Analysis of Child Belt Fit and Posture on a Selection of Belt-Positioning Boosters from the US and Swedish Markets

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Abstract

Background Previous studies have shown that belt-positioning booster design features may influence the posture and seatbelt fit for children. Many of these quantitative evaluations have investigated boosters and children in the United States. However, differences in booster certification standards, manufacturer user height and weight ranges, general vehicle design requirements, and consumer preferences may contribute to differences in booster user populations and design features between the US and other markets.

Purpose The goal of this study was to compare belt fit and postural outcomes for two cohorts of children evaluated on modern belt-positioning boosters with diverse designs from the US and Swedish markets.

Methods Two cohorts of child volunteers were recruited and evaluated independently in Columbus, Ohio, USA (n=26) and Göteborg, Sweden (n=25). Boosters were installed on a vehicle rear bench seat in a laboratory setting. A 3D coordinate measurement system quantified instantaneous positions of anatomic, seatbelt, booster, and vehicle reference points. Additionally, a non-invasive 3D motion capture system quantified all body segment orientations and joint angles. Additional postural, belt fit, and booster design measurements were calculated from instantaneous reference points.

Results The position of the anterior superior iliac spine (ASIS) and head top varied by booster, with high-back boosters producing more fore positions of all landmarks on average. Boosters from the SE study tended to produce more rear ASIS positions, especially for backless designs. The most reclined pelvis orientations were observed on one backless and one low-profile US booster (44.6° and 54.3°, respectively), while the remaining boosters fell within a similar range (25.8–38.5° on average). Shoulder belt score (SBS) fell within a similar range for most boosters while lap belt score (LBS) varied significantly across boosters, with one low-back and one low-profile US booster providing the significantly most inferior/distal LBS. Belt gap metrics varied significantly across boosters; however, no consistent trends were observed by booster type.

Discussion Belt fit and postural outcomes generally fell within similar ranges across boosters. However, some trends in postural and belt fit outcomes were observed between US and SE boosters. More fore pelvis positions and more reclined pelvis orientations were observed on US backless boosters, suggesting that children assumed more slouched postures on these designs. Differences in booster design parameters may influence these outcomes. US backless designs either had small amounts of boost or long seat lengths with more horizontal seat pan orientations which may not allow children to comfortably bend their knees over the front edge of the booster or vehicle seat. Lap belt fit was most different between US and SE backless boosters and was likely influenced by the position of lap belt routing features. Belt gap outcomes varied by booster, with some boosters providing larger and longer gap outcomes; however no consistent trends were observed between US and SE designs.

Conclusions Boosters from the US and SE markets generally provided belt fit and postural outcomes within a similar range; however, some significant differences were observed in postural and lap belt fit outcomes for boosters without backs.

Primary Theme/Topic Accident Research and Biomechanics
Keywords Belt-Positioning Boosters, Belt Fit, Posture

Background

Belt-positioning boosters help to improve the occupant protection of children in motor vehicles by helping to raise the child's seated height to position the vehicle shoulder and lap belts more appropriately with respect to the child's anatomy. Additionally, boosters help to control the position of children in the vehicle and promote upright postures which also help to achieve better fit of the shoulder and lap belts. Previous studies have quantified the posture and belt fit for children restrained by boosters and shown that boosters improve the belt fit and posture of children compared to when restrained on the vehicle seat alone (Jones et al. 2020; Klinich et al. 1994; Reed et al. 2013). Specific booster design features have also been shown to influence the posture and seatbelt fit for children. In particular, low-profile boosters have been shown to produce more fore pelvis positions (Jones et al. 2020), high-back boosters have been shown to produce more fore positions of the pelvis and torso compared to backless designs (Baker et al. 2021), and specific booster belt routing designs have been shown to influence belt fit and belt gap outcomes (Baker et al. 2021; Reed et al. 2009).

Many of the quantitative and laboratory-based evaluations of posture and belt fit have investigated boosters and children in the United States (Baker et al. 2021; Jones et al. 2020; Klinich et al. 1994, 2016; Reed et al. 2005, 2013). Other studies have investigated posture and/or belt fit of children in boosters using a variety of methods for other populations and markets, including Sweden (Andersson et al. 2010; Jakobsson et al. 2011; Osvalder et al. 2013), Australia (Albanese et al. 2020, 2022; Arbogast et al. 2016; Fong et al. 2017), and Spain (Forman et al. 2011). However, many of these studies have focused on naturalistic settings and methods, and no direct comparison has been made between posture and belt fit provided by boosters to children across different populations and between boosters manufactured for different consumer markets.

Differences in booster certification standards, manufacturer user height and weight ranges, general vehicle design requirements, and consumer preferences may contribute to differences in booster user populations and design features across different countries. In the United States, boosters are certified through the Federal Motor Vehicle Safety Standard (FMVSS) 213, which evaluates booster designs in a frontal impact sled test using the Hybrid III (HIII) 6-year-old (HIII06) and the HIII 10-year-old (HIII10) anthropomorphic test devices (ATDs). In Europe, boosters were previously subject to ECE Regulation 44 and are now subject to ECE Regulation 129, which evaluates booster designs using the Q-Series 6-year-old (Q6) and 10-year-old (Q10) ATDs. The HIII and Q-Series ATDs have different overall anthropometries and construction, which may influence how booster designs position the shoulder and lap belts or position occupants in the vehicle between US and European booster designs. Requirements to conduct and pass the certification standards FMVSS 213, ECE R44, and ECE R129 also differ in terms of their pulse, test boundary conditions, and maximum allowable kinematic, kinetic, and injury measures (National Highway Traffic Safety Administration (NHTSA) 2015; United Nations 2008, 2013), which may promote boosters with differing design features between the US and Europe.

Differences in cultural approach and public education efforts may also influence booster user populations and booster design features between countries. In the US, boosters are typically recommended for children who have outgrown their forward-facing harnessed child restraint and through at least 8 years of age (Durbin and Hoffman 2018; National Highway Traffic Safety Administration 2019). In Sweden, rear-facing child restraints are recommended for a longer period compared to the US, as long as possible or until at least four years of age (Transportsyrelsen (Swedish Transport Agency) 2017). Boosters in Sweden are recommended for children after outgrowing their rear-facing restraint (at least 4 years of age) and are required until they reach 135 cm stature and recommended until 10–12 years of age. This variation in recommendations between countries may influence when consumers expect to utilize a booster to restrain their child and may also influence which child anthropometries manufacturers design their boosters to appropriately restrain.

Thus far, no study has directly compared child posture and belt fit across two different booster populations and markets. Therefore, the goal of this study was to compare belt fit and postural outcomes for two cohorts of children representing different populations and evaluated on boosters with diverse designs from the US and Swedish markets.

Methods

Belt-Positioning Boosters

Six boosters available for purchase on the US market in 2019 were selected to represent various manufacturers, general booster designs, and belt routing features. Two 3-in-1 (3in1), one combination (comb), one dedicated high-back (HB), one dedicated low-back (LB), and one low-profile (Low) design were selected (Appendix, Table A-1). None were installed using LATCH. Each child was tested on up to six randomized boosters. Full methodology is available in Baker et al. 2021.

Five boosters available for purchase on the Swedish market in 2021 were selected to represent different manufacturers, general booster designs, and belt routing features. Two high-back (HB), two low-back (LB), and one integrated (INT) design were selected for evaluation (Appendix, Table A-2). The INT booster was part of the test vehicle in the outboard rear seating positions and included a higher or lower stage, which was selected based on the child's stature. Booster SE01-HB included a lap belt positioning device on the booster seat pan and removable padding around the shoulder belt. Use of the lap belt positioner is recommended but not required by the manufacturer; however, results are presented without utilizing the lap belt positioner to enable more direct comparison of the other boosters included in the study. Results are also presented without the use of the shoulder belt padding. The manufacturer instructions require the use of this padding which should be placed between the chin and the chest of the child; however, results are presented without the padding to enable more direct comparison to the remaining boosters and because use of this padding would have impeded the measurements of the position of the shoulder belt and anatomic landmarks on the child's torso. Boosters SE01-HB, SE02-LB, and SE03-HB used connectors to attach boosters to the ISOFIX anchorages in the vehicle. Booster SE05-LB allows for the shoulder belt to be routed either above or under the inboard belt routing, and the routing that produced the best shoulder belt fit was selected for each child. Each child was tested on two randomized booster designs.

The geometry of the booster designs is summarized below (Table 1). HB boosters tended to provide the greatest amount of average boost, followed by LB designs. The higher setting of the integrated booster (SE04-INT) provided a boost more similar to the HB boosters while the boost provided by the lower setting was more similar to the LB boosters. The low-profile booster (US05-Low) provided the lowest amount of boost of all designs. Seat length varied by boosters; however, LB designs tended to have the longest seat length on average compared to HB designs, the integrated booster, and the low-profile design. Orientation of the booster seat pan and seat back varied by booster design.

Table 1: Booster Geometries

Booster	Setting	Boost (mm)				Seat Length (mm)	Orientation* (°)	
		Front	Middle	Back	Average		Booster Back	Booster Seat Pan
SE01-HB	NA	94	124	142	120	272	-2.8	10.3
SE02-LB	NA	71	109	112	97	358	NA	6.8
SE03-HB	NA	77	108	106	97	285	0.6	5.6
SE04-INT	Higher	57	NA	68	62	259	NA	2.7
	Lower	96	NA	110	103	259		
SE05-LB	NA	76	92	91	86	292	NA	2.6
US01-HB	NA	106	81	55	85	254	2.9	13.1
US02-HB	NA	100	125	106	111	316	-1.0	0.0
US03-LB	NA	58	63	45	55	333	NA	3.4
US04-HB	NA	139	120	91	118	296	0.5	10.9
US05-Low	NA	5	10	13	20	197	NA	-3.9
US06-HB	NA	175	138	79	130	277	12.9	22.0

**Orientation with respect to vehicle seat back or seat pan, respectively.*

Recruitment and Sample Definition

Two cohorts of child volunteers were recruited and evaluated independently. Ethics approval was overseen by the Ohio State University for both cohorts, and in each case caregiver permission and verbal child assent were obtained (Protocols 201980207, 2019H0440). Children were eligible to participate if they were 4–12 years of age, 100–150 cm, and 15–36 kg. Twenty-six children were evaluated in the US cohort, and 25 children were evaluated in the SE cohort, for a combined 105 trials.

Test Setup

All boosters were installed on a vehicle rear bench seat in a laboratory setting. The US boosters were evaluated on a test fixture which included cushions from modern sedan rear seat and incorporated an integrated seatbelt outlet in the rear shelf, a production seatbelt and retractor assembly, and a simulated rigid buckle stalk (Figure 1a). The SE boosters were evaluated on the rear seat of a modern SUV which was parked in a laboratory setting (Figure 1b). The SE vehicle seat provided a more reclined seat pan angle and shorter seat length compared to the US vehicle seat (Table 2).

(a) (b)

Figure 1: Vehicle Seats from the US (a) and SE (b) Test Setups

Table 2: Vehicle Comparison

Measurement	**US**	**SE**
Vehicle Type	Sedan	Compact SUV
Seat Type	Bench	Bench
Seating Position	Left outboard	Right outboard
Seat Length (mm)	495	454
Seat Pan Angle (°)	7.6	13.7
Upper Seat Back Angle (°)	26.3	18.8
Lower Seat Back Angle (°)	26.3	23.2

A child passenger safety technician assisted each child to sit in the booster, routed the belt through any applicable belt routings and removed slack from the belt. Children were instructed and encouraged to sit in an upright, stationary position and were given the opportunity to watch a movie throughout the duration of each trial. In the SE setup, the front right passenger vehicle seat was placed in its foremost track position.

Measurement

A 3D coordinate measurement system (FARO Arm, Lake Mary, Florida) was used to quantify instantaneous positions of anatomic, seatbelt, booster, and vehicle reference points. All 3D positional data are presented with respect to the location of the seat bight centerline of each vehicle seat and utilizing a coordinate system where X points forward, Y points to the occupant's right, and Z points downward (Society of Automotive Engineers (SAE) 2014). Postural, belt fit, and booster feature measurements were calculated from instantaneous reference points. Shoulder belt score (SBS) represents the lateral distance between the inboard edge of the shoulder belt with the suprasternale landmark (Reed et al. 2009). Lap belt score (LBS) represents the distance between the superior edge of the lap belt and the ASIS landmark (Reed et al. 2009). Belt gap metrics were calculated as described previously (Baker et al. 2021). Briefly, gap size represents the maximum 3D distance between corresponding points along the shoulder belt and the torso. Gap length represents the length along the shoulder belt where there was no contact between the belt and the torso.

Additionally, a non-invasive 3D motion capture system (XSENS MVN Awinda) was utilized to quantify all body segment orientations and joint angles continuously at 60 Hz for the duration of each trial. Continuous XSENS postural outcomes were averaged across the duration of each trial.

Statistical Analysis

All statistical evaluations were performed in JMP Pro 16 (SAS Institute Inc., Cary, North Carolina). Two-sided Welch's t-tests were utilized to compare anthropometries between US and SE cohorts. One-way ANOVAs with Post-Hoc Tukey HSD tests were used to investigate relationships between boosters and average postural and belt fit outcomes. The alpha level was set to 0.05. In this analysis, boosters were categorized as "backless" if they were a LB, Low, or INT design.

Results

Participant Anthropometry

The participant anthropometry is summarized below (Table 3). Children did not significantly differ in terms of their age, mass, or stature. The children from the SE cohort displayed a significantly greater seated height by 3.5 cm on average, while US children had longer thigh lengths by 4.2 cm on average.

Table 3: Summary of Participant Anthropometry (Mean ± Std Dev)

Measurement	**US Cohort**	**SE Cohort**	**Welch's t-test Comparison***			
N	26	25	***n***	***DF***	***t Ratio***	***Prob > |t|***
Age (yr)	7.5 ± 2.0	6.8 ± 1.9	51	49.00	1.34	0.1868
Mass (kg)	25.2 ± 4.8	25.5 ± 4.9	51	48.75	0.27	0.7903
Stature (cm)	126.8 ± 9.9	126.1 ± 11.8	51	46.93	0.23	0.8201
Seated Height (cm)	65.0 ± 4.1	68.5 ± 5.8	51	43.21	2.52	0.0154
Thigh Length (cm)	35.3 ± 4.6	31.1 ± 5.2	51	47.74	3.06	0.0036

**A Two-sided Welch's t-test was completed for each metric, with cohort as the independent variable. Red shaded values represent p<0.05.*

Posture

The position of the anterior superior iliac spine (ASIS) and head top varied significantly by booster and are summarized in the Appendix, Table A-3. HB boosters provided more superior ASIS positions compared to LB, Low, and INT designs by 59 mm on average (Figure 2), and this difference was significant for most comparisons between HB and backless designs (Appendix, Table A-3). HB boosters also tended to provide more fore ASIS positions by 78 mm on average compared to boosters without backs. Considering only boosters without backs (LB, Low, and INT), backless boosters from the US study tended to allow for significantly more forward ASIS positions compared to the SE designs (by 75 mm on average). Similar trends were observed for the position of the head top (Figure 3), with HB designs tending to provide more fore (by 101 mm on average) and superior (by 91 mm on average) positions compared to boosters without backs (Appendix, Table A-3).

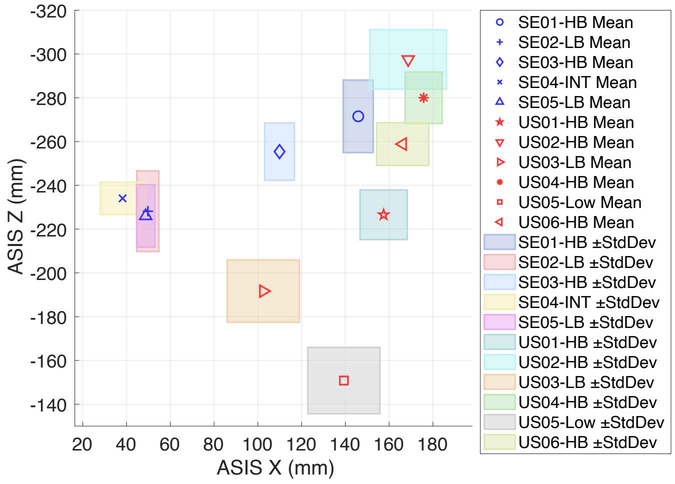

Figure 2: Sagittal ASIS Position with respect to Seat Bight Centerline by Booster and Study

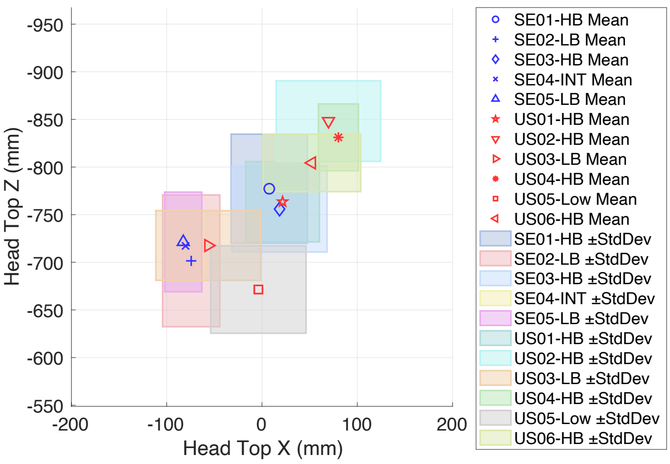

Figure 3: Sagittal Head Top Position with respect to Seat Bight Centerline by Booster and Study

In terms of continuous postural metrics, anterior/posterior (A/P) orientation of the pelvis with respect to the booster seat pan varied significantly by booster (Table 4). The most reclined pelvis orientations were observed on the US05-Low and US03-LB boosters (an average of 54.3° and 44.6°, respectively), and the US05-Low boosters provided significantly more reclined pelvis orientations compared to almost all other booster designs. The remaining boosters fell within a similar range of pelvis orientations (25.8–38.5° on average).

Table 4: Mean ± Std Dev Pelvis Orientation with respect to Booster Seat Pan (°)

Booster	**Pelvis A/P with respect to Booster Seat Pan**	
SE01-HB	25.8 ± 7.0	D
SE02-LB	34.8 ± 8.8	BCD
SE03-HB	28.8 ± 6.4	CD
SE04-INT	31.1 ± 5.7	CD
SE05-LB	33.3 ± 8.7	BCD
US01-HB	30.2 ± 4.3	CD
US02-HB	38.5 ± 6.8	BC
US03-LB	44.6 ± 9.1	AB
US04-HB	33.8 ± 8.3	BCD
US05-Low	54.3 ± 9.5	A
US06-HB	25.8 ± 5.3	D
ANOVA DF	100	
R^2_{Adj}	50.15%	
p-Value	<0.0001	

A one-way ANOVA was completed with booster as the independent variable. ANOVA DF, R^2_{Adj}, and p-Values are summarized above. Red shaded values represent $p<0.05$. Levels not connected by the same letter are significantly different ($p<0.05$ with Tukey correction for multiple comparisons).

Belt Fit Metrics

Belt fit and belt gap metrics varied significantly across booster designs and are summarized in Table 5. SBS fell within a similar range for most boosters (15–40 mm); however, the SBS on the US03-LB design was significantly more inboard compared to most other boosters (-1 mm).

LBS varied significantly across boosters, with the US05-Low and US03-LB designs providing the significantly most inferior/distal LBS (49 mm and 54.5 mm, respectively). Belt gap metrics (gap size, gap length, torso contact) varied significantly across boosters (Table 5). Boosters that produced larger gap sizes also provided longer gap lengths and lower percent torso contact outcomes. No strong trends were observed by overall booster type in terms of belt gap outcomes.

Table 5: Mean ± StdDev Belt Fit and Belt Gap Metrics

Booster	**SBS (mm)**		**LBS (mm)**		**Max Gap (mm)**		**Gap Length (mm)**		**Torso Contact (%)**	
SE01-HB	29 ± 8	A	16 ± 16	BCDE	30 ± 9	BC	76 ± 48	A	87 ± 9	ABC
SE02-LB	28 ± 24	A	11 ± 7	CDE	21 ± 6	BCD	88 ± 73	A	80 ± 17	C
SE03-HB	16 ± 11	AB	-1 ± 4	E	20 ± 9	BCD	39 ± 41	AB	93 ± 8	ABC
SE04-INT	29 ± 23	A	10 ± 6	CDE	23 ± 12	BCD	73 ± 65	AB	91 ± 12	ABC
SE05-LB	26 ± 18	A	28 ± 8	B	16 ± 6	CD	44 ± 52	AB	91 ± 13	ABC
US01-HB	40 ± 8	A	27 ± 14	BC	32 ± 13	B	95 ± 63	A	81 ± 12	BC
US02-HB	36 ± 15	A	8 ± 10	DE	12 ± 7	D	23 ± 32	AB	96 ± 6	AB
US03-LB	-1 ± 23	B	54 ± 13	A	19 ± 8	BCD	28 ± 46	AB	93 ± 12	ABC
US04-HB	36 ± 18	A	7 ± 12	DE	16 ± 5	D	26 ± 24	AB	98 ± 3	A
US05-Low	15 ± 17	AB	49 ± 18	A	12 ± 4	D	0 ± 0	B	100 ± 0	A
US06-HB	27 ± 13	A	22 ± 10	BCD	48 ± 17	A	80 ± 41	A	82 ± 9	BC
ANOVA DF	104		104		104		104		104	
R^2_{Adj}	23.66%		66.37%		49.99%		21.92%		23.69%	
p-Value	<0.0001		<0.0001		<0.0001		0.0002		<0.0001	

A one-way ANOVA was completed for each metric, with booster as the independent variable.
ANOVA DF, R^2_{Adj}, and p-Value are summarized above. Red shaded values represent p<0.05.
For each metric, levels not connected by the same letter are significantly different (p<0.05 with Tukey correction for multiple comparisons).

Discussion

Postural outcomes varied across booster designs, and some trends were observed between different booster types. In particular, HB boosters tended to provide more forward and more superior positions of the ASIS and head top compared to boosters without backs (LB, Low, and INT designs). This is consistent with previous studies which have also observed more superior positions of the head, sternum, pelvis, and knees on boosters with backs (Baker et al. 2021; Jones et al. 2020). The more superior positions of these landmarks are likely due to the increased degree of boost provided by HB designs compared to LB and Low boosters (Table 1).

Differences in the fore/aft position of the anatomic landmarks were also observed between booster designs. HB boosters tended to provide more fore positions on average of the ASIS (by 78 mm) and head top (by 101 mm), due to the presence of the booster back which positions the child further forward with respect to the vehicle seat back compared to boosters without backs. These more forward initial positions of children on HB boosters may place children closer to the back of the front passenger or driver's seats and may have implications for dynamic outcomes during vehicle maneuvers and crashes as larger forward excursions have been observed for pediatric ATDs on HB boosters compared to backless designs (Baker et al. 2022).

Additionally, some trends were observed between ASIS and head top positions between US and SE booster designs. Children on US boosters tended to have more fore ASIS and head top positions, both on boosters with and without backs, compared to SE children and boosters. On HB designs, these more fore positions of children on US boosters may be influenced by the geometry and orientation of the booster back and the fit of the exterior booster geometry with the vehicle seat orientation and contours. On backless designs, the more fore positions of the landmarks on the US boosters may suggest that children are assuming more slouched positions by translating their pelvis forward to a greater degree.

Pelvis A/P orientation also varied significantly across boosters. Two US booster designs (US03-LB and US05-Low) produced the most reclined pelvis A/P orientations with respect to the booster seat pan. These designs also produced the most forward position of the pelvis for boosters without backs. This combination of forward ASIS position and reclined pelvis suggests that children assumed more slouched postures on these boosters compared to other backless boosters (SE02-LB, SE04-INT, SE05-LB) or HB designs. Images of exemplary children on the boosters that provided the most (US03-LB and US05-Low) and least (SE01-HB and US06-HB) reclined pelvis orientations with respect to the booster seat pan are shown in Table 6.

Table 6: Exemplary Pelvis Orientations with respect to the Booster Seat Pan

More Reclined Pelvis Orientation*		**Less Reclined Pelvis Orientation***	
US03-LB	***US05-Low***	***SE01-HB***	***US06-HB***
			

**Children approximately represent the average pelvis orientation with respect to the booster seat pan.*

Differences in booster design parameters may influence the observed variation in postural outcomes. Slouching has previously been observed for children when seated on vehicle seats or boosters whose seat lengths are too long to allow the children to comfortably bend their knees (Jones et al. 2020; Klinich et al. 1994, 2016). In the current evaluation, the US LB/Low boosters provided combinations of design parameters (either small amounts of boost or long booster lengths with more horizontal seat pan orientations, see Table 7) which also may not allow children to comfortably bend their knees over the front edge of the booster or vehicle seat. Specifically, US03-LB had one of the longest seat lengths and more horizontal seat pan orientations, and US05-Low had the smallest amount of boost and shortest seat length. In contrast, the SE LB/INT boosters offered a different combination of design parameters which may have allowed children to sit more rear on the booster and more comfortably bend their knees without slouching. SE02-LB also had a long seat length; however, it also had a more reclined seat pan. SE04-INT had a short seat length but also provided a larger amount of boost compared to the US05-Low design. Overall, the combinations of design features observed on the SE backless designs seem to have helped to prevent slouching, observed by children assuming more rear ASIS positions and less reclined pelvis orientations on these designs. Differences in vehicle seat geometry may have also influenced these differences in postural outcomes observed between backless boosters from the US and SE studies Specifically, the more reclined vehicle seat cushion orientation of the SE vehicle (Table 2) effectively provides a more reclined global booster seat pan orientation and may reduce the likelihood of children assuming slouched postures. This likely also contributed to the less reclined pelvis orientations (with respect to booster seat pan) and more rear ASIS positions observed for children on the SE backless booster designs. This influence of vehicle seat pan orientation on the postural outcomes emphasizes the importance of evaluating boosters across a variety of vehicle environments.

Table 7: Lateral-Oblique Views of Boosters without Backs (LB, Low, INT)

US03-LB	US05-Low	SE01-LB	SE05-LB	SE04-INT
				

Significant differences were also observed between boosters in terms of belt fit and belt gap outcomes (Table 5). SBS varied significantly by booster; however, most boosters fell within a similar range. The largest differences between boosters were observed for LBS. The US05-Low and US03-LB designs provided more inferior/distal LBS compared to SE LB boosters (SE01-LB and SE05-LB). This difference in lap belt position is likely influenced by the lap belt routing features which were placed more fore with respect to the booster back on the US LB/Low boosters compared to the SE LB designs (Table 7).

Belt gap metrics varied by booster design, with some boosters providing larger and longer gap outcomes (Table 5). Boosters which provided greater maximum gap size also tended to provide longer gap lengths and smaller percent torso contact outcomes, which are consistent with previous investigations (Baker et al. 2021). While no consistent trends were observed between US and SE boosters in terms of belt gap outcomes, US boosters tended to provide a greater range of average belt gap outcomes compared to SE designs. Average maximum gap size ranged from 12–48 mm for US designs compared to 16–30 mm for SE designs. Similarly, average gap length on US boosters ranged from 0–95 mm while SE boosters ranged from 39–88 mm. This difference in the range of average belt gap outcomes may in part be attributed to the differences in selection of booster designs between the two studies, as the US study included boosters which can also be used in rear-facing and/or forward-facing harnessed mode while the SE study only included dedicated booster designs, which are more popular in the SE market due to the differences in national recommendations and usage patterns which emphasize extended rear-facing harnessed restraint and then transition to a booster.

Conclusions

Overall, good booster designs should promote consistent posture and belt fit for children across a range of ages and anthropometries. Differences in booster design features may influence both posture and belt fit for children. Boosters from the US and SE markets generally provided belt fit and postural outcomes within similar ranges; however, some significant differences were observed in postural and lap belt fit outcomes for boosters without backs. In particular, children seated on boosters with long seat lengths and less reclined seating surface angles, or designs which do not provide enough boost tended to assume more slouched postures. Additionally, LB/Low boosters with lap belt routings placed further forward with respect to the back of the booster produced more inferior/distal LBS.

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Appendix

Table A-1: US Boosters

Booster	Manufacturer, Model	Type	Mass Range (kg)	Stature Range (cm)	Image
US01-HB	Baby Trend, PROtect Yumi	HB	13.6–45.4	96.5–144.8	
US02-HB	Chicco, MyFit	Comb/ HB	18.1–45.4	96.5–144.8	
US03-LB	Cosco, Topside	LB	18.1–45.4	109.2–144.8	
US04-HB	Evenflo, EveryStage DLX	3in1/ HB	18.1–54.4	111.8–144.8	
US05-Low	Mifold	Low	18.1–45.4	101.6–144.8	
US06-HB	Safety1st, Grow and Go EX	3in1/ HB	18.1–45.4	109.2–132.1	

Table A-2: SE Boosters

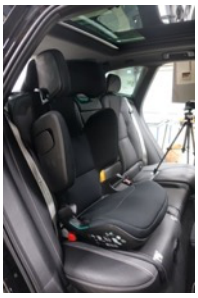
Booster	Manufacturer, Model	Type	Mass Range (kg)	Stature Range (cm)	Image
SE01-HB	BeSafe, iZi Flex FIX i-Size	HB	NA	100–150	
SE02-LB	Britax Römer , KidFix M i-Size	LB	15–36	135–150	
SE03-HB	Britax Römer, KidFix M i-Size	HB	15–36	100–150	
SE04-INT	Volvo, Integrated Booster (Lower Stage)	INT	22–36	115+	
SE04-INT	Volvo, Integrated Booster (Higher Stage)	INT	15–25	95–120	
SE05-LB	Volvo, Booster Cushion	LB	15–36	NA	

Table A-3: Mean ± Std Dev Position of Anatomic Landmarks (mm)

Booster	**ASIS**				**Head Top**			
	X		**Z**		**X**		**Z**	
SE01-HB	146 ± 7	CD	-272 ± 17	DE	8 ± 40	C	-777 ± 57	CDE
SE02-LB	50 ± 5	F	-228 ± 18	C	-74 ± 30	E	-702 ± 69	AB
SE03-HB	110 ± 7	E	-255 ± 13	D	18 ± 50	BC	-756 ± 45	BCD
SE04-INT	38 ± 10	F	-234 ± 7	C	-80 ± 19	E	-717 ± 33	ABC
SE05-LB	49 ± 4	F	-226 ± 14	C	-83 ± 19	E	-721 ± 52	ABC
US01-HB	157 ± 11	BC	-227 ± 11	C	22 ± 39	ABC	-764 ± 42	BCDE
US02-HB	169 ± 18	AB	-298 ± 14	F	70 ± 55	AB	-848 ± 42	F
US03-LB	102 ± 16	E	-192 ± 14	B	-56 ± 55	DE	-718 ± 37	ABC
US04-HB	176 ± 8	A	-280 ± 12	EF	80 ± 21	A	-831 ± 35	EF
US05-Low	139 ± 16	D	-151 ± 15	A	-4 ± 50	CD	-671 ± 46	A
US06-HB	166 ± 12	AB	-259 ± 10	D	52 ± 51	ABC	-804 ± 30	DEF
ANOVA DF	104		104		104		104	
R^2_{Adj}	95.33%		89.13%		66.12%		55.18%	
p-Value	<0.0001		<0.0001		<0.0001		<0.0001	

A one-way ANOVA was completed for each metric, with booster as the independent variable. ANOVA DF, R^2_{Adj}, and p-Values are summarized above. Red shaded values represent $p<0.05$. For each metric, levels not connected by the same letter are significantly different ($p<0.05$ with Tukey correction for multiple comparisons).