some metrics exceeded the proposed 2023 Euro NCAP thresholds for child occupant protection [26] (Appendix, Table A.V). During frontal tests on some boosters, the Q6 and Q10 exceeded proposed Euro NCAP thresholds for 3 ms head acceleration, HIC15, upper neck tension, upper neck flexion moment, resultant 3 ms chest acceleration, and upper chest deflection (Table II). Additionally, the LODC10 upper neck extension moment and Q10 chest deflections on some boosters also exceeded published injury thresholds for 10-year-olds (Table II).

No consistent trends were observed between smaller and larger gap boosters in terms of peak resultant head acceleration, HIC15, HIC36, or upper neck FZ. ATDs on HB booster seats experienced greater head excursion compared to LB and Low boosters (Appendix, Table A.XXI). This increased forward excursion is likely related to the initially more forward head position of ATDs on HB booster seats, and further research is required to evaluate potential consequences. No consistent trends were observed between smaller and larger gap boosters in terms of peak resultant chest acceleration. Differences were observed between smaller and larger gap boosters in peak chest deflection, Lumbar MZ, and Lumbar FY, thoracic rotation, and shoulder rotation.

Larger gap booster seats tended to produce greater Lumbar FY and MZ peaks compared to smaller gap boosters for the LODC10 and Q10 (Table II); however, initial SBS likely influenced these outcomes as well. Previous work has suggested that Lumbar MZ and Lumbar FY may be useful metrics to identify differences in kinematics associated with torso rollout and shoulder belt slip-off for booster-seated occupants [13]. For tests with the HIII10, positive values of Lumbar MZ were associated with tests where the shoulder belt loaded the neck, while values between -10 Nm and -20 Nm were associated with tests where the belt loaded the centre of the shoulder [13]. The current study observed positive Lumbar MZ peaks for the LODC10 and Q10 and evidence of the shoulder belt loading close to the neck (Appendix, Table A.XXV, Table A.XXVI) during frontal impacts on the smaller gap booster 2–LB, which also provided the most inboard initial SBS for both ATDs. An initial positive increase in Lumbar MZ was also observed for the LODC10 on the other smaller gap booster seats (4–Low, 5–HB) and for the Q10 on smaller gap booster 5–HB (Fig. 3).The initial positive increase in Lumbar MZ suggests that the ATDs rotated initially in the "into shoulder belt" direction (which was routed over the right shoulder). The Lumbar MZ proceeded to decrease after this initial positive phase, indicating that the ATDs then began rotating in the "out-of-belt" direction until the point of maximum forward excursion. The LODC10 Lumbar MZ peaks for smaller gap boosters (4–Low and 5–HB) fell within the -10 to -20 Nm threshold proposed previously as describing the belt loading the

centre of the shoulder for the HIII10 [13], which has similar anthropometry to the LODC10. While these were smaller gap booster seats, boosters 4–Low and 5–HB displayed more outboard initial SBS compared to booster 2–LB, which may have contributed to the more negative Lumbar MZ peaks for these boosters. The Q10 also produced more positive Lumbar MZ for smaller gap booster 5–HB compared to larger gap designs; however, smaller gap booster 4–Low produced a negative Lumbar MZ peak similar to the larger gap designs. This difference may be attributed to the more outboard initial SBS observed for the Q10 on booster 4–Low.

Larger gap boosters tended to produce the most negative Lumbar MZ peaks for the LODC10 and Q10 (Table II). The LODC10 Lumbar MZ peaks for larger gap boosters (1–HB, 3–LB, 6–LB) produced the greatest negative peaks (exceeding -30 Nm), suggesting the greatest axial rotation compared to other booster seat designs. This trend was also observed for the Q10, with the larger gap boosters (1–HB, 3–LB, 6–LB) producing the greatest negative peaks; however, all peaks were lower than the LODC10 on the corresponding booster seats. This may suggest that the LODC10 design allows for more axial flexibility in the lumbar spine compared to the Q10. Similar differences between smaller and larger gap boosters were observed in the peak Lumbar FY for the LODC10 and Q10, with larger gap boosters producing more positive peak Lumbar FY (Table II).

These differences in lumbar FY and MZ between larger and smaller gap booster seats are supported by the ATD acromion displacement, shoulder rotation, and the LODC10 thoracic rotation, which exhibited similar differences between smaller and larger gap boosters. Smaller gap boosters displayed less left acromion forward displacement (Appendix, Table A.XIX) and smaller transverse shoulder rotation (Appendix, Table A.XVII). The LODC10 thoracic angular rate sensors also exhibited this trend, with smaller gap boosters producing less thoracic rotation at T1, T6, and T12 (Appendix, Table A.XIII). Together, these results suggest that larger gap booster seats allowed the ATDs to axially rotate to a greater degree before the shoulder belt began to restrain the lower torso, contributing to greater Lumbar FY and MZ peaks and peak thoracic and shoulder rotation.

Previous work has identified that, compared to children restrained by a booster seat which did not provide an initial gap near the lower torso, children restrained by a booster with an initial gap slipped out of the shoulder belt more often during evasive steering manoeuvres [8]. This suggests that lack of initial contact between the shoulder belt and the torso may also have implications for shoulder belt slip-off potential during full-scale impacts. While no shoulder belt slip-off occurred for the ATDs in this study, the greater shoulder rotation and peak lumbar MZ observed for ATDs on larger gap boosters may indicate a greater propensity for shoulder belt slip-off in more severe impact scenarios, crashes preceded by oblique manoeuvres, or with more extreme variations in initial occupant posture and belt positioning. Lumbar MZ has been suggested as a useful metric to discriminate between occupant kinematics, helping to identify scenarios in which the shoulder belt loads the neck versus kinematics associated with torso rollout or potential shoulder belt slip-off [13]. The results presented here suggest that booster seats which provided larger initial belt gap influenced the shoulder rotation and lumbar MZ for the LODC10 and Q10 ATDs during frontal impacts and should be investigated further to continue to elucidate the relationships between initial belt fit and gap, lumbar MZ, and shoulder belt slip-off.

The Q10 experienced greater upper chest deflection for larger gap compared to smaller gap boosters (Table II). This increase in upper chest deflection may be influenced by the increased forward displacement of the torso before restraint is provided by the shoulder belt to the lower torso, due to the initial lack of contact between the shoulder belt and the torso. However, previous work has identified that chest deflection measures are sensitive to the placement of the shoulder belt with respect to the chest deflection sensor position on the ATD torso [27-28]. Specifically, reduced chest deflections have been observed when the shoulder belt displaces upward and/or inboard toward the neck [27-28]. Generally, the vertical position of the shoulder belt was placed more superiorly on the torso for booster seats which provided more inboard SBS, which may have contributed to the reduced peak chest deflections observed for the Q10 on boosters 2–LB and 5–HB. Additionally, the Q6 displayed more inboard SBS and more superior shoulder belt placement on the torso compared to the Q10 and LODC10 which, in combination with the relatively lower position of the Q6 chest deflection sensor, may also contribute to the smaller chest deflection values observed for the Q6 on all booster seats.

The Q6 did not have a lumbar load cell or thoracic angular rate sensors available for analysis, and results from the chest deflection, shoulder rotation, and left acromion displacement were not consistent when comparing smaller versus larger gap booster seats (Table II, Appendix, Table A.XVII, Table A.XIX). This suggests that either the Q6 was less sensitive to changes in initial belt fit and belt gap metrics provided by the selected booster seats, that dynamic outcomes vary with ATD anthropometry, or that the Q6 requires additional sensing capabilities to

enable evaluations of these different initial conditions. Future work is required to continue to investigate the effects of initial belt gap conditions for 6-year-old occupants.

No consistent trends were observed between smaller and larger gap boosters in terms of peak resultant pelvis acceleration (Table II). Knee forward displacements were similar between left and right sides for ATDs (Appendix Table A.XIX). Knee displacements were greater for LB boosters compared to HB boosters, but no trends were observed between larger and smaller gap boosters. Knee-head excursion was greater for LB boosters compared to HB boosters (Appendix, Table A.XXI). Previous work has identified knee-head excursion as a possible metric to identify potential submarining kinematics and has proposed thresholds of 125 mm for the HIII06, 180 mm for the HIII10, and 100–110 mm for the Q6 ATDs during frontal tests [13][21][29]. The Q6 exceeded the 110 mm threshold during frontal tests on all boosters except for the HB designs (1–HB, 5–HB). The LODC10 exceeded the 180 mm threshold only on booster 6–LB during frontal tests, and the Q10 exceeded the 180 mm threshold on all boosters during frontal tests. Differences in ATD anthropometry may contribute to the larger excursions experienced for the Q10, and specific thresholds should be investigated further.

Limitations

The main differences between smaller and larger gap boosters in this study were observed for Lumbar FY and MZ. The purpose of this test series was to identify potential differences between booster seats that provided smaller and larger amounts of belt gap for a variety of ATDs restrained by a selection of boosters in frontal impact conditions. Thus, no repeated tests have been conducted during this series, which limits the ability to draw concrete conclusions about the influence of initial belt gap provided by booster seats. However, previous work with the HIII06, evaluated under the FMVSS 213 frontal crash pulse, has presented the repeatability of the Lumbar FY and MZ [13][30]. The range of Lumbar FY has been reported as 4–234 N for up to three repeated tests of 11 booster seats [13], and from 61.6– 198.8 N for two repeated tests of two boosters in two installation conditions [30]. The range of Lumbar MZ was reported as 0.0–1.9 Nm for up to three repeated tests of 11 boosters [13] and from 1.4–3.8 Nm for two repeated tests of two boosters in two installation conditions [30]. While these studies have evaluated the repeatability of a different ATD than the ones utilized in the current study, the average differences observed between smaller and larger gap boosters for ATDs in frontal and oblique impacts in the present study (Lumbar FY: 338.5–624.4 N difference between larger and smaller gap boosters, Lumbar MZ: 8.3–28.3 Nm difference between larger and smaller gap boosters) were greater than the ranges of these metrics presented previously under repeated conditions. Future work should utilize repeated testing and a wider range of booster seat designs to further elucidate the influence of initial belt gap on kinematic and kinetic outcomes during motor vehicle crashes.

Additionally, limitations in ATD biofidelity may influence the results presented here. In particular, the lap belt was observed to become entrapped in the non-biofidelic gap between the thighs and pelvis for the ATDs during some tests, and use of hip liners or shields may prevent this issue. The anthropometry and flexibility of the ATD shoulder complex may also limit the ability of the ATDs to accurately represent the likelihood of potential shoulder belt slip-off during these events. Future work utilizing paediatric human body models may provide additional insight into the interaction between the seatbelt and the shoulder complex and its relationships with initial belt fit and belt gap provided by booster seats. Additionally, use of the abdominal pressure sensors for the Q Series ATDs may be helpful for future evaluations to further elucidate differences in belt-to-torso interaction for these ATDs.

A limited number of boosters have been evaluated in this study, and differences in booster seat design features may contribute to differential outcomes during impacts that are not represented by the data presented here. Additionally, while belt fit and belt gap metrics varied across different booster designs, it was not possible to truly isolate the effects of specific belt fit, belt gap, and other booster design characteristics on the dynamic outcomes presented here. Booster seats were selected in this study to provide a variety of belt fit and belt gap initial conditions based on previous child data; however, they also vary significantly in terms of their overall design and the boundary conditions which they provide the occupants. Booster seat design characteristics, such as amount of boost, seat inclination, compressibility, or belt guide design, may also influence dynamic outcomes that were not directly investigated here. Future work should continue to isolate the influence of each of these parameters by constructing physical tests or computer simulations which can vary these belt fit and belt gap metrics while maintaining similar overall booster seat design parameters. Additionally, only dedicated booster seats were evaluated here, and these investigations should be expanded to include combination and 3-in-1

designs. Finally, evaluation of boosters on different types of vehicle seats (for example, a bench seat) or with vehicle seats of different geometries or seat belt anchorage locations may also influence the outcomes presented here. In particular, the vehicle seats utilized here included contours on the seatback and seat pan which may have influenced how booster seats of different widths interacted with the vehicle seat during the impacts.

V. Conclusions

This is the first study to directly evaluate the influence of varying initial belt gap conditions provided by different booster seats on kinematic and kinetic outcomes for paediatrics ATDs. Results from this study suggest that booster seats that provided larger initial belt gap contributed to greater torso rotation and lumbar moment for the LODC10 and Q10 during frontal impacts. While no belt slip-off occurred for ATDs in this study, larger shoulder rotations and peak lumbar MZ may indicate greater propensity for shoulder belt slip-off in more severe crashes, oblique manoeuvres, or with variations in initial occupant posture. Ultimately, future work is required to continue to isolate the influences of initial belt fit and belt gap conditions and to continue evaluation of lumbar FY and MZ as potentially useful metrics for discrimination between booster seats which provide different dynamic outcomes.

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VIII. APPENDIX

TABLE A.I
TEST MATRIX

Impact Direction	ATD	Booster Seat	Repetitions / Condition	Total Tests
Frontal (0°)	Q6 Q10 LODC10	1–HB 2–LB 3–LB 4–Low 5–HB 6–LB	1	18

Fig. A.1 Exemplary Frontal Sled Test Set-up.

TABLE A.II
SEATBELT ANCHORAGE LOCATIONS FOR THE SLED TESTING AND VOLUNTEER LABORATORY SEATS, WITH RESPECT TO THE SEAT BIGHT CENTRELINE

Anchorage Location	Sled Testing			Lab Seat Set-up		
	X (mm)	Y* (mm)	Z (mm)	X (mm)	Y* (mm)	Z (mm)
Outboard Lower	-128.6	346.0	179.4	31.3	69.9–249.3	-13.9
Inboard Lower	-120.2	354.8	178.5	38.8	158.0–422.3	-94.7
Upper	-359.3	204.5	-593.0	-341.8	208.7	-566.9

**Absolute value.*

TABLE A.III
TARGET ATD ASIS X POSITION (MM) BASED ON VOLUNTEER DATA FROM [15]

Booster Seat	Mean ± Std Dev	Target Range
1–HB	157.3 ± 13.1	144.3–170.4
2–LB	106.1 ± 13.7	92.4–119.8
3–LB	94.7 ± 21.1	73.6–115.8
4–Low	135.7 ± 18.0	117.6–153.7
5–HB	151.5 ± 16.5	135.0–168.0
6–LB	*	*

**Booster seat not included in previous volunteer study [15].*

TABLE A.IV
SENSORS INCLUDED FOR EACH ATD

Sensor	**Type and Direction**	**ATDs**
Head	ACC XYZ	Q6, Q10, LODC10
	ARS XYZ	Q6 (Y only), LODC10
Upper Neck	Force XZY	Q6, Q10, LODC10
	Moment XYZ	Q6, Q10, LODC10
Lower Neck	Force XZY	Q10, LODC10
	Moment XYZ	Q10, LODC10
Chest	ACC XYZ	Q6, Q10, LODC10
	Upper Deflection	Q6, Q10, LODC10
	Lower Deflection	Q10
Abdomen	Pressure	LODC10
T1	ACC XYZ	LODC10
	ARS XYZ	LODC10
T6	ACC XYZ	LODC10
	ARS XYZ	LODC10
T12	ACC XYZ	LODC10
	ARS XYZ	LODC10
Pelvis	ACC XYZ	Q6, Q10, LODC10
	ARS XYZ	LODC10
	ASIS Force X	LODC10

TABLE A.V

INJURY AND CERTIFICATION REFERENCE THRESHOLDS

Metric	**FMVSS 213** [17]	**R44** [24]	**R129** [25]	**EURO NCAP Proposed 2023** [26] **Q6**	**Q10**	**Mertz *et al.* 2016** [23] **6yo**	**10yo**
Crash Type	Frontal	Frontal	Frontal	MPDB Offset (50% overlap)	MPDB Offset (50% overlap)	NA	NA
Delta V (kph)	48	52	52	50	50	NA	NA
HIC15	NA	NA	800	Higher rating: 500 Lower rating: 700	Higher rating: 500 Lower rating: 700	723	741
HIC36	1000	NA	NA	NA	NA	NA	NA
Resultant Head ACC 3 ms (g)	NA	NA	80	Higher rating: 60 Lower rating: 80	Higher rating: 60 Lower rating: 80	189	189
Upper Neck FZ Tension (kN)	NA	NA	NA	Higher rating: 1.7 Lower rating: 2.62	Higher rating: 1.7 Lower rating: 2.62	1.89	2.29
Upper Neck MY Flexion (Nm)	NA	NA	NA	36	49	60	78
Upper Neck MY Extension (Nm)	NA	NA	NA	NA	NA	30	40
Resultant Chest ACC 3ms (g)	60	55	55	NA	Higher rating: 41 Lower rating: 55	93	82
Chest Deflection (mm)	NA	NA	NA	30	56	31	36
Symbols used in tables	§	¶	#	♠		♥	

TABLE A.VI

INITIAL ATD ASIS X POSITION WITH RESPECT TO VEHICLE SEAT BIGHT AND COMPARISON TO CHILD VOLUNTEER DATA (MM)

ATD	Booster Seat	ATD	Child Mean ± Std Dev*	ATD within Child Mean ± Std Dev	Difference between ATD and Child Mean
LODC10	1–HB	159.2	157.3 ± 13.1	Yes	-1.9
	2–LB	110.2	106.1 ± 13.7	Yes	-4.1
	3–LB	94.1	94.7 ± 21.1	Yes	0.6
	4–Low	126.8	135.7 ± 17.9	Yes	8.8
	5–HB	158.9	151.5 ± 16.5	Yes	-7.4
	6–LB	98.2	†	†	†
Q6	1–HB	153.1	157.3 ± 13.1	Yes	4.3
	2–LB	104.2	106.1 ± 13.7	Yes	1.8
	3–LB	113.3	94.7 ± 21.1	Yes	-18.6
	4–Low	121.8	135.7 ± 17.9	Yes	13.8
	5–HB	167.6	151.5 ± 16.5	Yes	-16.1
	6–LB	107.1	†	†	†
Q10	1–HB	171.0	157.3 ± 13.1	No	-13.7
	2–LB	123.2	106.1 ± 13.7	No	-17.1
	3–LB	107.8	94.7 ± 21.1	Yes	-13.0
	4–Low	135.5	135.7 ± 17.9	Yes	0.1
	5–HB	171.8	151.5 ± 16.5	No	-20.3
	6–LB	119.9	†	†	†

**Data from child volunteer study* [15].

†Booster seat not included in child volunteer study [15].

TABLE A.VII

INITIAL ATD SBS AND COMPARISON TO CHILD VOLUNTEER DATA (MM)

ATD	Booster Seat	ATD	Child Mean ± Std Dev*	ATD within Child Mean ± Std Dev	Difference between ATD and Child Mean
LODC10	1–HB	34.0	38.9 ± 14.8	Yes	-4.9 inboard
	2–LB	12.6	2.3 ± 17.8	Yes	10.3 outboard
	3–LB	33.4	44.0 ± 17.3	Yes	-10.6 inboard
	4–Low	24.1	26.0 ± 13.1	Yes	-1.9 inboard
	5–HB	31.3	30.3 ± 17.7	Yes	1.0 outboard
	6–LB	27.0	†	†	†
Q6	1–HB	28.2	38.9 ± 14.8	Yes	-10.7 inboard
	2–LB	-2.5	2.3 ± 17.8	Yes	-4.8 inboard
	3–LB	19.9	44.0 ± 17.3	No	-24.1 inboard
	4–Low	13.5	26.0 ± 13.1	Yes	-12.5 inboard
	5–HB	21.0	30.3 ± 17.7	Yes	-9.3 inboard
	6–LB	12.0	†	†	†
Q10	1–HB	46.1	38.9 ± 14.8	Yes	7.2 outboard
	2–LB	15.6	2.3 ± 17.8	Yes	13.3 outboard
	3–LB	57.1	44.0 ± 17.3	Yes	13.1 outboard
	4–Low	48.0	26.0 ± 13.1	No	22.0 outboard
	5–HB	30.7	30.3 ± 17.7	Yes	0.4 outboard
	6–LB	55.8	†	†	†

**Data from child volunteer study* [15].

†Booster seat not included in child volunteer study [15].

TABLE A.VIII

INITIAL ATD LBS AND COMPARISON TO CHILD VOLUNTEER DATA (MM)

ATD	Booster Seat	ATD	Child Mean ± Std Dev*	ATD within Child Mean ± Std Dev	Difference between ATD and Child Mean
LODC10	1–HB	58.5	27.0 ± 11.7	No	31.4 inferior
	2–LB	62.0	54.0 ± 13.0	Yes	8.0 inferior
	3–LB	85.3	51.8 ± 23.0	No	33.6 inferior
	4–Low	64.0	27.7 ± 13.0	No	36.3 inferior
	5–HB	44.4	8.7 ± 10.9	No	35.7 inferior
	6–LB	78.6	†	†	†
Q6	1–HB	32.1	27.0 ± 11.7	Yes	5.0 inferior
	2–LB	46.6	54.0 ± 13.0	Yes	-7.3 superior
	3–LB	23.1	51.8 ± 23.0	No	-28.6 superior
	4–Low	19.7	27.7 ± 13.0	Yes	-8.0 superior
	5–HB	-4.1	8.7 ± 10.9	No	-12.8 superior
	6–LB	57.1	†	†	†
Q10	1–HB	23.6	27.0 ± 11.7	Yes	-3.4 superior
	2–LB	40.2	54.0 ± 13.0	No	-13.8 superior
	3–LB	61.5	51.8 ± 23.0	Yes	9.7 inferior
	4–Low	31.9	27.7 ± 13.0	Yes	4.2 inferior
	5–HB	4.9	8.7 ± 10.9	Yes	-3.9 superior
	6–LB	61.0	†	†	†

**Data from child volunteer study* [15].

†Booster Seat not included in child volunteer study [15].

TABLE A.IX

INITIAL ATD MAXIMUM GAP SIZE AND COMPARISON TO CHILD VOLUNTEER DATA (MM)

ATD	Booster Seat	ATD	Child Mean ± Std Dev*	ATD within Child Mean ± Std Dev	Difference between ATD and Child Mean
LODC10	1–HB	42.1	28.8 ± 11.0	No	13.3 larger
	2–LB	34.4	16.5 ± 6.6	No	17.9 larger
	3–LB	48.4	26.6 ± 8.0	No	21.8 larger
	4–Low	22.6	13.2 ± 5.8	No	9.4 larger
	5–HB	30.4	14.0 ± 8.0	No	16.4 larger
	6–LB	26.2	†	†	†
Q6	1–HB	33.8	28.8 ± 11.0	Yes	5.0 larger
	2–LB	22.0	16.5 ± 6.6	Yes	5.5 larger
	3–LB	42.0	26.6 ± 8.0	No	15.4 larger
	4–Low	35.4	13.2 ± 5.8	No	22.2 larger
	5–HB	25.9	14.0 ± 8.0	No	11.9 larger
	6–LB	46.5	†	†	†
Q10	1–HB	37.6	28.8 ± 11.0	Yes	8.8 larger
	2–LB	35.0	16.5 ± 6.6	No	18.5 larger
	3–LB	47.5	26.6 ± 8.0	No	20.9 larger
	4–Low	17.2	13.2 ± 5.8	Yes	4.0 larger
	5–HB	36.7	14.0 ± 8.0	No	22.7 larger
	6–LB	31.8	†	†	†

**Data from child volunteer study* [15].

†Booster seat not included in child volunteer study [15].

TABLE A.X

INITIAL ATD GAP LENGTH AND COMPARISON TO CHILD VOLUNTEER DATA (MM)

ATD	Booster Seat	ATD	Child Mean ± Std Dev*	ATD within Child Mean ± Std Dev	Difference between ATD and Child Mean
LODC10	1–HB	125.3	111.8 ± 55.9	Yes	13.4 longer
	2–LB	83.6	16.5 ± 35.5	No	67.1 longer
	3–LB	144.7	156.9 ± 86.7	Yes	-12.1 shorter
	4–Low	82.1	25.1 ± 45.5	No	56.9 longer
	5–HB	82.2	4.9 ± 16.2	No	77.3 longer
	6–LB	100.9	†	†	†
Q6	1–HB	0.0	111.8 ± 55.9	No	-111.8 shorter
	2–LB	42.9	16.5 ± 35.5	Yes	26.4 longer
	3–LB	87.1	156.9 ± 86.7	Yes	-69.7 shorter
	4–Low	64.0	25.1 ± 45.5	Yes	38.9 longer
	5–HB	46.5	4.9 ± 16.2	No	41.6 longer
	6–LB	68.4	†	†	†
Q10	1–HB	127.4	111.8 ± 55.9	Yes	15.6 longer
	2–LB	83.9	16.5 ± 35.5	No	67.4 longer
	3–LB	130.0	156.9 ± 86.7	Yes	-26.8 shorter
	4–Low	0.0	25.1 ± 45.5	Yes	-25.1 shorter
	5–HB	62.5	4.9 ± 16.2	No	57.6 longer
	6–LB	84.9	†	†	†

**Data from child volunteer study* [15].

†Booster seat not included in child volunteer study [15].

TABLE A.XI

INITIAL ATD TORSO CONTACT AND COMPARISON TO CHILD VOLUNTEER DATA (%)

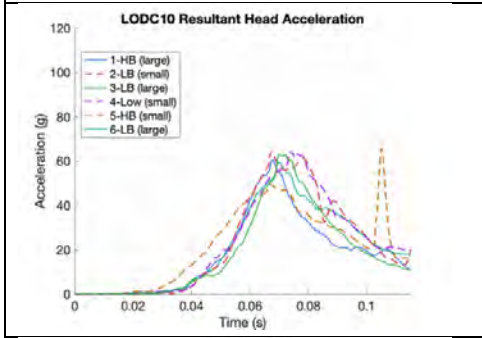
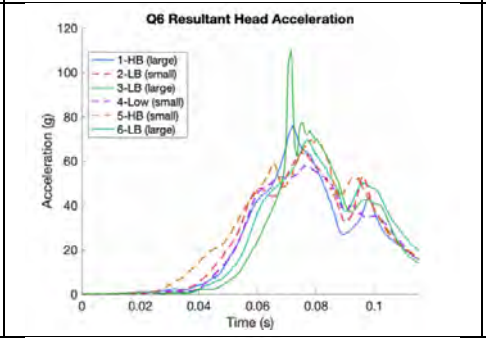
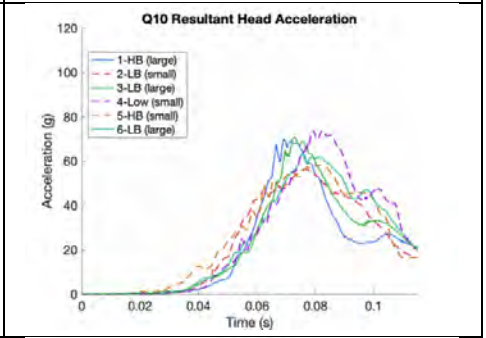
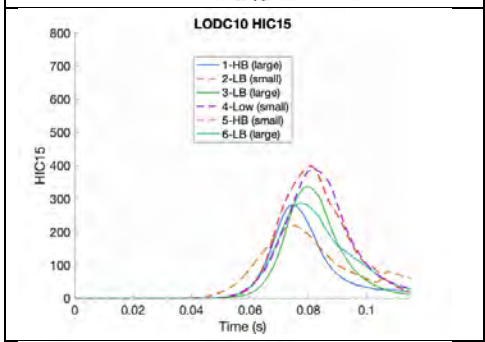
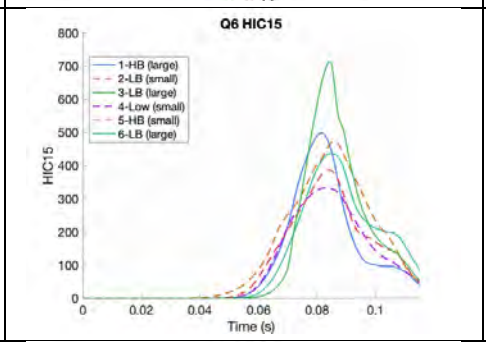
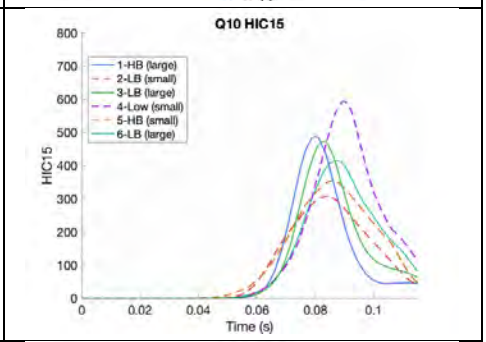
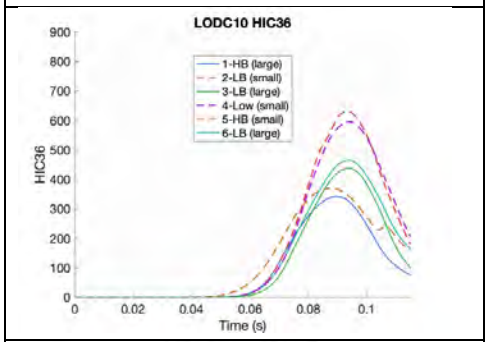
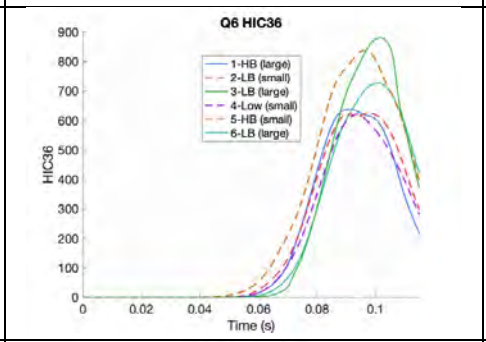
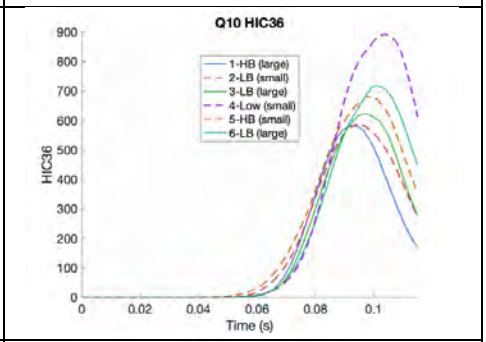
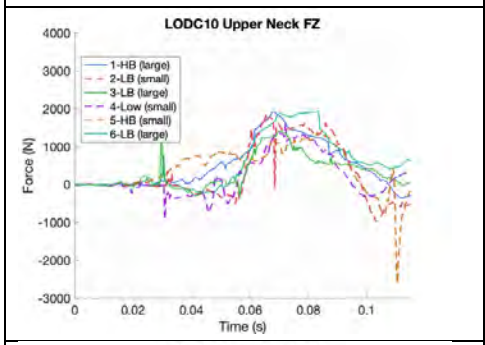
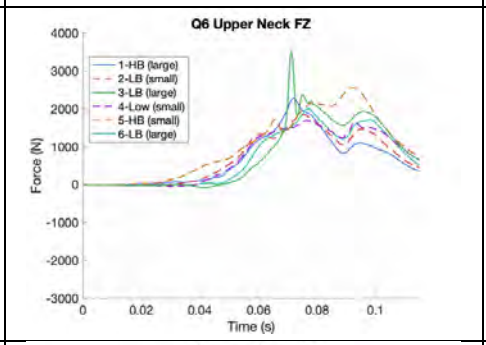
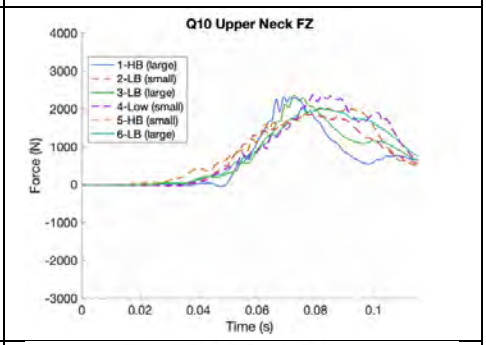
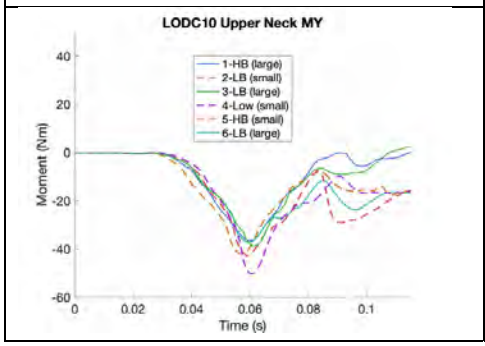
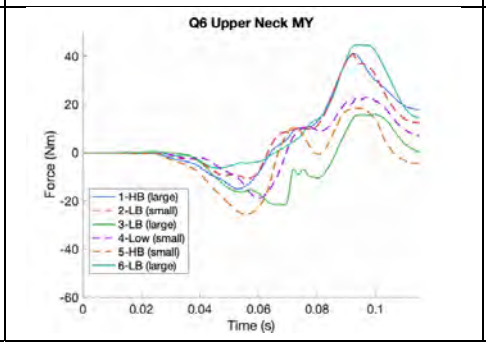
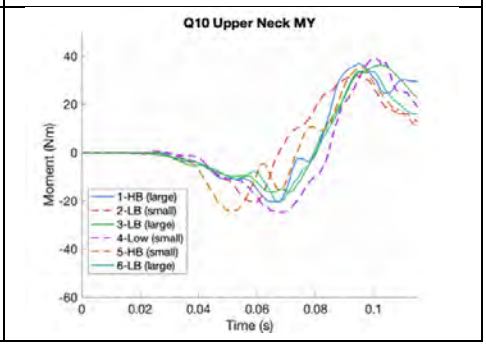
ATD	Booster Seat	ATD	Child Mean ± Std Dev*	ATD within Child Mean ± Std Dev	Difference between ATD and Child Mean
LODC10	1–HB	82.8	80.3 ± 11.8	Yes	2.5 more
	2–LB	85.5	96.4 ± 8.6	No	-11.0 less
	3–LB	76.7	72.5 ± 14.9	Yes	4.2 more
	4–Low	91.2	97.9 ± 6.2	No	-6.7 less
	5–HB	95.3	99.7 ± 1.7	No	-4.4 less
	6–LB	85.7	†	†	†
Q6	1–HB	100.0	80.3 ± 11.8	No	19.7 more
	2–LB	87.3	96.4 ± 8.6	No	-9.1 less
	3–LB	77.0	72.5 ± 14.9	Yes	4.5 more
	4–Low	88.6	97.9 ± 6.2	No	-9.3 less
	5–HB	94.8	99.7 ± 1.7	No	-4.9 less
	6–LB	82.1	†	†	†
Q10	1–HB	79.8	80.3 ± 11.8	Yes	-0.5 less
	2–LB	90.9	96.4 ± 8.6	Yes	-5.5 less
	3–LB	76.3	72.5 ± 14.9	Yes	3.8 more
	4–Low	100.0	97.9 ± 6.2	Yes	2.1 more
	5–HB	91.6	99.7 ± 1.7	No	-8.1 less
	6–LB	81.5	†	†	†

**Data from child volunteer study* [15].

†Booster seat not included in child volunteer study [15].

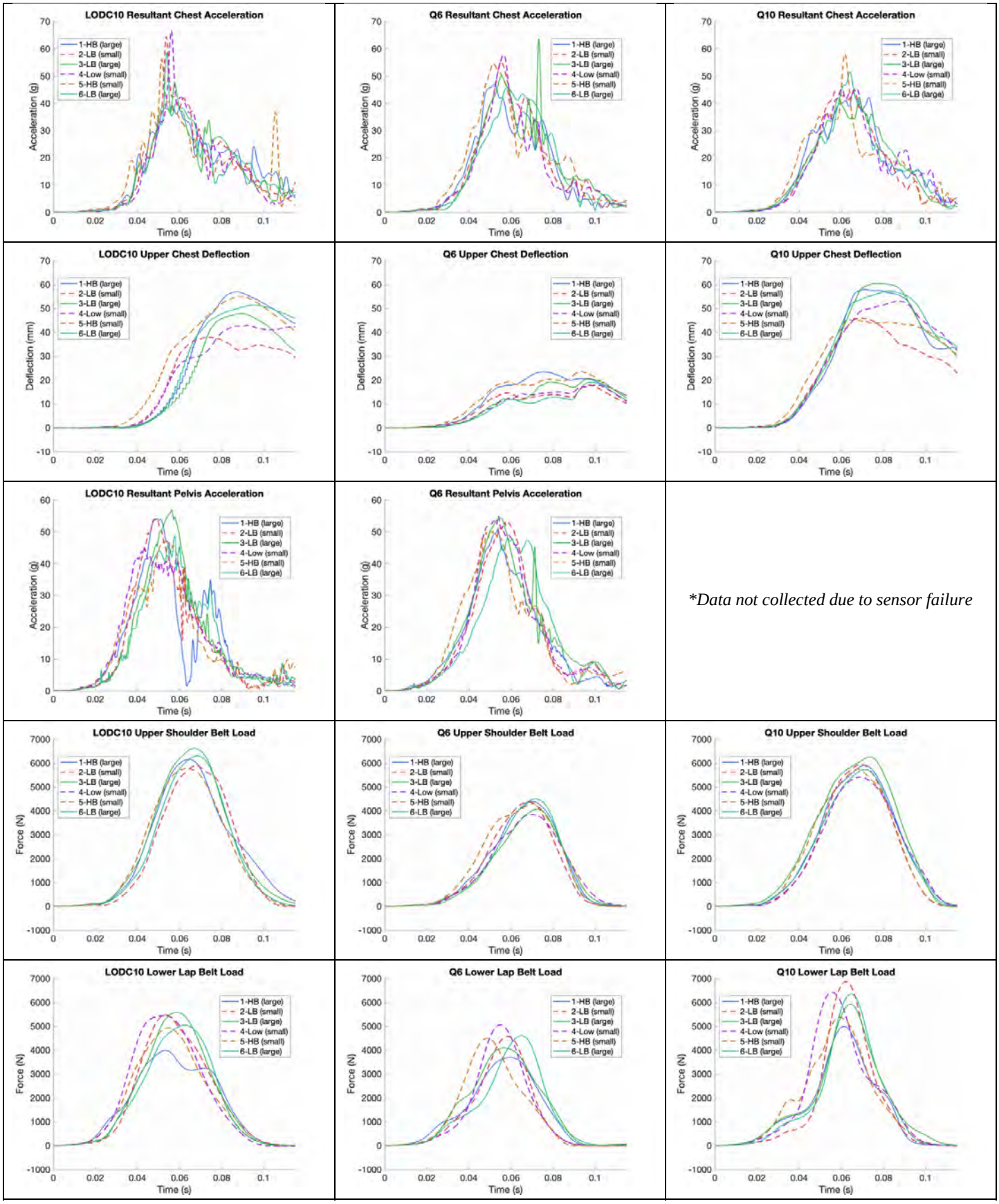
TABLE A.XII

ATD KINETIC METRICS, WITH LARGER GAP BOOSTERS REPRESENTED BY SOLID LINES AND SMALLER GAP BOOSTERS REPRESENTED BY DASHED LINES

LODC10	Q6	Q10
		
		
		
		
		

Continued

TABLE A.XII, *CONTINUED*



**Data not collected due to sensor failure*

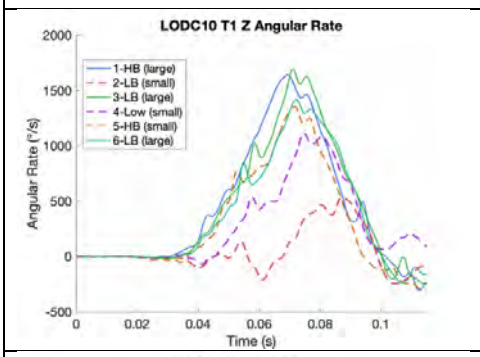
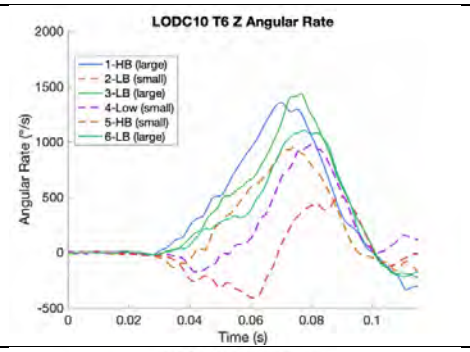
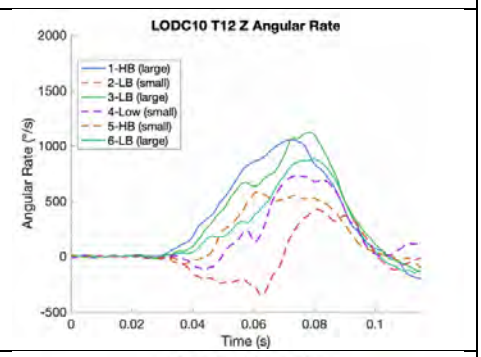
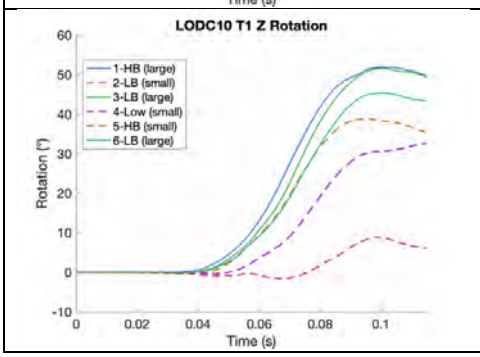
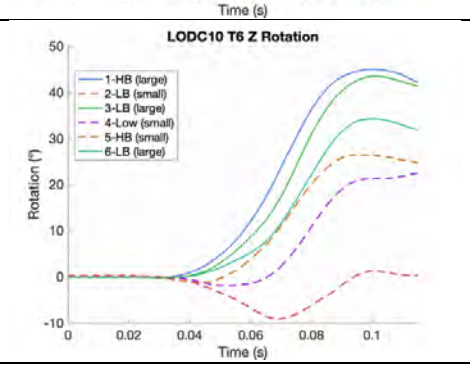
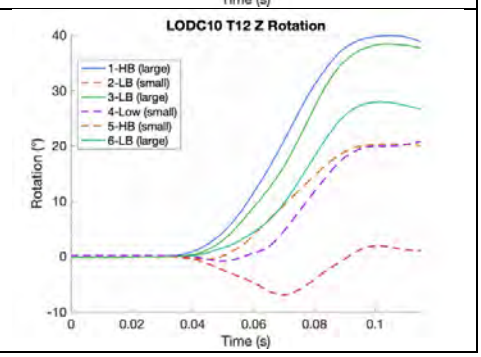
TABLE A.XIII

ADDITIONAL KINETIC METRICS FOR THE LODC10, PEAK VALUES

Metric	1–HB	2–LB	3–LB	4–Low	5–HB	6–LB
Pelvis Y Rotation (°)	-22.2	-21.5	-12.9	-19.1	-3.8	-11.5
T1 Z ARS (°/s)	1643.1	542.2	1693.8	1112.2	1355.3	1415.9
T6 Z ARS (°/s)	1356.0	504.7	1434.1	969.6	948.6	1105.6
T12 Z ARS (°/s)	1055.3	425.9	1123.3	729.6	585.5	882.6
T1 Z Rotation (°)	51.9	8.8	51.7	32.8	38.9	45.4
T6 Z Rotation (°)	45.0	1.2	43.5	23.0	26.5	34.2
T12 Z Rotation (°)	40.0	2.0	38.4	21.6	20.4	28.0
Left ASIS Upper FX (N)	173.6	-62.6	295.2	283.9	396.8	287.1
Left ASIS Lower FX (N)	466.7	82.8	155.9	462.8	531.8	1630.8
Right ASIS Upper FX (N)	157.0	123.8	133.7	223.5	222.7	195.5
Right ASIS Lower FX (N)	415.1	109.5	130.9	735.0	554.4	1354.3
Left Abdomen Pressure (bar)	1.0	0.4	0.8	0.6	1.1	0.9
Right Abdomen Pressure (bar)	2.7	2.0	2.6	2.4	2.7	2.8

TABLE A.XIV

LODC10 T1, T6, AND T12 ANGULAR RATE AND ROTATION, WITH LARGER GAP BOOSTERS REPRESENTED BY SOLID LINES AND SMALLER GAP BOOSTERS REPRESENTED BY DASHED LINES

T1	T6	T12
		
		

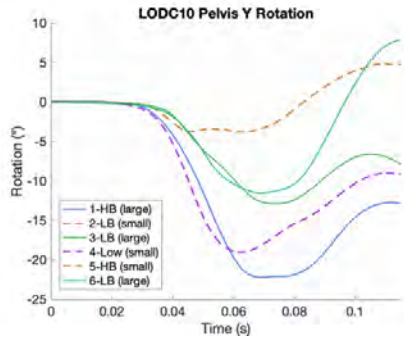


Fig. A.2. LODC10 Pelvis Y Rotation, with larger gap boosters represented by solid lines and smaller gap boosters represented by dashed lines. Booster seat 2–LB lost due to sensor failure.

TABLE A.XV

LODC10 ABDOMINAL PRESSURE AND ASIS FORCES, WITH LARGER GAP BOOSTERS REPRESENTED BY SOLID LINES AND SMALLER GAP BOOSTERS REPRESENTED BY DASHED LINES

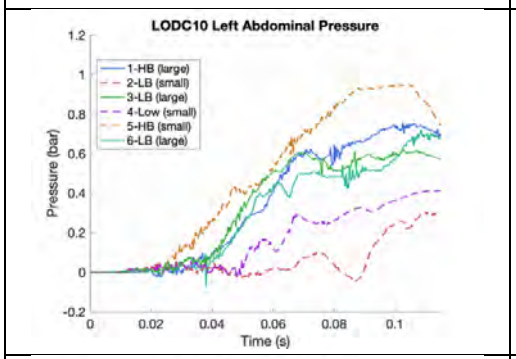
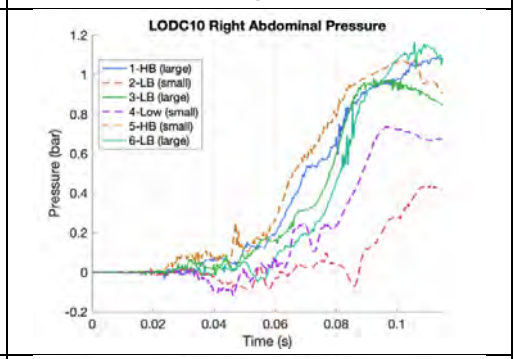
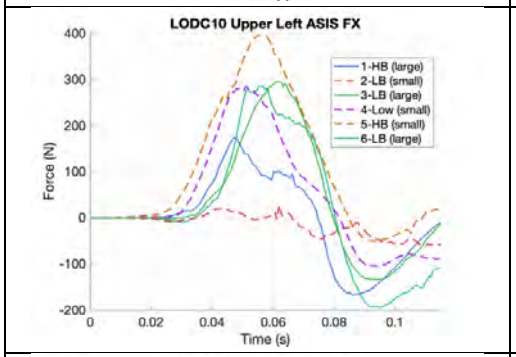
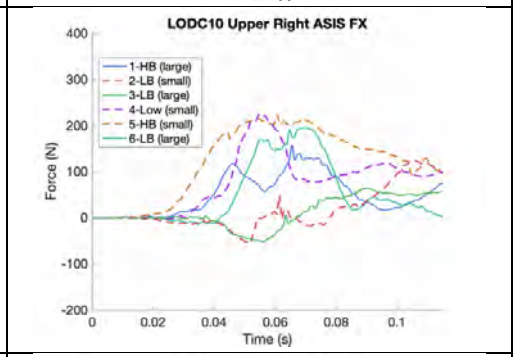
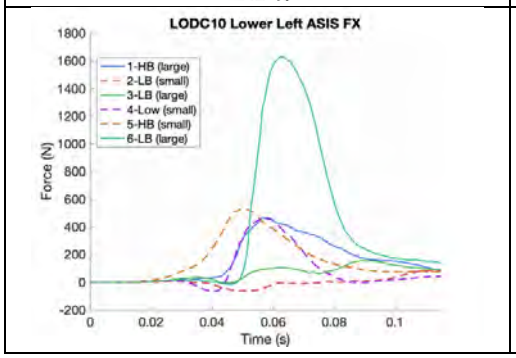
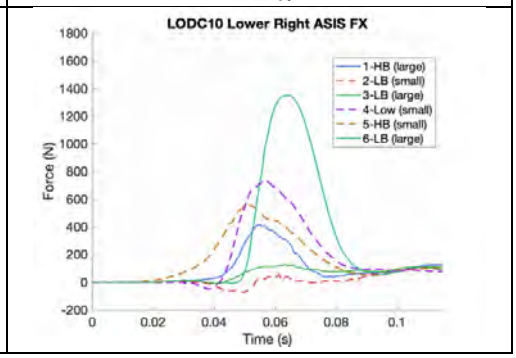
Left	Right
	
	
	

TABLE A.XVI
PEAK SEATBELT LOADS

ATD	Booster Seat	SB Load (N)	LB Load (N)
LODC10	1–HB	6160.5	4003.2
	2–LB	5901.2	5481.6
	3–LB	6622.5	5585.6
	4–Low	*	5448.2
	5–HB	5774.0	4936.3
	6–LB	6311.5	5051.4
Q6	1–HB	4406.7	3693.5
	2–LB	4375.9	4591.3
	3–LB	4076.3	4095.2
	4–Low	3847.1	5064.4
	5–HB	4301.1	4497.7
	6–LB	4499.5	4616.4
Q10	1–HB	5911.6	4993.0
	2–LB	5951.5	6876.9
	3–LB	6263.0	5927.0
	4–Low	5417.5	6430.9
	5–HB	5749.9	5380.8
	6–LB	5737.6	6358.4

TABLE A.XVII
PEAK TRANSVERSE SHOULDER ROTATION

ATD	Booster Seat	Shoulder Rotation (°)	Time (s)
LODC10	1-HB	31.4*	0.066*
	2-LB	14.4	0.121
	3-LB	53.0	0.107
	4-Low	46.7	0.141
	5-HB	41.9	0.095
	6-LB	50.7	0.102
Q6	1-HB	18.7	0.071
	2-LB	28.1	0.133
	3-LB	32.3	0.107
	4-Low	36.9	0.136
	5-HB	33.8*	0.086*
	6-LB	30.4	0.111
Q10	1-HB	41.4*	0.083*
	2-LB	13.5	0.102
	3-LB	51.0	0.088
	4-Low	41.2	0.093
	5-HB	39.1	0.091
	6-LB	42.2	0.092

**Marker out of view before maximum forward position.*

TABLE A.XVIII

ATD DISPLACEMENTS, FROM INITIAL POSITION TO MAXIMUM FORWARD HEAD POSITION, WITH LARGER GAP BOOSTERS REPRESENTED BY SOLID LINES AND SMALLER GAP BOOSTERS REPRESENTED BY DASHED LINES

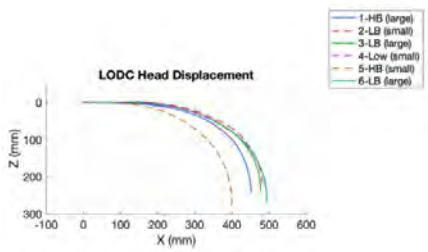
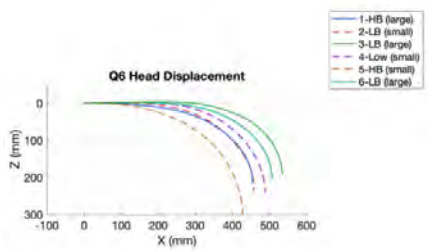
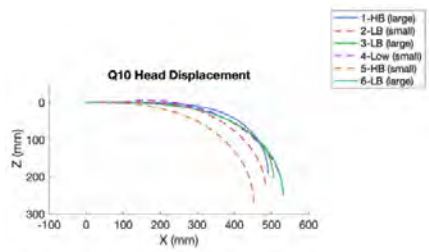
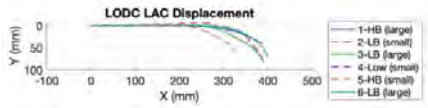
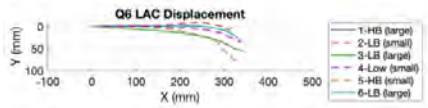
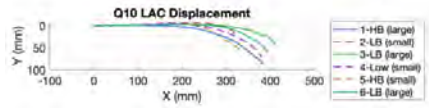
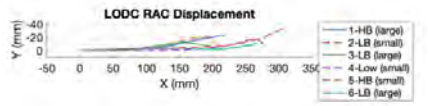
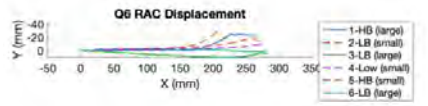
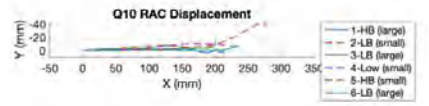
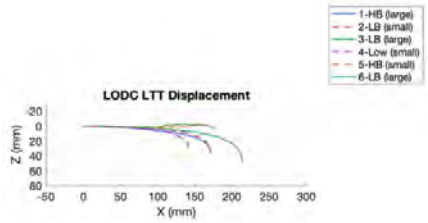
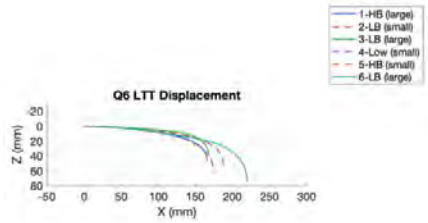
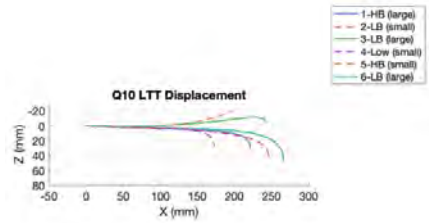
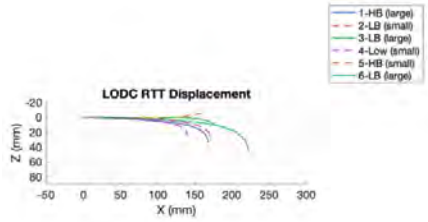
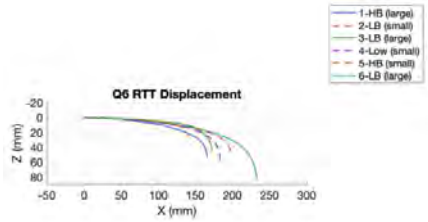
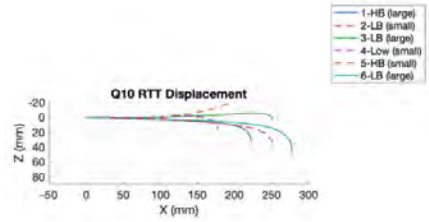
LODC10	Q6	Q10
		
		
		
		
		

TABLE A.XIX
MAXIMUM FORWARD X DISPLACEMENT

ATD	Booster Seat	Head Top (mm)	Left Acromion (mm)	Right Acromion (mm)	Left Knee (mm)	Right Knee (m)
LODC10	1-HB	451.6	389.4*	218.9	171.6	168.2
	2-LB	482.9	311.4	308.7	169.9	172.1
	3-LB	477.3	390.3	215.1	176.7	178.0
	4-Low	493.6	387.5	276.6	141.7	139.7
	5-HB	399.9	323.9	203.8	162.6	161.7
	6-LB	495.2	399.3	266.9	214.1	222.5
Q6	1-HB	455.1	313.5	263.1*	166.0	166.2
	2-LB	457.5	318.7	269.6	187.8	197.9
	3-LB	534.6	345.2	281.4	168.0	172.5
	4-Low	488.3	337.6	271.5	174.6	183.1
	5-HB	427.8	336.3	209.7	149.2	144.4
	6-LB	506.9	334.7	280.7	220.0	233.0
Q10	1-HB	491.0	382.9	213.8	221.7	222.4
	2-LB	484.0	322.9	276.7	246.0	251.8
	3-LB	506.2	413.3	200.6	242.4	251.4
	4-Low	531.8	379.9	235.9	173.8	178.9
	5-HB	452.0	337.9	202.4	198.0	192.4
	6-LB	530.6	392.8	237.2	265.9	277.5

**Marker out of view before maximum forward position.*

TABLE A.XX

ATD EXCURSIONS WITH RESPECT TO SEAT BIGHT CENTRELINE, FROM INITIAL POSITION TO MAXIMUM FORWARD HEAD POSITION, WITH LARGER GAP BOOSTERS REPRESENTED BY SOLID LINES AND SMALLER GAP BOOSTERS REPRESENTED BY DASHED LINES

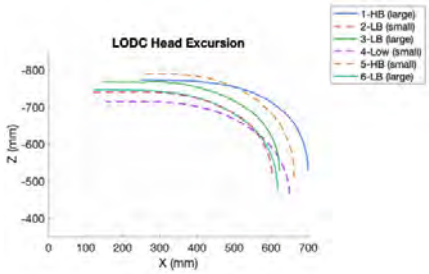
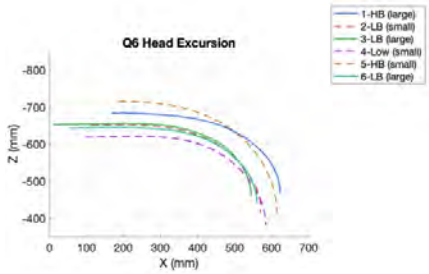
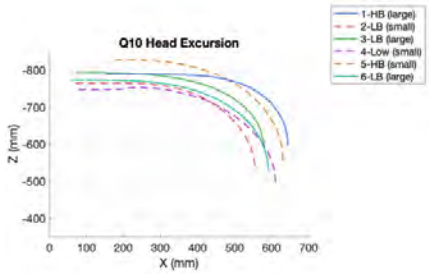
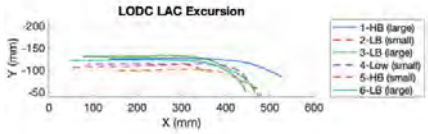
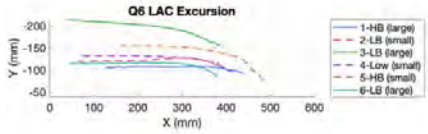
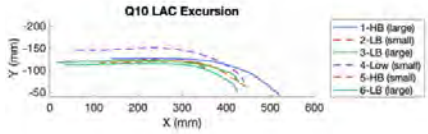
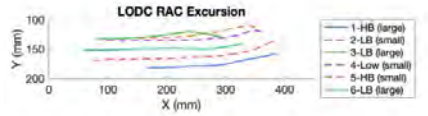
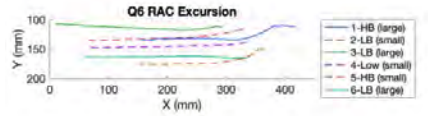
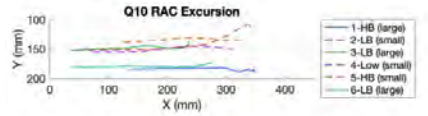
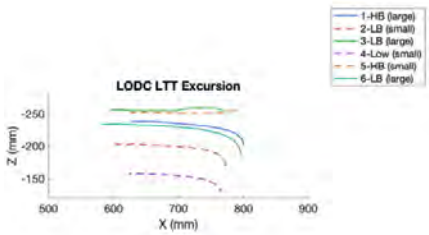
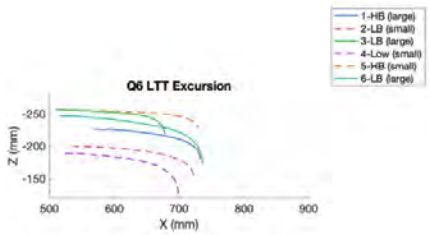
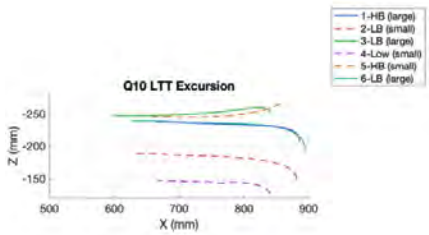
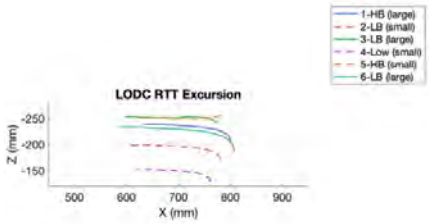
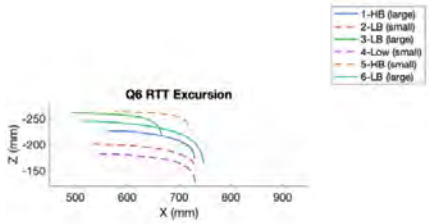
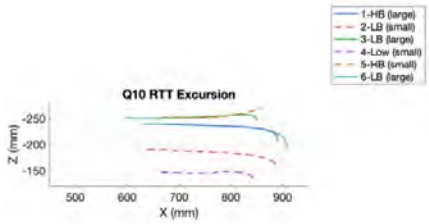
LODC10	Q6	Q10
		
		
		
		
		

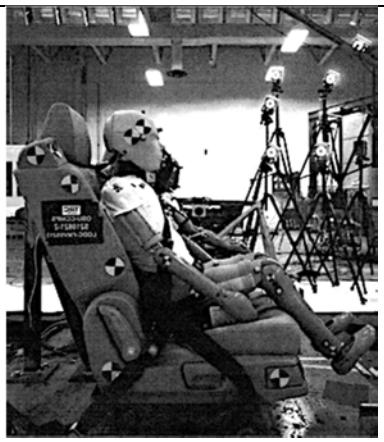
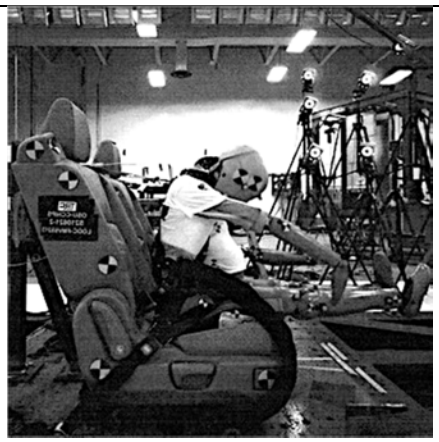
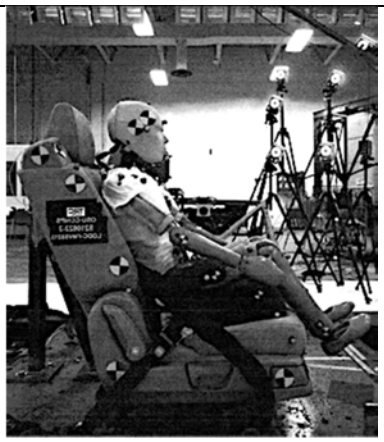
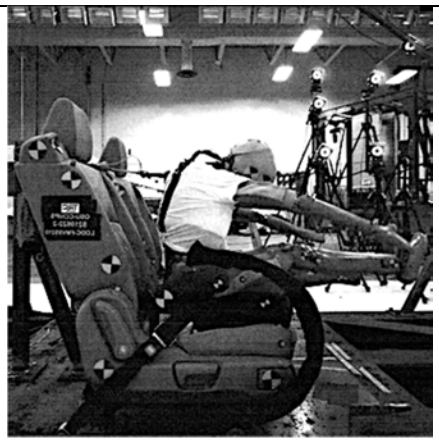
TABLE A.XXI

MAXIMUM FORWARD X EXCURSION, WITH RESPECT TO SEAT BIGHT CENTRELINE

ATD	Booster Seat	Head Top (mm)	Left Knee (mm)	Right Knee (mm)	Avg. Knee–Head Excursion (mm)
LODC10	1-HB	699.8	800.4	800.8	100.8
	2-LB	603.7	773.0	781.1	173.4
	3-LB	560.7	711.5	712.9	151.5
	4-Low	649.8	765.2	761.7	113.7
	5-HB	662.0	789.1	788.1	126.6
	6-LB	618.4	796.7	807.9	183.9
Q6	1-HB	623.7	733.0	730.1	107.9
	2-LB	570.7	723.5	732.1	157.1
	3-LB	546.0	679.2	667.0	127.1
	4-Low	585.0	699.0	731.0	130.0
	5-HB	615.1	729.1	720.2	109.6
	6-LB	561.4	736.6	747.8	180.9
Q10	1-HB	644.3	886.4	891.1	244.4
	2-LB	555.5	881.6	890.0	330.3
	3-LB	580.0	840.4	850.0	265.1
	4-Low	549.4	780.6	782.7	232.3
	5-HB	631.0	858.6	859.6	228.1
	6-LB	591.9	894.3	907.9	309.2

TABLE A.XXII

INITIAL AND MAXIMUM FORWARD POSITION SAGITTAL IMAGES OF THE LODC10

ATD	Booster Seat	Initial Position	Maximum Forward Head Position
LODC10	1–HB	 *	 *
LODC10	2–LB	 *	 *
LODC10	3–LB	 *	 *

Continued

TABLE A.XXII, *Continued*

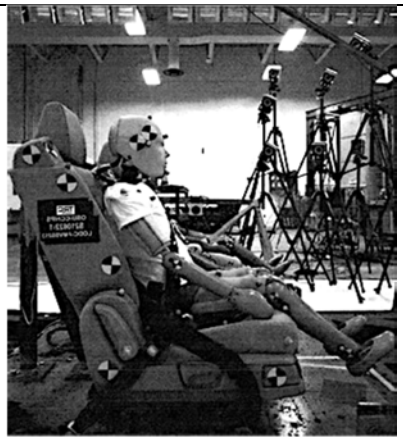
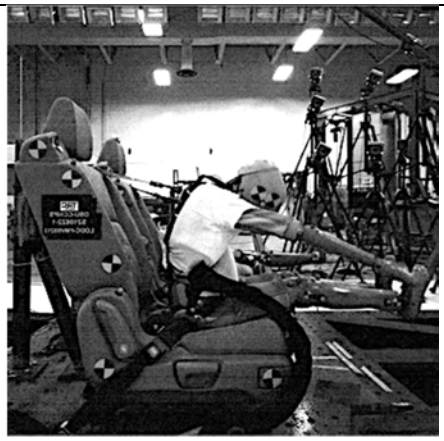
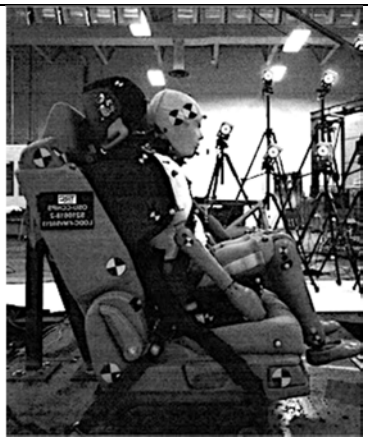
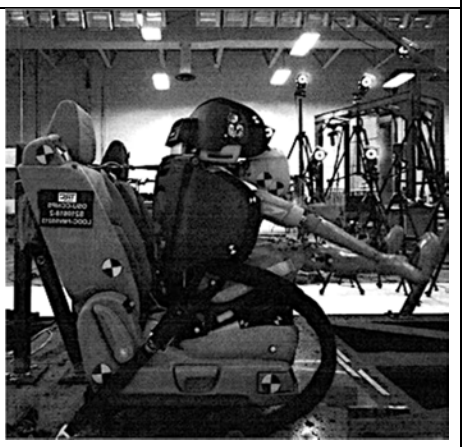
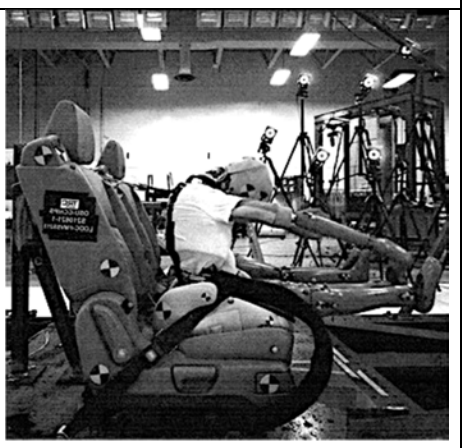
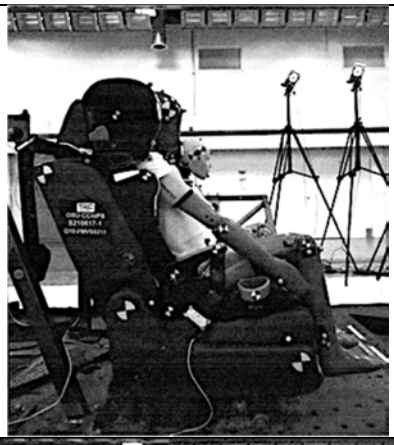
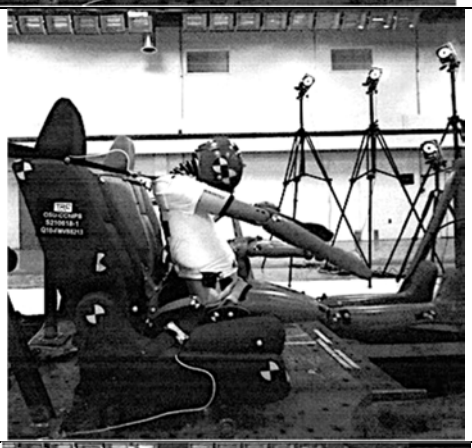
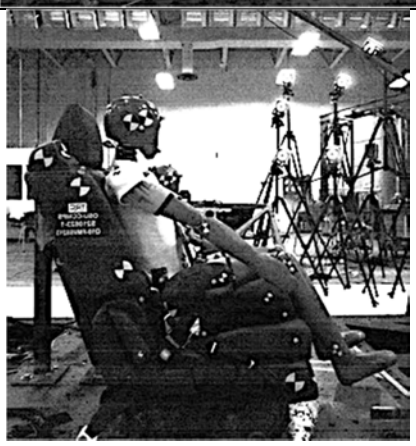
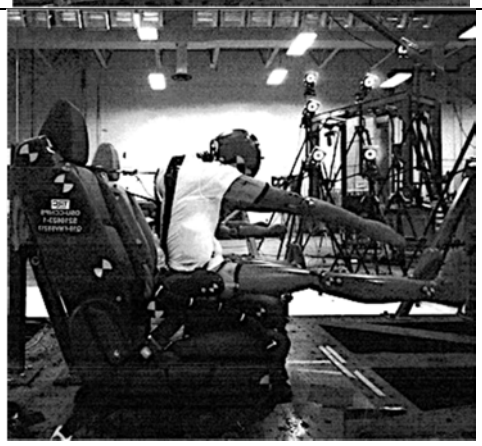
LODC10	4–Low	 *	 *
LODC10	5–HB	 *	 *
LODC10	6–LB	 *	 *

**Image flipped left/right for comparison.*

TABLE A.XXIII

INITIAL AND MAXIMUM FORWARD POSITION SAGITTAL IMAGES OF THE Q10

ATD	Booster Seat	Initial Position	Maximum Forward Head Position
Q10	1–HB		
Q10	2–LB		
Q10	3–LB	 *	 *

Continued

TABLE A.XXIII, *Continued*

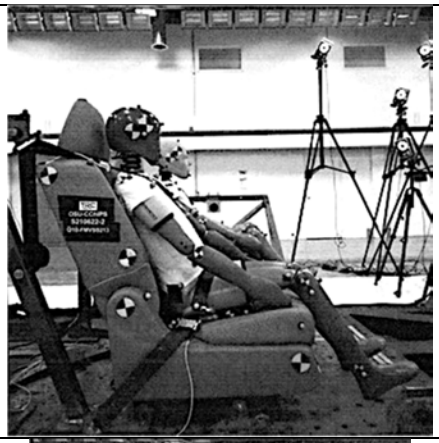
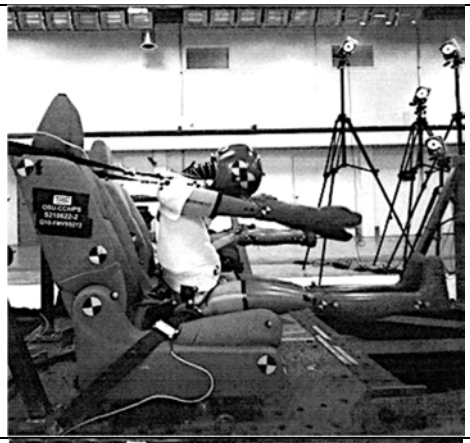
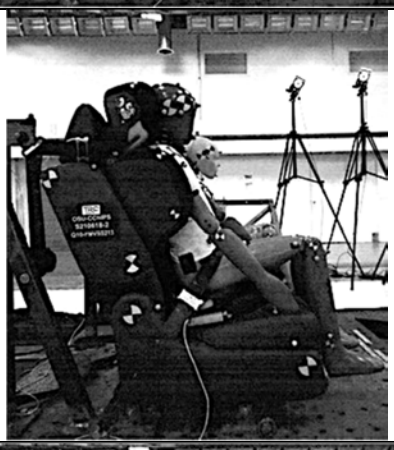
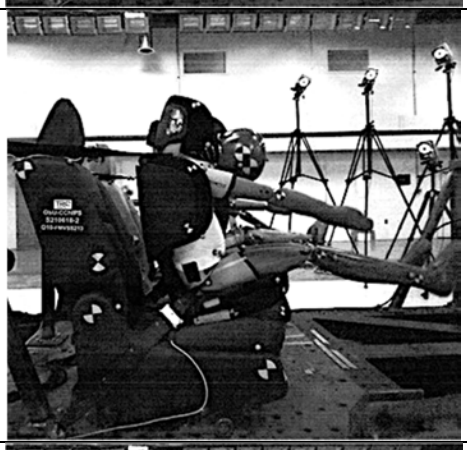
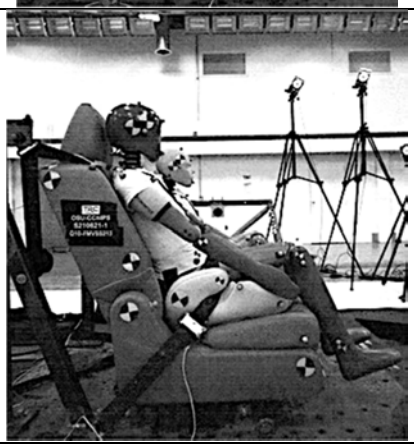
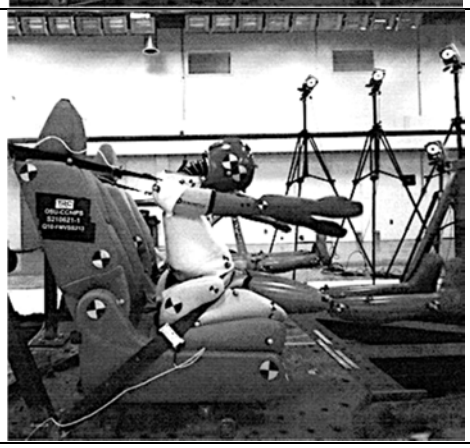
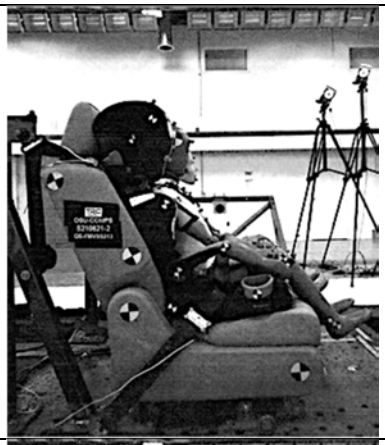
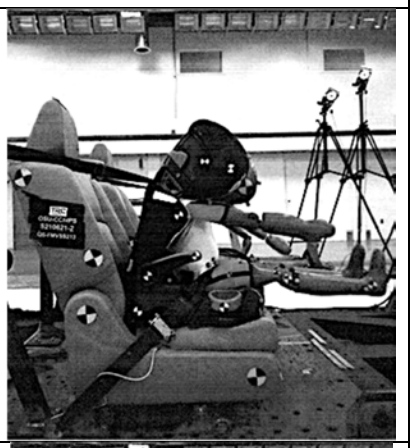
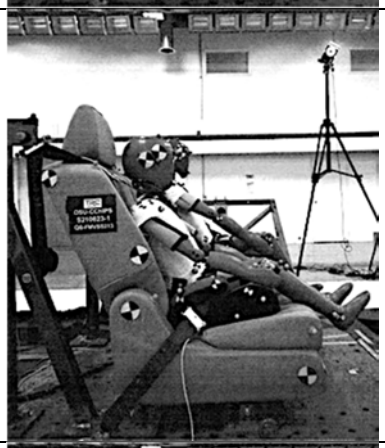
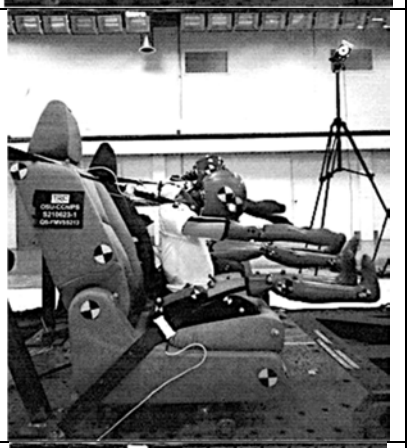
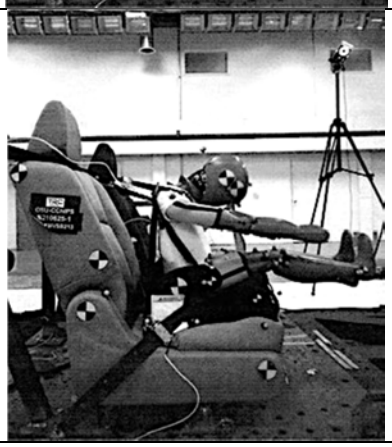
Q10	4–Low		
Q10	5–HB		
Q10	6–LB		

**Image flipped left/right for comparison.*

TABLE A.XXIV

INITIAL AND MAXIMUM FORWARD POSITION SAGITTAL IMAGES OF THE Q6

ATD	Booster Seat	Initial Position	Maximum Forward Head Position
Q6	1–HB		
Q6	2–LB		
Q6	3–LB		

Continued

TABLE A.XXIV, *Continued*

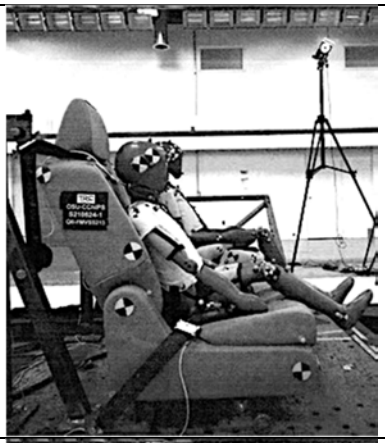
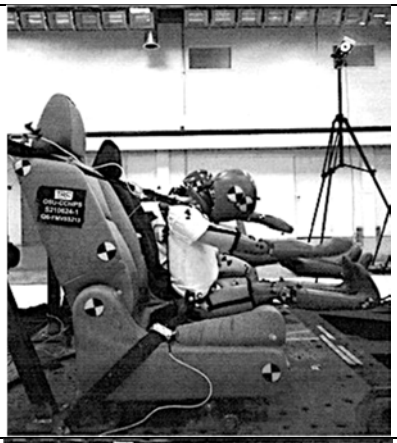
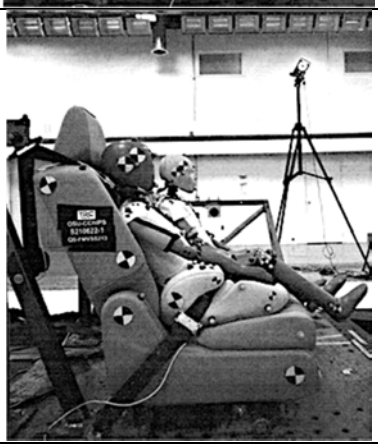
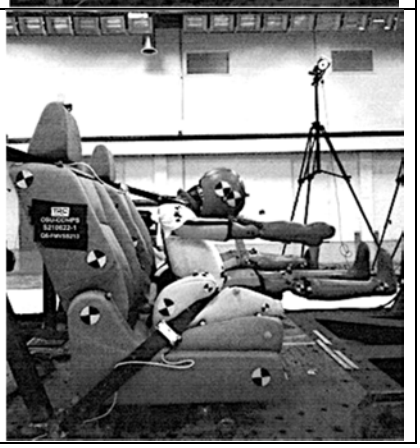
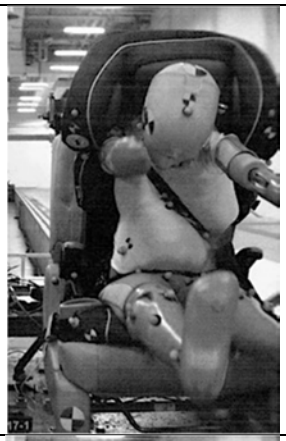
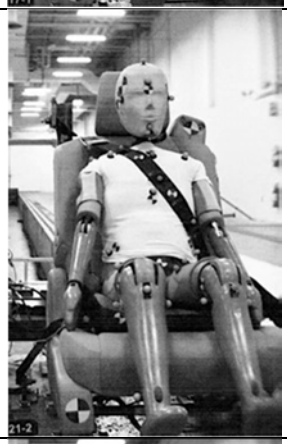
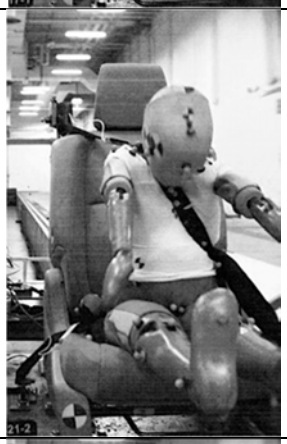
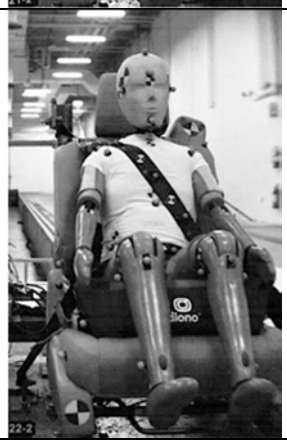
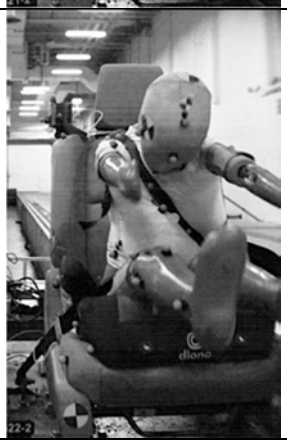
Q6	4–Low		
Q6	5–HB		
Q6	6–LB		

TABLE A.XXV

INITIAL AND MAXIMUM FORWARD POSITION FRONTAL IMAGES OF THE LODC10

ATD	Booster Seat	Initial Position	Maximum Forward Head Position
LODC10	1–HB		
LODC10	2–LB		
LODC10	3–LB		

Continued

TABLE A.XXV, *Continued*

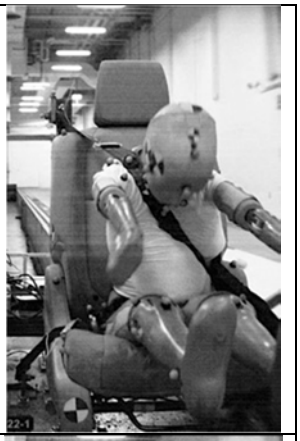
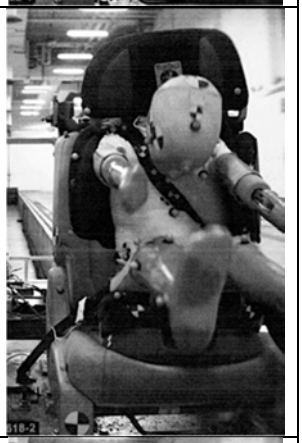
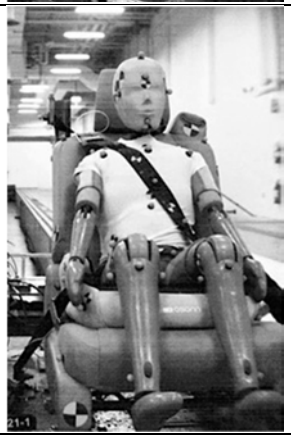
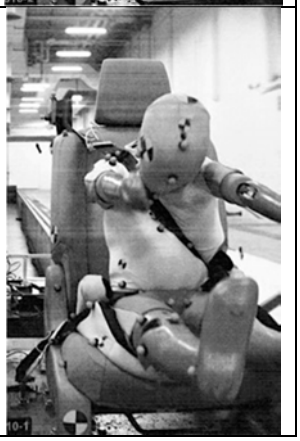
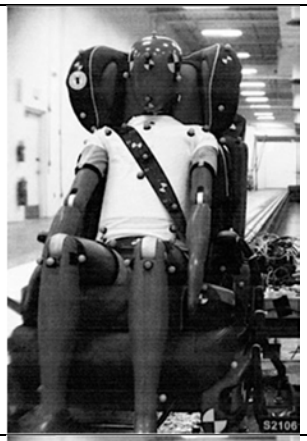
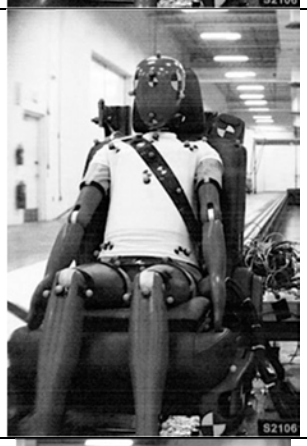
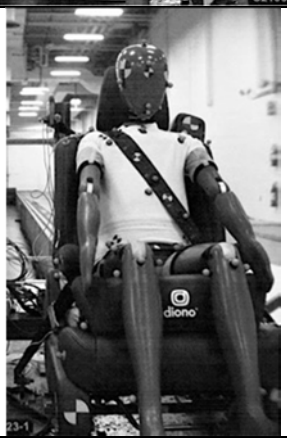
LODC10	4–Low		
LODC10	5–HB		
LODC10	6–LB		

TABLE A.XXVI

INITIAL AND MAXIMUM FORWARD POSITION FRONTAL IMAGES OF THE Q10

ATD	Booster Seat	Initial Position	Maximum Forward Head Position
Q10	1–HB		
Q10	2–LB		
Q10	3–LB		

Continued

TABLE A.XXVI, *Continued*

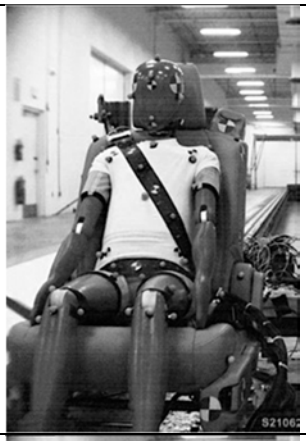
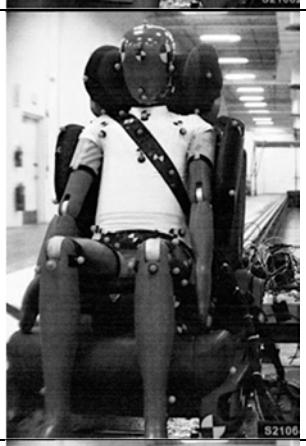
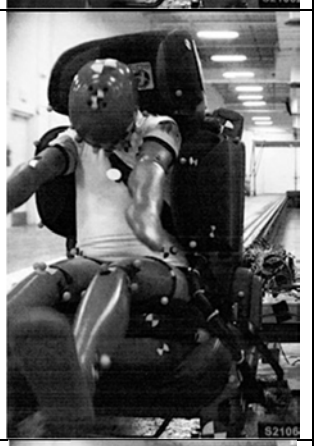
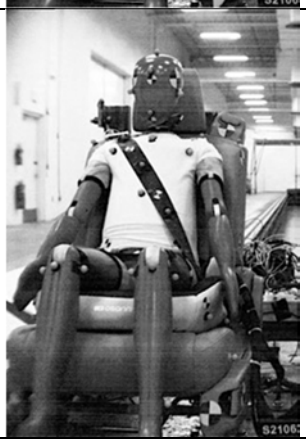
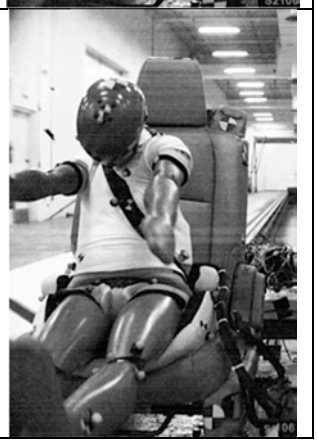
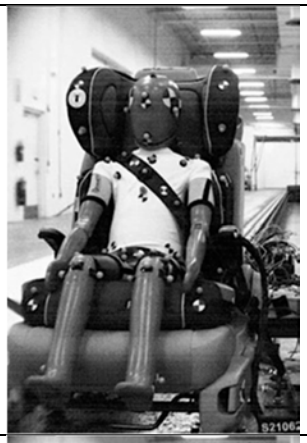
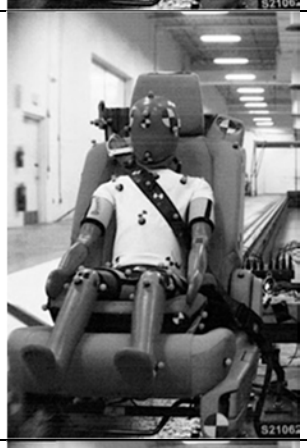
Q10	4–Low		
Q10	5–HB		
Q10	6–LB		

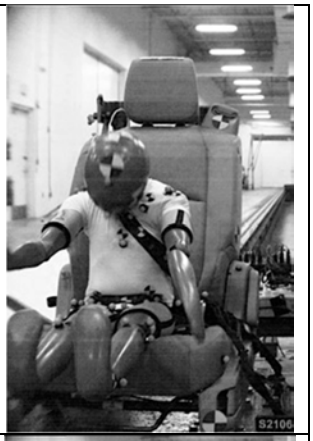
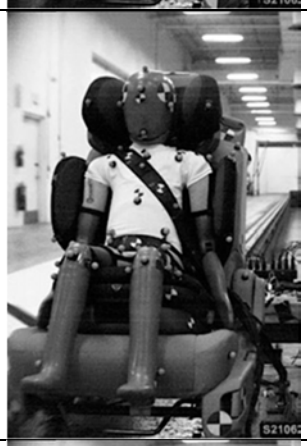
TABLE A.XXVII

INITIAL AND MAXIMUM FORWARD POSITION FRONTAL IMAGES OF THE Q6

ATD	Booster Seat	Initial Position	Maximum Forward Head Position
Q6	1–HB		
Q6	2–LB		
Q6	3–LB		

Continued

TABLE A.XXVII, *Continued*

Q6	4–Low		
Q6	5–HB		
Q6	6–LB