Comparison of Self-Selected, Holding Device, and Nominal Conditions on the Belt Fit and Posture of Children on Belt-Positioning Boosters

Gretchen H. Baker, Katarina Bohman, Julie A. Mansfield, Lotta Jakobsson, John H. Bolte IV

Abstract Children assume a range of postures when utilising belt-positioning boosters, which may influence belt fit and have implications for dynamic performance. This study evaluates the belt fit and posture of children on boosters while assuming different postures: self-selected, holding device, and nominal. Children (n=25) were recruited (4–11 years, 103.0–146.5 cm, 17.8–33.6 kg) and evaluated on two of five randomised boosters. A 3D coordinate measurement device and an inertial measurement unit-based motion capture system quantified posture, e.g., head, torso, and pelvis positions and orientations, and belt fit, e.g., shoulder belt score, lap belt score, maximum gap size, gap length. Outcomes were compared across postural conditions and boosters using repeated-measures ANOVA. The device condition produced significantly more forward and flexed head postures compared to self-selected and nominal (by 58 mm and 15.0° on average). Variation was small in terms of belt fit and belt gap metrics between postural conditions, suggesting that belt routing features provided similar belt placement despite postural adjustment; however, greater variation is expected in naturalistic settings. This study is the first to directly evaluate the posture and belt fit of children while holding electronic devices and to investigate the influence of different postural conditions on belt fit and postural outcomes.

Keywords Belt-positioning boosters, child restraint systems, posture, seat belt fit.

I. INTRODUCTION

Belt-positioning booster seats help to adapt the child to the vehicle environment to provide improved posture and positioning with respect to the seatbelt and increased comfort for children. While boosters have been shown to help centralise the child's position in the vehicle seat and reduce the likelihood of slouched postures, children still assume a variety of postures while restrained by boosters. In particular, booster-seated children have been shown to most often sit in upright postures with the upper back and shoulders in contact with the seatback and with the seatbelt in *close-to-neck* or *mid-shoulder* positions [1,2]; however, forward head positions have been observed [3] in addition to instances of extreme forward or forward/lateral leaning postures [1–3].

Child posture in boosters may be influenced by a variety of factors, including occupant behaviours such as sleeping, looking out the window, interacting with other occupants, and utilising portable electronic devices. In particular, children have been shown to qualitatively produce more forward head and shoulder positions when utilising electronics [4]. Quantification of naturalistic child postures, such as when they are utilising electronics, will help to understand the postural variability expected during driving and provide valuable data for investigation of the influence of naturalistic postures on dynamic outcomes during manoeuvres or crashes.

Previous work has evaluated self-selected and upright child postures in a laboratory setting in different booster conditions [5]. Generally, children assumed more slouched postures with looser belt fit in self-selected, compared to upright postures [5]. For one backless booster, the head top position was more inferior (7 mm, on average), and the abdomen and pelvis were more reclined (by 3.9° and 8.0° on average, respectively) in self-selected postures, compared to upright [5]. Previous studies have evaluated the effect of self-selected child postures on belt fit compared to standardised postures, with a focus on quantifying anatomic angles and lap belt fit [5]; however, effects of posture on shoulder belt position and torso engagement with the belt have not been fully investigated. Thus, the goal of this study was to investigate the influence of naturalistic child postures on belt fit, belt gap, and postural outcomes for children restrained by boosters in a vehicle setting.

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II. METHODS

Experimental Design and Test Setup

Ethics approval was obtained from the Ohio State University, USA, (Protocol 2019H0440). Twenty-five child volunteers between the ages of 4–12 years, 100–150 cm stature, and 15–36 kg were recruited and evaluated on the outboard right hand rear seating position of a modern compact SUV which was parked in a laboratory setting (Fig. 2). The vehicle seat was a bench style which included a seatbelt outlet integrated into the rear shelf and an integrated booster in the outboard rear seating positions. The vehicle seatback angle was 19.0° from vertical, the seat cushion angle was 13.7° from horizontal, and the seat cushion length was 454 mm. Boosters (n=5) were selected for evaluation from designs available for purchase on the Swedish market in 2021. Boosters represented different manufacturers and belt routing guide designs. Two high-back (HB), two low-back (LB), and one integrated (INT) design were selected (Table I, Fig. 1). All boosters were evaluated on the same vehicle.

TABLE I
BELT-POSITIONING BOOSTERS

Booster	01-HB	02-LB	03-HB	04-INT	05-LB
Manufacturer	Be Safe	Britax Romer	Britax Romer	Volvo	Volvo
Model	iZi Flex FIX i-Size	KidFix M i-Size (without back)	KidFix M i-Size (with back)	Integrated Booster	Booster Cushion
Type Approval	ECE R129	ECE R44	ECE R44	ECE R44	ECE R44


(a) 01-HB (b) 02-LB (c) 03-HB (d) 04-INT lower (e) 04-INT higher (f) 05-LB
Fig. 1. Exemplary Booster Images.

The integrated booster included two height settings. The manufacturer instructions recommend the lower setting for children greater than 115 cm stature and between 15–36 kg or higher stage for children between 95–120 cm stature and 15–25 kg. Children less than 115 cm or less than 22 kg were evaluated on the higher stage for this study while the remaining were evaluated on the lower stage. Booster 01-HB included a lap belt positioning device on the 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 utilising the lap belt positioner (unless noted) to enable more direct comparison to 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 01-HB, 02-LB, and 03-HB used connectors to attach boosters to the ISOFIX anchorages in the vehicle to reduce booster motion during child entry and egress. Booster 05-LB allows for the shoulder belt to be routed either above or under the inboard arm rest, and the routing that produced the best shoulder belt fit was selected for each child. Each child was tested on two randomised booster designs, for a total of 50 trials included in the full dataset.

Data Collection

The seat belt was marked along its midline at 2 cm increments to obtain consistent measurements along the shoulder and lap belts. A 3D coordinate measurement device (FARO Quantum Arm, Lake Mary, Florida, USA) was used to capture three dimensional measurements of landmarks on the vehicle, boosters, seatbelts, and children (Table A-II). All data is presented with respect to the SAE J211 coordinate system (Society of Automotive Engineers

(SAE) 2014), where +X points forward, +Y points to the occupant's right, and +Z points downward. The origin was located at the vehicle seat bight centreline.

An inertial measurement unit (IMU)-based 3D motion capture system (XSENS MVN Awinda) was used to quantify the posture of the children. The sensor placement protocol was followed as described in the user manual [6], with one exception. The pelvis sensor was directly taped to the skin, such that the sensor was placed over the sacrum and the top of the sensor was in line with the posterior superior iliac spine (PSIS) landmarks. A certified child passenger safety technician (CPST) adjusted booster settings, installed the booster following manufacturer instructions, and placed the seatbelt on the child.

Children were assessed in the following three postural conditions: self-selected posture (*Self-selected*), self-selected posture while holding a tablet computer (*Device*), and an upright and centralised posture (*Nominal*). In each condition, instantaneous measurements of anatomic landmarks (Table A-II) and the position of the seatbelt were captured with the FARO Arm. In the Self-selected condition, children were allowed to settle into their posture and watched a film of their choosing on a portable tablet computer which was attached to the back of the front passenger seat (Fig. 3). In the Device posture, children held the tablet computer while still watching the film. In the Nominal posture children were instructed to sit with their hips, shoulders, and head all the way back against the booster or vehicle seat, and to maintain an upright and still posture as much as possible. In the Nominal condition the children watched the tablet computer, which was also attached to the back of the front passenger seat. Children were seated in each postural condition for approximately 7 minutes, on average.

Fig. 2. Vehicle test environment.

Fig. 3. Location of tablet computer during Self-selected and Nominal conditions.

Data Analysis

Booster characteristics were calculated by capturing additional measurements with the Faro Arm on each booster while no occupant was seated on the booster. These measurements were then transformed to each trial's data using booster reference measurements obtained during each trial with an occupant. Booster characteristics were calculated, as described in previous studies [7,8] including amount of boost, booster seat cushion length, booster seat cushion angle, and booster back angle.

Belt fit (shoulder belt score, lap belt score) and belt gap (maximum gap size, gap length, and percent torso contact) metrics were calculated as described in previous studies [8,9] but are described briefly here. Shoulder belt score (SBS) was defined as the lateral distance between the inboard edge of the shoulder belt and the suprasternale landmark on the superior sternum [9]. Lap belt score (LBS) is the distance from the superior edge of the lap belt to the ASIS landmark on the front of the pelvis and was averaged for left and right sides [9]. Maximum gap size represents the largest 3D distance between corresponding points on the shoulder belt and the occupant's torso [8]. Gap length was defined as the length along the shoulder belt that was not in contact with the occupant's torso [8]. Percent torso contact is the percentage of the shoulder belt, along the length from the superior shoulder to the pelvis, that was directly in contact with the occupant's torso [8].

Postural measurements were obtained from instantaneous measurements from the FARO Arm and continuous postural measurements from the XSENS motion capture system. Instantaneous measurements include the sagittal position of the head top, suprasternal, average left/right ASIS, average left/right patella, and right lateral malleolus. Instantaneous measurements were also used to calculate the thigh anterior/posterior (A/P) orientation, which was obtained by evaluating the angle in the sagittal plane with respect to horizontal of a line fit to a stream of measurements along the anterior surface of the proximal thighs. Knee flexion/extension (F/E) angle was also calculated by evaluating the sagittal plane angle with respect to horizontal of a line connecting the average patella location and right lateral malleolus. For instantaneous measurements, all participant trials were averaged for each booster and postural condition for comparison.

Continuous measurements included: the anterior posterior orientation of the head, sternum, and pelvis, and the F/E joint angles for the T1/C7 and C1/Head joints. Additionally, the A/P orientation of the pelvis with respect to the booster seating surface was calculated by subtracting the global sagittal booster seat pan orientation from the global A/P pelvis orientation. For continuous measurements, all metrics were first averaged across each trial (across the period required to obtain all instantaneous measurements) which was on average 7 minutes. Next, all continuous measurements were averaged for each unique booster and postural condition for comparison.

All statistical evaluations were performed in JMP Pro 17. Comparisons of postural measurements, belt fit, and belt gap metrics were compared using Repeated Measures ANOVA, with booster and postural condition as the independent categorical variables and participant included as a random effect. Individual means were compared for each level of booster and postural condition using Post-Hoc Tukey-Kramer tests to generate connecting letters reports. The alpha level was set a priori to 0.05.

III. RESULTS

Participants

Twenty-five child volunteers were evaluated, and their anthropometry is summarised below (Table II). Participants were normally distributed in terms of the recruitment characteristics: age, mass, and stature. Participants spanned the allowable mass and stature recommendations of the boosters and ranged from 4th to 99th CDC percentile [10].

TABLE II
SUMMARY OF CHILD PARTICIPANT ANTHROPOMETRY

Metric	Mean ± Std Dev	Range
Age (yr)	6.8 ± 1.9	4–11
Mass (kg)	25.5 ± 4.9	17.8–33.6
Stature (cm)	126.1 ± 11.8	103.0–146.5
Seated Height (cm)	68.5 ± 5.8	58.0–77.5
Acromion Width (cm)	25.5 ± 3.3	14.7–29.6
ASIS Width (cm)	17.8 ± 1.5	15.2–20.4
Thigh Length (cm)	31.1 ± 5.2	25.7–41.8
BMI (kg/m^2)	15.9 ± 1.3	13.8–19.3
CDC %-ile	53.3 ± 29.0	4.0–99.0

Booster Characteristics

Booster characteristics are summarised in the Appendix (Table A-I). HB boosters provided greater boost and shorter seat lengths compared to LB boosters. The integrated booster provided the smallest boost, shortest seat length, and most horizontal seat angle. Generally, booster 01-HB provided the highest and most forward position of the shoulder belt in the lower belt guide. Booster 05-LB provided two different positions, depending on if the shoulder belt was routed above or below the arm rest. When the belt was routed above the arm rest, booster 05-LB provided the most rear belt position in the belt guide. When the belt was routed under the armrest, booster 05-LB provided belt positions similar to boosters 02-LB and 03-HB. Booster 04-INT provided the rearmost (with the exception of booster 05-LB with the belt routed over the arm rest) and lowest belt position on average.

General Postural Observations

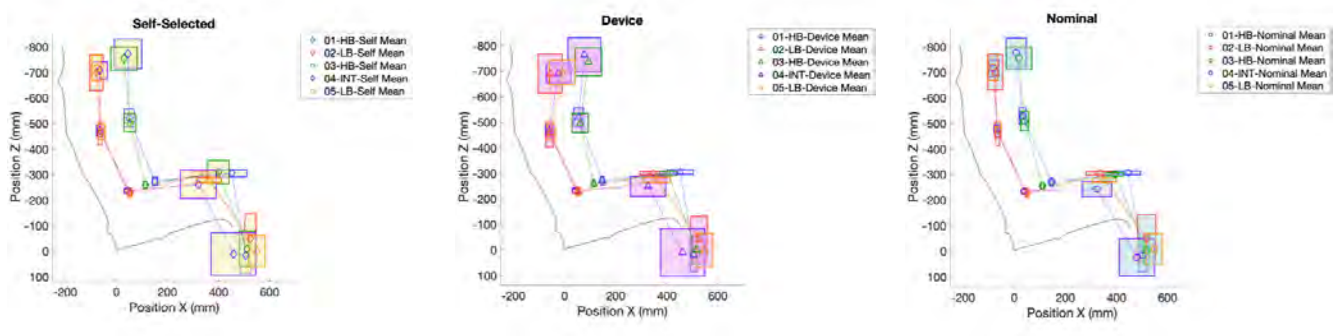
A summary of exemplary postures observed for children can be found in the Appendix (Fig. A-1–Fig. A-9). Children generally assumed upright postures, with their head, shoulders, and extremities within the side wings of the boosters (if present) and maintained centralised positions with respect to the vehicle seat centreline (Fig. A-1). Slouched postures were visually observed for some children on some boosters (Fig. A-2). Overall, small differences were observed between Self-selected and Nominal postural conditions.

In the Device postural condition, children tended to have more forward head and torso positions (Fig. A-3, Fig. A-4, Fig. A-5); however, children employed different strategies to assume comfortable holding device postures.

Some children let the device rest on their thighs without holding it (n=22, Fig. A-11), other children rested part of the device on their thighs while holding it in an upright orientation (n=26, Fig. A-4), and a few children held the device without resting it on their thighs (n=2, Fig. A-5). Other children adjusted their lower extremity postures, either by extending their legs to place their feet on the back of the passenger seat (n=3, Fig. A-6), flexing their hips and knees to place their feet on the front edge of the vehicle seat cushion (n=1, Fig. A-7), or by rotating their lower extremities sideways (n=1, Fig. A-8). On booster 04-INT, some children (n=8) naturally placed their feet on the front edge of the vehicle seat, on a small shelf created when the integrated booster is in use (Fig. A-9). This posture was observed more often for shorter children seated on the integrated booster in its higher stage.

Postural Outcomes by Booster

The head top, suprasternale, ASIS, knee, and right lateral malleolus positions varied by booster and postural condition (Table A-IV). HB boosters tended to provide significantly more superior and more fore positions of the head top, suprasternale, and ASIS landmarks compared to other LB and INT boosters (Table A-III, Fig. 4). Similar to head top position, suprasternale position also tended to be significantly more fore and more superior on HB boosters compared to the remaining LB and INT boosters (Table A-III, Fig. 4). Average ASIS position varied between boosters, with HB Boosters (01-HB, 03-HB) providing more fore and more superior positions compared to the integrated (04-INT) and LB (02-LB, 05-LB) designs (Table A-III, Fig. 4). Both booster and postural condition significantly ($p<0.05$) explained variation in the sagittal ASIS position (Table A-IV). ASIS X position significantly ($p<0.05$) differed between all booster designs, with the exception of LB boosters (02-LB, 05-LB) which were not significantly different ($p>0.05$) from each other. ASIS Z position significantly divided boosters into groups, with HB boosters providing the most superior position (01-HB, 03-HB), boosters 02-LB and 04-INT providing a more inferior position, and booster 05-LB providing the most inferior position on average.



(a) Self-Selected condition, all boosters *(b) Device condition, all boosters* *(c) Nominal condition, all boosters*

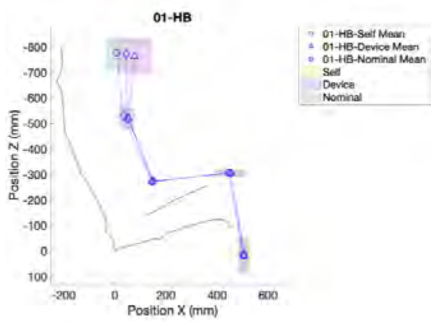
Fig. 4. Mean (scatter point) ± standard deviation (shaded rectangle) head top, suprasternale, average ASIS, average patella, and right lateral malleolus position for all boosters by postural condition (vehicle seat contour in grey, rectangle line colours represent booster, and shaded rectangle colours and symbols represent postural condition).

Average patella X position varied between boosters, with HB boosters producing more fore positions compared to the other designs (Table A-III). Booster and posture both significantly explained variation in the patella X position ($p<0.05$), but only booster significantly explained variation in patella Z position (Table A-IV). Sagittal lateral malleolus positions fell within a similar range across boosters (Table A-III). Booster significantly explained variation ($p<0.05$) in lateral malleolus sagittal position while postural condition did not (Table A-IV).

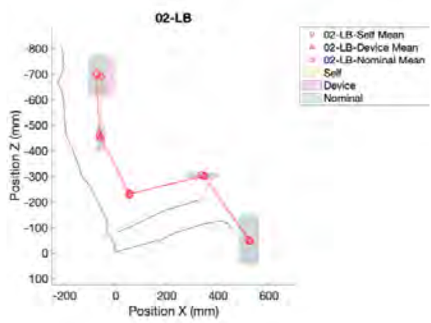
Average thigh A/P orientation fell within a similar range across boosters (Table A-VI). Booster 05-LB tended to provide the most positive orientation (thighs angled above vertical) while booster 04-INT tended to produce the smallest positive orientation (thighs angled more horizontally). Booster significantly explained variation ($p<0.05$) in average thigh A/P orientation, while postural condition did not (Table A-IV, Table A-VII). Average knee F/E angle also varied across boosters but tended to fall within a similar range (Table A-VI). HB boosters tended to produce the most knee flexion on average while LB boosters tended to produce the least knee flexion.

Postural Outcomes by Postural Condition

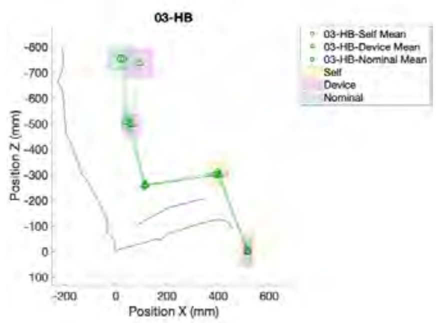
Some significant differences ($p<0.05$) were also observed between postural conditions, with the Device posture producing more fore and inferior head top and suprasternale positions compared to the Nominal and Self posture conditions (Table A-IV). On average, the head top X position was 58 mm more fore and 19 more inferior in the Device posture compared to the Nominal posture condition (Table A-V, Fig. 5). Sagittal suprasternale position was also significantly (p<0.05) different between postural conditions. The Device posture condition provided the most fore and most inferior suprasternale positions, followed by the Self and Nominal conditions, and all differences between conditions were significant (p<0.05). On average, the Device posture suprasternale position was 14 mm more fore and 11 more inferior than the Nominal posture condition (Table A-V, Fig. 5). Significant differences (p<0.05) between postural conditions were also observed between Self and Nominal. Self-selected postures produced significantly more fore and more superior ASIS positions than the Nominal posture condition but neither were significantly different to the Device posture condition. Patella X position was also significantly (p<0.05) more fore in the Device compared to the Nominal condition (by 9 mm on average) (Table A-V, Fig. 5).



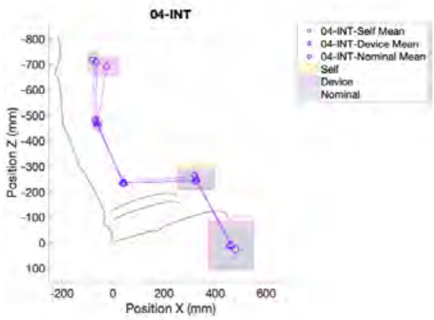
(e) Booster 01-HB, all conditions



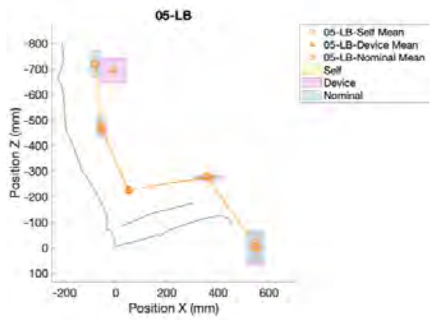
(b) Booster 02-LB, all conditions



(c) Booster 03-HB, all conditions



(4) Booster 04-INT, all conditions



(e) Booster 05-LB, all conditions

Fig. 5. Mean (scatter point) ± standard deviation (shaded rectangle) head top, suprasternale, average ASIS, average patella, and right lateral malleolus position for all postural conditions by booster (vehicle seat and booster seat cushion contours in grey, and shaded rectangle colours and symbols represent postural condition).

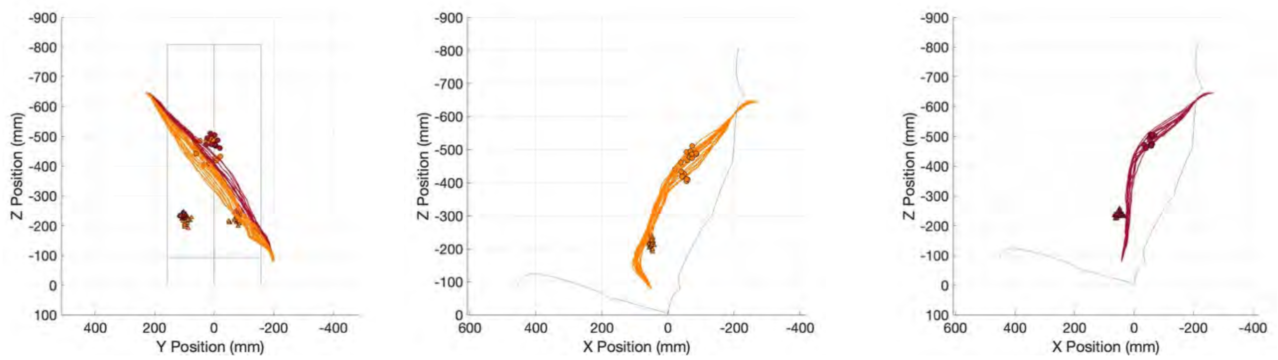
Average continuous postural measurements are summarised in Table A-VIII and tended to vary across booster and posture conditions (Table A-IX). Boosters produced head A/P orientations generally within a similar range (Table A-VIII); however, significant differences were observed between booster and postural conditions (Table A-IX). In particular, the Device postural condition produced more negative head orientations (the Frankfurt plane angled further below horizontal) compared to Nominal and Self-selected postures. On average, the head orientation in the Device posture was 15.0° more negative than in the Nominal posture condition (Table A-X). Similarly, F/E angles between the Head and C1 and between C7 and T1 were within a similar range across boosters (Table A-VIII) and were also significantly different (p<0.05) between booster and postural conditions. Device postures again were significantly different (p<0.05) than Nominal and Self-selected posture conditions by producing more flexed Head/C1 and C7/T1 angles (Table A-IX). On average, Device postures produced 8.7° more flexion at Head/C1 and 5.0° more flexion at C7/T1 compared to Nominal postures (Table A-X). Booster 03-HB produced the significantly smallest (p<0.05) flexion, or in some cases largest extension, C1/Head angle compared to other boosters on average.

Global sternum A/P orientation also fell within a similar range across boosters (Table A-VIII); however, significant differences between booster and posture conditions were observed (Table A-IX). Again, booster 03-HB was significantly different (p<0.05) than other boosters by producing a more negative (more upright) torso orientation. In terms of postural condition, Self-selected postures were significantly (p<0.05) more positive (reclined) compared to Device and Nominal postures. On average, Self-selected sternum orientations were 3.5° more positive (reclined) compared to Nominal (Table A-X). Global pelvis A/P orientation with respect to the booster seating surface were similar across boosters (Table A-VIII), but significant differences ($p<0.05$) were observed between booster and postural conditions (Table A-IX). Pelvis A/P orientation with respect to booster was significantly different ($p<0.05$) between Device and Nominal postural conditions, with the Device postural condition producing 2.8° more reclined pelvis orientations compared to Nominal on average (Table A-X).

Belt Fit

Belt fit and belt gap metrics are summarised in the Appendix (Table A-XI) and generally fell within similar ranges and tended to vary by booster and not by postural condition (Table A-XII). SBS was most inboard for booster 03-HB and most outboard on average for boosters 02-LB and 04-INT (Table A-XI). SBS was significantly influenced by booster ($p<0.05$) but not by postural condition, and Boosters 03-HB and 04-INT were the only boosters significantly different from each other in terms of SBS (Table A-XII).

Of the boosters without an upper shoulder belt guide, booster 05-LB allows for two different routings of the shoulder belt (either under or over the inboard arm rest), depending on the size of the child and position of the belt on the shoulder (Fig. 6). This option to allow for an either over- or under-arm rest routing helped to adapt the shoulder belt placement to the anthropometry of the child, without incorporating an upper shoulder belt guide or positioner. As a result, the SBS of booster 05-LB tended to be less outboard on average and produced a smaller standard deviation and range compared to the other boosters without upper belt guides (Table A-XI).



(a) Frontal view, both routings *(b) Sagittal view, under belt routing* *(c) Sagittal view, over belt routing*

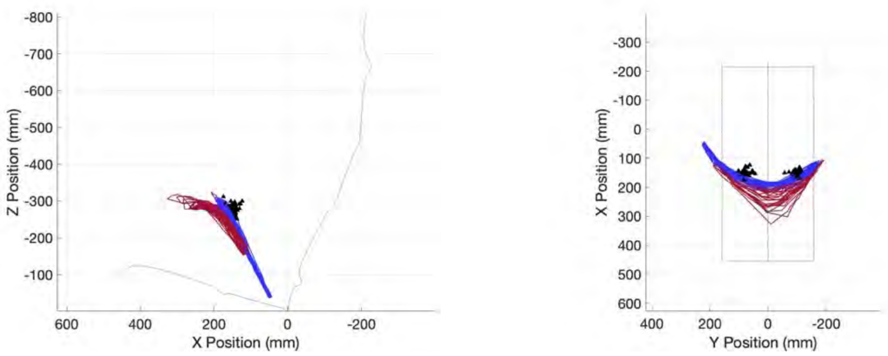
Fig. 6. Booster 05-LB over (red) and under (orange) belt routings, suprasternale (circles), and ASIS (triangles) positions.

While booster 04-INT does offer adjustability for child anthropometry between its two height settings, the routing of the shoulder belt is not altered (such as, through a different belt routing feature) between these two height settings (Fig. 7). This suggests that maintaining optimal shoulder belt placement for children on boosters may be influenced both by raising the child's seated height with respect to the belt outlet or D-Ring and by adjusting the path of the shoulder belt near the shoulder and/or pelvis through specific belt guides or routing the belt around an arm rest.

(a) Frontal view, both higher (red) and lower (purple) height settings *(b) Higher height setting* *(c) lower height setting*

Fig. 7. Booster 04-INT higher (red) and lower (purple) height setting shoulder belt routings, suprasternale (circles), and left ASIS (triangles) positions, and images of exemplary children.

LBS was most inferior/distal for the LB and INT boosters compared to the HB designs evaluated here (Table A-XI). Booster significantly influenced LBS (p<0.05) while postural condition did not (Table A-XII). All boosters were significantly different in terms of LBS, with the exception of 02-LB and 04-INT. LBS was not significantly different between posture conditions (p>0.05). For booster 01-HB, LBS was more inferior/distal when the lap belt positioner was used; however, slack was introduced into the belt, and a lack of contact between the belt and pelvis centreline was observed (Table A-XIII, Fig. 8).



(a) Sagittal view, *(b) Top view*

Fig. 8. Booster 01-HB with (red) and without (blue) lap belt positioner lap belt routings, ASIS (triangles).

Maximum gap size fell within a similar range for all boosters (Table A-XI). Booster 01-HB had the largest maximum gap size on average while booster 05-LB had the smallest (Table A-XI). Neither booster nor posture condition significantly contributed (p>0.05) to maximum gap size (Table A-XII). Gap Length fell within a similar range for most boosters (Table A-XI). Boosters 02-LB and 04-INT produced the longest gap length on average while booster 03-HB produced the smallest gap length on average (Table A-XI). Booster significantly explained variation in gap length (p<0.05), while postural condition did not; however, only booster 03-HB was significantly different to boosters 02-LB and 04-INT (Table A-XII). Percent torso contact fell within a similar range for all boosters (Table A-XI). Boosters 01-HB and booster 03-HB produced the highest percent torso contact while booster 02-LB produced the lowest, on average (Table A-XI). Booster significantly explained variation in percent torso contact (p<0.05), while posture condition did not (Table A-XII).

IV. DISCUSSION

Overall, children in this study assumed generally centralised and upright postures, with a few instances of slouching and variation in lower extremity position observed (Fig. A-2–Fig. A-9). Differences in child posture were observed between boosters, and booster significantly (p<0.05) explained variation in all instantaneous (Table A-IV) and continuous (Table A-XII) postural metrics. This suggests that, when accounting for variation due to postural condition and subject, booster design features significantly influenced postural outcomes. In particular, differences were observed between HB boosters compared to LB and integrated designs. HB boosters tended to produce more superior and fore positions of the head top, suprasternale, and ASIS, in addition to more fore positions of the patella, compared to LB and integrated designs. This is likely due to the presence of the booster back which does not allow the child to sit as rearward on the vehicle seat. This supports findings from previous work, which have also observed more forward and superior head, pelvis, and knee positions on boosters with backs [8,11,12]. Previous work has identified that a majority of head contacts sustained by children in the rear seat during motor vehicle crashes (MVCs) occur on the back of the first-row vehicle seats or side of the vehicle interior [13]. Greater head excursions have been observed for highback boosters compared to backless boosters in frontal sled tests of paediatric anthropomorphic test devices (ATDs) (54-92 mm greater on average considering all boosters evaluated for each ATD), which may be attributed in part due to their initially more forward head positions due to the presence of the booster back [14,15]. Prior studies have also observed variation in head positions for children in boosters in naturalistic driving studies, and common forward-leaning postures placed the head 100 mm more forward [3,4,16]. More forward head positions may be influenced by the presence and size of the side wings in addition to occupant behaviours, such as interacting with other occupants, engaging in lap-based activities, or looking out of the window. This variation in initial head positions for children in boosters suggest the need to quantify and account for the range of possible head positions of children on all booster types and for a range of user postures. Highback boosters may present a combination of initially more forward head positions due to the presence of the booster back in addition to the potential for more forward head positions due to typical postural and behavioural variation of children, which may present more challenging initial head positions prior to a crash and may not be captured in evaluations with ATDs placed in standard, upright postures. Thus, the initial position of body landmarks with respect to the vehicle interior is one important aspect to consider when evaluating areas of improvement for booster design.

Slouching

Slouched postures have been observed previously for children on boosters and have been associated with more forward pelvis locations and lower head positions [11,12,17]. While significant differences in potential slouching metrics were observed between boosters in the present study, the magnitudes of the differences between boosters were relatively small. In particular, average pelvis orientations across boosters in the Nominal condition ranged from 26.1–35.2° (Table A-VIII). When comparing LB boosters to the INT design, the LB designs in the Nominal condition produced ASIS positions on average 12 mm more fore compared to the INT booster (Table A-III). This difference in ASIS X position is smaller than differences observed previously between low-profile and LB designs, which were about 40 mm on average [7]. While more extreme slouched postures were not observed in the present study, the participants were aware of being observed, evaluated in a laboratory setting, and were only observed for a short duration. Greater variation in postures (including slouching) is expected during longer-duration evaluations and more naturalistic settings, as has been observed previously [1–4].

Device and Self-Selected Posture Conditions

In the Device posture condition, children tended to assume more forward head and torso postures and displayed various strategies to hold the portable electronic device. Even when accounting for variation due to booster and subject, the Device condition produced significantly different postural outcomes in terms of the head and torso positions, head orientation, C1/Head flexion, and T1/C7 flexion (Table A-IV, Table A-IX). When holding the Device, children tended to translate and rotate their heads forward (by 58 mm and 15.0° on average, respectively) to watch the screen, which was in most cases resting or partially resting on their thighs. This change in head position and orientation can also be observed in the increase in C1/Head flexion for the Device condition by 8.7° on average compared to the Nominal condition. This difference in fore/aft head position observed in the Device postural condition is within the range of head positions observed in prior naturalistic driving studies of booster-seated children in vehicles but is smaller than the most commonly observed forward leaning posture which placed the head approximately 100 mm more fore [4]. The initially more forward head positions of children observed while in the Device condition, in addition to the increased distance between the child's head and the head restraint, may expose the child to generally higher injury risk.

In Self-selected postures, children generally displayed similar postures to the Nominal condition, with a few variations. The head A/P orientation, C1/Head flexion, C7/T1 flexion, and pelvis A/P orientation were similar between Nominal and Self-Selected conditions (Table A-X); however, children tended to assume slightly more forward head, suprasternale, ASIS, and knee positions compared to the Nominal posture (Table A-V). Again, the small differences in self-selected postures observed here were likely influenced by the short duration and laboratory setting, and a greater range of self-selected postures are expected during naturalistic settings.

Belt Fit

Variation in belt fit and belt gap metrics was significantly associated with booster design but not postural condition when accounting for subject variation (Table A-XII). However, the postural variation captured in this study does not represent the range of naturalistic postures observed in previous studies with more naturalistic settings, during extended driving, and/or where children were unaware of being observed [1–4]. Previous naturalistic studies have qualitatively observed more extreme belt fit scenarios compared to those measured here, for example, cases where the shoulder belt has been misused or slipped off the shoulder [1,2]. Thus, this study does not represent the true range of belt fit and belt gap outcomes that might be expected during normal driving. However, these results do suggest that that the booster design features were generally able to maintain similar belt fit and belt gap outcomes, regardless of the variation in the child's posture captured here. This small variation in belt fit and belt gap outcomes observed across these changes in child posture suggest that belt fit and belt gap measurements captured in a laboratory setting can be considered representative of nominal child belt fit, regardless of small postural variations that may occur during the period of measurement.

While significant differences in belt fit and belt gap metrics were not observed across posture conditions, variation between boosters was observed (Table A-XII). In terms of SBS, HB boosters provided the smallest range and standard deviation of SBS, and booster 03-HB provided the most inboard SBS, on average (Table A-XI). The smaller variation in SBS for HB boosters suggests that the presence and vertical adjustability of the upper shoulder belt guide helps to maintain more consistent SBS across children of different anthropometry compared to the LB and integrated boosters evaluated in this study which did not include any upper shoulder belt guide features.

Significant differences in LBS were observed between boosters after accounting for postural condition and subject variability (Table A-XII). Specifically, HB boosters tended to provide more superior LBS compared to LB and integrated designs, which provided more inferior/distal lap belt positions (Table A-XI). This may be attributed in part to the more rear ASIS positions allowed on LB boosters compared to HB designs (Table A-III). Additionally, the LB boosters in this study routed the lap belt under the arm rests which may also contribute to placing the belt more inferiorly on the pelvis or forward on the thighs (Table A-XI). This supports previous work which has also identified larger inferior/distal LBS on backless booster designs compared to boosters with backs [8]. Prior studies have also suggested that boosters which provide too superior or too inferior of LBS may contribute to suboptimal crash outcomes. In this study, booster 01-HB provided LBS which were superior of the ASIS, for a majority of children when the belt positioner was not used. If the LBS is placed too superiorly, the child may have an increased propensity for submarining under the lap belt during a crash [9,18]. When the lap belt positioner was used, the LBS increased to 16 mm on average in the Nominal condition, which was more in line with the LBS of the LB and INT boosters (Table A-XI, Table A-XIII). While use of the lap belt positioner resulted in an improvement in LBS in this case, use of the lap belt positioner for some children was difficult, due to the short length of the positioner and its more rear position on the booster seat cushion. This caused the lap belt path to be pulled forward away from the pelvis, causing a distinct change in the lap belt path, contributing to a lack of contact between the lap belt and the pelvis, and introducing distinct slack in the belt system (Fig. A-10). Use of such positioners may also increase the likelihood of misuse when placing the lap belt and have the potential to contribute to child discomfort.

In terms of belt gap outcomes, boosters provided a similar range of maximum gap size (Table A-XI); however, some boosters displayed significant differences between gap length and percent torso contact (Table A-XII). The longest average gap length and smallest percent torso contact was observed for booster 02-LB while the smallest gap length and largest percent torso contact was on booster 03-HB (Table A-XI). Overall, average gap sizes (17–27 mm) and lengths (39–88 mm) generally fell within the smaller range of those observed previously (gap size: 11–41 mm; gap length: 0–157 mm) for a group of 50 children on 10 boosters [8]. This may be explained by the differences in the position of the shoulder belt as it passes through the lower belt guide of the boosters. Generally, the boosters included in the present study placed the shoulder belt more rearward compared to the boosters measured previously (Table A-XI) and more closely aligned with the position of the boosters which provided smaller gap size and length outcomes [8]. This difference in lower belt guide position for the boosters in the present study may be due to the fact that all were dedicated boosters while the previous study also included CRS which transitioned from forward- and rear-facing harnessed modes. Additionally, boosters in the present study were purchased from the European market and may have design features influenced by differences in the certification standards and ATDs utilised in Europe [19,20] compared to the US [21].

Variation in initial belt gap size and length has previously been identified to contribute to differential shoulder belt interaction and belt slip-off potential for booster-seated children during evasive vehicle manoeuvres [22–

25]. Specifically, less initial belt-to-torso contact contributed to greater lateral displacement and more instances of shoulder belt slip-off during evasive steering manoeuvres, while greater initial belt-to-torso contact helped the belt to stay on the shoulder and the children to displace inboard to a lesser degree [22,25]. However, further work is required to identify the influence of these initial belt gap conditions on dynamic outcomes for paediatric occupants during MVCs.

Limitations

This study has important limitations to consider alongside the results. Only five boosters have been investigated, and boosters with other design features may provide different belt fit, belt gap, and postural outcomes which may not be captured in the data presented here. In addition, children were evaluated for a short duration (7 minutes, on average) in a laboratory setting and were aware of being observed. Thus, the range of child postures observed here may not represent the expected range of user postures children may exhibit as vehicle occupants. In addition, children wore sensors which were strapped or taped to their body, which may also influence their postures and behaviours. This study has also only presented the average of the continuous postural metrics for each posture condition. Variations in child posture throughout the measurement period may also provide additional valuable information and show differences between postural conditions. Finally, the children evaluated in this study may not be representative of all booster users. Children who are smaller than booster manufacturer requirements have been known to utilise boosters prematurely, and their posture and belt fit outcomes may differ significantly from the children who are within the manufacturer size requirements. In Sweden, children are typically recommended to be restrained on a booster after transitioning out of their rear-facing, harnessed child restraint, at approximately 4 years of age or older. Based on data from 2022 of 1,676 children in Sweden, 68% of children aged 4–7 years and 12% of children aged 8–11 years were restrained in boosters [26]. This rate of booster use is higher for the 4–7 years age range compared to the United States, which was reported at 37% in 2019 [27]. In the United States, a greater proportion of children aged 4–7 years were restrained using forward-facing harnessed restraints (32.5%) compared to Sweden (3%) [26,27]. These differences in restraint usage patterns may influence the degree of applicability of the results presented here to other countries and populations.

V. CONCLUSIONS

Overall, children displayed generally greater variation in posture and belt fit outcomes across boosters compared to those observed between the different postural conditions assessed here (Self-Selected, Device, and Nominal). In general, highback designs produced more fore and superior positions of the head top, suprasternale, and ASIS compared to backless and integrated designs. Additionally, the observed postural differences across the Self-Selected, Device, and Nominal postural conditions were relatively small. However, the largest difference between postural conditions occurred during the Device condition, which resulted in more forward and flexed postures of the head. Children also displayed different strategies to hold the portable electronic device, with a majority resting the device fully or partially on their thighs. However, children displayed similar belt fit and belt gap metrics across postural conditions, suggesting that booster belt routing features were able to maintain similar belt placement regardless of the child's postural adjustments. These relatively small differences in belt fit and posture across postural conditions were likely influenced by the short duration of evaluation, laboratory setting, and awareness of the children of being observed and are thus not representative of the full range of user postures and belt fit expected during typical driving or when boosters are potentially misused.

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VIII. APPENDIX

TABLE A-I
BOOSTER CHARACTERISTICS

Booster	Setting	Boost (mm)				Seat Length (mm)	Orientation* (°)		Avg. Position of Belt in Lower Belt Guide	
		Front	Middle	Back	Average		Seat Pan	Back	X (mm)	Z (mm)
01-HB	NA	94	124	142	120	272	10.3	-2.8	90	-190
02-LB	NA	71	109	112	97	358	6.8	NA	63	-112
03-HB	NA	77	108	106	97	285	5.6	0.6	77	-128
04-INT	Lower	57	NA	68	62	259	2.7	NA	28	-193
	Higher	96	NA	110	103	259	2.7	NA		
05-LB	Over†	76	92	91	86	292	2.6	NA	25	-158
	Under†								82	-134

** Booster seat pan or back orientation with respect to vehicle seat pan or vehicle seat back, respectively.*
†Shoulder belt routed either over or under the inboard armrest, as allowed by manufacturer.

TABLE A-II
REFERENCE POINTS MEASURED WITH THE FARO ARM

Booster Reference	Subject	Belt Fit Metrics
	Head Top	Shoulder Belt crosses clavicle
Corner references	Tragion R	Shoulder Belt leaves shoulder
Lower Belt Guide	Suprasternale	Shoulder Belt crosses at suprasternale
Upper Belt Guide	Acromion L/R	Shoulder Belt crosses torso midline
*Seating Surface Front**	ASIS L/R	Lap Belt Crosses ASIS L/R
*Seating Surface Mid**	Patella L/R	Shoulder Belt Stream‡
*Seating Surface Back**	Lateral Malleolus R	Lap Belt Stream‡
	Lap Streams†	Torso Stream§

** Obtained without occupant present and transformed to each trial's data using common booster reference points*
† Lap Streams captured as described in previous work, a stream of measurements along the lower abdomen and thigh along the sagittal plane defined by the position of the ASIS [28]
‡ Shoulder Belt *and Lap Belt Streams were captured every 2 cm along the belt midline, as described in previous work* [8]
§ Torso Stream was captures every 2 cm along the shoulder belt midline, with the belt pressed to fully contact the torso, as described in previous work [8]

Fig. A-1. Exemplary Nominal.

Fig. A-2. Exemplary Slouched.

Fig. A-3. Exemplary Device, resting device completely on thighs.

Fig. A-4. Exemplary Device, resting device partially on thighs.

Fig. A-5. Exemplary Device, holding device without resting on thighs.

Fig. A-6. Exemplary Self-selected, legs extended and feet on front seat.

Fig. A-7. Exemplary Self-selected, knees flexed and feet placed on seat cushion.

Fig. A-8. Exemplary Self-selected, knees rotated inboard.

Fig. A-9. Exemplary Self-selected, feet naturally placed on seat cushion.

TABLE A-III

MEAN ± STANDARD DEVIATION ANATOMIC LANDMARK POSITIONS

Booster	Posture	Head Top		Suprasternale		ASIS		Patella		Right Lateral Malleolus	
		X (mm)	Z (mm)	X (mm)	Z (mm)	X (mm)	Z (mm)	X (mm)	Z (mm)	X (mm)	Z (mm)
01-HB	*Self*	46 ± 54	50 ± 19	50 ± 19	-522 ± 35	151 ± 10	-275 ± 16	452 ± 59	-305 ± 14	507 ± 22	15 ± 69
	Device	77 ± 64	54 ± 19	54 ± 19	-520 ± 38	147 ± 7	-273 ± 16	452 ± 52	-305 ± 9	505 ± 15	18 ± 66
	Nominal	8 ± 40	32 ± 14	32 ± 14	-530 ± 32	146 ± 7	-272 ± 17	445 ± 49	-307 ± 8	502 ± 18	16 ± 65
02-LB	*Self*	-78 ± 26	-64 ± 8	-64 ± 8	-461 ± 45	53 ± 7	-233 ± 14	347 ± 49	-302 ± 10	525 ± 22	-49 ± 99
	Device	-57 ± 47	-60 ± 14	-60 ± 14	-453 ± 50	53 ± 9	-231 ± 16	346 ± 51	-301 ± 7	526 ± 33	-45 ± 87
	Nominal	-74 ± 30	-65 ± 8	-65 ± 8	-460 ± 47	50 ± 5	-228 ± 18	334 ± 53	-305 ± 7	518 ± 36	-53 ± 91
03-HB	*Self*	29 ± 52	52 ± 24	52 ± 24	-503 ± 35	114 ± 7	-261 ± 15	399 ± 42	-310 ± 45	512 ± 32	-9 ± 71
	Device	93 ± 52	61 ± 32	61 ± 32	-497 ± 38	113 ± 5	-261 ± 14	405 ± 33	-299 ± 9	515 ± 17	0 ± 56
	Nominal	18 ± 50	41 ± 16	41 ± 16	-509 ± 38	110 ± 7	-255 ± 13	394 ± 33	-301 ± 7	516 ± 11	-2 ± 54
04-INT	*Self*	-66 ± 31	-64 ± 14	-64 ± 14	-473 ± 21	42 ± 13	-237 ± 8	320 ± 70	-263 ± 55	458 ± 88	10 ± 83
	Device	-24 ± 47	-60 ± 15	-60 ± 15	-468 ± 25	42 ± 13	-233 ± 8	326 ± 69	-250 ± 40	461 ± 87	10 ± 94
	Nominal	-80 ± 19	-70 ± 10	-70 ± 10	-481 ± 18	38 ± 10	-234 ± 7	323 ± 58	-244 ± 31	480 ± 69	25 ± 73
05-LB	*Self*	-78 ± 18	-58 ± 14	-58 ± 14	-469 ± 30	52 ± 7	-227 ± 15	363 ± 47	-278 ± 9	550 ± 32	0 ± 62
	Device	-9 ± 51	-52 ± 16	-52 ± 16	-462 ± 31	51 ± 5	-226 ± 13	362 ± 53	-275 ± 10	547 ± 33	2 ± 67
	Nominal	-83 ± 19	-63 ± 12	-63 ± 12	-474 ± 32	49 ± 4	-226 ± 14	353 ± 46	-279 ± 7	547 ± 33	-7 ± 61

TABLE A-IV

REPEATED MEASURES ANOVA OF INSTANTANEOUS POSTURE BY BOOSTER AND POSTURE

Dependent Variable		Total	R Square	Booster			Posture			Booster Connecting Letters*					Posture Connecting Letters*		
		N	Adj	DF	F Ratio	p-Value	DF	F Ratio	p-Value	01-HB	02-LB	03-HB	04-INT	05-LB	Self	Device	Nominal
ASIS	*X*	150	97.64%	4	1040.4020	<0.0001	2	4.4603	0.0136	A	C	B	D	C	A	A B	B
	Z	150	92.10%	4	140.5338	<0.0001	2	3.9310	0.0222	C	B	C	B	A	B	A B	A
Supra-sternale	*X*	150	96.54%	4	604.4651	<0.0001	2	18.0980	<0.0001	A	B	A	B	B	B	A	C
	Z	150	95.77%	4	136.8810	<0.0001	2	17.0410	<0.0001	C	A	C	B	A	B	A	C
Head Top	*X*	150	79.18%	4	64.5591	<0.0001	2	38.4409	<0.0001	A	B	A	B	B	B	A	B
	Z	150	95.92%	4	80.0881	<0.0001	2	27.0799	<0.0001	C	A	C	B	A	B	A	B
Patella	*X*	150	93.69%	4	126.2768	<0.0001	2	3.1446	0.0467	A	C	B	C	C	A B	A	B
	Z	150	56.52%	4	29.3665	<0.0001	2	0.9445	0.3918	C	C	C	A	B	A	A	A
Lateral Malleolus	*X*	150	71.36%	4	17.5528	<0.0001	2	0.1052	0.9002	B	A B	B	C	A	A	A	A
	Z	150	87.97%	4	18.5895	<0.0001	2	0.1779	0.8373	A B	D	B C	A	C D	A	A	A
Knee Thigh	*F/E Angle*	150	89.21%	4	87.4595	<0.0001	2	2.5182	0.0849	A	C	B	B	C	A	A	A
	A/P Orient.	150	68.73%	4	13.8212	<0.0001	2	0.5415	0.5833	B	A	A B	C	A B	A	A	A

Each row represents a separate Repeated Measures ANOVA where the predictors (Booster, Posture) are categorical independent variables.

Values highlighted in red correspond to p<0.05.

**Levels (columns within each variable) not connected by the same letter are significantly different (p<0.05 with Tukey correction for multiple comparisons).*

TABLE A-V

MEAN ± STANDARD DEVIATION OF DIFFERENCES IN ANATOMIC LANDMARK POSITIONS BETWEEN POSTURAL CONDITIONS

Booster	Posture wrt Nominal	Head Top		Suprasternale		ASIS		Patella		Right Lateral Malleolus	
		X (mm)	Z (mm)	X (mm)	Z (mm)	X (mm)	Z (mm)	X (mm)	Z (mm)	X (mm)	Z (mm)
01-HB	*Self – Nominal*	38 ± 51	4 ± 12	17 ± 13	8 ± 8	5 ± 9	-3 ± 8	8 ± 18	1 ± 15	4 ± 31	0 ± 21
	Device – Nominal	70 ± 76	13 ± 19	22 ± 19	10 ± 11	1 ± 6	-2 ± 8	8 ± 11	1 ± 11	3 ± 23	2 ± 17
02-LB	*Self – Nominal*	-4 ± 21	2 ± 10	0 ± 6	-1 ± 10	3 ± 6	-5 ± 7	13 ± 13	3 ± 7	7 ± 22	4 ± 31
	Device – Nominal	18 ± 43	10 ± 14	5 ± 10	8 ± 9	3 ± 7	-3 ± 5	12 ± 19	4 ± 5	8 ± 27	9 ± 22
03-HB	*Self – Nominal*	11 ± 26	1 ± 5	12 ± 17	6 ± 8	4 ± 6	-6 ± 4	5 ± 33	-10 ± 48	-4 ± 26	-7 ± 56
	Device – Nominal	68 ± 52	94 ± 225	17 ± 28	63 ± 148	-7 ± 35	20 ± 81	-28 ± 127	32 ± 93	-51 ± 162	4 ± 18
04-INT	*Self – Nominal*	14 ± 24	9 ± 9	5 ± 11	8 ± 7	4 ± 9	-3 ± 5	-3 ± 37	-19 ± 57	-22 ± 57	-14 ± 51
	Device – Nominal	56 ± 58	24 ± 20	10 ± 13	13 ± 12	4 ± 8	1 ± 5	3 ± 21	-6 ± 35	-18 ± 58	-15 ± 67
05-LB	*Self – Nominal*	4 ± 27	4 ± 8	5 ± 9	5 ± 8	4 ± 7	-1 ± 6	11 ± 18	0 ± 7	3 ± 7	7 ± 13
	Device – Nominal	73 ± 48	26 ± 22	11 ± 14	12 ± 11	2 ± 5	0 ± 7	10 ± 18	4 ± 6	0 ± 5	8 ± 11

TABLE A-VI

MEAN ± STANDARD DEVIATION INSTANTANEOUS ORIENTATION AND JOINT ANGLE

Booster	Posture	Thigh A/P Orientation	Knee F/E Angle
01-HB	*Self*	11.0 ± 6.2	79.1 ± 9.8
	Device	11.0 ± 5.5	79.4 ± 9.2
	Nominal	12.3 ± 5.4	78.5 ± 10.1
02-LB	*Self*	17.4 ± 6.2	52.5 ± 17.2
	Device	16.2 ± 5.4	53.2 ± 13.2
	Upright	18.0 ± 6.7	51.7 ± 13.1
03-HB	*Self*	12.6 ± 10.4	68.9 ± 6.5
	Device	10.9 ± 4.1	69.2 ± 6.5
	Nominal	11.2 ± 4.0	67.1 ± 7.9
04-INT	*Self*	8.8 ± 12.0	63.0 ± 6.1
	Device	8.7 ± 10.9	63.1 ± 7.8
	Nominal	3.5 ± 6.4	59.2 ± 7.6
05-LB	*Self*	11.0 ± 5.0	55.3 ± 8.7
	Device	10.1 ± 4.8	55.2 ± 9.7
	Nominal	11.4 ± 4.3	53.5 ± 8.5

TABLE A-VII

MEAN ± STANDARD DEVIATION DIFFERENCE OF INSTANTANEOUS LOWER EXTREMITY ORIENTATION AND JOINT ANGLE BETWEEN POSTURES

Booster	Posture wrt Nominal	Thigh Orientation (°) Mean ± Std Dev	Knee Angle (°) Mean ± Std Dev
01-HB	*Self – Nominal*	-1.3 ± 3.3	0.6 ± 3.7
	Device – Nominal	-1.3 ± 2.6	0.9 ± 3.2
02-LB	*Self – Nominal*	-0.6 ± 2.4	0.7 ± 7.8
	Device – Nominal	-1.8 ± 3.2	1.4 ± 4.8
03-HB	*Self – Nominal*	1.3 ± 9.2	1.8 ± 3.2
	Device – Nominal	-0.3 ± 2.3	2.1 ± 4.0
04-INT	*Self – Nominal*	5.3 ± 12.0	3.8 ± 4.8
	Device – Nominal	5.2 ± 9.9	3.9 ± 7.2
05-LB	*Self – Nominal*	-0.4 ± 2.3	1.8 ± 2.8
	Device – Nominal	-1.3 ± 1.5	1.6 ± 2.7

TABLE A-VIII
AVERAGE CONTINUOUS ANTERIOR/POSTERIOR ORIENTATIONS AND JOINT ANGLES BY BOOSTER AND POSTURE

Booster	Posture	Head A/P (°)	Sternum A/P (°)	Pelvis wrt Booster A/P (°)	C1/Head F/E (°)	T1/C7 F/E (°)
01-HB	*Self*	-15.3 ± 7.1	12.0 ± 11.4	26.6 ± 5.7	5.2 ± 7.1	22.2 ± 3.8
	Device	-29.1 ± 6.6	17.1 ± 8.9	30.2 ± 5.6	13.0 ± 5.5	26.6 ± 3.1
	Nominal	-13.9 ± 7.0	18.2 ± 11.5	26.1 ± 7.4	8.1 ± 5.0	23.6 ± 2.5
02-LB	*Self*	-7.5 ± 5.3	18.1 ± 9.8	35.8 ± 11.6	4.2 ± 6.6	21.5 ± 3.6
	Device	-17.8 ± 8.1	22.2 ± 9.5	39.3 ± 11.2	13.3 ± 8.4	26.4 ± 4.2
	Nominal	-4.0 ± 8.6	20.0 ± 10.2	35.2 ± 9.0	2.9 ± 8.7	20.6 ± 4.5
03-HB	*Self*	-7.9 ± 12.7	4.5 ± 9.3	30.9 ± 8.5	-5.0 ± 6.4	16.7 ± 3.4
	Device	-22.4 ± 10.1	8.9 ± 11.6	32.0 ± 9.5	8.1 ± 8.1	23.7 ± 4.4
	Nominal	-8.2 ± 10.3	9.5 ± 9.9	28.8 ± 7.8	-1.6 ± 6.0	18.4 ± 3.0
04-INT	*Self*	-9.9 ± 5.9	13.2 ± 5.7	31.6 ± 6.9	2.2 ± 6.9	20.4 ± 4.0
	Device	-26.7 ± 10.2	14.3 ± 6.4	32.8 ± 7.7	9.5 ± 4.1	25.0 ± 2.1
	Nominal	-8.8 ± 6.6	15.6 ± 5.1	31.9 ± 5.6	1.5 ± 4.8	19.8 ± 2.8
05-LB	*Self*	-8.8 ± 7.7	10.7 ± 8.1	33.2 ± 9.3	0.3 ± 7.8	19.3 ± 4.3
	Device	-23.5 ± 9.4	13.1 ± 10.8	35.4 ± 9.7	12.1 ± 9.2	25.6 ± 4.8
	Nominal	-9.5 ± 6.1	12.4 ± 9.3	33.5 ± 8.3	2.0 ± 6.8	19.9 ± 4.0

TABLE A-IX

REPEATED MEASURES ANOVA OF CONTINUOUS POSTURE BY BOOSTER AND POSTURE

Dependent Variable	Total N	R Square Adj	Booster			Posture			Booster Connecting Letters*					Posture Connecting Letters*		
			DF	F Ratio	p-Value	DF	F Ratio	p-Value	01-HB	02-LB	03-HB	04-INT	05-LB	Self	Device	Nominal
Head A/P Orient.	150	79.12%	4	4.0903	0.0037	2	118.2031	<0.0001	B	A	A	A B	A	A	B	A
C1/Head F/E Angle	150	73.84%	4	8.4259	<0.0001	2	60.6145	<0.0001	A	A	B	A	A	B	A	B
T1/C7 F/E Angle	150	75.00%	4	8.8076	<0.0001	2	68.9279	<0.0001	A	AB	C	A B	B	B	A	B
Sternum A/P Orient.	150	77.78%	4	11.2393	<0.0001	2	5.9533	0.0034	A B	A	C	A B	B	B	A	A
Pelvis A/P Orient. Wrt Booster	150	73.07%	4	11.7135	<0.0001	2	4.6698	0.0112	B C	A	C	A B	A	A B	A	B

Each row represents a separate Repeated Measures ANOVA where the predictors (Booster, Posture) are categorical independent variables.
Values highlighted in red correspond to p<0.05.
**Levels not connected by the same letter are significantly different (p<0.05 with Tukey correction for multiple comparisons).*

TABLE A-X

AVERAGE DIFFERENCE IN CONTINUOUS POSTURAL MEASUREMENTS BETWEEN POSTURE CONDITIONS

Booster	Posture	Head A/P Orient. (°) Mean ± Std Dev	Sternum A/P Orient. (°) Mean ± Std Dev	Pelvis A/P Orient. Wrt Booster (°) Mean ± Std Dev	C1/Head F/E Angle (°) Mean ± Std Dev	C7/T1 F/E Angle (°) Mean ± Std Dev
01-HB	*Self – Nominal*	-1.4 ± 4.1	-6.2 ± 4.2	0.5 ± 5.4	-2.8 ± 5.0	-1.3 ± 2.7
	Device – Nominal	-15.2 ± 6.0	-1.1 ± 8.4	4.0 ± 2.7	5.1 ± 7.1	3.1 ± 3.6
02-LB	*Self – Nominal*	-3.5 ± 7.6	-1.9 ± 3.1	0.6 ± 5.4	1.3 ± 3.9	0.9 ± 1.8
	Device – Nominal	-13.8 ± 10.9	2.2 ± 2.7	4.0 ± 4.6	10.4 ± 7.2	5.8 ± 3.7
03-HB	*Self – Nominal*	1.1 ± 5.8	-5.5 ± 7.3	-1.0 ± 9.7	-2.5 ± 5.8	-3.3 ± 6.0
	Device – Nominal	-14.2 ± 11.8	-0.6 ± 8.7	3.2 ± 4.7	9.7 ± 8.7	5.3 ± 4.6
04-Int	*Self – Nominal*	-1.2 ± 2.4	-2.4 ± 3.3	-0.4 ± 5.3	0.7 ± 5.2	0.6 ± 2.8
	Device – Nominal	-17.9 ± 9.4	-1.3 ± 4.5	0.8 ± 3.3	8.1 ± 2.7	5.2 ± 1.9
05-LB	*Self – Nominal*	0.7 ± 5.0	-1.6 ± 3.5	-0.3 ± 5.6	-1.7 ± 2.6	-0.6 ± 1.9
	Device – Nominal	-13.9 ± 5.6	0.8 ± 5.5	1.9 ± 5.2	10.1 ± 6.5	5.8 ± 3.5

TABLE A-XI
AVERAGE CHILD BELT FIT AND BELT GAP METRICS BY BOOSTER AND POSTURE

Booster	Posture	SBS (mm)	LBS (mm)	Max Gap (mm)	Gap Length (mm)	Torso Contact (%)
	Nominal	29 ± 8	-3 ± 7	31 ± 10	86 ± 63	84 ± 12
01-HB	*Self*	30 ± 10	-4 ± 4	26 ± 9	46 ± 32	92 ± 6
	Device	27 ± 9	-1 ± 4	23 ± 8	34 ± 30	96 ± 5
	Nominal	28 ± 24	12 ± 6	21 ± 6	88 ± 73	80 ± 17
02-LB	*Self*	32 ± 24	14 ± 8	22 ± 10	92 ± 77	78 ± 20
	Device	27 ± 25	14 ± 10	19 ± 10	76 ± 76	83 ± 19
	Nominal	16 ± 11	1 ± 3	20 ± 9	39 ± 41	93 ± 8
03-HB	*Self*	18 ± 8	2 ± 6	18 ± 8	42 ± 51	87 ± 22
	Device	12 ± 13	3 ± 4	19 ± 9	37 ± 55	92 ± 13
	Nominal	29 ± 23	10 ± 6	23 ± 12	73 ± 65	91 ± 12
04-INT	*Self*	32 ± 22	11 ± 6	24 ± 9	89 ± 80	88 ± 14
	Device	29 ± 19	11 ± 8	22 ± 11	103 ± 86	79 ± 18
	Nominal	26 ± 18	28 ± 6	16 ± 6	44 ± 52	91 ± 13
05-LB	*Self*	28 ± 12	28 ± 11	18 ± 8	43 ± 49	92 ± 10
	Device	20 ± 12	27 ± 11	16 ± 7	72 ± 83	83 ± 19

TABLE A-XII

REPEATED MEASURES ANOVA OF CHILD BELT FIT AND BELT GAP METRICS BY BOOSTER AND POSTURE

Dependent Variable	Total N	R Square Adj	Booster			Posture			Booster Connecting Letters*					Posture Connecting Letters*		
			DF	F Ratio	p-Value	DF	F Ratio	p-Value	01-HB	02-LB	03-HB	04-INT	05-LB	Self	Device	Nominal
SBS	150	66.03%	4	2.8465	0.0265	2	2.4061	0.0945	A B	A B	B	A	A B	A	A	A
LBS	150	85.84%	4	117.5238	<0.0001	2	0.5932	0.5542	D	B	C	B	A	A	A	A
Max Gap	150	43.28%	4	2.2545	0.0662	2	1.2945	0.2779	A	A	A	A	A	A	A	A
Gap Length	150	34.90%	4	3.8732	0.0051	2	0.0600	0.9418	A B	A	B	A	A B	A	A	A
Torso Contact	150	29.92%	4	3.1249	0.0169	2	0.0908	0.9132	A B	B	A	A B	A B	A	A	A

Each row represents a separate Repeated Measures ANOVA where the predictors (Booster, Posture) are categorical independent variables.
Values highlighted in red correspond to p<0.05.
**Levels (columns within each variable) not connected by the same letter are significantly different (p<0.05 with Tukey correction for multiple comparisons).*

TABLE A-XIII
BOOSTER 01-HB LBS WITH AND WITHOUT LAP BELT POSITIONER

Condition	Posture	Mean ± Std Dev
Without Lap Belt Positioner	Upright	-3 ± 7
	Self	-4 ± 4
	Device	-1 ± 5
With Lap Belt Positioner	Upright	16 ± 16
	Self	15 ± 10
	Device	19 ± 14
Difference	Upright	19 ± 15
	Self	19 ± 11
	Device	19 ± 14

(a) Lap belt positioner placed snugly against pelvis *(b) Lap belt positioner pulling lap belt away from pelvis*

Fig. A-10. Exemplary children on booster 01-HB with lap belt positioner.

(a) Exemplary under belt routing

(b) Exemplary over belt routing

Fig. A-11. Exemplary children on Booster 05-LB with over and under shoulder belt routings.