Comparison of Child and ATD Static Belt Fit and Belt Torso Contact on Belt-Positioning Booster Seats.

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Abstract Shoulder and lap belt scores have been previously quantified for anthropomorphic test devices on belt-positioning booster seats; however, they may not fully discriminate between good vs. poor dynamic outcomes. To determine the influence of initial belt fit and gap on dynamic outcomes, the ability of anthropomorphic test devices to represent realistic child belt fit and gap on belt-positioning booster seats must first be understood. This study compares posture, belt fit, and belt torso contact between the Hybrid III (HIII) 6-year-old, HIII 10-year-old, HIII 5th percentile Female, and the Large Omni Directional Child 10-year-old anthropomorphic test devices to a cohort of 50 children on ten belt-positioning booster seats and three seatbelt anchor locations. Novel belt fit metrics (e.g., gap size, gap length, and belt torso contact) and conventional shoulder and lap belt scores were quantified using a 3D coordinate measurement system. Overall, the anthropomorphic test devices had more inboard shoulder belt position, overestimated gap size and length, and underestimated belt torso contact compared to children; however, anthropomorphic test device posture, belt fit, and belt gap outcomes were moderately or strongly associated with child outcomes, suggesting that they can be used to represent realistic variation in initial belt fit and gap conditions.

Keywords Anthropomorphic Test Device (ATD), Belt-Positioning Booster Seat (BPB), Seatbelt Fit

I. INTRODUCTION

Belt-positioning booster seats (BPBs) have been shown to reduce injuries for children in motor vehicle crashes mainly by increasing a child's seated height to improve the fit of the vehicle seatbelt, allowing crash forces to be transferred to stronger bony regions instead of loading the abdomen and potentially creating soft-tissue injuries [1][2]. Good belt fit on BPBs has previously been characterised by placing the shoulder belt on the middle of the clavicle which can prevent the seatbelt from slipping off the shoulder during a crash and avoid irritation of the neck, which may lead to misuse or non-use of the shoulder belt [3–7]. Good belt fit on BPBs has also been described as placing the lap belt below the anterior superior iliac spine (ASIS) on the pelvis which can help prevent submarining characteristics during crash [3][4][7][8]. In order to best evaluate the potential for poor belt fit on BPBs and its influence on kinematic and injurious outcomes for paediatric occupants, anthropomorphic test devices (ATDs) should simulate realistic child static belt fit.

Previous studies and consumer evaluation programmes have quantified belt fit of paediatric ATDs on a variety of BPBs mainly by quantifying the position of the seatbelt relative to anatomic landmarks. Previous studies have evaluated belt fit for the Hybrid III 6-year-old (HIII06) [4][9–11] and the Hybrid III 10-year-old (HIII10) [4][10] ATDs on a variety of BPBs in static, laboratory or vehicle settings. Studies have also compared ATD and child volunteer belt fit [4][9][10]. The main measurements of interest in these studies were the shoulder belt score (SBS), the lateral distance between the shoulder belt and the suprasternale, and lap belt score (LBS), the vertical distance between the lap belt and ASIS. Generally, the HIII06 and HIII10 have shown strong linear relationships with child belt fit [4][9][10], suggesting that ATDs represented realistic differences in belt fit between BPBs. Additionally, evaluations performed by Consumer Reports and the Insurance Institute of Highway Safety have also utilised paediatric ATDs or the Juvenile Anthropomorphic Seat-belt Position Evaluation Rig to quantify belt fit on a range of BPBs [12]. These evaluations provide an overall rating for the BPB for a range of vehicle seating environments but have also mainly relied on quantification of static belt fit utilising SBS and LBS.

To provide the best protection, BPBs should not only provide good static belt fit but also maintain optimal belt positioning on the shoulder, torso, and pelvis during normal driving, evasive manoeuvres, and crashes. Previous work has indicated that vehicle manoeuvres prior to crash may result in varying belt placements and restraint interactions due to children assuming nonstandard pre-crash postures [13]. Evaluation of the kinematics and belt interaction for BPB-seated children has suggested that initial belt fit may influence shoulder belt slip-off and kinematic response during evasive vehicle manoeuvres [13][14]. Specifically, shoulder belt slip-off and less

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engagement between the belt and torso were observed for children on BPBs with belt guides which pulled the belt forward and away from the lower torso, creating a gap [14]. Previous studies have indicated that unstable pre-crash restraint scenarios (such as the belt slipping off of the shoulder) may increase the likelihood of sustaining a head injury in the case of a crash [15], which is the most commonly injured body region for children, even when restrained in the rear seat [1][16]. This suggests that evaluation of initial belt-to-torso contact may help to understand how belt fit contributes to kinematic and injury outcomes during crash.

Similar to previous evaluations of BPB-seated children, the HIII and Q-Series 6- and 10-year-old ATDs were seated on BPBs and exposed to evasive vehicle manoeuvres [17]. Compared to the HIII ATDs, the Q ATDs had more initial contact with the belt and torso due to their wider shoulder and more pronounced abdomen design. As a result, the Q ATDs had a more inboard initial shoulder belt position, smaller inboard head and torso displacement and maintained the belt on the shoulder during evasive steering while the HIII ATDs had a more outboard shoulder belt position, greater inboard head and torso displacement, and ended with the shoulder belt off of the shoulder [17]. This suggests that, similar to children [13][14], BPBs provided different initial belt fit and belt-to-torso contact for paediatric ATDs which may have contributed to variation in kinematic and restraint interaction outcomes during evasive manoeuvres; however, initial belt fit was not fully quantified in these evaluations, and no quantification of the initial belt fit or gap was performed. These differences in kinematic and restraint interaction outcomes for ATDs during evasive manoeuvres also suggest that evaluation of initial belt-to-torso contact (or, belt gap) may be important for understanding optimal belt fit and how this relates to dynamic outcomes for BPB-seated occupants.

Paediatric ATDs have also been evaluated during frontal sled tests on a selection of BPBs with varying initial belt fit conditions [5][10][18][19]. Results from these evaluations suggest that initial belt positioning can produce differences in kinematic outcomes and shoulder belt slip-off during frontal and oblique impacts [5][18]; however, BPBs with similar SBS and LBS did not necessarily display similar kinematic or injury outcomes [10][19]. This suggests that evaluation of additional belt fit metrics (such as belt gap) for paediatric ATDs may help to elucidate differences in kinematic and injury outcomes for BPB-seated occupants during crashes.

This study utilises novel measures of static belt fit, specifically to quantify belt-to-torso contact and belt gap for BPB-seated ATDs and to compare belt fit and belt gap outcomes to a cohort of children evaluated on the same BPB conditions. Variations in initial belt fit and belt gap have been shown to influence the interaction between the belt and torso in addition to kinematics for BPB-seated occupants in evasive vehicle manoeuvres [13][14][17] and may also have implications for kinematic and injury outcomes during crashes. An updated evaluation of static belt fit for paediatric ATDs, including quantification of belt gap, is important to evaluate their ability to represent realistic child belt fit and belt gap conditions provided by BPBs.

II. METHODS

Ten BPBs were selected for evaluation from BPBs available for purchase on the US market in 2019. Two BPBs from each of the following CRS types were selected: 3in1 (transitions from rear-facing harnessed to forward-facing harnessed to BPB), combination (Comb, transitions from forward-facing harness to BPB), high-back (HB), low-back (LB), and low-profile (Other). BPBs were also selected such that they represented various manufacturers, height and weight recommendations, and belt routing schemes (Table I, Table AI).

TABLE I
BELT-POSITIONING BOOSTER SEAT INFORMATION AND OCCUPANT REQUIREMENTS

	BPB	CRS Type	Mass (kg)	Stature (cm)
1	Baby Trend, PROtect Yumi	HB	13.6 – 45.4	96.5 – 114.8
2	Britax, Frontier ClickTight	Comb	18.1 – 54.4	114.3 – 157.5
3	Chicco, MyFit	Comb	18.1 – 45.4	96.5 – 114.8
4	Cosco, Topside	LB	18.1 – 45.4	109.2 – 114.8
5	Diono, Solana 2	LB	18.1 – 54.4	96.5 – 160.0
6	Evenflo, EveryStage DLX	3in1	18.1 – 54.4	111.8 – 114.8
7	Graco, Turbobooster Grow Seatbelt Trainer	Other	22.7 – 54.4	109.2 – 152.4
8	Mifold	Other	18.1 – 45.4	101.6 – 114.8
9	Peg Perego Viaggio, Flex 120	HB	18.1 – 54.4	99.1 – 160.0
10	Safety1st, Grow and Go EX	3in1	18.1 – 45.4	109.2 – 132.1

Rear seat cushions from a recent model year sedan were fixed onto a stationary support structure. The seat assembly included a production seatbelt and retractor integrated into the simulated rear shelf and a simulated rigid buckle stalk. The vehicle seat length was 495 mm, seat angle was 7.6° from horizontal, and the seat back was 26.3° from vertical. The bottom vehicle seat cushion was modified to allow for three lower anchor locations: baseline, forward, and wide (Table AII, Fig. A1). The seatbelt anchor locations represented the middle and maximum of the range of allowable angles defined by FMVSS 210 [20] and the minimum and maximum anchor widths measured previously for 50, model year 2008-2015 vehicles [21][22]. The seatbelt outlet location was held constant for all trials (Fig. A2).

The HIII06, HIII10, Large Omni Directional Child 10-year-old (LODC10), and Hybrid III 5th percentile female (HIII5F) ATDs were evaluated on all BPBs for which they met the manufacturer height and weight requirements (Table II). ATDs were evaluated in each of the three seatbelt anchor locations for all eligible BPBs.

TABLE II

BELT-POSITIONING BOOSTER SEATS EVALUATED FOR EACH ATD

ATD	Stature (mm)	Mass (kg)	BPBs Evaluated
HIII06	1140.5	23.4	1, 2*, 3, 4, 5, 6, 7, 8, 9, 10
HIII10	1304.3	35.2	1, 2, 3, 4, 5, 6, 7, 8, 9, 10
LODC10	1300.0	34.6	1, 2, 3, 4, 5, 7, 8, 9, 10
HIII5F	1498.6	49.0	2, 5, 7, 9

**HIII06 included despite BPB minimum height requirement of 114.3 cm*

Experimental Testing

A cohort of 50 child volunteers was evaluated previously, and identical methods were followed for ATDs [23]. The children fell within the BPB height and weight recommendations of the selected BPBs (Table I), and comparisons of average child and ATD anthropometry can be found in Table III. A certified child passenger safety technician (CPST) placed the BPB on the vehicle seat and installed the ATD into the BPB in a centralised, upright posture. The CPST routed the seatbelt through the BPB belt routings, buckled the seatbelt, removed slack, and adjusted relevant settings to most appropriately fit the ATD per manufacturer instructions.

TABLE III

CHILD AND ATD ANTHROPOMETRY

ATD	N	Age (yr)		Stature (mm)		Seated Height (mm)		Mass (kg)	
	Child*	ATD	Child*	ATD	Child*	ATD	Child*	ATD	Child*
HIII06	50	6	8.5 ± 2.5	1140.5	1329.5 ± 133.5	635.0	678.9 ± 65.1	23.4	30.3 ± 9.2
HIII10	50	10	8.5 ± 2.5	1304.3	1329.5 ± 133.5	716.3	678.9 ± 65.1	35.2	30.3 ± 9.2
LODC10	50	10	8.6 ± 2.5	1300.0	1336.0 ± 136.3	679.0	682.2 ± 66.7	34.6	30.9 ± 9.3
HIII5F	35	12	10.0 ± 2.4	1498.6	1423.9 ± 124.2	787.4	724.8 ± 65.5	49.0	36.9 ± 9.2

**Only children tested on the same BPBs as ATDs included in comparison. Data from* [23].

A non-invasive three-dimensional coordinate measurement system (FARO Edge Arm, Lake Mary, Florida) captured three-dimensional positions of the ATD, seatbelt, BPB, and the vehicle seat reference points (Table AIII). Main measurements of interest included the position of the suprasternale, ASIS, and streams of measurements every 2 cm along the midline of the lap belt (LB Stream), shoulder belt in its natural position (SB Stream), and the shoulder belt while pressed to be completely in contact with the torso (Torso Stream). The SB Stream (Fig. A3, Fig. A5) and LB Stream were captured at visually marked points every 2 cm along the midline of the lap and shoulder belts. The Torso Stream was captured at every marked point along the shoulder belt midline while the shoulder belt was pushed into contact along the length of the torso, without modifying the belt's natural path (Fig. A4, Fig. A6). The Torso Stream was captured from the point where the shoulder belt leaves the torso to the point where the shoulder belt touches the lower, inboard belt guide on the BPB. Corresponding marked seatbelt points at each of these locations were recorded. The Lap Streams were captured, similar to previous studies, along the inferior abdomen and proximal thigh along the sagittal plane of each ASIS [4].

Belt Fit and Belt Torso Contact Analysis

All reference points were recorded with respect to a global coordinate system recommended by SAE J211 [24] where X points forward, Y points to the right, and Z points down and were processed utilising custom MATLAB scripts. Conventional belt fit measurements, shoulder belt score (SBS) and lap belt score (LBS), were calculated as described in previous studies [4][6]. The sagittal position of the lap belt with respect to the ASIS was calculated by subtracting the position where the superior edge of the lap belt crossed the ASIS from the ASIS position.

Novel belt gap metrics were calculated. The gap size was calculated between corresponding points on the SB Stream and Torso Stream by subtracting the position of the point on the Torso Stream from the corresponding point on the SB Stream in the X, Y, and Z directions (Fig. 1). The gap size is the total XYZ distance between the corresponding points. Maximum Gap Size was defined as the largest XYZ distance between the belt and torso (Fig. 1).

For calculation of gap length and torso contact, a region of gap was defined using SB Stream and Torso Stream measurements in addition to visually identified positions of marked seatbelt points with respect to the occupant. The gap region was restricted to the visually defined region of gap based on the marked belt points (gap start, gap end) plus/minus two marked belt points (4 cm) superiorly and inferiorly along the belt (Fig. 2). Next, the region of gap was further restricted to only include points with calculated gap size greater than 10 mm (Fig. 3). Finally, the region of gap was further restricted to include only regions where at least two consecutive points had been previously defined as gap (Fig. 4). For example, if in Figure 3 the top measurement was identified as a gap by exceeding the gap threshold, it would not be included in the final gap region in Figure 4 as the next consecutive measurement was not defined as a gap exceeding the gap threshold. Trials without an identified region of gap were treated to have a gap length of 0 mm and a percent torso contact of 100%.

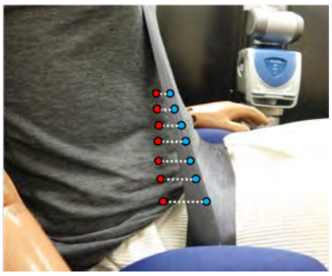
Fig. 1. Gap Size


Fig. 2. Visual Gap Region

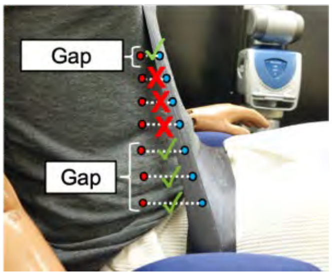

Fig. 3. Gap Region Restricted by threshold

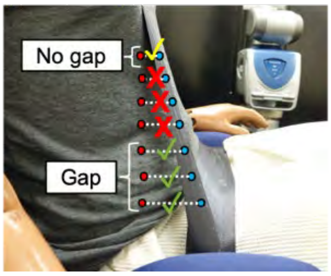

Fig. 4. Gap Region further restricted

Gap Length was defined as the length along the shoulder belt (using the SB Stream data) in the region of the gap (Fig. 5). Percentage of the Belt Torso Contact was defined, using SB Stream data, as the length along the shoulder belt which was not defined as a region of gap divided by the length along the shoulder belt bounded by where the belt leaves the shoulder and the end of the Torso Stream or the most inferior SB Stream measurement superior to the ASIS (Fig. 6). Gap Start Location was defined as the XYZ location of the most superior point of the region of gap with respect to the suprasternale (Fig. 7). Max Gap Location was defined as the XYZ location of maximum gap size with respect to the right ASIS (Fig. 7).

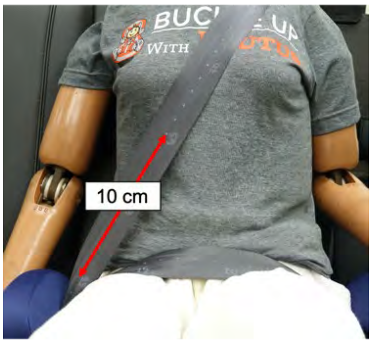

Fig. 5. Gap Length

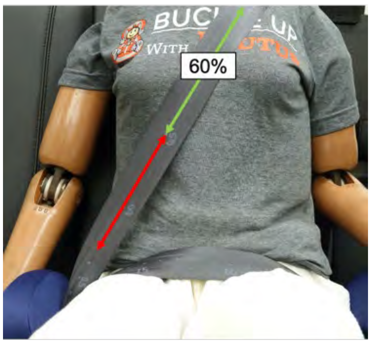

Fig. 6. Torso Contact

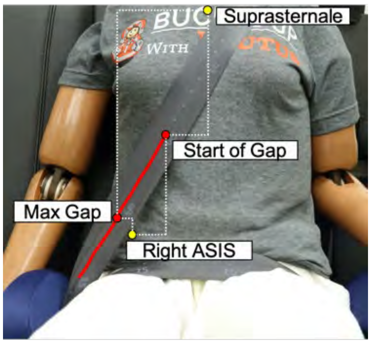

Fig. 7. Gap Location

Postural Analysis

The global position of the ASIS and suprasternale ATD landmarks were quantified using the coordinate measurement system. The upright torso angle was defined as the angle with respect to vertical about the Y-axis of the line connecting the suprasternale and the mean ASIS position in the sagittal plane. A positive upright torso angle represents a reclined posture. The lateral torso angle was defined as the angle with respect to vertical about the X-axis of the line connecting the suprasternale and the lateral midpoint of the left and right ASIS in the frontal plane. A positive lateral torso angle represents inboard leaning.

ATD and Child Comparisons

Posture and belt fit outcomes for each ATD were compared to child cohort data from [23]. Each child was measured on six unique randomized BPB and seatbelt anchor location combinations, providing a total of 10 children evaluated per condition. For BPB-level comparisons, all seatbelt anchor locations were included, providing 30 child measurements per BPB. Statistical evaluations were performed in JMP Pro 15. Pearson's correlation coefficients (r) were used to evaluate relationships between the mean ATD and child belt fit, gap, and posture outcomes for each BPB and seatbelt anchor location combination. The alpha level was set *a priori* to 0.05.

The ability of ATDs to represent realistic child anatomic landmark position, belt fit, and belt gap outcomes on individual BPBs were also evaluated by determining if the mean ATD values for each BPB fell within an acceptable range based on the child data. For these comparisons, the acceptable range was considered to be the child mean ± one standard deviation for each metric, as the ATDs represent the average 6-year-old, 10-year-old, and 5th percentile female (approximately representative of a 50th percentile 12-year-old by stature) anthropometry.

III. RESULTS

ATDs Posture Comparison to Children

On average, the difference in the position of anatomical landmarks between ATDs and children varied by ATD (Table IV). Generally, the ASIS of the ATDs tended to be superior to that of the children (Table IV, Fig. A7). The ASIS of the HIII06 and HIII10 were slightly rear of the children while the HIII5F and LODC10 were fore. The suprasternale tended to be fore and superior to that of the children, with the exception of the HIII06 which was rear and inferior. The suprasternale was more outboard for all ATDs compared to children on average.

TABLE IV
CORRELATION AND COMPARISON OF MEAN ATD AND MEAN CHILD ANATOMICAL LANDMARK POSITIONS FOR ALL BELT-POSITIONING BOOSTERS

ATD	Comparison		ASIS X (mm)	ASIS Z (mm)	Suprasternale X (mm)	Suprasternale Y (mm)	Suprasternale Z (mm)
HIII06	*Magnitude*	*Avg. Difference*	-8.6 ± 47.2 rear	-9.0 ± 66.4 superior	-2.6 ± 67.9 rear	-1.2 ± 22.5 outboard	20.8 ± 82.5 inferior
		# BPBs within Range	7 of 10	5 of 10	9 of 10	10 of 10	7 of 10
	Correlation	*p-Value*	<0.0001	<0.0001	<0.0001	0.0004	<0.0001
		r-Value	0.9159	0.9753	0.9812	0.6084	0.8662
HIII10	*Magnitude*	*Avg. Difference*	-4.7 ± 45.4 rear	-18.4 ± 66.3 superior	31.4 ± 71.2 fore	-9.0 ± 23.2 outboard	-23.6 ± 84.8 superior
		# BPBs within Range	8 of 10	4 of 10	1 of 10	8 of 10	4 of 10
	Correlation	*p-Value*	<0.0001	<0.0001	<0.0001	0.0002	<0.0001
		r-Value	0.9560	0.9742	0.9645	0.6376	0.8807
HIII5F	*Magnitude*	*Avg. Difference*	24.3 ± 48.5 fore	-16.7 ± 55.2 superior	72.7 ± 93.2 fore	-3.9 ± 25.3 outboard	-53.4 ± 78.7 superior
		# BPBs within Range	1 of 4	2 of 4	0 of 4	4 of 4	2 of 4
	Correlation	*p-Value*	<0.0001	<0.0001	<0.0001	0.0338	<0.0001
		r-Value	0.9870	0.9898	0.9823	0.6136	0.9686
LODC10	*Magnitude*	*Avg. Difference*	43.4 ± 42.4 fore	-10.1 ± 65.2 superior	54.9 ± 73.8 fore	-19.5 ± 23.5 outboard	-12.9 ± 87.3 superior
		# BPBs within Range	0 of 9	5 of 9	0 of 9	4 of 9	4 of 9
	Correlation	*p-Value*	<0.0001	<0.0001	<0.0001	0.0014	<0.0001
		r-Value	0.8856	0.9617	0.9690	0.5837	0.8686

Values highlighted in yellow correspond to p<0.05 and in red correspond to p<0.001.

Correlation between ATD and child ASIS (Table IV) were significant (p<0.01) and very strong in the X (r=0.8856–0.9870) and Z directions (r=0.9617–0.9898). The correlations between the ATD and child mean suprasternale positions were significant (p<0.01) and very strong in the X (r=0.9645–0.9823) and Z directions (r=0.8662–0.9686). The correlation between the ATD and child suprasternale Y positions were significant (p<0.04) and moderate to strong (r=0.5837–0.6376).

The suprasternale X position was fore of the children for the HIII10, LODC10, and HIII5F, while the HIII06 was rear compared to the children. The HIII06 mean fell within the acceptable child range for a majority of BPBs while the HIII10, HIII5F, and LODC10 did not. The Y position of the suprasternale was on average outboard relative to the children and fell within the acceptable child range for ATDs on a majority of BPBs. The suprasternale Z position was superior compared to children for the HIII10, HIII5F, and LODC10 ATDs while the HIII06 was inferior to children on average.

The HIII10, LODC10, and HIII5F generally had a more vertical upright torso angle compared to the children, while the HIII06 was typically more reclined (Table AVII). The HIII5F was the most vertical on average (by -11.3°) while the HIII06 was the most reclined (by 2.2°) relative to the children. Average lateral torso angles for ATDs by BPB ranged from -3–1.8° with respect to vertical (Table AVII), and the average difference between ATD and child lateral torso angle was less than 1° considering all BPBs together. Generally, the ATDs did not lean inboard to as great a degree as the children, with the exception of the HIII5F. The LODC10's lateral torso angle was most vertical compared to the children.

ATD Belt Fit Comparison to Children

For each BPB, ATD belt fit results were compared to the children (Table V). In general, ATDs had more inboard SBS and overestimated gap size and length, thereby underestimating torso contact. The HIII06 and HIII10 ATDs had more inferior LBS while the LODC10 and HIII5F had more superior LBS compared to the children on average.

TABLE V

CORRELATION AND COMPARISON OF MEAN ATD AND MEAN CHILD BELT FIT FOR ALL BELT-POSITIONING BOOSTERS

ATD	Comparison		SBS (mm)	LBS (mm)	Max Gap (mm)	Gap Length (mm)	Torso Contact (%)
HIII06	*Magnitude*	*Avg. Difference*	15.3 ± 25.4 inboard	2.9 ± 28.7 inferior	17.5 ± 19.3 larger	34.2 ± 85.1 longer	4.8 ± 15.8 less
		# BPBs within Range	6 of 10	10 of 10	0 of 10	5 of 10	6 of 10
	Correlation	*p-Value*	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
		r-Value	0.6615	0.9003	0.7149	0.6666	0.6820
HIII10	*Magnitude*	*Avg. Difference*	12.9 ± 25.9 inboard	5.8 ± 28.2 inferior	10.2 ± 18.8 larger	45.2 ± 93.2 longer	3.2 ± 16.0 less
		# BPBs within Range	6 of 10	8 of 10	5 of 10	4 of 10	8 of 10
	Correlation	*p-Value*	0.0003	<0.0001	<0.0001	<0.0001	<0.0001
		r-Value	0.6295	0.9082	0.8063	0.7718	0.8060
HIII5F	*Magnitude*	*Avg. Difference*	5.6 ± 18.1 inboard	11.0 ± 26.1 superior	9.3 ± 14.6 larger	70.5 ± 127.0 longer	4.9 ± 20.3 less
		# BPBs within Range	3 of 4	3 of 4	3 of 4	2 of 4	3 of 4
	Correlation	*p-Value*	0.1626	<0.0001	<0.0001	0.0005	0.0002
		r-Value	0.4303	0.9269	0.9236	0.8476	0.8802
LODC10	*Magnitude*	*Avg. Difference*	27.1 ± 25.1 inboard	34.5 ± 24.5 superior	11.5 ± 19.2 larger	48.5 ± 109.0 longer	5.3 ± 18.5 less
		# BPBs within Range	0 of 9	0 of 9	5 of 9	3 of 9	6 of 9
	Correlation	*p-Value*	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
		r-Value	0.7166	0.7872	0.8470	0.8173	0.8507

Values highlighted in yellow correspond to p<0.05 and in red correspond to p<0.001.

Relationships between the mean ATD and child belt fit outcomes for all BPBs are summarised in Table V. Significant (p<0.01) correlations were observed between the ATDs and children for all belt fit and belt gap outcomes, except for the HIII5F SBS (p=0.1626). The ATDs had the strongest correlation to child data for LBS (r=0.7872–0.9269), maximum gap size (r=0.7149–0.9236), gap length (r=0.6666–0.8476), and torso contact (r=0.6820–0.8802). Significant correlation between ATD and child SBS was weakest for the HIII10 (r=0.6295) and strongest for the LODC10 (r=0.7166).

Generally, the HIII06, HIII10, and HIII5F SBS fell within the acceptable child range for at least half of the BPBs while the LODC10 did not for any BPBs (Fig. A8, Table AVII). ATDs had more inboard shoulder belt position compared to the child participants on all BPBs, except for the HIII10 on BPB 8. ATD LBS varied relative to the child volunteers (Fig. A9, Table AVII). The HIII06 and HIII10 tended to have more inferior LBS compared to children, with some exceptions. The HIII5F and LODC10 had more superior LBS compared to children on all BPBs. The LBS of the HIII06, HIII10, and LODC10 fell within the acceptable child range on a majority of BPBs while the LODC10 did not.

The position of the lap belt with respect to the ASIS varied by ATDs (Fig. A10, Table AVIII). Generally, the lap belt on the LODC10 was rear and superior to the ASIS. In contrast, the lap belt was fore and inferior of the ASIS for the HIII06, HIII10, and HIII5F. Compared to the children, the lap belt placement was more rear and more inferior relative to the ASIS for all ATDs. The HIII06 and HIII10 lap belt with respect to ASIS X position fell within the acceptable child range on the majority of BPBs while the HIII5F and LODC10 did not on any BPBs. For the Z position of the lap belt with respect to the ASIS, the ATDs fell within the acceptable child range on approximately half of the BPBs.

Overall, ATDs tended to overestimate maximum gap size on all BPBs and fell within the acceptable child range on approximately half of BPBs, with the exception of HIII06 which did not for any BPBs (Fig. A11, Table AIX). ATDs also overestimated gap length on all BPBs, except for the HIII06 on BPB 5 and the HIII10 and LODC10 on BPB 9 (Fig. A12, Table AX). ATDs generally fell within the acceptable child range for about half of the BPBs evaluated. As ATDs overestimated gap length, they also underestimated torso contact on most BPBs (Fig. A13, Table AXI). The ATDs torso contact fell within the acceptable child range for most BPBs.

The location of the gap start was generally closer to the suprasternale in the Y and Z directions for ATDs compared to children (Table AXII). The average difference between ATDs and children in the Y direction ranged from -30.7–86.1 mm and in the Z direction from -46.2–185.4 mm. The location of the gap start with respect to the suprasternale fell within the acceptable child range for the ATDs on the majority of BPBs in the Y direction and on approximately half of the BPBs in the Z direction.

The location of the maximum gap with respect to the right ASIS for ATDs was further inboard and inferior compared to the children (Table AXIII). The average difference between ATDs and children in the Y direction ranged from -46.1–66.6 mm and in the Z direction from 2.3–104.9 mm. The Y direction of the maximum gap location fell within the acceptable child range on 1 BPB each for the HIII06 and LODC, while a majority of BPBs were within the child range for the HIII10 and HIII5F. A majority of BPBs had the maximum gap Z location within the acceptable child range.

IV. DISCUSSION

In order to evaluate the dynamic implications of differences in initial static belt fit and belt gap, ATDs should represent realistic child belt fit. Ideally, ATDs should represent realistic magnitudes of belt fit and gap measurements and also provide similar differences in belt fit and belt gap between BPBs (strong correlations to child data). This study provides comparisons of four paediatric-sized ATDs to a cohort of children to evaluate the ATDs' abilities to represent realistic magnitudes of belt fit and gap metrics and correlations between child and ATD belt fit and gap outcomes. This study also provides quantification of belt fit and gap metrics for ATDs which can help to define boundary conditions for future dynamic evaluations of various belt fit and belt gap conditions for BPB-seated occupants.

SBS and Torso Posture

Overall, ATDs generally had more inboard shoulder belt positions (Table V) compared to the children, similar to previous comparisons of the HIII06 and HIII10 to child belt fit [4][10]. This suggests that, in terms of initial SBS, these ATDs may be providing a *better case* scenario compared to children when evaluating the potential for shoulder belt slip off during evasive manoeuvres or crashes. The HIII06, HIII10, and HIII5F ATDs had SBS within the acceptable child range on at least half of the BPBs evaluated (Table V), while the LODC10 did not. This suggests that the HIII ATDs better represented the magnitude of SBS observed in children than the LODC10 under these test conditions; however, the HIII ATDs were only able to represent realistic child SBS on half of the BPBs evaluated. These results also suggest that differences in ATD design may influence SBS outcomes. In particular, the shape and contour of the LODC10 shoulder may be influencing the shoulder belt position in a different manner than the HIII ATDs.

The more inboard SBS for the ATDs may also be attributed to differences in posture between ATDs and children, especially the suprasternale position. In general, the ATD suprasternale lateral position was more moderately correlated with children and was more outboard compared to children on the same BPBs (Table IV), with the LODC10 producing the most outboard position on average relative to the children. This may be due to anthropometric differences and the larger torso posture variability of children compared to ATDs. While they were encouraged to maintain upright postures, children generally leaned inboard to a greater degree and showed greater variability in their lateral torso posture than ATDs (Table AVI), which may contribute to the relative outboard suprasternale position and more inboard SBS of the ATDs compared to the children.

The mean sagittal positions of the ATD suprasternale were significantly ($p<0.01$) and strongly correlated to the child means (Table IV), suggesting that ATD suprasternale sagittal positions varied across BPBs in a similar manner to children; however, the ability of the ATD torso posture to fall within the acceptable child range varied by BPB (Table AV). Difference in the suprasternale Z position varied by ATD and BPB and had greater magnitude differences compared to children than the ASIS Z position (Table AV). Generally, the HIII10, HIII5F, and LODC10 had more superior suprasternale Z positions compared to children while the HIII06 was more inferior on the majority of BPBs. On average, the HIII10, LODC10, and HIII5F had taller seated heights than children tested on the same BPBs (Table III), likely contributing to the more superior suprasternale positions.

The ATD suprasternale X position varied by BPB and ATD compared to the child average (Table AV). This may be due to anthropometric differences and variability in the upright torso angle. Generally, the ATD upright torso angle was within 3.7° of the child average. The HIII10, HIII5F, and LODC10 had more fore suprasternale X positions (Table IV) and more vertical upright torso angles (Table AVI), suggesting that these ATDs had more upright torso postures compared to children. The HIII06 had the smallest average difference in suprasternale X position and had more reclined upright torso angles compared to the children. However, the HIII06 upright torso angle was more vertical compared to children on BPBs 7 and 8 (both backless, low-profile designs), suggesting that the children may have assumed more slouched postures than ATDs on these BPBs. Overall, the differences in suprasternale sagittal position and upright torso angle may influence the ATD torso position with respect to the belt and potentially contribute to differences in SBS.

LBS and ASIS Position

Comparison of LBS and lap belt position with respect to the ASIS outcomes between ATDs and children varied by ATD (Tables AVII, AVIII). The HIII06 and HIII10 had more inferior average LBS than children, as found in previous belt fit evaluations [4][10] and is likely due to a more superior and rear position of the ASIS landmark on the ATD compared to children. On the other hand, the LODC10 and HIII5F had more superior LBS compared to children which may be attributed to the superior and fore position of the ATD ASIS with respect to the children.

The LBS for the HIII ATDs generally fell within the acceptable child range on the majority of BPBs (Table V), but the LODC10 LBS did not fall within the child range and had a more superior LBS than children on all BPBs. Again, this suggests that the HIII ATDs were better able to represent child magnitudes of LBS for these test conditions. Additionally, the LODC10 had an average superior LBS on all BPBs except for BPBs 4, 5, and 8, where the average LBS was at most 6.4 mm inferior. BPBs 4, 5, and 8 had the most inferior/distal LBS for children (average of 51.6 mm) due to their combination of backless design which allows for more rear ASIS positions and belt routing features which pull the lap belt forward under an arm rest or through a routing clip and away from the pelvis [23]. The more superior LODC10 LBS on these backless BPBs may be in part explained by the differences in ASIS position between the LODC10 and the children. The LODC10 had a more fore position of the ASIS than the acceptable child range on all BPBs and was on average 50.5 mm fore of the children on BPBs 4, 5, and 8. The LODC10 thoracic spine incorporates flexible elements and allows for adjustment of the lumbar angle [25], which may allow for more slouched postures of this ATD and contribute to the more fore positions of the ASIS. A more reclined posture of the LODC10 pelvis may allow for the more fore position of the ASIS and for the lap belt to be more easily placed superior to the ASIS, contributing to the more superior LBS.

The mean positions of the ATD ASIS were significantly ($p<0.01$) and strongly correlated to the child means (Table IV), suggesting that ATDs ASIS positions varied across BPBs in a similar manner to children; however, the ability of ATD posture to fall within the acceptable child range varied by BPB (Tables AIV-AVI). On average, differences in ASIS X position between the HIII06 and HIII10 and children had small magnitude differences compared to children with a few exceptions (Table AIV). The HIII06 ASIS X position was within the acceptable child range on all BPBs except for BPBs 7 and 8, both backless, low-profile designs (Table AIV). On these BPBs, the HIII06 ASIS was rear to the children (-33.7 mm on average), suggesting that the ATD was less able to assume a slouched posture compared to the children. This supports previous work which also found the HIII06 to have more rear hip positions compared to BPB-seated children, and this difference was greatest on two low-profile BPBs (40 mm and 52 mm rear) [10][11]. The HIII06 pelvis is moulded into a 90° seated posture, making it unable to slouch or assume more realistic child postures [26]. Similarly, the HIII10 ATD ASIS X position was within the acceptable child range for all BPBs except for BPB 7 where its pelvis was more rear than the children, again suggesting that these ATDs assumed a less slouched posture than the children on this backless, low-profile BPB. Similar to the LODC10, the HIII5F had greater magnitude differences in ASIS X position compared to children on average (Table IV). The HIII5F ASIS X position only fell within the acceptable child range on BPB 5, and was fore of the child mean on all BPBs (Table AIV). This may be influenced by the greater hip width of the HIII5F ATD which may not allow for as rear of pelvis positions compared to children or other ATDs.

The ATD ASIS Z position tended to be superior of the children and fell within the acceptable range on approximately half of the BPBs (Table IV). BPBs 2, 5, 7, and 9 each had a majority of ATDs within the acceptable child range for ASIS Z position (Table AIV), which may in part be due to the larger seated height of children evaluated on these BPBs (Table III). Generally, ATDs had larger seated heights than children on average; however, the differences in BPB manufacturer recommendations meant that larger children tended to be evaluated on BPBs 2, 5, 7, and 9, making this difference in seated height between ATDs and children smaller on these designs. The LODC10 fell within the acceptable child range for ASIS Z position on more BPBs than for ASIS X position (Table AIV). This suggests that the Z location of the ASIS landmark may be improved in the LODC10 compared to the HIII designs, but the overall pelvis and lumbar spine flexibility are potentially placing the LODC10 pelvis in a more slouched orientation, contributing to the greater fore ASIS X position compared to children in this study. Children in [23] were encouraged to maintain upright postures as much as possible, so the LODC10 ASIS position may be more representative of self-selected child postures on BPBs which may be more slouched.

Belt Gap and Torso Contact

ATDs generally overestimated maximum gap size compared to children (Table AIX) and fell within the acceptable child range on approximately half of the BPBs, with the exception of the HIII06 which did not for any BPB (Table V). The overestimation of maximum gap size by ATDs may be explained due to differences in the torso and abdomen contour. The ATDs generally have flatter torso and abdominal contours compared to children, which may contribute to less of the torso remaining in contact with the seatbelt as it is routed toward the buckle. Additionally, the HIII ATDs have less ability to assume slouched postures compared to children, which may also increase the distance between the seatbelt with the inferior torso and the pelvis.

Overall, ATDs overestimated gap length compared to children and fell within the acceptable child range of gap length on approximately half of the BPBs (Table AX, Table V). Compared to the children, the region of belt gap started closer to the suprasternale in the Y direction for the ATDs, with the exception of the HIII10 (Table AXII). The region of belt gap also started closer to the suprasternale in the Z direction for all ATDs compared to the children. Additionally, the location of the maximum gap was further inboard and more inferior relative to the inboard ASIS for all ATDs compared to children (Table AXIII). This supports the gap length results which were longer for ATDs compared to children.

Due to their overestimation of gap size and length, ATDs underestimated percent torso contact compared to children (Table AXI). ATD results fell into the acceptable child range more often than other gap metrics, with the HIII06 on 6 of 10, the HIII10 on 8 of 10, the HIII5F on 3 of 4, and the LODC10 on 6 of 9 BPBs (Table V). The ATDs overestimation of gap size and gap length and underestimation of torso contact suggest that they may represent a more extreme belt gap scenario compared to observed gap characteristics for BPB-seated children in [23].

ATD and Child Belt Fit Correlations

Overall, strong correlations were observed between ATD and child belt fit and belt gap outcomes (Table V). The strongest correlations were observed between ATD and child outcomes for LBS, maximum gap size, gap length, and torso contact. These strong correlations suggest that ATDs display similar differences to children in LBS and gap metrics across BPBs, supporting that ATDs are valuable tools for evaluation of variation in static LBS, belt gap, and torso contact between BPBs. In terms of LBS, the LODC10 had the weakest correlation to child data, while the HIII06, HIII10, and HIII5F had similar, stronger correlations. Considering belt gap outcomes, the HIII10 and HIII5F tended to have stronger correlations, while the HIII06 tended to have the weakest. The strength and significance of correlation between ATD and child SBS varied by ATD. The LODC10 had the strongest correlation with child SBS, suggesting the LODC10 may be providing more similar differences in SBS between BPBs to children than the HIII06 ATDs. The HIII5F SBS was the only metric not significantly correlated to child outcomes, which suggests that the HIII5F SBS did not change between BPBs in a similar manner to the children. This may be due to the HIII5F's taller seated height or more inboard leaning lateral torso angle compared to children. Overall, the weaker correlations for SBS compared to other metrics suggest that differences in ATD design, posture, and anthropometry compared to children may influence ATD SBS more than LBS and gap metrics.

Limitations

The static belt fit and gap measurements made in this study cannot necessarily predict a BPBs ability to maintain initial belt fit during manoeuvres or crashes. However, initial belt fit and belt gap have been suggested to influence restraint interaction for BPB-seated children and ATDs during vehicle manoeuvres [13][14][27][28] which may imply that differences in static belt fit and belt gap have dynamic implications for BPB-seated occupants during impacts. Previous evaluations of frontal and oblique sled tests of BPB-seated ATDs with different initial static belt fit have also shown varied kinematic and injury outcomes [5][10][18][19]. The ATDs evaluated in this study showed differences in belt gap outcomes between BPBs, similar to the children evaluated in [23]; however, no studies have yet evaluated the dynamic implications of initial belt gap for BPB-seated occupants. Future work should evaluate the kinematic and injury outcomes for BPB-seated occupants with various initial belt gap conditions before the desirability of belt gap can be determined.

This study evaluated one seatbelt outlet position. Position of the seatbelt outlet or D-Ring has previously been shown to influence SBS [3][4] and may also influence belt gap outcomes. Additionally, the BPBs evaluated in this study are not necessarily representative of belt fit provided by all designs on the market. In particular, belt fit outcomes may be altered by differences in belt routing design features on BPBs. Finally, belt fit and gap metrics in this study represent instantaneous belt fit and thus do not represent the range of all possible belt fit scenarios experienced during normal driving.

V. CONCLUSIONS

This study evaluated posture, belt fit, and belt gap outcomes for BPB-seated paediatric ATDs and the HIII5F and compared outcomes to children. Additionally, this is the first study to evaluate belt gap and belt-torso contact for BBP-seated paediatric ATDs and the HIII5F. Overall, ATD posture, belt fit, and belt gap outcomes were moderately or strongly associated with child outcomes; however, differences in ATD design, anthropometry, and posture relative to children contributed to variation in belt fit and gap magnitudes between ATDs and children. Overall, each evaluated ATD had more inboard SBS and overestimated gap metrics compared to children while LBS with respect to children varied by ATD. The LODC10 displayed more slouched postures, more fore ASIS positions, and more superior LBS than other ATDs and children while the HIII06 and HIII10 showed less slouched pelvis postures than children on backless, low-profile BPBs. Results from this investigation suggest that, while there are important magnitude differences in belt fit and gap metrics compared to children, paediatric ATDs and the HIII5F are able to represent realistic differences in belt fit, belt gap, and torso contact between BPBs. Thus, these ATDs can represent appropriate variation in initial restraint conditions (which vary in terms of belt fit and belt gap) for future evaluation to determine the influence of initial belt fit and belt-torso contact on kinematic and injury outcomes for BPB-seated occupants during crashes.

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VIII. Appendix

TABLE AI
BELT-POSITIONING BOOSTER SEAT BELT ROUTING INFORMATION

BPB	Upper Shoulder Belt Guide	Lower Shoulder Belt Guide	Lower Lap Belt Guide	Front View	Side View
1	Headrest Slot	Slot	Vertical Face		
2	Headrest Slot	Vertical Face	Vertical Face		
3	Headrest Slot	Vertical Face	Vertical Face		
4	None	Over Armrest	Under Armrest		
5	Webbing Clip	Under Armrest	Under Armrest		
6	Headrest Slot	Vertical Face	Vertical Face		
7	None	Under Guide	Under Guide		
8	Webbing Clip	None	Under Clip		
9	Headrest Slot	None	None		
10	Headrest Slot	Slot	Vertical Face		

TABLE AII

LOWER SEATBELT ANCHOR LOCATIONS

Seatbelt Anchor Location	X position with respect to Seating Reference Point (mm)	Angle from Seating Reference Point to Seatbelt Anchor Location (°)	Width (cm)
Baseline	-114	52	39
Forward	-39	75	39
Wide	-114	52	56

(a) (b) (c)

Fig. A1 Lower Seatbelt Anchor Locations (a) Baseline, (b) Forward, (c) Wide

Fig. A2 Seatbelt Outlet Location

TABLE AIII

REFERENCE POINTS MEASURED WITH THE COORDINATE MEASUREMENT SYSTEM

Vehicle Seat Reference	BPB Reference	Subject	Belt Fit Metrics
Vehicle Head Restraint L/R Vehicle Seatbelt Outlet L/R Vehicle Seat Top L/R Vehicle Seat Bight L/R Vehicle Seat Front L/F	BPB Back Top L/R BPB Back Bottom L/R BPB Front Top L/R BPB Front Bottom L/R BPB Lower Inboard Belt Guide BPB Upper Shoulder Belt Guide Top Seating Surface Front L/R* Top Seating Surface Mid L/R* Top Seating Surface Back L/R* Centreline Backrest*	Head Top Head Back Glabella Tragion L/R Suprasternale Substernale Clavicle L/R Acromion L/R ASIS L/R Lap Streams**	SB crosses clavicle SB leaves shoulder SB crosses at suprasternale SB crosses torso midline Lap Belt Crosses ASIS L/R SB Stream*** LB Stream*** Torso Stream***

* Obtained without occupant present and transformed to each trial's data using common BPB reference points

** Lap Streams captured as described in [4]

*** SB, LB, and Torso Streams were a stream of measurements captured at each marked seatbelt point, every 2 cm along the belt midline

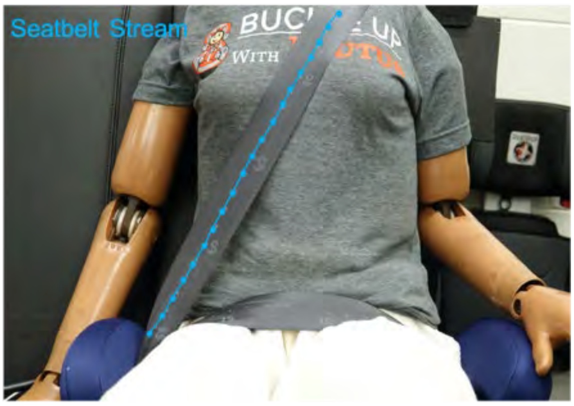

Fig. A3. SB Stream FARO Measurements

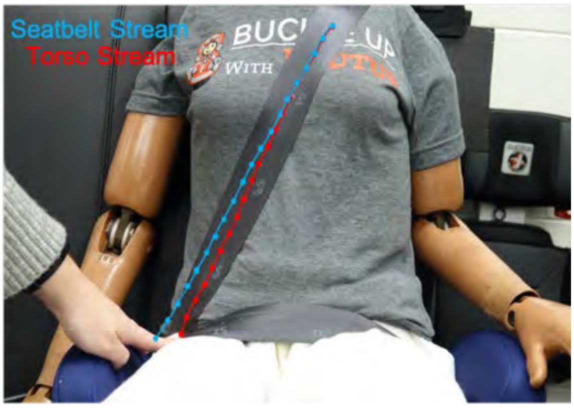

Fig. A4. Torso Stream FARO Measurements

Fig. A5 .SB Stream FARO Measurement

Fig. A6. Torso Stream FARO Measurement

TABLE AIV
GLOBAL ASIS POSITION BY BELT-POSITIONING BOOSTER SEAT
FOR ATDS (MEAN) AND CHILDREN (MEAN ± STD DEV)

Direction	BPB	HIII06 (mm)	HIII10 (mm)	HIII5F (mm)	LODC10 (mm)	Child N	Children (mm)
	1	189.8	190.0		228.2	30	203.1 ± 13.1
	2	221.7*	223.4*	247.3	258.5	30	219.9 ± 16.6
	3	215.4*	217.2*		260.1	30	214.5 ± 15.5
	4	143.8*	149.5*		200.7	30	151.9 ± 13.7
X	*5*	130.5*	129.1*	159.4*	181.8	30	140.5 ± 21.1
	6	221.1*	223.1*			30	223.7 ± 12.5
	7	147.6	160.3	201.8	215.4	30	181.4 ± 18.0
	8	156.7	176.7*		251.5	30	190.2 ± 17.9
	9	201.2*	198.7*	228.0	244.3	30	197.3 ± 16.5
	10	221.9*	221.2*		262.4	30	213.2 ± 12.1
	1	313.6*	327.8		317.0	30	301.6 ± 12.7
	2	357.8*	367.2*	373.4*	356.1*	30	356.7 ± 16.8
	3	380.7	386.8		376.9*	30	368.1 ± 12.2
	4	289.2	295.9		290.8	30	269.9 ± 15.8
Z	*5*	319.2*	327.2*	344.1	321.0*	30	320.3 ± 21.0
	6	377.3	385.7			30	358.4 ± 11.1
	7	264.1*	274.4*	281.3	268.1*	30	267.4 ± 13.3
	8	243.0	251.2		246.0	30	225.6 ± 14.2
	9	348.2*	357.0*	366.1*	347.6*	30	353.8 ± 18.8
	10	354.8	368.3		366.9	30	336.1 ± 9.2

**ATD Mean within child mean ± 1 standard deviation*

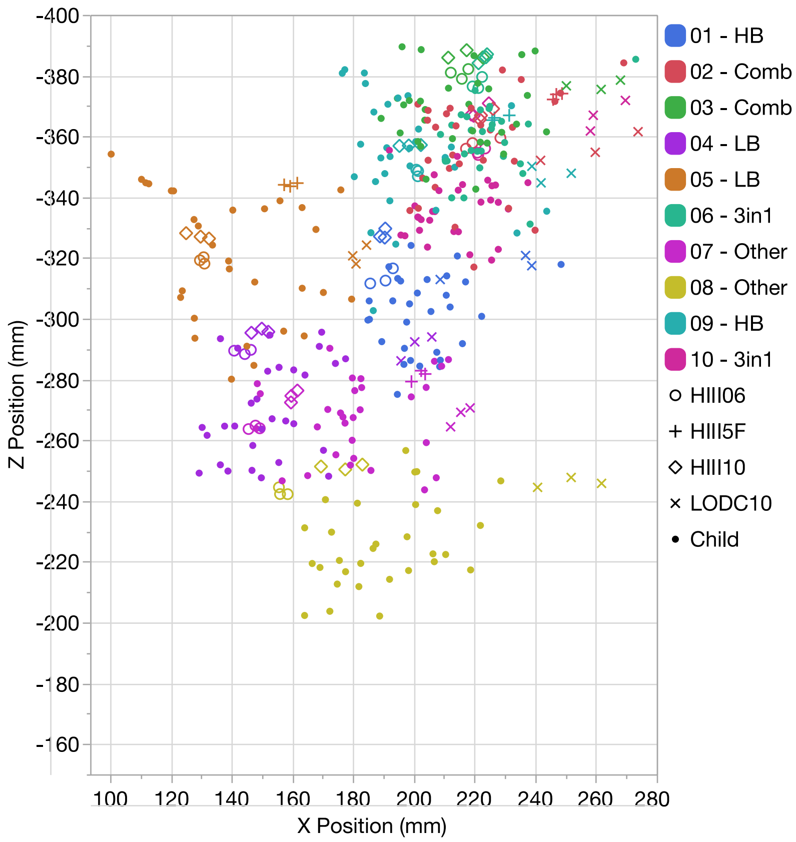

Fig. A7. Global ASIS Positions by Belt-Positioning Booster Seat and Occupant for all Seatbelt Anchor Locations

TABLE AV
GLOBAL SUPRASTERNALE POSITION BY BELT-POSITIONING BOOSTER SEAT
FOR ATDS (MEAN) AND CHILDREN (MEAN ± STD DEV)

Direction	BPB	HIII06 (mm)	HIII10 (mm)	HIII5F (mm)	LODC10 (mm)	Child N	Children (mm)
X	*1*	66.2*	103.1		124.0	30	72.6 ± 14.5
	2	119.0*	156.4	213.3	180.8	30	134.2 ± 20.9
	3	84.2*	140.4		169.9	30	103.3 ± 22.1
	4	-0.7*	30.1		49.5	30	-0.5 ± 15.4
	5	-12.1*	17.7	33.8	34.1	30	-18.0 ± 21.2
	6	94.4*	132.0			30	111.3 ± 17.0
	7	19.6	47.3	84.6	62.3	30	1.0 ± 16.4
	8	33.9*	56.7		75.1	30	33.3 ± 16.4
	9	65.5*	105.3	128.7	130.0	30	52.4 ± 23.2
	10	84.4*	104.7*		137.0	30	90.6 ± 18.7
Y	*1*	235.2*	224.6*		206.6	30	229.1 ± 11.5
	2	226.8*	227.2*	219.4*	209.6	30	231.9 ± 13.3
	3	233.9*	224.2*		214.4	30	241.1 ± 17.1
	4	237.1*	217.1*		205.5	30	232.9 ± 19.3
	5	222.2*	211.0*	212.3*	197.0*	30	212.0 ± 28.8
	6	243.0*	234.3			30	251.7 ± 13.6
	7	233.4*	217.1*	218.0*	205.3	30	229.7 ± 14.2
	8	230.0*	227.8*		215.5*	30	239.6 ± 26.2
	9	226.3*	228.4*	234.3*	218.9*	30	225.8 ± 17.7
	10	230.5*	228.5		230.7*	30	236.5 ± 16.7
Z	*1*	-525.1*	-577.0		-567.5	30	-531.3 ± 33.2
	2	-579.4	-622.2*	-674.6*	-614.3*	30	-637.1 ± 49.5
	3	-591.6*	-638.9		-632.1	30	-593.5 ± 36.6
	4	-491.0*	-533.3		-527.9	30	-500.8 ± 25.6
	5	-520.8*	-570.1*	-635.0	-557.3*	30	-567.5 ± 64.4
	6	-586.7*	-631.8			30	-584.3 ± 29.1
	7	-478.0	-516.4*	-583.8	-505.8*	30	-514.6 ± 26.2
	8	-459.5*	-489.6		-477.8	30	-441.6 ± 31.5
	9	-555.6	-607.8*	-664.2*	-596.6*	30	-624.8 ± 51.9
	10	-557.1*	-601.8		-605.2	30	-557.1 ± 26.0

**ATD Mean within child mean ± 1 standard deviation*

TABLE AVI
MEAN TORSO ANGLES BY BELT-POSITIONING BOOSTER SEAT FOR ATDS (MEAN) AND CHILDREN (MEAN ± STD DEV)

Torso Angle	BPB	HIII06 (°)	HIII10 (°)	HIII5F (°)	LODC10 (°)	Child N	Children (°)
	1	30.3*	19.2		22.6	30	29.7 ± 4.9
	2	24.9	14.7*	6.4	16.7*	30	17.2 ± 4.9
	3	31.9	16.9		19.4	30	26.4 ± 5.1
	4	35.6*	26.7		32.5*	30	33.2 ± 3.6
	5	35.3*	24.6	23.4	32.0*	30	33.2 ± 5.4
Upright	*6*	31.2*	20.3			30	26.6 ± 5.4
	7	30.9	25	21.2	32.8*	30	36.0 ± 4.2
	8	29.6	26.7		37.2*	30	35.9 ± 5.2
	9	33.2	20.4	18.4	24.7	30	28.2 ± 3.1
	10	34.2	26.5*		27.7*	30	29.1 ± 3.3
	All	31.7 ± 3.2	22.1 ± 4.6	17.3 ± 6.9	27.3 ± 7.1	300	29.5 ± 7.0
	1	2.0*	0.6*	2.1*	1.1*	30	-0.1 ± 4.6
	2	3.0*	2.0*		2.5*	30	1.0 ± 3.9
	3	1.1*	0.9*		2.0*	30	1.5 ± 5.1
	4	0.8*	-0.6*	2.4*	-0.3*	30	2.3 ± 5.0
	5	1.6*	1.1*		0.8*	30	2.5 ± 5.2
Lateral	*6*	0.2*	2.3*	1.8*		30	0.5 ± 5.8
	7	1.3*	0.3*		-1.0*	30	2.0 ± 3.3
	8	0.8*	1.6*	2.2*	-1.8*	30	2.9 ± 5.1
	9	-0.4*	1.1*		0.9*	30	-0.5 ± 4.0
	10	0.1*	1.6*	2.1*	-0.9*	30	1.7 ± 4.4
	All	1.0 ± 1.3	1.1 ± 1.1	2.1 ± 0.5	0.4 ± 1.9	300	1.4 ± 4.7

**ATD Mean within child mean ± 1 standard deviation*

TABLE AVII
BELT FIT METRICS FOR ATDS (MEAN) AND CHILDREN (MEAN ± STD DEV)

Metric	BPB	HIII06 (mm)	HIII10 (mm)	HIII5F (mm)	LODC10 (mm)	Child N	Children (mm)
SBS	*1*	39.1*	34.2*		14.3	30	38.9 ± 14.8
	2	21.0	14.8	22.2	9.0	30	37.1 ± 13.9
	3	28.7*	14.5		13.1	30	32.6 ± 15.7
	4	-8.3*	-10.9*		-17.9	30	2.3 ± 17.8
	5	15.5	36.4*	36.9*	9.5	30	44.0 ± 17.3
	6	20.5*	19.3*			30	34.0 ± 17.5
	7	2.0	1.2	29.3*	-0.3	30	26.0 ± 13.1
	8	3.9*	19.7*		-22.1	29	18.4 ± 22.0
	9	7.4	20.9*	26.9*	-0.3	30	30.3 ± 17.7
	10	1.3*	-3.8		0.5	28	19.4 ± 18.5
LBS	*1*	37.8*	41.8		-3.7	30	27.0 ± 11.7
	2	16.9*	21.1*	11.3*	-6.5	30	15.6 ± 11.3
	3	15.4*	19.8*		-12.9	30	8.5 ± 11.9
	4	44.5*	48.6*		0.9	30	54.0 ± 13.0
	5	50.6*	54.6*	36.5*	5.4	30	51.8 ± 23.0
	6	16.2*	20.2			30	8.9 ± 9.5
	7	33.6*	32.5*	9.3	-8.5	30	27.7 ± 13.0
	8	62.5*	61.0*		6.4	30	49.0 ± 19.8
	9	7.5*	9.7*	2.6*	-20.4	30	8.7 ± 10.9
	10	14.6*	18.9*		-9.6	30	19.2 ± 10.8

**ATD mean within child mean ± 1 standard deviation*

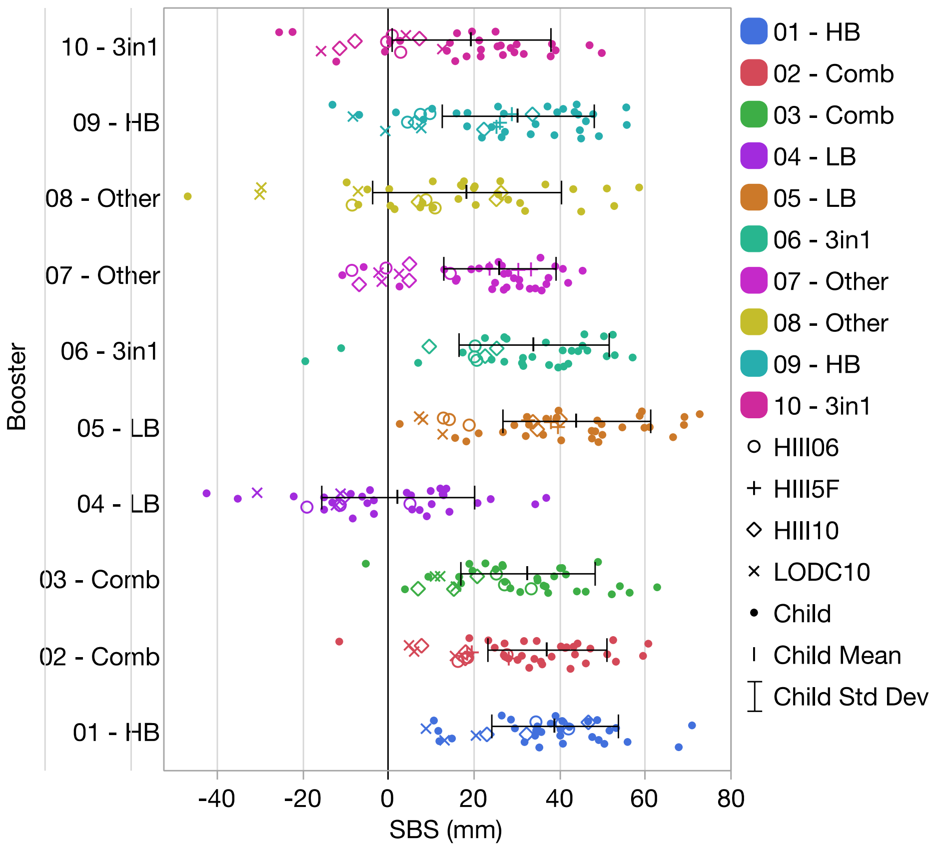

Fig. A8. SBS by Belt-Positioning Booster Seat and Occupant for all Seatbelt Anchor Locations

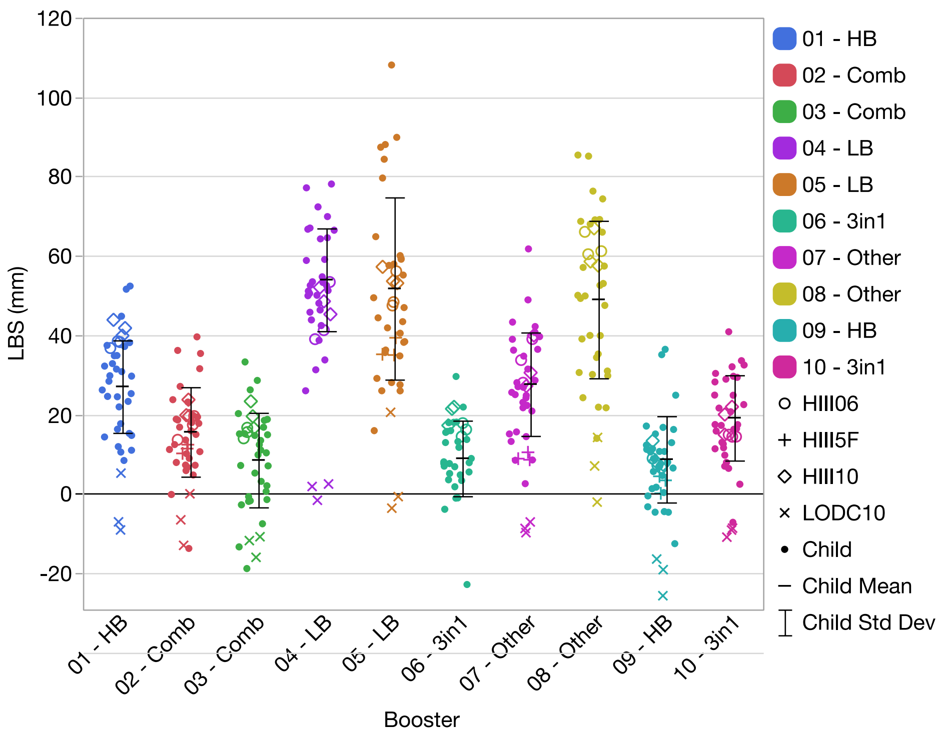

Fig. A9. LBS by Belt-Positioning Booster and Occupant for all Seatbelt Anchor Locations

TABLE AVIII
POSITION OF LAP BELT WITH RESPECT TO ASIS
FOR ATDS (MEAN) AND CHILDREN (MEAN ± STD DEV)

Direction	BPB	HIII06 (mm)	HIII10 (mm)	HIII5F (mm)	LODC10 (mm)	Child N	Children (mm)
	1	23.2*	33.9*		-3.0	30	31.0 ± 9.0
	2	11.3	18.4*	3.1	-5.0	30	21.5 ± 8.9
	3	10.4*	21.3*		-11.9	30	16.2 ± 12.8
	4	32.7	40.3		3.7	30	58.4 ± 11.0
X	*5*	40.9*	50.4*	25.8	0.0	30	54.8 ± 18.3
	6	12.7*	18.9*			30	18.1 ± 10.8
	7	22.8*	26.4*	5.1	-8.5	30	33.4 ± 11.4
	8	46*	52.1*		7.7	30	54.0 ± 19.5
	9	10.1*	11.5*	3.0	-14.8	30	14.8 ± 11.6
	10	14.0	21.9*		-12.4	30	25.8 ± 9.6
	1	-24.4	-14.1*		5.9	30	-8.9 ± 10.0
	2	-9.6*	-8.7*	-9.3*	8.2	30	-2.7 ± 10.0
	3	-11.0*	-6.0*		10.3	30	-6.5 ± 8.7
	4	-25.9	-17.1*		1*	30	-7.3 ± 12.7
Z	*5*	-23.5	-18.3	-20.6	3.8*	30	-5.1 ± 12.7
	6	-12.0*	-3.1*			30	-9.7 ± 7.4
	7	-24.5	-15.9	-11.3	4.6*	30	1.5 ± 12.5
	8	-28.2	-14.2*		-0.7*	30	-6.1 ± 11.1
	9	-3.7*	-4.7*	-2.0*	7.8*	30	-2.7 ± 10.6
	10	-7.9*	1.4		4.9	30	-14.3 ± 7.7

**ATD mean within child mean ± 1 standard deviation*

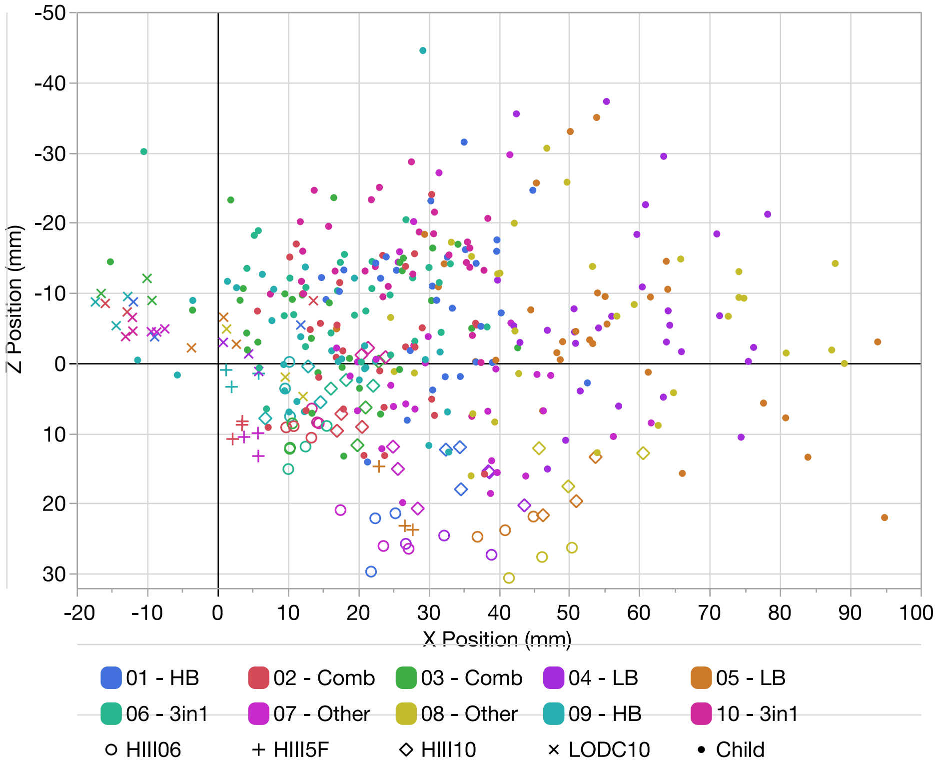

Fig. A10. Position of Lap Belt with respect to the ASIS by Belt-Positioning Booster and Occupant

TABLE AIX
MEAN MAXIMUM GAP SIZE BY BELT-POSITIONING BOOSTER SEAT
FOR ATDS (MEAN) AND CHILDREN (MEAN ± STD DEV)

BPB	HIII06 (mm)	HIII10 (mm)	HIII5F (mm)	LODC10 (mm)	Child N	Children (mm)
1	58.4	41.2*		42.3*	30	28.8 ± 11.0
2	43.9	35.2	34.6	37.8	30	21.2 ± 8.1
3	26.0	25.0		14.4*	30	12.7 ± 6.1
4	28.6	21.5*		26.2*	30	16.5 ± 6.6
5	39.9	34.4*	41.2*	33.1*	30	26.6 ± 8.0
6	34.7	30.7			30	16.1 ± 7.4
7	41.8	25.1	18.8*	24.3	30	13.2 ± 5.8
8	27.2	18.2*		26.8	30	11.3 ± 4.5
9	18.3	12.0*	17.5*	20.9	30	14.0 ± 8.0
10	57.0	59.7*		62.0*	29	41.1 ± 13.6

**ATD Mean within child mean ± 1 standard deviation*

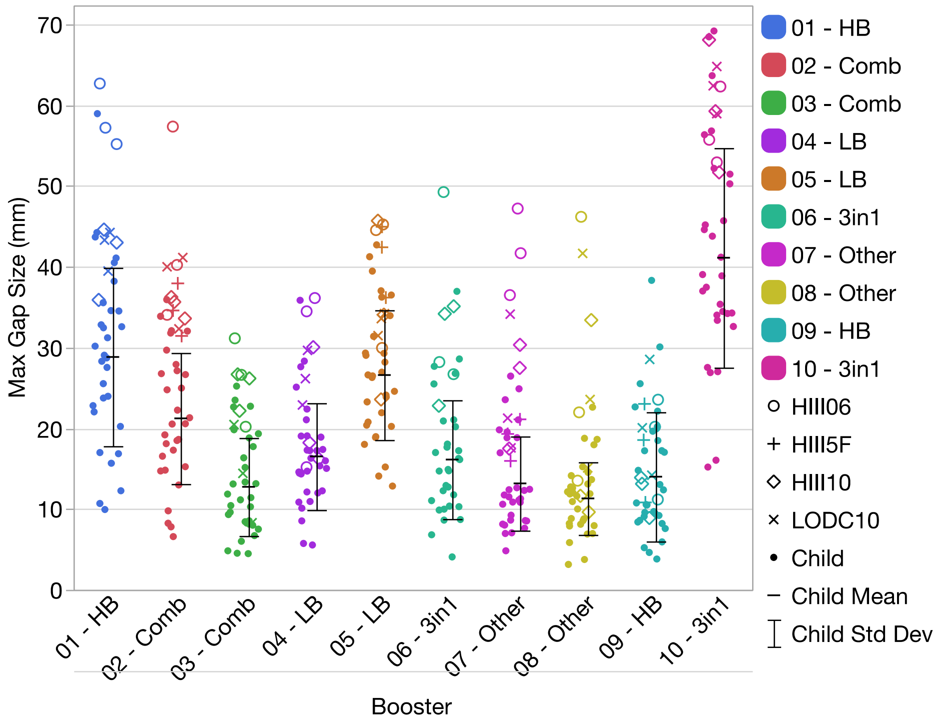

Fig. A11. Mean Maximum Gap Size by Belt-Positioning Booster and Occupant for all Seatbelt Anchor Locations

TABLE AX
MEAN GAP LENGTH BY BELT-POSITIONING BOOSTER SEAT
FOR ATDS (MEAN) AND CHILDREN (MEAN ± STD DEV)

BPB	HIII06 (mm)	HIII10 (mm)	HIII5F (mm)	LODC10 (mm)	Child N	Children (mm)
1	152.7*	204.6		225	30	111.8 ± 55.9
2	101.5*	109.5*	203.1	153.2	30	84.1 ± 54.5
3	108.4	82.7		60.4	30	22.4 ± 31.9
4	20.7*	48.8*		39.4*	30	16.5 ± 35.5
5	143.7*	169.7*	232.0*	210.7*	30	156.9 ± 86.7
6	90.7	95.6			30	32.8 ± 41.1
7	123.1	133.4	117.7	87.0	30	25.1 ± 45.5
8	27.5	14.4		33.7	30	0.0 ± 0.0
9	21.9	0.0*	0.0*	0.0*	30	4.9 ± 16.2
10	77.9*	118.8		121.7	30	73.7 ± 33.3

**ATD Mean within child mean ± 1 standard deviation*

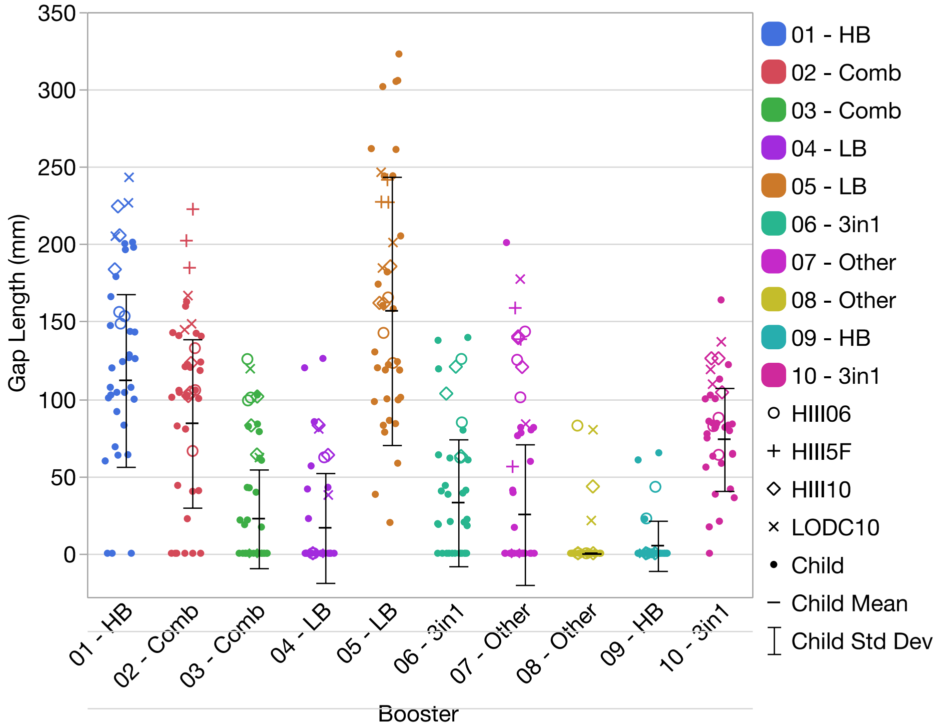

Fig. A12. Mean Gap Length by Belt-Positioning Booster and Occupant for all Seatbelt Anchor Locations

TABLE AXI
MEAN TORSO CONTACT BY BELT-POSITIONING BOOSTER SEAT
FOR ATDS (MEAN) AND CHILDREN (MEAN ± STD DEV)

BPB	HIII06 (%)	HIII10 (%)	HIII5F (%)	LODC10 (%)	Child N	Children (%)
1	74.5*	73.4*		67.6	30	80.3 ± 11.8
2	85.0*	84.5*	72	75.5*	30	85.3 ± 10.6
3	88.5	91.7*		94.8*	30	97.0 ± 5.6
4	98.3*	100.0*		94.5*	30	96.4 ± 8.6
5	73.3*	77.0*	70.3*	68.1*	30	72.5 ± 14.9
6	88.6*	89.8*			30	95.0 ± 8.1
7	79.6	84.9	93.5*	91.4	30	97.9 ± 6.2
8	93.4	96.9		95.6	30	100.0 ± 0.0
9	96.3	100.0*	100.0*	100.0*	30	99.7 ± 1.7
10	81.5*	76.5*		76.8*	30	83.0 ± 7.4

**ATD Mean within child mean ± 1 standard deviation*

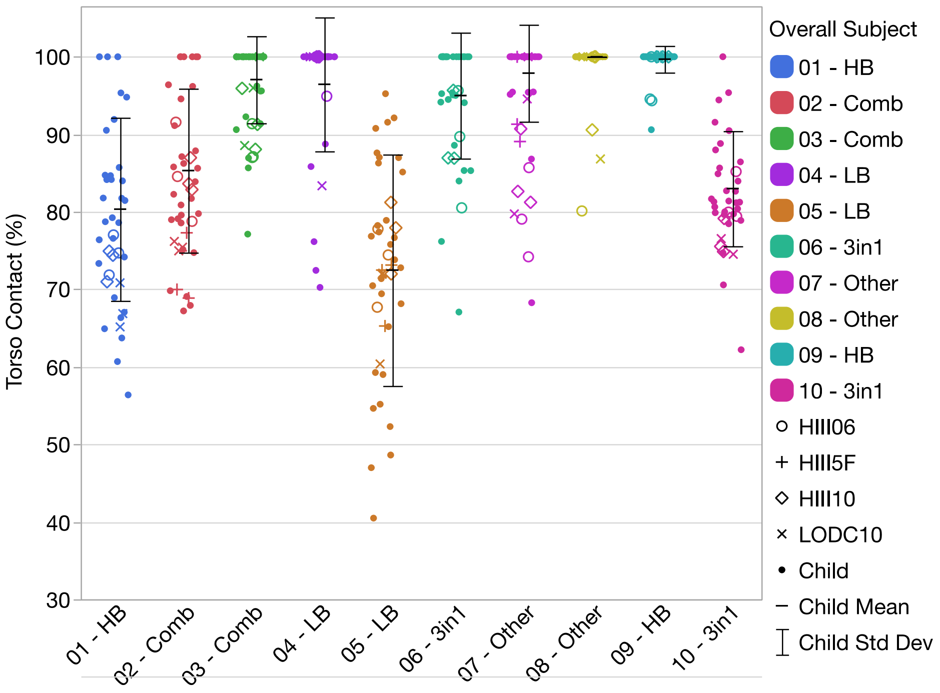

Fig. A13. Torso Contact by Belt-Positioning Booster Seat and Occupant for all Seatbelt Anchor Locations

TABLE AXII

POSITION OF GAP START WITH RESPECT TO SUPRASTERNALE BY BELT-POSITIONING BOOSTER SEAT FOR ATDS (MEAN) AND CHILDREN (MEAN ± STD DEV)

Direction	BPB	HIII06 (mm)	HIII10 (mm)	HIII5F (mm)	LODC10 (mm)	Child N	Child (mm)
Y	*1*	-50.4*	-52.8*		-40.3*	27	-69.4 ± 31.6
	2	-75.8*	-85.98*	-44.1	-58.7*	24	-77.1 ± 21.7
	3	-82.5*	-98.6*		-83.5*	13	-89.2 ± 27.0
	4	-102.8*	-128		-127.4	7	-97.3 ± 24.0
	5	-56.7*	-55.3*	-41.4*	-48.0*	30	-53.6 ± 41.7
	6	-83.1*	-89.2*			18	-86.1 ± 28.4
	7	-71.5*	-84.8*	-97.6*	-90.5*	10	-98.6 ± 29.3
	8	-92.8	-130.7		-132.2	0	
	9	-105.2*				3	-121.6 ± 24.7
	10	-80.0*	-82.3*		-85.5*	28	-76.3 ± 18.6
Z	*1*	-118.5*	-145.9*		-119.6*	27	-147.8 ± 45.3
	2	-153.4	-188.9*	-170.7*	-155.2	24	-206.8 ± 49.6
	3	-156.5	-205.4*		-213.6*	13	-196.2 ± 30.7
	4	-175.4*	-230		-216.7	7	-183.8 ± 68.9
	5	-122.9*	-159.5*	-159.6*	-134.8*	30	-153.8 ± 45.5
	6	-157.9*	-203.8*			18	-185.4 ± 39.1
	7	-147.1	-180.8	-266.9	-195.2*	10	-223.7 ± 42.4
	8	-151.1	-204		-235	0	
	9	-179				3	-225.0 ± 42.9
	10	-90.9*	-106.6*		-130.5*	28	-106.1 ± 27.3

**ATD Mean within child mean ± 1 standard deviation*

TABLE AXIII

POSITION OF MAXIMUM GAP WITH RESPECT TO RIGHT ASIS BY BELT-POSITIONING BOOSTER SEAT FOR ATDS (MEAN) AND CHILDREN (MEAN ± STD DEV)

Direction	BPB	HIII06 (mm)	HIII10 (mm)	HIII5F (mm)	LODC10 (mm)	Child N	Child (mm)
Y	*1*	74.7	51.2*		78.0	30	43.6 ± 18.4
	2	68.0	61.3	56.8	74.1	30	21.0 ± 30.7
	3	63.8	44.0*		47.6*	30	13.4 ± 37.0
	4	62.2	63.0		87.8	30	37.5 ± 19.2
	5	66.6	40.2*	39.8*	54.4	30	13.0 ± 29.2
	6	61.0	52.9*			30	21.8 ± 36.7
	7	63.1	47.8*	42.8*	89.3	30	29.5 ± 28.3
	8	66.1	43.2*		77.2	30	20.3 ± 42.9
	9	51.1	49.8	34.0*	81.2	30	14.7 ± 32.6
	10	61.2*	69.4		83.2	29	46.1 ± 15.1
Z	*1*	17.1	16.1		25.2*	30	-4.3 ± 29.4
	2	6.3*	19.4*	19.1*	15.4*	30	-23.5 ± 39.5
	3	33.8*	2.9*		-14.9*	30	-25.2 ± 43.9
	4	33.7*	58.4		36.3*	30	-2.3 ± 40.9
	5	36.5*	17.1*	-1.1*	1.6*	30	-27.3 ± 27.8
	6	22.3*	27.7*			30	-17.1 ± 48.9
	7	22.3*	32.1*	17.2*	63.9	30	2.8 ± 53.1
	8	49.3*	-4.6*		44.1*	30	-37.5 ± 63.2
	9	13.6	46.1*	-4.8*	78.0	30	-26.8 ± 83.2
	10	-61.3	-43.7		-29.9	29	-69.1 ± 13.3

**ATD Mean within child mean ± 1 standard deviation*