Child Belt Fit and Posture in Reclined Vehicle Seats

Gretchen H. Baker, Julie A. Mansfield, Valentina Graci

Abstract Children adopt a range of postures and seatbelt fit with and without boosters. This study explored the effect of vehicle seatback recline angle on static child posture and belt fit, which has not yet been assessed. Forty-three children (4–12 years) were evaluated both with and without a backless booster across three vehicle seatback recline angles: 25°, 45°, 60°. Posture and belt fit were quantified using a 3D coordinate measurement device and wireless 3D motion-capture system. Average shoulder belt position became more outboard with increasing recline for both booster (+11 mm) and no-booster conditions (+10 mm). Average lap belt position became more inferior/distal with increasing recline on the booster (+17 mm); however, the lap belt was similarly and more superiorly positioned for the no-booster condition regardless of recline (+0 mm). Decreased average lumbar (-7°) and thoracic (-4°) spine flexion and decreased hip flexion (-9°) were also observed with increasing recline angle on both booster and no-booster conditions. The less optimal initial posture and belt fit configurations observed in the 45° and 60° recline conditions may contribute to suboptimal crash outcomes. These findings can inform pre-test positioning of reclined child occupant surrogates in the assessment of reclined vehicle seating configurations.

Keywords Belt fit, belt-positioning boosters, child passenger safety, occupant posture, reclined seatback

I. INTRODUCTION

The increased possibilities offered by advanced and autonomous driver assistance systems (ADAS) may allow future vehicle occupants to engage in a wider range of activities and assume a greater range of postures. Previous work has identified that passengers may choose more reclined vehicle seating positions [1]. The effect of reclined vehicle seating configurations on adult posture has been assessed, identifying more posterior pelvis orientations and decreased lumbar spine flexion with more reclined seatback angles [2]. Additionally, parametric models of children (3–12 years) in reclined seated postures have been developed [3]; however, these models are based on data from child volunteers seated on a specially constructed fixture to minimize occlusion during 3D laser scanning. Children may assume different postures when sitting on vehicle seats with or without boosters with various seatback recline angles. The influence of reclined vehicle seats on the static posture and belt fit for children has yet to be evaluated. Previous studies have identified that children on booster seats and seated directly on the vehicle seat may assume slouched postures in nominal seatback orientations [4–7]. However, it is unknown if and how slouched or other user postures will be assumed by child occupants in reclined seatback configurations, highlighting the need to examine postures in novel seating configurations.

Multiple efforts have begun to assess the influence of reclined vehicle seats on dynamic outcomes for adult post-mortem human subjects (PMHS) and human body models (HBMs) [8–11] and for child volunteers, anthropomorphic test devices (ATDs), and HBMs [12–17]. Reclined seating configurations led to increased posterior rotation of the pelvis in both adult [10,11] and non-booster-seated child [13] ATDs in frontal impacts. These findings suggest greater potential injury risk due to submarining under the lap belt. Additionally, efforts to evaluate the effect of initial slouched postures for children have been investigated using ATDs [18] and HBMs [19,20] in nominal seatback configurations. However, many of these assessments of slouched and reclined child occupants have not verified the initial posture compared to real child data. Slouched postures have been defined by translating the pelvis forward (up to 50 mm) without an accompanying change in pelvis orientation [20] or by placing the ATD/HBM such that the knees bend over the edge of the vehicle seat without describing the pelvis position or orientation [18–20].

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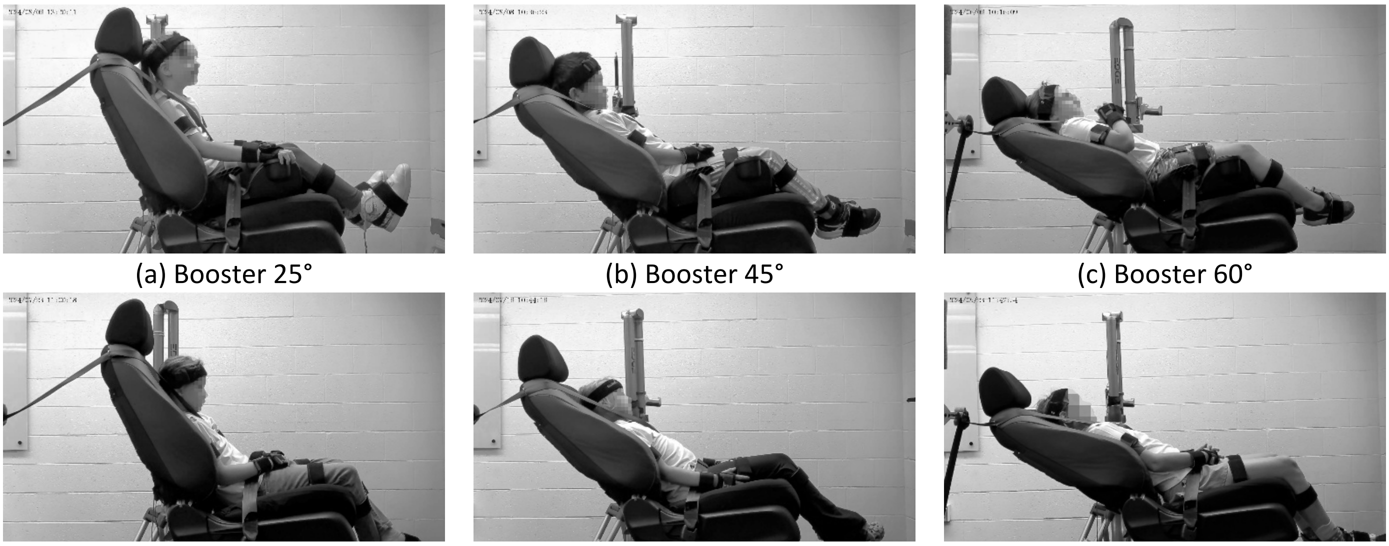
Another study evaluated a paediatric HBM on two vehicle seat recline angles (25° and 40°), resulting in initial pelvis orientations of 39° and 48°, respectively [12]. However, the expected range of pelvis orientations and other postural metrics for real children in reclined settings still need to be evaluated to provide validation of these initial reclined postures. Additionally, defining target ranges of posture and belt fit in reclined vehicle scenarios from real child data can help to improve engineering test tools (e.g., ATDs and HBMs) which should be assessed in terms of their ability to reproduce the posture and belt fit of real children in reclined vehicle configurations. The aim of this study is to quantify the posture and belt fit of children in reclined vehicle seating configurations to provide a novel dataset of child static posture and belt fit conditions that could be used to more realistically position child surrogates (e.g., ATDs and HBMs) in ongoing dynamic assessments of reclined scenarios.

II. METHODS

Participants and test conditions

Ethics approval was obtained from The Ohio State University (Protocol: 2023H0261). Forty-three children (4–12 years, 112–145 cm, 18.0–54.4 kg) were evaluated while assuming self-selected postures both with and without a backless booster (Fig. A1, Appendix) on a stationary vehicle seat fixture in a laboratory setting. Children were evaluated both with and without the booster for three seatback recline conditions: upright (25°), moderately reclined (45°), and reclined (60°) (Fig. 1). Each child completed six randomised trials; however, all booster trials were grouped together and all no-booster trials were grouped together to reduce the participants' time commitment. The order of booster or no-booster conditions was randomised, as was the order of the recline angles within the booster and no-booster groups.



(a) Booster 25° (b) Booster 45° (c) Booster 60°

(d) No-booster 25° (e) No-booster 45° (f) No-booster 60°

Fig. 1. Examples of children in recline and seating conditions.

Test Environment

The seat fixture included a 2023 original equipment manufacturer front passenger manual vehicle seat that was available in the United States; however, some modifications were made to the seat to enable measurements of the occupant. The seat was selected to represent a hypothetical futuristic seating environment that may allow for reclined occupants by incorporating larger side bolsters, which may influence comfort and help to reduce lateral excursion in oblique or lateral impacts [17]. Additionally, the seat was selected for its construction at the centreline of the seat, which allowed for an opening to be made along the seatback centreline to enable measurement of spinal landmarks. For this purpose, the centre of the plastic seatback support was cut out, and a strip of foam (approximately 2.54 cm wide) was removed from along the seatback centreline (Fig. A2., Appendix). Additionally, approximately 10 mm of foam was removed from the bottom of each side bolster to reduce interference with the booster and remove the gap between the booster bight and the seat bight. A simulated integrated belt outlet position was constructed on the top rear surface of the seat (Fig. A3., Table AI) because prior dynamic evaluations have identified that integrated belts and/or rearward D-Ring positions are essential to enable good torso-shoulder contact for reclined passengers [10–13,21]. The location of the seatbelt outlet was verified using the Hybrid III 5th percentile female ATD to ensure the belt outlet position created an appropriate shoulder belt fit. The lower belt anchorage position was targeted to match its actual position in the vehicle (Table AI).

The vehicle seat was attached to a support structure that raised the assembly approximately 55 cm to allow easier access to the posterior seatback to measure spine landmarks through the opening in the vehicle seatback. The 25° vehicle seatback recline setting was determined using a H-Point Manikin Seat Positioning Test Device [22] to identify the seatback recline setting that corresponded to a torso angle of 25°. The angle of the vehicle seat head restraint post with respect to vertical was measured in this position. Vehicle seatback angles of 45° and 60° were defined as the relative difference to the 25° head restraint post angle. The angle of the head restraint post was verified after each adjustment of the seatback angle and prior to obtaining measurements in each condition. The booster seat model complied with FMVSS 213 [23], could be used in either high-back and backless modes (only used in backless mode in this study), and was manufactured in 2023. Key booster and vehicle seat information is summarised in Table AI in the Appendix.

Data Collection

Standing and seated anthropometric measurements of participants were obtained using a stadiometer, tape measures, and anthropometer. Locations of posterior spine (C7, T3, T6, T10, T12, L1, L4, S2) and pelvis landmarks (anterior superior iliac spine [ASIS], posterior superior iliac spine [PSIS]) were identified via palpation and visually marked. Participants were then instrumented using a non-invasive inertial measurement unit (IMU)-based motion-capture system (XSENS MVN Awinda, Movella Inc. Henderson, NV, USA) comprised of 17 lightweight, wireless sensors placed on the participant's head, torso, pelvis, and extremities. This system allows for quantification of all joint angles and body segment orientations at 60 Hz.

During each trial, a certified child passenger safety technician (CPST) routed the seatbelt through the belt routings on the booster (if applicable) and placed the lap and shoulder belt on the child, removed all slack from the seatbelt, and then instructed the participant to assume a comfortable and relaxed posture. Participants were allowed to settle into their self-selected posture for a few minutes prior to any measurements being captured. Participants were allowed to watch a movie on a screen positioned at approximately eye-level in front of the vehicle seat to reduce potential boredom.

Throughout each trial, data were collected from the XSENS motion-capture system as well as frontal and lateral video recordings. Additionally, instantaneous measurements of the participant's anatomic landmarks and the position of the seatbelts were obtained using a 3D coordinate measurement device (FARO Edge Arm, Lake Mary, Florida, USA). The primary measurements of interest included landmarks on the head (top, back, nasion, tragions), torso (suprasternale, xiphoid, acromia), spinous processes (C7, T3, T6, T10, T12, L1, L4, S2), a stream of points along the spine, pelvis (PSIS, ASIS), and lower extremities (patella, femoral condyle, lateral malleolus). Additional measurements were made on the shoulder belt (position at suprasternale, position at midline, shoulder belt stream: stream along centreline, torso stream: stream along centreline while pushing belt to contact torso), lap belt (position at ASIS, lap belt stream: stream along centreline), booster (four reference points), and vehicle seat (bight, centreline).

Belt Fit and Postural Analysis

All FARO measurements were transformed into a coordinate system consistent with SAE J211, with X pointing forward, Y pointing to the participant's right, and Z pointing down [24]. The origin was set at the intersection of the vehicle seat bight and the centreline. All XSENS body segment orientations are reported to be consistent with the SAE J211 coordinate system [24], and all joint angles are reported such that flexion is positive and extension is negative. Average joint angles and body segment orientations were calculated as the mean of each measurement between the timing of the first and last FARO measurement (average duration 5.7 ± 0.9 minutes).

Belt fit and belt gap metrics were calculated using FARO measurements as in previous studies [4,6], but brief definitions are summarised below in Table I. An additional belt gap metric to assess "maximum shoulder gap size" was also quantified. "Maximum shoulder gap size" was defined as the maximum 3D distance between corresponding points on the shoulder belt and the shoulder in a similar manner to the "lower gap size" methodology but limited to the region of the shoulder belt positioned directly over the participant's right shoulder. Exemplary shoulder and lower gap regions can be found in the Appendix (Fig. A4., Fig. A5.).

TABLE I
BELT FIT AND BELT GAP MEASUREMENTS

Metric	Basic Description	Full Description
Shoulder belt score (SBS)	Lateral distance from suprasternale to inboard shoulder belt	[6]
Lap belt score (LBS)	Distance from the ASIS to superior lap belt	[6]
Max. lower gap size	Maximum 3D distance between the shoulder belt and lower torso	[4], Fig. A5.
Lower gap length	Length along the shoulder belt not contacting the torso	[4]
Percent torso contact	Percent along the shoulder belt contacting the torso	[4]
Max. shoulder gap size	Max. 3D distance between the shoulder belt and shoulder	Fig. A4.

Statistical Analysis

All statistics were performed using JMP Pro Version 17 (JMP Statistical Discovery, Cary NC). Descriptive statistics were used to summarise the participant's posture and belt fit across seating and recline conditions as well as anthropometry and child and caregiver survey responses. Repeated measures ANOVA were used to assess variation in posture and belt fit outcomes with seating condition and recline angle for the child participant data. The alpha level was set to 0.05.

III. RESULTS

Child Participant Anthropometry

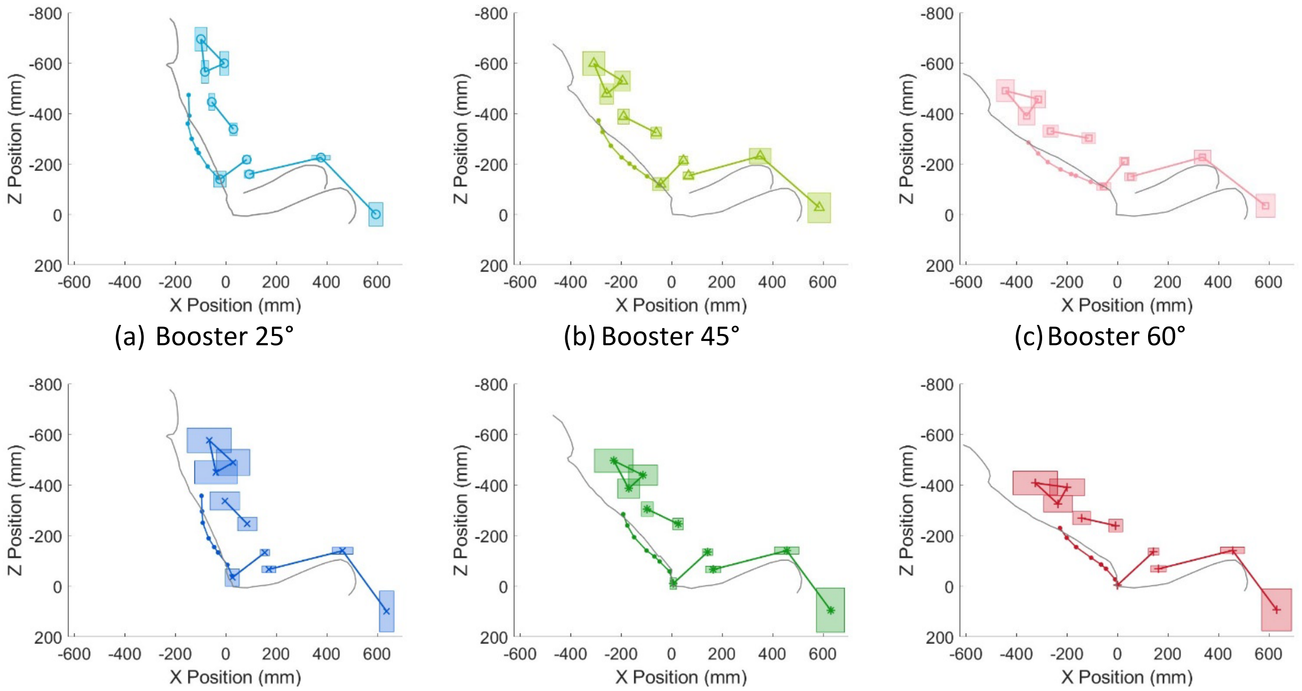
Child participant anthropometry is summarised in Table AII, Appendix. Child participants included 23 females and 20 males, with an average age of 8.0 ± 2.0y, stature of 130.8 ± 9.2 cm, mass of 28.5 ± 6.8 kg, and CDC percentiles ranging from 2% to 97.3%. Participants spanned the range of mass and stature allowed by the booster manufacturer guidelines (112–145 cm stature, 18.0–54.4 kg) and the range of representative mass and stature of paediatric ATDs and 5th percentile female ATDs (approximate size of a 12-year-old) (Fig. A6., Appendix).

Posture

The children assumed a variety of postures throughout the trials, including variation in their lower extremity postures, slouching, and various head and upper extremity positioning (Fig. A7, Appendix). Instantaneous positions of the main anatomic landmarks of interest are summarised by seating and recline conditions (Table II). The summary of all anatomic landmarks by recline and seating conditions can be found in the Appendix (Table AIII). Some inferior spine landmarks were inaccessible to measure due to the child's reclined posture, as demonstrated by the low N for the L4, S2, and PSIS landmarks in the no-booster condition, especially for increased recline angles. Average ± one standard deviation positions of the main landmarks of interest are also plotted by condition (Fig. 2), where the scatter point represents the average position and the size of the shaded box represents the SD in the X and Z directions. In Fig. 2, the average spinal landmarks are also shown, but the SD boxes are not shown to improve visibility.

TABLE II
MEAN ± STANDARD DEVIATION INSTANTANEOUS POSITIONS BY CONDITION

Landmark	Direction	Booster			No-booster		
		25°	45°	60°	25°	45°	60°
Head Top	X	-99 ± 24	-308 ± 44	-444 ± 35	-66 ± 88	-229 ± 77	-326 ± 89
	Z	-696 ± 47	-599 ± 47	-491 ± 44	-577 ± 49	-497 ± 47	-408 ± 47
Sternal Notch	X	-56 ± 11	-190 ± 23	-265 ± 30	-4 ± 59	-97 ± 24	-142 ± 35
	Z	-447 ± 34	-389 ± 30	-331 ± 23	-338 ± 36	-305 ± 29	-270 ± 27
Avg. ASIS	X	83 ± 14	47 ± 18	28 ± 19	155 ± 18	143 ± 20	143 ± 22
	Z	-218 ± 16	-214 ± 17	-211 ± 16	-133 ± 13	-135 ± 14	-137 ± 13
Avg. Lateral Epicondyle	X	377 ± 37	351 ± 42	338 ± 33	463 ± 41	456 ± 49	456 ± 48
	Z	-226 ± 9	-232 ± 31	-228 ± 27	-140 ± 14	-141 ± 14	-142 ± 13
Avg. Lateral Malleolus	X	595 ± 28	586 ± 45	587 ± 38	638 ± 29	630 ± 56	631 ± 60
	Z	-1 ± 47	-27 ± 60	-35 ± 46	100 ± 81	95 ± 89	93 ± 84



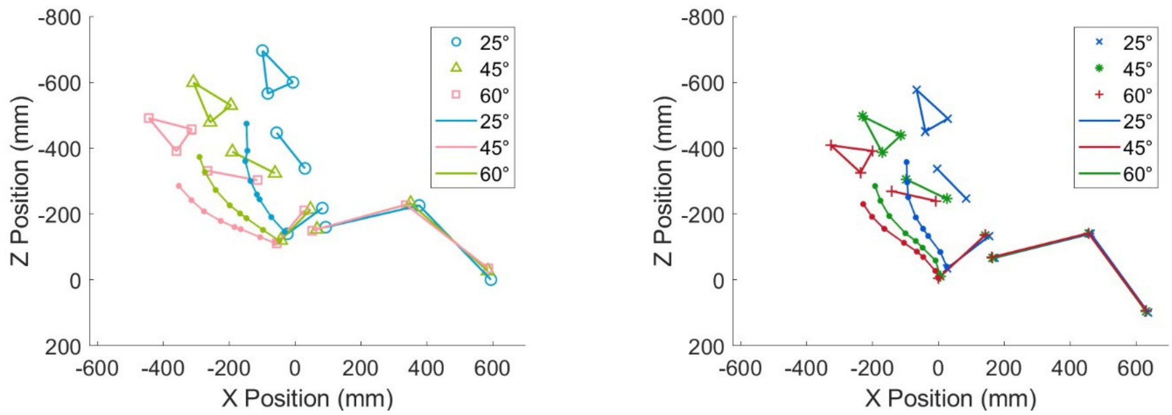
(a) Booster 25° (b) Booster 45° (c) Booster 60°

(d) No-booster 25° (e) No-booster 45° (f) No-booster 60°

Fig. 2. Mean ± SD anatomic landmark positions by condition (head top, nasion, average EAM, sternal notch, xiphoid, average PSIS, average ASIS, average GT, average lateral epicondyle, average lateral malleolus, spine [C7, T3, T6, T10, T12, L1, L4, S2]).

Repeated measures ANOVA of the position of the main anatomic landmarks of interest are summarised in the Appendix (Table AIV, Table AV). Seating condition explained significant variation across all positions ($p<0.05$), recline condition explained significant variation with the exception of ASIS-Z, Lateral Epicondyle Z, and Lateral Malleolus X positions, and the interaction between seating and recline conditions was significant for all variables.

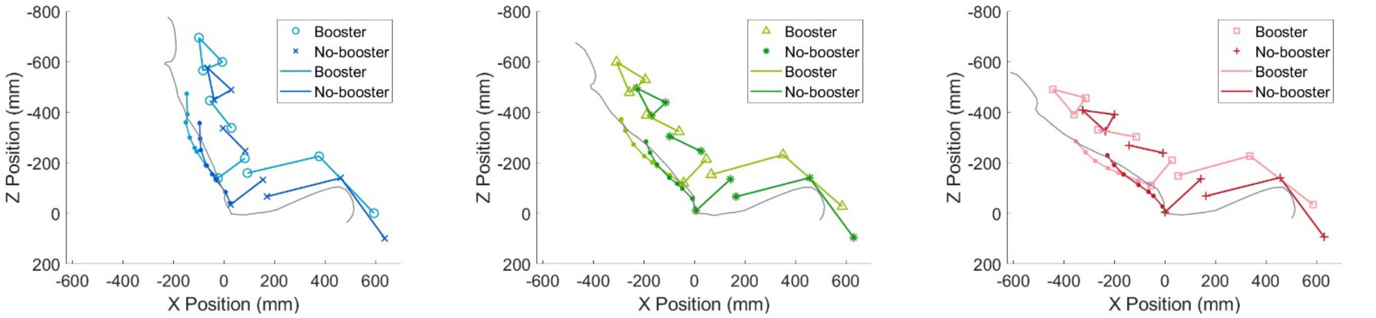
Comparing booster and no-booster conditions, the booster provided more superior (by 94 mm on average) and more rearward (by 82 mm on average) positions of all landmarks (Fig. 3, Fig. 4). Comparing across recline conditions, increasing seatback recline angle generally provided more rear and inferior positions of landmarks, with the greatest differences observed in the position of the head top and sternal notch (Fig. 4). On the booster condition, the ASIS was also positioned more rearward with increasing recline (-46 mm on average), while there were smaller differences in ASIS X position with increasing recline on the no-booster condition (-12 mm on average).



(a) Booster (b) No-booster*

Fig. 3. Comparison of recline condition mean anatomic landmark positions by seating condition (head top, nasion, average EAM, sternal notch, xiphoid, average PSIS, average ASIS, average GT, average lateral epicondyle, average lateral malleolus, spine [C7, T3, T6, T10, T12, L1, L4, S2]).

*Note lower sample sizes represented for inferior spine landmarks in the no-booster condition (see Appendix, Table AIII for more details).



(a) 25° (b) 45°* (c) 60°*

Fig. 4. Comparison of seating condition mean anatomic landmark positions by recline condition (head top, nasion, average EAM, sternal notch, xiphoid, average acromia, average olecranon, average radial styloid process, average PSIS, average ASIS, average GT, average lateral epicondyle, average lateral malleolus, spine [C7, T3, T6, T10, T12, L1, L4, S2]).
*Note lower sample sizes represented for inferior spine landmarks in the no-booster condition (see Appendix, Table AIII for more details).

Six of the 258 trials (<3%) were removed due to quality issues with the XSENS data collection/processing. The remaining average continuous postural metrics were summarised across seating and recline conditions (Appendix, Table AVI). Repeated Measures ANOVA for continuous postural metrics are summarised in the Appendix (Table AVII, Table AVIII). Overall, most body segment orientations were significantly influenced by recline condition and by the interaction between recline and seating condition but not by seating condition alone. However, the anterior/posterior (A/P) orientation of the neck, head, arms, thighs, and legs was also significantly influenced by the seating condition. Body segment orientations tended to become more posteriorly oriented in the 45° and 60° conditions compared to the 25° condition (Appendix, Fig. A8.–Fig. A11.). In particular, the average pelvis orientation became more posterior with increasing seatback recline angle on the booster condition (45° with respect to [wrt] 25°: -11°, 60° wrt 25°: -16°), while smaller changes in pelvis orientation were observed in the no-booster condition (45° wrt 25°: -6°, 60° wrt 25°: -8°). Changes in torso orientation closely followed changes in seatback recline angle both on the booster (45° wrt 25°: -26°, 60° wrt 25°: -43°) and no-booster (45° wrt 25°: -21°, 60° wrt 25°: -35°) conditions.

Additionally, spine flexion (L5/S1, L4/L3, L1/T12, T9/T8, T1/C7, and C1/Head) was also significantly influenced by recline condition but not by seating condition alone or the interaction between seating and recline conditions in most cases (Appendix, Table AVII). However, similar to body segment orientations, spinal flexion for T1/C7 and C1/Head was also influenced by seating condition alone. In general, spinal flexion angles decreased with increasing recline angle for L5/S1, L4/L3, L1/T12, and T9/T8 angles on average, while flexion tended to increase at T1/C7 and at the C1/Head joints. Negligible differences were observed in average spinal flexion angles between the booster and no-booster conditions, although slightly more flexion (4°) was observed at the C1/Head joint for the booster compared to the no-booster condition, on average. Additionally, hip flexion was significantly influenced only by recline condition, which tended to decrease with increasing recline angle (Appendix, Fig. A12.), and knee flexion was significantly influenced only by seating condition, which tended to be more flexed (by 12° on average) on the no-booster compared to the booster condition (Appendix, Fig. A13.).

Belt Fit

Belt fit and belt gap metrics were summarised across seating and recline conditions (Table III). Statistical comparisons of belt fit by recline and seating condition can be found in the Appendix, Table AIX, and Table AX.

SBS (Fig. 5, Table AIX) was significantly influenced by seating and recline conditions ($p<0.05$) but not their interaction. More inboard SBS were observed on the no-booster compared to the booster condition (average difference = 43 mm), but more outboard SBS were observed with more reclined seatback angles (average difference = 10 mm). LBS (Fig. 6, Table AIX) was significantly influenced by seating and recline conditions and their interaction term ($p<0.05$). LBS was more inferior/distal on the booster compared to no-booster condition (average difference = 42 mm). As recline angle increased, LBS also became more inferior/distal on the booster condition (average difference = 17 mm); however, LBS remained similar across recline angles in the no-booster condition (average difference = 0 mm).

TABLE III
MEAN ± STANDARD DEVIATION BELT FIT BY CONDITION

Metric	Booster			No-booster		
	25°	45°	60°	25°	45°	60°
SBS (mm)	38 ± 18	44 ± 19	54 ± 18	-4 ± 20	3 ± 20	8 ± 15
Avg. LBS (mm)	24 ± 9	38 ± 13	44 ± 13	-7 ± 9	-6 ± 8	-8 ± 12
Avg. LB wrt ASIS X (mm)	37 ± 11	55 ± 17	64 ± 18	-8 ± 14	-7 ± 12	-11 ± 17
Avg. LB wrt ASIS Z (mm)	-7 ± 7	-10 ± 7	-12 ± 7	-9 ± 6	-6 ± 5	-6 ± 6
Max. Shoulder Gap Size (mm)	25 ± 12	33 ± 13	25 ± 14	45 ± 14	45 ± 18	35 ± 14
Max. Lower Gap Size (mm)	22 ± 12	21 ± 10	16 ± 11	21 ± 12	24 ± 15	25 ± 13
Lower Gap Length (mm)	72 ± 51	59 ± 43	50 ± 45	43 ± 37	47 ± 43	52 ± 37
Percent Torso Contact (%)	80 ± 14	84 ± 11	88 ± 10	85 ± 11	84 ± 14	84 ± 11

The position of the lap belt with respect to the ASIS in the X direction (Table III) followed similar trends to the LBS, with LB wrt ASIS X significantly influenced by seating condition, recline condition, and their interaction. Similar differences were also observed between conditions, with more fore positions of the LB wrt the ASIS X on the booster compared to no-booster condition (average difference = 61 mm). Again, differences in LB wrt ASIS X were greater between recline conditions on the booster (average difference = 23 mm) compared to the no-booster condition (average difference = -2 mm). The position of the lap belt with respect to the ASIS in the Z direction (Table III) showed different trends and explained less overall variation (R^2_{Adj} = 56.87%) compared to LB wrt ASIS X (R^2_{Adj} = 90.90%) and LBS (R^2_{Adj} = 90.81%) metrics (Table AIX). LB wrt ASIS Z was significantly influenced by seating condition and the interaction between seating condition and recline condition ($p<0.05$), but not by the recline condition alone (Table AIX). Additionally, average differences between conditions were smaller compared to those observed in LB wrt ASIS X and LBS metrics.

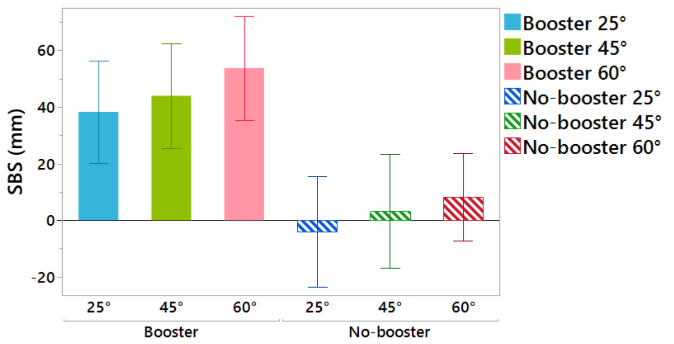


Fig. 5. Mean ±SD SBS by seating and recline condition (positive values are more outboard)

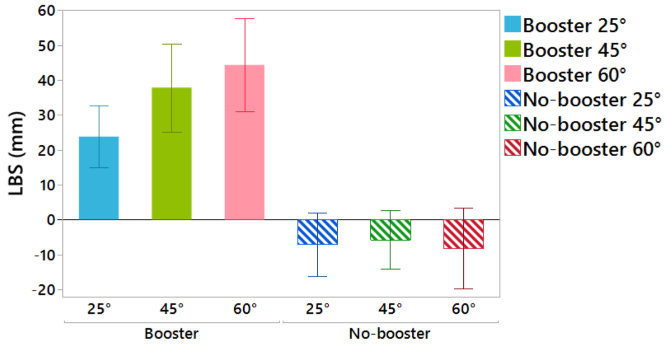


Fig. 6. Mean ±SD LBS by seating and recline condition (positive values are more inferior/distal)

Shoulder belt gap size (Fig. 7, Table AIX) varied with seating condition, recline condition, and the interaction between recline and seating conditions ($p<0.05$). Larger shoulder gap sizes were observed on the no-booster compared to the booster condition (average difference = 14 mm), but the size of the shoulder gap size varied with changes in recline angle. Lower belt gap size (Fig. 8, Table AIX) and gap length (Fig. 9, Table AIX) were significantly influenced by seating condition and by the interaction between seating and recline conditions ($p<0.05$) but not by recline condition alone. However, R^2_{Adj} were smaller for these gap metrics (size: R^2_{Adj} = 20.01%, length: R^2_{Adj} = 25.78%) compared to shoulder gap size (R^2_{Adj} = 52.43%) and shoulder and lap belt fit metrics (R^2_{Adj} = 77.66–90.81%). Overall, lower gap size was larger on the no-booster condition (average difference: 4 mm), but gap length was longer on the booster condition (average difference: 13 mm). Maximum lower gap size and gap length decreased with recline angle in the booster condition (average difference in size: -4 mm, length: -17 mm) but increased with recline angle in the no-booster condition (average difference in size: 3 mm, length: 6 mm). Percent torso contact (Fig. 10, Table AIX) was only significantly influenced by the interaction between seating and recline conditions and displayed similar R^2_{Adj} to the other lower gap metrics (R^2_{Adj} = 21.02%). Percent torso contact increased slightly with recline on the booster condition (average difference = 6%) but remained similar across recline angles in the no-booster condition (average difference = -1%).

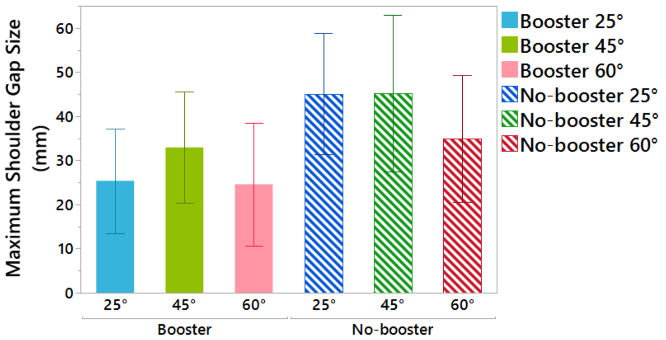


Fig. 7. Mean ±SD maximum shoulder gap size by seating and recline condition.

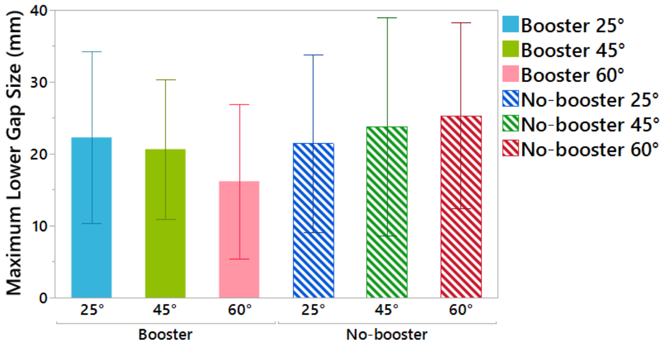


Fig. 8. Mean ±SD maximum lower gap size by seating and recline condition.

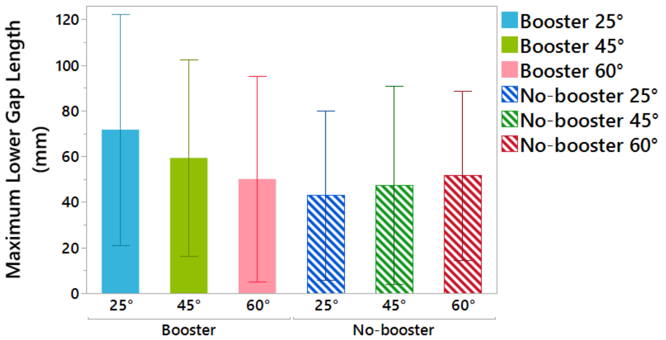


Fig. 9. Mean ±SD lower gap length by seating and recline condition.

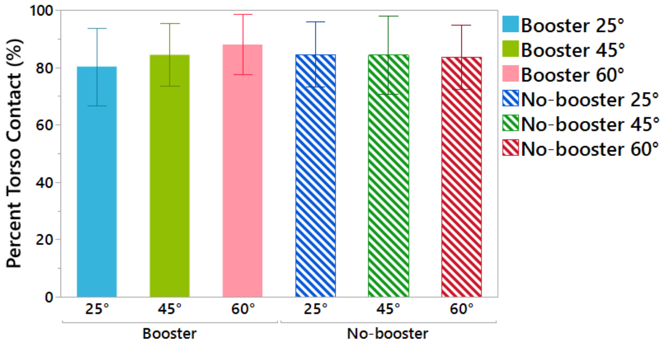


Fig. 10. Mean ±SD percent torso contact by seating and recline condition.

IV. DISCUSSION

Posture

Overall, children assumed more reclined postures in the 45° and 60° conditions compared to the 25° condition. This was evidenced by the more posterior orientations of the head, shoulder, and torso body segment orientations and more rear positions of the head and torso anatomic landmark positions. In addition to being positioned in more reclined postures, children also exhibited decreased lumbar and thoracic spine flexion as well as decreased hip flexion. However, increased spinal flexion was observed at the T1/C7 and C1/Head joints for increased recline angles. This may be due to some children assuming more flexion in the neck to more easily view the screen during the trials (e.g. Appendix, Fig. A7(f)).

In general, lower extremity positions and orientations remained relatively similar between recline conditions, with much of the change in posture occurring in the pelvis and more superior body regions. In particular, the average X position of the ASIS became more rear with increasing recline angle on the booster, in conjunction with the pelvis becoming more posteriorly oriented compared to the 25° condition. However, on the no-booster condition the ASIS X position and the pelvis orientation changed marginally across recline conditions. This may be due to the differences in baseline 25° postures for children on the booster compared to the no-booster condition. On the no-booster condition, the ASIS was more fore and children displayed greater knee flexion. Together, these suggest that children assumed more fore positions of their pelvis and lower extremities to more comfortably bend their knees over the front edge of the vehicle seat pan. As children reclined on the booster condition, there was more space for their pelvis to rotate posteriorly since they were positioned higher with respect to the vehicle seatback. Additionally, children may have been employing different strategies to assume a comfortable posture as the vehicle seatback reclined on the booster versus no-booster condition, which may have also contributed to the differences in change in pelvis orientation across the recline conditions.

One prior study evaluated the posture and belt fit of 24 adults (18–71y) across a similar range of vehicle seatback recline angles (23°, 33°, 43°, and 53°) [2]. Adults were observed to posteriorly rotate their pelvis and display decreased lumbar spine flexion with increasing recline angle, which is similar to the trends observed for children in this study. For adults, changes in pelvis orientation with an increasing recline angle were observed to be approximately one-third of the change in seatback angle [2]. In the current study, children displayed an average relative change in pelvis orientation with respect to the change in seatback recline angle of approximately one-half on the booster and one-quarter on the no-booster condition. This indicates that on the booster condition, children posteriorly rotated their pelvis to a greater degree with increasing recline angle compared to the adults in [2]; however, on the no-booster condition, children posteriorly rotated their pelvis to a lesser degree compared to the adults in [2]. Some of these variations between adults and children may be attributed to differences in the pelvis angle measurement methodology, as the current study utilised an IMU sensor taped to the posterior aspect of the sacrum while [2] utilised relationships between 3D coordinate measurements of the ASIS, PSIS, L5/S1 and thigh length on a "hard seat" that provided access to measure the posterior landmarks and the vehicle seat.

Differences in posture across vehicle seatback recline angles between adults and children were expected due to their different relative proportions and how this influences their interaction with vehicle seating environments. In particular, the greater relative change in pelvis orientation observed for children on the booster may be related to their more superior positioning of the pelvis with respect to the vehicle seat compared to the adults (and compared to children on the no-booster condition), which would allow more space for the pelvis to rotate rearward. Children on the no-booster condition had more posterior pelvis orientations compared to booster condition in the 25° condition, suggesting that children were already in a slouched posture in the baseline condition, which may explain their smaller relative change in pelvis orientation across recline angles compared to adults. This is supported by the more posterior pelvis orientation observed here for children on the no-booster 25° condition (-63.2°) compared to children on the booster 25° condition (-58.3°) and to the average pelvis orientation of adults (-51.0°) at a 23° recline angle [2].

Similarly, lumbar spine flexion for adults was observed to decrease by 17° with an increase in recline angle of 30° [2]. Changes in lumbar spine flexion were generally smaller for the children observed in this study (average change of 7° between the 25° and 45° conditions, average change of 12° between the 25° and 60° conditions). Again, this may be due to difference in methodology and vehicle seat geometries between the studies and/or differences in postural adjustment to recline angles between adult and paediatric populations.

Belt Fit

As the recline angle of the seatback increased, children experienced a detriment in the quality of their belt fit. In particular, the SBS became more outboard (by 10 mm on average) both on the booster and no-booster conditions despite the shoulder belt outlet being integrated to the seatback. The Insurance Institute for Highway Safety (IIHS) booster belt fit protocol defines the range of acceptable shoulder belt positions with respect to the torso midline for a 6-year-old occupant as between -10 – 30 mm (with fair shoulder belt positions between -20 – -10 mm or 30 – 40 mm, and poor < -20 mm or > 40 mm) [25]. The average SBS observed in the upright 25° booster and no-booster conditions would fall within the fair/acceptable range (38 mm and -3 mm, respectively); however, SBS for the 45° and 60° booster conditions would correspond to the "poor" range due to being positioned further outboard (44 mm and 54 mm, respectively). While the 45° and 60° no-booster SBS also became more outboard, they were still within the "acceptable" range; however, the shoulder belt remained relatively placed close to the neck in these conditions, which has been shown to increase potential discomfort that may cause children to place the shoulder belt under their arm or behind their back which has increased injury risk [26,27]. However, the range of acceptable static SBS may vary for different child occupant sizes, and as this study included occupants between 4–12 years, comparison of the IIHS-defined ranges to the SBS observed in this study may be limited. Additionally, prior work has also shown varied outcomes in frontal sled tests for upright booster-seated ATDs despite similar initial belt fit conditions [28], suggesting that defining the range of optimal SBS based on optimal dynamic outcomes may be more nuanced.

Yet, the more outboard shoulder belt positions observed with increasing recline angle in this study may have implications for the likelihood of the shoulder belt slipping off the torso in the case of a vehicle manoeuvre or crash. Prior work has identified reduced lateral excursions of the head and torso with increased seatback recline angles (45° and 60°) for children and the THORAV-5F evaluated on boosters during low-speed (2 g) far-side lateral-oblique impacts due to the occupant experiencing more axial rotation (versus lateral bending) and increased interaction with the vehicle seatback and side bolsters [16,17]. However, shoulder belt slip-off was observed for the THORAV-5F in some reclined seatback angles [16] and for the LODC when evaluated on a booster with reclined seatback angles during lateral oblique impacts at 31.3 km/h [15]. Limitations in ATD biofidelity may have influenced the belt slip-off observed for the LODC and the THORAV-5F during these studies as reduced torso rotations were observed compared to child volunteers during low-speed tests [16]. Yet, the shoulder belt was initially placed optimally for the occupants in all these tests, and future work should continue to investigate if the same reduction in displacement occurs for reclined seatback angles when the belt is placed initially more outboard on the shoulder and how this relates to the potential for shoulder belt slip-off.

A previous study of adults in reclined vehicle seatback configurations observed the shoulder belt to become positioned more inboard with increasing recline angle [2], which contradicts the observations made for children in this study. The SBS for adults changed from approximately 40 mm in the 23° to -25 mm in the 53° condition, while the children in this study changed from 38 mm on the 25° booster to 54 mm on the 60° booster condition. Both studies utilised a shoulder belt outlet position that rotated with the seatback; however, differences in the vehicle seat geometry and the position of the belt outlet with respect to the vehicle seat may influence the differences in SBS observed between adults and children. Additionally, adults in [2] first sat in the 23° seatback angle, got comfortable, then the seatback angle was adjusted to the more reclined setting, participants again got comfortable, and finally participants donned the belt. In this study, the seatback angle was adjusted to the desired setting prior to the child sitting down, then a CPST ensured the belt was routed consistently prior to each test, and finally the child settled into their comfortable posture. These methodological differences may have also influenced adult and child postures and respective SBS in different manners, and future work should continue to investigate these relationships.

LBS also became more inferior/distal with increasing recline angle on the booster (by 17 mm on average). While the average LBS did not change appreciably with recline angle on the no-booster condition, LBS were worse on the no-booster (on average 42 mm more superior) compared to the booster condition, and changing the recline angle did not improve LBS on the no-booster condition. Similar trends were observed for the position of the lap belt with respect to the ASIS in the X direction, with the booster providing more fore and inferior positions of the LB wrt the ASIS, on average. This change in lap belt fit across recline conditions can be explained by the more posterior rotation of the pelvis (and corresponding more rear position of the ASIS in the X direction) observed for children on the booster condition. As the pelvis rotated posteriorly, the ASIS moved rearward away from the lap belt that was held in place by the lower belt guides on the booster. The IIHS booster belt fit protocol defines good lap belt fit for a 6-year-old occupant as 20–50 mm (with fair 10–20 mm or 50–60 mm, and poor < 10 mm or > 60 mm) [25]. While the average LBS on the booster condition fell within the “good” range for all recline conditions (25°: 24 mm, 45°: 38 mm, 25°: 44 mm), the relatively more forward position of the lap belt on the thighs may delay engagement between the belt and the pelvis during a crash, which may influence injury risk.

On the no-booster condition, there was less change in orientation of the pelvis and X position of the ASIS across recline conditions, likely due to children assuming different postures to more comfortably bend their knees over the longer vehicle seat pan (which was observed by the increased knee flexion on the no-booster condition). This led to less change in lap belt fit across recline conditions without the booster because the pelvis did not change orientation/position to as great a degree and because the lap belt was not held in place by any belt guides, meaning it was likely free to move with the child’s pelvis during any postural adjustments. However, the no-booster condition provided a less optimal belt fit (positioned superior to the ASIS on average) across all recline angles compared to the booster condition. The average LBS on the no-booster condition corresponds to a “poor” IIHS lap belt score (<10 mm) for all recline conditions (25°: -7 mm, 45°: -6 mm, 25°: -8 mm) [25]. This more superior position of the lap belt may influence the likelihood of the child submarining under the lap belt and increasing injury risk during a crash [19]. Again, comparisons to the IIHS ideal belt fit ranges may be influenced by occupant size, and additional analyses are required to identify how static LBS are related to variation in crash outcomes.

The position of the lap belt with respect to the ASIS for adults in reclined vehicle configurations has been observed to become more rear (-25.5 mm for 53° wrt 23°) with increasing recline angle, while the vertical position was not significantly affected [2]. Again, this suggests that child lap belt fit in reclined vehicle configurations likely changes in different ways than adults’, as in this study children on boosters were observed to have more fore positioning of the lap belt with respect to the ASIS on the booster condition (+27 mm for 60° wrt 25°), and no significant changes were observed on the no-booster condition (-4 mm for 60° wrt 25°).

Finally, the average lower gap size (25 cm) and length (72 mm) provided by the booster in this study during the 25° condition was within the range of "larger gap" boosters evaluated in a prior study of a range of booster designs [4]. While decreases in the gap size and length with increasing recline angle were observed in the booster condition, less distinct trends were observed on the no-booster condition. Larger lower gap size and length may influence how soon the belt provides restraint to the torso during an impact, which may have implications for occupant excursion and kinematics [29,30] but should be further investigated in reclined seatback configurations.

Limitations

This study presents some limitations. Only one booster and one vehicle environment were evaluated, and other booster/vehicle geometries may influence posture and belt fit in ways not presented here. This limitation is especially relevant for futuristic designs of reclined vehicle seats. Additionally, children were aware of being measured, evaluated in a laboratory setting, and assessed for a relatively short duration, so the range of belt fit and posture conditions observed here are likely smaller than those expected during more naturalistic environments or actual trips.

V. CONCLUSION

This study was the first to assess static belt fit and posture of children in reclined vehicle configurations. Overall, children assumed more reclined postures with increasing seatback recline angle, which was exemplified by more rear and inferior positions of the head and torso, more posterior orientations of the head, shoulders and torso, decreased lumbar and thoracic spinal flexion, increased cervical spinal flexion, and decreased hip flexion. Additionally, differences in posture were also observed between the booster and no-booster conditions. On the booster, children assumed more superior and rearward positions of the anatomic landmarks, more rearward positions of the ASIS with increasing recline angle, more posterior orientations of the pelvis with increasing recline angle, and less knee flexion. Of note, children experienced a detrimental effect of seatback recline on belt fit, as evidenced by more outboard SBS, more inferior/distal LBS with increasing recline angle on the booster, and no improvement of superior lap belt positioning with respect to the ASIS with recline angle on the no-booster condition. Overall, these changes in belt fit and posture observed in more reclined seatback angles may contribute to suboptimal crash outcomes and increased lumbar spine loading. These findings can inform pre-test positioning techniques of reclined child occupant surrogates (including HBMs) and assist CRS and vehicle manufacturers to assess more realistic reclined vehicle seating configurations for booster-aged children. Additionally, these findings highlight the differences in posture and belt fit in reclined seatback configurations for children compared to previous studies of adult volunteers, emphasising the continued need to assess children alongside adults in novel vehicle configurations. Overall, while the booster showed improved posture and belt fit compared to the no-booster condition, the detrimental effect of recline angle on seat belt fit regardless of the booster indicates that reclined vehicle seatback configurations may not be appropriate for booster-sized occupants.

VI. ACKNOWLEDGEMENTS

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VIII. APPENDIX

Fig. A1. Backless booster seat (Evenflo GoTime).

TABLE AI
BOOSTER AND VEHICLE MEASUREMENTS

Metric		Booster	Vehicle
Seat pan length (cm)		37.3	45.3
Seat pan angle (°)	Rear	8	4
	Front	12	20
Seat pan height (cm)	Rear	8.5	NA
	Front	12.3	NA
Upper belt outlet position wrt origin (mm)	X	NA	-301
	Y		181
	Z		-561
Lower belt anchorage position wrt origin (mm)	X	NA	90
	Y		363
	Z		124

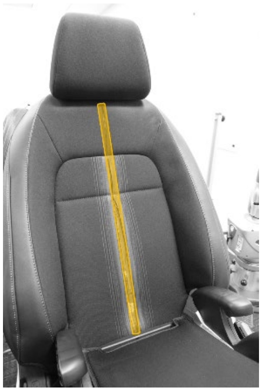


Fig. A2. Location of seatback foam cut.

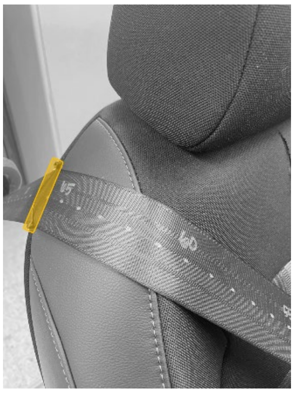


Fig. A3. Simulated integrated belt outlet.

Fig. A4. Exemplary shoulder gap.

Fig. A5. Exemplary lower gap.

TABLE AII
CHILD PARTICIPANT ANTHROPOMETRY

Metric		Unit	N	Mean ± SD	[Min., Max.]
Age		yr	43	8.0 ± 2.0	[5.0, 12.0]
BMI		kg/m^2	43	16.4 ± 2.5	[13.3, 24.1]
CDC Percentile		%ile	43	47.6 ± 32.7	[2.0, 97.3]
Standing	Mass	kg	43	28.5 ± 6.8	[18.2, 50.6]
	Stature	cm	43	130.8 ± 9.2	[113.5, 145.0]
	C7 height	cm	43	108.7 ± 8.8	[89.5, 122.0]
	ASIS height	cm	42	72.3 ± 6.5	[61.8, 85.4]
	ASIS breadth	cm	43	17.2 ± 1.7	[14.2, 22.7]
	PSIS breadth	cm	43	8.0 ± 0.9	[6.0, 9.8]
	GT height	cm	43	67.9 ± 6.0	[56.2, 79.0]
	GT breadth	cm	43	24.6 ± 2.6	[20.5, 32.2]
	Lateral femoral condyle height	cm	43	40.3 ± 4.0	[31.3, 50.7]
	Lateral malleolus height	cm	43	5.7 ± 0.8	[4.3, 8.4]
	Foot length	cm	43	20.8 ± 1.7	[17.3, 24.4]
	Arm span	cm	43	125.7 ± 10.1	[104.1, 151.3]
	Wrist span	cm	43	98.0 ± 8.5	[80.2, 120.5]
	Elbow span	cm	43	61.1 ± 5.0	[50.8, 71.4]
	Acromial breadth	cm	43	27.6 ± 2.0	[23.2, 31.3]
	Chest breadth at axilla	cm	43	22.4 ± 2.3	[16.8, 27.1]
	Chest breadth at substernale	cm	43	21.4 ± 1.9	[18.0, 26.9]
	Chest depth at suprasternale	cm	43	10.5 ± 1.0	[9.1, 13.5]
	Chest depth at substernale	cm	43	15.0 ± 1.6	[11.2, 19.5]
	Abdominal depth at umbilicus	cm	43	14.8 ± 1.8	[12.3, 20.1]
Seated	Shoulder height	cm	43	45.3 ± 4.1	[36.4, 53.7]
	ASIS breadth	cm	43	17.8 ± 2.0	[13.8, 22.4]
	GT breadth	cm	43	26.0 ± 3.0	[21.4, 36.9]
	Acromial breadth	cm	43	27.3 ± 2.0	[21.3, 31.1]
	Head height from seat	cm	42	69.3 ± 4.9	[56.9, 78.8]
	Buttock to popliteal length	cm	43	35.5 ± 3.9	[23.5, 42.6]
	Lateral shoulder (humerus) breadth	cm	43	31.4 ± 2.5	[26.4, 37.3]
	Acromioclavicular joint breadth	cm	43	24.9 ± 2.1	[18.7, 29.1]

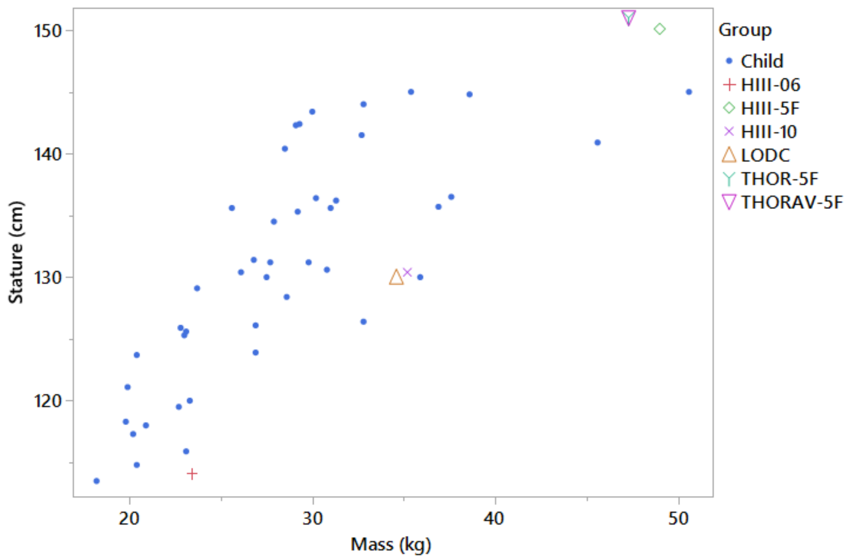


Fig. A6. Comparison of child and ATD overall anthropometry.

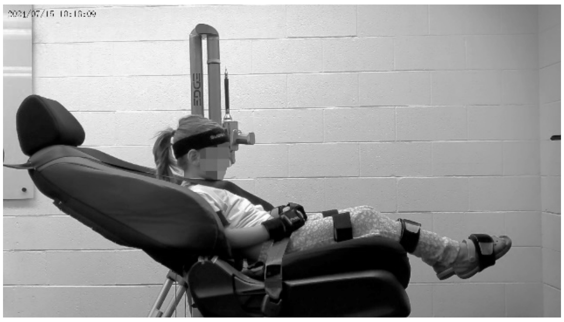
(a) Booster 60°: Arms behind head.

(b) Booster 45°: Knees flexed, feet on seat.

(c) No-booster 25°: Leaning forward.

(d) No-booster 60°: Leading sideways, leg bent.

(e) No-booster 60°: Legs crossed.



(f) No-booster 60°: Neck flexed.

(g) Booster 45°: One leg crossed over.

(h) No-booster 25°: Thighs crossed.

Fig. A7. Exemplary varied user postures

TABLE AIII

SUMMARY OF LANDMARK POSITIONS BY CONDITION

Position		Booster						No-booster					
		25°		45°		60°		25°		45°		60°	
		N	Mean ± SD	N	Mean ± SD	N	Mean ± SD	N	Mean ± SD	N	Mean ± SD	N	Mean ± SD
Head Top	X	43	-99 ± 24	43	-308 ± 44	43	-444 ± 35	43	-66 ± 88	43	-229 ± 77	43	-326 ± 89
	Z	43	-696 ± 47	43	-599 ± 47	43	-491 ± 44	43	-577 ± 49	43	-497 ± 47	43	-408 ± 47
C7	X	43	-147 ± 14	43	-290 ± 26	43	-353 ± 37	43	-96 ± 63	43	-192 ± 29	43	-228 ± 40
	Z	43	-474 ± 40	43	-373 ± 34	43	-285 ± 27	43	-358 ± 42	43	-285 ± 31	43	-230 ± 30
T3	X	40	-156 ± 14	43	-274 ± 28	42	-322 ± 34	41	-99 ± 60	43	-176 ± 29	43	-201 ± 38
	Z	40	-421 ± 39	43	-327 ± 31	42	-248 ± 23	41	-311 ± 42	43	-240 ± 31	43	-192 ± 26
T6	X	42	-154 ± 16	42	-247 ± 29	42	-283 ± 38	42	-94 ± 51	43	-149 ± 31	43	-164 ± 39
	Z	42	-369 ± 38	42	-280 ± 29	42	-213 ± 22	42	-257 ± 44	43	-194 ± 29	43	-155 ± 25
T10	X	42	-138 ± 18	42	-203 ± 33	43	-226 ± 40	42	-70 ± 41	42	-102 ± 36	41	-109 ± 39
	Z	42	-308 ± 35	42	-232 ± 27	43	-179 ± 18	42	-194 ± 45	42	-145 ± 29	41	-118 ± 22
T12	X	41	-121 ± 20	42	-171 ± 35	42	-188 ± 41	42	-47 ± 37	42	-70 ± 39	35	-80 ± 35
	Z	41	-272 ± 36	42	-207 ± 28	42	-164 ± 18	42	-159 ± 43	42	-121 ± 28	35	-105 ± 20
L1	X	42	-110 ± 22	42	-151 ± 36	43	-165 ± 40	41	-32 ± 35	39	-53 ± 35	30	-65 ± 29
	Z	42	-250 ± 35	42	-192 ± 28	43	-154 ± 18	41	-140 ± 42	39	-108 ± 26	30	-99 ± 17
L4	X	42	-74 ± 25	42	-100 ± 33	42	-109 ± 35	39	7 ± 26	32	-11 ± 24	14	-28 ± 23
	Z	42	-195 ± 28	42	-155 ± 22	42	-133 ± 14	39	-93 ± 29	32	-79 ± 18	14	-84 ± 16
S2	X	42	-32 ± 29	41	-50 ± 32	43	-62 ± 34	27	41 ± 26	9	25 ± 20	3	4 ± 18
	Z	42	-149 ± 24	41	-125 ± 19	43	-113 ± 14	27	-64 ± 25	9	-67 ± 14	3	-85 ± 2
Sternal Notch	X	43	-56 ± 11	43	-190 ± 23	43	-265 ± 30	43	-4 ± 59	43	-97 ± 24	43	-142 ± 35
	Z	43	-447 ± 34	43	-389 ± 30	43	-331 ± 23	43	-338 ± 36	43	-305 ± 29	43	-270 ± 27
Xiphoid	X	43	30 ± 14	43	-61 ± 21	43	-114 ± 27	43	86 ± 38	43	26 ± 21	43	-7 ± 28
	Z	43	-338 ± 25	43	-324 ± 23	43	-302 ± 22	43	-246 ± 27	43	-246 ± 23	43	-240 ± 25
Avg. Acromia	X	43	-87 ± 12	43	-223 ± 25	43	-304 ± 33	43	-28 ± 61	43	-128 ± 31	43	-179 ± 45
	Z	43	-453 ± 37	43	-393 ± 32	43	-330 ± 27	43	-349 ± 39	43	-309 ± 33	43	-270 ± 32
Avg. Olecranon	X	43	18 ± 22	43	-46 ± 29	43	-116 ± 83	43	94 ± 62	43	39 ± 56	43	-9 ± 103
	Z	43	-227 ± 26	43	-225 ± 51	43	-234 ± 80	43	-135 ± 30	43	-150 ± 88	43	-166 ± 103
Avg. Styloid Process	X	43	170 ± 38	43	79 ± 74	43	-19 ± 147	43	226 ± 60	43	139 ± 114	43	90 ± 159
	Z	43	-270 ± 26	43	-279 ± 41	43	-277 ± 51	43	-180 ± 38	43	-204 ± 69	43	-203 ± 57
Avg. ASIS	X	43	83 ± 14	43	47 ± 18	43	28 ± 19	43	155 ± 18	43	143 ± 20	43	143 ± 22
	Z	43	-218 ± 16	43	-214 ± 17	43	-211 ± 16	43	-133 ± 13	43	-135 ± 14	43	-137 ± 13
Avg. PSIS	X	40	-24 ± 25	40	-45 ± 32	41	-55 ± 30	21	45 ± 25	6	32 ± 15	2	-4 ± 11
	Z	40	-147 ± 18	40	-126 ± 13	41	-114 ± 9	21	-64 ± 23	6	-62 ± 17	2	-77 ± 3
Avg. Greater Trochanter	X	43	93 ± 19	43	67 ± 22	43	52 ± 23	43	171 ± 28	43	164 ± 30	43	162 ± 31
	Z	43	-160 ± 14	43	-154 ± 15	43	-150 ± 16	43	-67 ± 13	43	-66 ± 13	43	-68 ± 12
Avg. Lateral Epicondyle	X	43	377 ± 37	43	351 ± 42	43	338 ± 33	43	463 ± 41	43	456 ± 49	43	456 ± 48
	Z	43	-226 ± 9	43	-232 ± 31	43	-228 ± 27	43	-140 ± 14	43	-141 ± 14	43	-142 ± 13
Avg. Lateral Malleolus	X	43	595 ± 28	43	586 ± 45	43	587 ± 38	43	638 ± 29	43	630 ± 56	43	631 ± 60
	Z	43	-1 ± 47	43	-27 ± 60	43	-35 ± 46	43	100 ± 81	43	95 ± 89	43	93 ± 84

TABLE AIV

REPEATED MEASURES ANOVA OF LANDMARK POSITIONS BY SEATING AND RECLINE CONDITION

Landmark Position		R^2_{Adj}	Fixed Effects						Random Effect	
			Seating		Recline		Seating*Recline		Subject	
			F Ratio	Prob > F	F Ratio	Prob > F	F Ratio	Prob > F	Wald p-value	% of Total
Head Top	X	87.64%	125.99	<.0001	664.45	<.0001	12.91	0.0013	0.0018	26.70
	Z	95.58%	1189.78	<.0001	1343.09	<.0001	12.64	<.0001	<.0001	70.22
Sternal Notch	X	91.50%	626.56	<.0001	812.02	<.0001	33.26	0.0014	0.0017	27.34
	Z	97.65%	3923.53	<.0001	1537.51	<.0001	104.96	<.0001	<.0001	68.28
Avg. ASIS	X	94.92%	3399.26	<.0001	150.99	<.0001	60.69	<.0001	<.0001	54.57
	Z	98.40%	11825.67	<.0001	1.74	0.1788	17.81	<.0001	0.0001	46.88
Avg. Lateral Epicondyle	X	90.49%	1338.17	<.0001	23.84	<.0001	11.28	<.0001	<.0001	69.07
	Z	87.55%	1552.09	<.0001	0.79	0.4532	0.62	0.009	0.0025	24.96
Avg. Lateral Malleolus	X	51.38%	92.27	<.0001	1.40	0.2478	0.01	0.0008	0.0011	29.96
	Z	87.46%	706.94	<.0001	7.77	0.0006	3.69	<.0001	<.0001	67.76

Note: *each row represents a separate Repeated Measures ANOVA with seating condition, recline condition, and seating condition*recline condition included as fixed effects, subject included as a random effect, and a belt fit metric as a dependent variable. Highlighted cells correspond to p<0.05.*

TABLE AV

REPEATED MEASURES ANOVA PARAMETER ESTIMATES OF LANDMARK POSITIONS BY SEATING AND RECLINE CONDITION

Landmark Position		Parameter Estimates														
		Seating [Booster]			Recline [60°]			Recline [45°]			Seating [Booster]*Recline [60°]			Seating [Booster]*Recline [45°]		
		Estimate	t Ratio	Prob > |t|	Estimate	t Ratio	Prob > |t|	Estimate	t Ratio	Prob > |t|	Estimate	t Ratio	Prob > |t|	Estimate	t Ratio	Prob > |t|
Head Top	X	-38.39	-11.22	<.0001	-139.63	-28.87	<.0001	-23.43	-4.84	<.0001	-20.64	-4.27	<.0001	-1.25	-0.26	0.7965
	Z	-50.77	-34.49	<.0001	95.01	45.64	<.0001	-3.25	-1.56	0.1202	9.35	4.49	<.0001	-0.59	-0.28	0.7769
Sternal Notch	X	-44.74	-25.03	<.0001	-77.84	-30.80	<.0001	-17.98	-7.11	<.0001	-16.82	-6.66	<.0001	-1.90	-0.75	0.452
	Z	-42.34	-62.64	<.0001	46.10	48.22	<.0001	-0.38	-0.40	0.6894	11.71	12.25	<.0001	0.55	0.58	0.5653
Avg. ASIS	X	-47.27	-58.30	<.0001	-14.23	-12.41	<.0001	-4.97	-4.33	<.0001	-10.61	-9.25	<.0001	-0.64	-0.56	0.5772
	Z	-39.59	-108.75	<.0001	0.81	1.57	0.1172	0.04	0.08	0.9375	2.53	4.91	<.0001	0.25	0.48	0.6340
Avg. Lateral Epicondyle	X	-51.56	-36.58	<.0001	-9.98	-5.01	<.0001	-3.22	-1.61	0.1078	-7.65	-3.84	0.0002	-1.01	-0.51	0.6141
	Z	-43.82	-39.40	<.0001	0.03	0.02	0.9825	-1.73	-1.10	0.2715	0.79	0.50	0.6176	-1.75	-1.11	0.2682
Avg. Lateral Malleolus	X	-21.92	-9.61	<.0001	-2.16	-0.67	0.504	-3.21	-1.00	0.3204	-0.13	-0.04	0.9669	-0.28	-0.09	0.9299
	Z	-58.34	-26.59	<.0001	-8.16	-2.63	0.0092	-3.81	-1.23	0.2204	-5.68	-1.83	0.0688	-2.56	-0.83	0.4095

Note: *each row represents a separate Repeated Measures ANOVA with seating condition, recline condition, and seating condition*recline condition included as fixed effects, subject included as a random effect, and a belt fit metric as a dependent variable. Highlighted cells correspond to p<0.05.*

TABLE AVI
CONTINUOUS POSTURE METRICS BY SEATING AND RECLINE CONDITION

Metric		Booster						No-booster					
		25°		45°		60°		25°		45°		60°	
		N	Mean ± SD	N	Mean ± SD	N	Mean ± SD	N	Mean ± SD	N	Mean ± SD	N	Mean ± SD
Segment Anterior/ Posterior Orientation	Pelvis	42	-58.3 ± 8.3	43	-69.6 ± 7.5	43	-74.2 ± 9.0	42	-63.2 ± 12.5	42	-68.8 ± 9.5	40	-70.8 ± 9.9
	L5	42	-39.8 ± 6.5	43	-57.8 ± 6.3	43	-68.5 ± 7.8	42	-44.9 ± 11.6	42	-57.5 ± 6.8	40	-64.9 ± 6.2
	L3	42	-37.1 ± 6.5	43	-57.8 ± 5.8	43	-70.6 ± 7.7	42	-42.3 ± 11.5	42	-57.8 ± 5.9	40	-67.2 ± 5.3
	T12	42	-28.6 ± 6.9	43	-52.1 ± 5.8	43	-67.3 ± 7.8	42	-33.8 ± 11.7	42	-52.5 ± 5.9	40	-64.2 ± 5.6
	T8	42	-16.3 ± 7.5	43	-42.0 ± 6.2	43	-59.3 ± 8.2	42	-21.7 ± 12.1	42	-42.7 ± 6.3	40	-56.3 ± 6.6
	Neck	42	4.3 ± 6.0	43	-17.8 ± 6.6	43	-35.9 ± 7.7	42	-2.5 ± 9.4	42	-20.6 ± 7.9	40	-35.6 ± 8.8
	Head	42	6.8 ± 9.1	43	-8.0 ± 12.4	43	-25.5 ± 13.3	42	-1.9 ± 11.1	42	-13.4 ± 16.7	40	-29.0 ± 15.8
	Avg. Shoulder	42	-8.6 ± 10.0	43	-35.2 ± 9.7	43	-54.0 ± 8.2	42	-12.8 ± 10.4	42	-33.3 ± 8.2	40	-50.3 ± 9.2
	Avg. Arm	42	-27.8 ± 8.0	43	-45.6 ± 9.3	43	-48.2 ± 13.6	42	-28.5 ± 7.9	42	-40.9 ± 9.5	40	-41.9 ± 12.0
	Avg. Forearm	42	-54.0 ± 10.3	43	-45.8 ± 21.2	43	-31.7 ± 38.0	42	-48.8 ± 14.9	42	-37.5 ± 28.1	40	-30.0 ± 33.8
	Avg. Thigh	42	-72.1 ± 7.8	43	-70.8 ± 9.3	43	-68.8 ± 9.1	42	-72.7 ± 9.2	42	-73.3 ± 10.0	40	-72.8 ± 9.6
	Avg. Leg	42	-39.0 ± 6.4	43	-44.4 ± 7.1	43	-45.5 ± 6.9	42	-29.8 ± 14.0	42	-30.0 ± 13.3	40	-30.9 ± 11.7
Flexion/ Extension Joint Angle	L5/S1	42	19.3 ± 3.8	43	13.2 ± 4.2	43	7.7 ± 5.0	42	19.1 ± 4.8	42	12.1 ± 4.8	40	7.2 ± 5.9
	L4/L3	42	2.7 ± 1.7	43	0.0 ± 1.9	43	-2.4 ± 2.2	42	2.7 ± 2.1	42	-0.4 ± 2.1	40	-2.6 ± 2.6
	L1/T12	42	8.6 ± 1.7	43	5.8 ± 1.9	43	3.4 ± 2.2	42	8.5 ± 2.1	42	5.4 ± 2.1	40	3.2 ± 2.6
	T9/T8	42	12.3 ± 1.3	43	10.2 ± 1.4	43	8.4 ± 1.7	42	12.2 ± 1.6	42	9.9 ± 1.6	40	8.2 ± 2.0
	T1/C7	42	20.4 ± 3.9	43	24.0 ± 4.6	43	23.8 ± 5.2	42	19.1 ± 5.9	42	21.8 ± 6.3	40	20.9 ± 6.6
	C1/Head	42	2.0 ± 7.3	43	8.8 ± 8.5	43	8.3 ± 9.6	42	-0.4 ± 11.0	42	4.6 ± 11.8	40	2.6 ± 12.8
	Avg. Shoulder	42	20.9 ± 15.0	43	19.9 ± 17.4	43	24.2 ± 37.7	42	21.3 ± 13.4	42	23.8 ± 26.0	40	29.2 ± 35.5
	Avg. Elbow	42	63.7 ± 18.8	43	52.7 ± 34.0	43	54.9 ± 44.8	42	67.2 ± 23.4	42	66.9 ± 36.2	40	65.1 ± 39.2
	Avg. Hip	42	37.0 ± 11.3	43	30.0 ± 9.5	43	24.2 ± 8.8	42	35.3 ± 13.2	42	28.7 ± 10.6	40	25.4 ± 9.9
	Avg. Knee	42	58.3 ± 8.8	43	56.7 ± 10.9	43	55.7 ± 9.8	42	70.1 ± 13.2	42	69.2 ± 13.3	40	67.8 ± 12.2

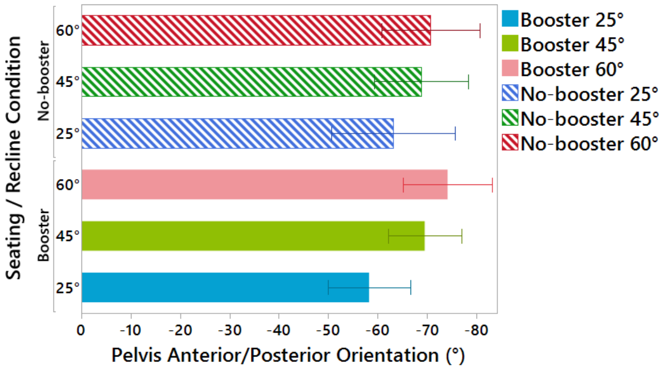


Fig. A8. Pelvis A/P orientation by seating and recline condition.

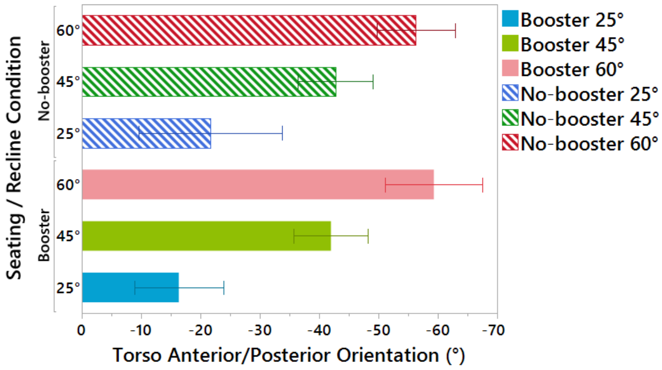


Fig. A9. Torso A/P orientation by seating and recline condition.

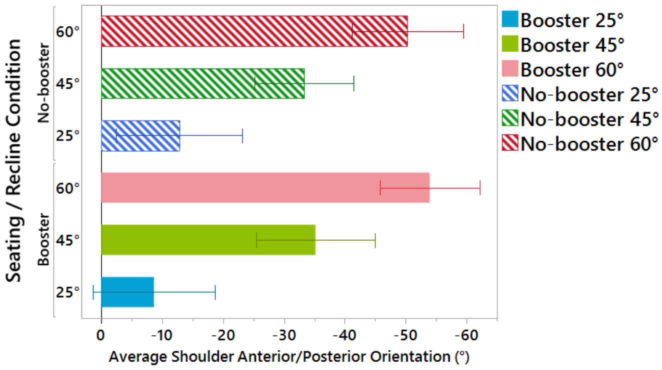


Fig. A10. Average shoulder A/P orientation by seating and recline condition.

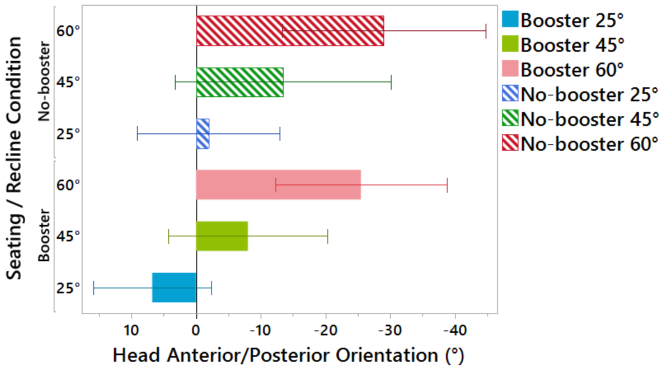


Fig. A11. Head A/P orientation by seating and recline condition.

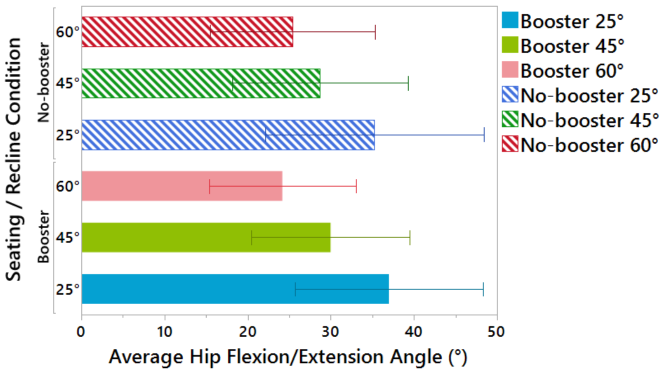


Fig. A12. Average hip flexion/extension by seating and recline condition.

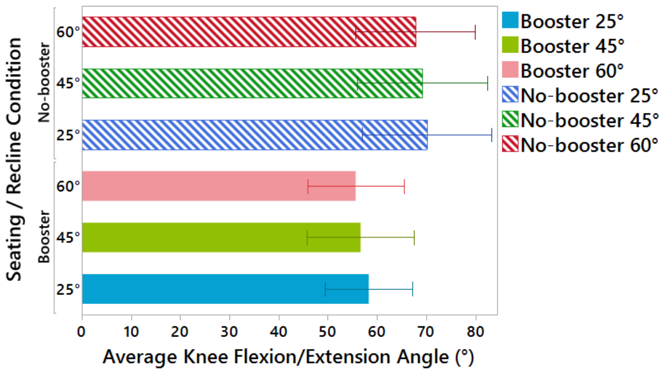


Fig. A13. Average knee flexion/extension by seating and recline condition.

TABLE AVII

REPEATED MEASURES ANOVA OF CONTINUOUS POSTURE BY SEATING AND RECLINE CONDITION

Dependent Variable		R^2_{Adj}	Fixed Effects						Random Effect	
			Seating Condition		Recline Condition		Seating*Recline Condition		Subject (random)	
			F Ratio	Prob > F	F Ratio	Prob > F	F Ratio	Prob > F	Wald p-value	% of Total
Segment Anterior/ Posterior Orientation	Pelvis	69.40%	0.00	0.9726	72.46	<.0001	8.28	0.0003	<.0001	54.06
	L5	82.17%	0.08	0.7796	370.85	<.0001	11.71	<.0001	0.0002	44.16
	L3	85.84%	0.35	0.5576	545.94	<.0001	11.16	<.0001	0.0003	40.25
	T12	88.50%	0.70	0.4028	722.93	<.0001	10.27	<.0001	0.0003	40.21
	T8	89.92%	0.96	0.3295	841.35	<.0001	9.63	0.0001	0.0002	42.77
	Neck	88.71%	14.14	0.0002	745.18	<.0001	6.85	0.0013	0.0004	38.84
	Head	70.20%	18.67	<.0001	164.68	<.0001	1.13	0.3235	0.0005	36.01
	Avg. Shoulder	89.22%	1.09	0.2972	756.35	<.0001	7.81	0.0005	0.0002	47.15
	Avg. Arm	61.99%	13.22	0.0004	98.95	<.0001	3.88	0.0222	0.0015	33.49
	Avg. Forearm	35.53%	3.28	0.0717	16.43	<.0001	0.42	0.6595	0.0057	21.29
	Avg. Thigh	55.82%	5.38	0.0213	1.52	0.2219	1.30	0.2747	0.0001	49.40
	Avg. Leg	67.88%	176.32	<.0001	6.35	0.0021	3.26	0.0406	0.0001	47.23
Flexion/ Extension Joint Angle	L5/S1	84.06%	1.72	0.1908	333.71	<.0001	0.45	0.6396	<.0001	62.10
	L4/L3	84.11%	1.75	0.1872	334.72	<.0001	0.44	0.6475	<.0001	62.21
	L1/T12	84.11%	1.75	0.1872	334.72	<.0001	0.44	0.6475	<.0001	62.21
	T9/T8	84.13%	1.77	0.1854	335.50	<.0001	0.43	0.6504	<.0001	62.23
	T1/C7	52.72%	16.87	<.0001	12.89	<.0001	0.81	0.4444	0.0003	40.48
	C1/Head	52.42%	17.60	<.0001	12.68	<.0001	0.96	0.3830	0.0003	39.98
	Avg. Shoulder	25.67%	1.05	0.3067	1.43	0.2408	0.22	0.8020	0.0108	18.20
	Avg. Elbow	45.89%	5.31	0.0223	1.08	0.3427	0.81	0.4473	0.0006	40.11
	Avg. Hip	60.42%	0.32	0.57	43.53	<.0001	0.73	0.4816	0.0001	45.46
	Avg. Knee	42.95%	86.48	<.0001	1.31	0.2728	0.03	0.9710	0.0082	19.45

Note: *each row represents a separate Repeated Measures ANOVA with seating condition, recline condition, and seating condition*recline condition included as fixed effects, subject included as a random effect, and a belt fit metric as a dependent variable. Highlighted cells correspond to p<0.05.*

TABLE AVIII

REPEATED MEASURES ANOVA PARAMETER ESTIMATES OF CONTINUOUS POSTURE BY SEATING AND RECLINE CONDITION

Dependent Variable		Parameter Estimates														
		Seating [Booster]			Recline [60°]			Recline [45°]			Seating [Booster]*Recline [60°]			Seating [Booster]*Recline [45°]		
		Estimate	t Ratio	Prob > |t|	Estimate	t Ratio	Prob > |t|	Estimate	t Ratio	Prob > |t|	Estimate	t Ratio	Prob > |t|	Estimate	t Ratio	Prob > |t|
Segment Anterior/ Posterior Orientation	Pelvis	0.01	0.03	0.9726	-5.05	-8.67	<.0001	-1.67	-2.89	0.0042	-1.75	-3.01	0.0029	-0.50	-0.87	0.3876
	L5	0.10	0.28	0.7796	-11.15	-21.33	<.0001	-2.07	-3.99	<.0001	-1.98	-3.79	0.0002	-0.37	-0.72	0.4748
	L3	0.21	0.59	0.5576	-13.45	-26.06	<.0001	-2.34	-4.56	<.0001	-1.95	-3.77	0.0002	-0.29	-0.58	0.5656
	T12	0.31	0.84	0.4028	-15.99	-30.24	<.0001	-2.54	-4.84	<.0001	-1.96	-3.71	0.0003	-0.21	-0.39	0.6935
	T8	0.38	0.98	0.3295	-18.08	-32.87	<.0001	-2.63	-4.81	<.0001	-2.03	-3.68	0.0003	-0.12	-0.22	0.8237
	Neck	1.46	3.76	0.0002	-17.73	-32.32	<.0001	-1.16	-2.12	0.035	-1.67	-3.05	0.0026	-0.16	-0.29	0.7741
	Head	2.90	4.32	<.0001	-15.49	-16.30	<.0001	1.18	1.25	0.2135	-1.08	-1.14	0.2561	-0.27	-0.28	0.7766
	Avg. Shoulder	-0.46	-1.05	0.2972	-19.70	-32.00	<.0001	-1.91	-3.13	0.002	-1.68	-2.72	0.007	-0.68	-1.12	0.2653
	Avg. Arm	-1.96	-3.64	0.0004	-6.23	-8.17	<.0001	-4.41	-5.83	<.0001	-1.45	-1.90	0.059	-0.62	-0.81	0.4163
	Avg. Forearm	-2.67	-1.81	0.0717	10.51	5.04	<.0001	-0.31	-0.15	0.8803	1.73	0.83	0.4092	-1.55	-0.75	0.4546
	Avg. Thigh	0.98	2.32	0.0213	1.01	1.70	0.0907	-0.31	-0.52	0.6029	0.76	1.28	0.2005	0.12	0.20	0.8403
	Avg. Leg	-6.31	-13.28	<.0001	-1.74	-2.59	0.0104	-0.55	-0.83	0.4089	-0.81	-1.21	0.2286	-0.90	-1.34	0.1810
Flexion/ Extension Joint Angle	L5/S1	0.24	1.31	0.1908	-5.63	-21.45	<.0001	-0.45	-1.73	0.0851	-0.08	-0.29	0.7698	0.24	0.93	0.3556
	L4/L3	0.11	1.32	0.1872	-2.50	-21.48	<.0001	-0.20	-1.74	0.0838	-0.04	-0.31	0.7597	0.11	0.92	0.3604
	L1/T12	0.11	1.32	0.1872	-2.50	-21.48	<.0001	-0.20	-1.74	0.0839	-0.04	-0.31	0.7597	0.11	0.92	0.3604
	T9/T8	0.08	1.33	0.1854	-1.88	-21.51	<.0001	-0.15	-1.74	0.0826	-0.03	-0.31	0.7546	0.08	0.91	0.3620
	T1/C7	1.10	4.11	<.0001	0.61	1.62	0.1061	1.26	3.35	0.001	0.42	1.10	0.2726	0.00	0.01	0.9920
	C1/Head	2.12	4.20	<.0001	1.09	1.53	0.1284	2.40	3.39	0.0008	0.86	1.21	0.2266	-0.01	-0.02	0.9831
	Avg. Shoulder	-1.52	-1.02	0.3067	3.53	1.68	0.0943	-1.38	-0.66	0.508	-0.97	-0.46	0.6448	-0.38	-0.18	0.8549
	Avg. Elbow	-3.94	-2.30	0.0223	-1.51	-0.63	0.5321	-2.01	-0.84	0.4041	-0.56	-0.23	0.8154	-2.32	-0.96	0.3358
	Avg. Hip	0.28	0.57	0.57	-5.29	-7.53	<.0001	-0.70	-1.00	0.3186	-0.85	-1.21	0.2287	0.36	0.52	0.6033
	Avg. Knee	-6.05	-9.30	<.0001	-1.30	-1.41	0.1589	0.03	0.03	0.9778	0.11	0.12	0.9052	-0.22	-0.24	0.8087

Note: *each row represents a separate Repeated Measures ANOVA with seating condition, recline condition, and seating condition*recline condition included as fixed effects, subject included as a random effect, and a belt fit metric as a dependent variable. Highlighted cells correspond to p<0.05.*

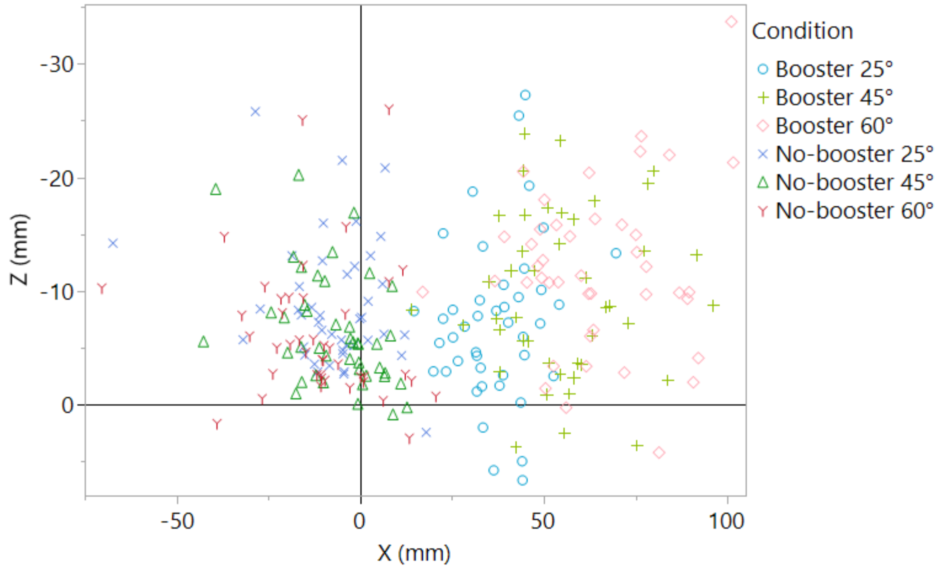


Fig. A14. Average lap-belt position wrt ASIS by seating and recline condition.

TABLE AIX

REPEATED MEASURES ANOVA OF BELT FIT BY SEATING AND RECLINE CONDITION

Belt Fit Metric	R^2_{Adj}	Fixed Effects						Random Effect	
		Seating		Recline		Seating*Recline		Subject	
		F Ratio	Prob > F	F Ratio	Prob > F	F Ratio	Prob > F	Wald P-value	% of Total
SBS	77.66%	558.41	<.0001	19.43	<.0001	0.61	0.5424	0.0004	37.31
Avg. LBS	90.81%	1793.79	<.0001	34.91	<.0001	39.11	<.0001	0.0001	45.15
Avg. LB wrt ASIS X	90.90%	1848.87	<.0001	25.92	<.0001	41.08	<.0001	0.0002	44.20
Avg. LB wrt ASIS Z	56.87%	17.86	<.0001	1.58	0.2092	12.62	<.0001	0.0001	45.99
Max. Shoulder Gap Size	52.43%	88.84	<.0001	13.14	<.0001	3.54	0.0307	0.0013	28.68
Max. Lower Gap Size	20.01%	7.04	0.0086	0.38	0.6876	3.98	0.0202	0.0613	10.87
Lower Gap Length	25.79%	6.97	0.0089	0.62	0.5389	3.09	0.0475	0.0162	16.19
Percent Torso Contact	21.02%	0.00	0.9552	1.99	0.1397	3.21	0.0422	0.0361	12.90

Note: *each row represents a separate Repeated Measures ANOVA with seating condition, recline condition, and seating condition*recline condition included as fixed effects, subject included as a random effect, and a belt fit metric as a dependent variable. Highlighted cells correspond to p<0.05.*

TABLE AX

REPEATED MEASURES ANOVA PARAMETER ESTIMATES OF BELT FIT BY SEATING AND RECLINE CONDITION

Belt Fit Metric	Parameter Estimates														
	Seating [Booster]			Recline [60°]			Recline [45°]			Seating [Booster]*Recline [60°]			Seating [Booster]*Recline [45°]		
	Est.	t Ratio	Prob > |t|	Est.	t Ratio	Prob > |t|	Est.	t Ratio	Prob > |t|	Est.	t Ratio	Prob > |t|	Est.	t Ratio	Prob > |t|
SBS	21.44	23.63	<.0001	7.09	5.52	<.0001	-0.33	-0.26	0.7972	1.35	1.05	0.2957	-1.07	-0.83	0.4051
Avg. LBS	21.19	42.35	<.0001	3.92	5.55	<.0001	1.88	2.67	0.0083	5.10	7.21	<.0001	0.61	0.86	0.3903
Avg. LB wrt ASIS X	30.36	43	<.0001	4.73	4.73	<.0001	2.33	2.33	0.0206	7.57	7.58	<.0001	0.50	0.50	0.6141
Avg. LB wrt ASIS Z	-1.25	-4.23	<.0001	-0.74	-1.78	0.0772	0.37	0.9	0.3704	-1.61	-3.87	0.0001	-0.35	-0.84	0.4034
Max. Shoulder Gap Size	-7.04	-9.43	<.0001	-4.91	-4.66	<.0001	4.40	4.18	<.0001	1.86	1.77	0.0787	0.90	0.85	0.3962
Max. Lower Gap Size	-1.92	-2.65	0.0086	-0.86	-0.85	0.3983	0.59	0.58	0.5621	-2.65	-2.6	0.0101	0.34	0.34	0.7366
Lower Gap Length	6.49	2.64	0.0089	-3.05	-0.88	0.3806	-0.55	-0.16	0.8751	-7.26	-2.09	0.0378	-0.45	-0.13	0.896
Percent Torso Contact	0.04	0.06	0.9552	1.59	1.62	0.1069	0.20	0.2	0.8379	2.17	2.21	0.0283	-0.02	-0.02	0.9869

Note: *each row represents a separate Repeated Measures ANOVA with seating condition, recline condition, and seating condition*recline condition included as fixed effects, subject included as a random effect, and a belt fit metric as a dependent variable. Highlighted cells correspond to p<0.05.*