Kinematics and Shoulder Belt Engagement of Children on Belt-positioning Boosters during Emergency Braking Events.

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Abstract Emergency braking can influence children's posture and seatbelt interaction. To better protect children in crashes preceded by emergency braking, this study aims to quantify kinematics and seatbelt engagement during braking events. Eighteen rear-seated children were exposed to braking events with 1 g deceleration in a passenger vehicle, restrained by the seatbelt on a booster cushion and an integrated booster cushion. Vehicle acceleration and video data were analysed to measure head displacement and shoulder belt position. On the booster cushion the belt was generally mid-shoulder and lower on the torso with a gap, while on the integrated booster cushion it was closer to the neck and higher on the torso without a gap. Average forward head displacement was 160 mm on the booster cushion and 150 mm on the integrated booster cushion. Generally, the belt maintained the same position on the shoulder throughout braking, with exceptions influenced by shifted initial positions or non-standard motions. Braking events placed the head approximately 150-190 mm forward from the initial position, influenced by booster, stature, and initial seatbelt positioning. This reinforces the importance of maintaining mid-shoulder or close to neck belt positions and upright, centred postures prior to emergency braking, which may influence the likelihood of impacting the vehicle interior and sustaining head injuries in a subsequent crash.

Keywords braking, child restraint systems, child safety, kinematics, rear seat, shoulder belt position

I. INTRODUCTION

Fatalities of children in motor vehicle crashes have decreased due to use of child safety seats [1]. In particular, belt-positioning boosters have been shown to decrease injury risks for children aged 4-8 years [2-3] by increasing their seated height relative to the seatbelt outlet, thereby positioning the belt on anatomic regions where the restraint force can be transferred to the skeleton rather than soft tissue [4-5]. However, appropriately restrained children still sustain injuries in motor vehicle crashes [6-7], most often head injuries [8-9]. Vehicle manoeuvres prior to crash have been identified as contributing factors which influenced position and restraint interaction of rear-seated, restrained children that sustained head injuries due to contact with the car interior [10]. Previous studies have also noted the importance of controlling head and upper body motion of child occupants to prevent suboptimal interaction with the restraint and vehicle interior, which contributed to injury in the real world [11].

One previous study has investigated kinematics and seatbelt interaction of children during emergency braking events [12]. Reference [12] found that forward displacement of children during braking events was affected by initial position of the head and was influenced by the type of belt-positioning booster the children were restrained by. The authors also noted differences in type of head motion observed during braking, with shorter children moving more forward and down with their head than older children [12].

Emergency braking prior to crash can expose rear-seated children to motions that influence their position and interaction with the seatbelt. In the future, the frequency of emergency braking is likely to increase due to rise in implementation of automatic braking technologies in the modern vehicle fleet. Better understanding of how emergency braking affects the kinematics of children can inform the improvement of current, and the development of new, restraint systems to better control suboptimal motion, maintain optimal seatbelt positions,

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and promote good seatbelt engagement with the body. With the overall purpose of enhancing the protection of rear-seated child occupants in crashes preceded by emergency braking, this study aims to quantify how braking events influence child kinematics and their interaction with the booster and seatbelt by evaluating head kinematics and seatbelt position on the torso and shoulder.

II. METHODS

A series of braking events and steering manoeuvres were performed while children were seated in the rear seat of a passenger vehicle. Child kinematics and seatbelt interaction were analysed from video and acceleration data. The present study includes the results from the braking events, and the results from the steering manoeuvres can be found in [13].

The study protocol was reviewed and approved by the Ethics Board of Gothenburg, Sweden.

Test Setup

Eighteen child volunteers were recruited to participate in a driving study on a closed-circuit test track. Selection criteria were based on age (5-10 years) and stature (110-120 cm and 135-145 cm), with intervals selected to represent 6- and 10-year-old anthropomorphic test devices (ATDs). The children in the 110-120 cm group will hereafter be referred to as *shorter children* and those in the 135-145 cm group as *taller children*. Anthropometric measurements of the child volunteers are summarised in Table I. The children were tested while seated on the right-side rear seat of the test vehicle and restrained by the three point seatbelt on two different belt-positioning boosters, a backless booster cushion (BC) and a two-stage integrated booster cushion (IBC) as seen in Fig. 1.

Fig. 1. Accessory booster cushion (left) and standard Volvo XC70 integrated booster cushion (right).

The test vehicle was a Volvo XC70 (model year 2010) equipped with leather upholstery seats and a two-stage integrated booster cushion. The test vehicle was driven by a professional driver and was equipped with two measurement systems comprising synchronised cameras and accelerometers. The first system included two small cameras with a recording frequency of 12.5 Hz (Monacor TVCCD-30, Monacor International, Bremen, Germany), which were fixed inside the vehicle to provide front and perpendicular lateral views of the right-side rear seat. These cameras provided a view of the entire body of the child and the booster. An accelerometer was placed on the floor in the luggage compartment to measure lateral and longitudinal acceleration (DRS-MM3.R8K Robert Bosch GmbH, Gerlingen, Germany) with frequency of 50 Hz, which was downsampled to 10 Hz when analysed. Video and acceleration data were captured each time the engine was turned on until the engine was turned off. The second measurement system included two UT-5220CP-C Gigabit Ethernet CMOS cameras (IDS GmbH, Oversulm, Germany) with wide-angle lenses (LM5NCL, Kowa Co., Toyko, Japan), which provided front and perpendicular lateral views of the right-side rear seat with a sampling frequency of 50 Hz. These cameras provided a closer, higher resolution view of the head and torso of the child. The second measurement system also included an accelerometer installed approximately 0.1 m above the floor between the front seats, capturing lateral and longitudinal vehicle accelerations at 2000 Hz. This data was acquired in 20 second sequences triggered by the driver pushing a switch.

Test Procedure

Prior to the tests, each child and parent received detailed descriptions of the test procedure. The children and parents were informed that the test would include steering manoeuvres and braking events but were not informed of the timing or order of the events. Specific instructions on how to behave in the vehicle were not provided. Targets were painted on the nasion and external auditory meatus (EAM) of each child. Anthropometric measurements were captured by collecting images of the children while standing in front of a chequered board and analysing the images with TEMA v.3.17 (Image Systems, 2012).

TABLE I
ANTHROPOMETRY AND BRAKING EVENTS OF CHILD VOLUNTEERS

Child number	Age (years)	Weight (kg)	Standing height (m)	Torso width° (cm)	Braking events BC	Braking events IBC
1	7	21	1.15	12.3	1*	1*
2	5	19	1.11	12.5	1*	1
3	5	19	1.17	10.7	1	1
4	10	29	1.44	14.1	1	1
5	8	29	1.38	14.1	1	1
6	7	32	1.34	13.6	1	1
7	10	35	1.42	12.9	1*	1
8	5	23	1.12	12.8	1	1
9	5	21	1.12	12.3	1	1
10	8	32	1.37	13.3	1	1
11	5	16	1.11	11.7	1	1
12	5	18	1.14	12.7	1	1
13	5	21	1.20	11.4	1	1
14	9	29	1.32	12.9	1	1
15	5	18	1.15	12.0	1	1
16	5	21	1.20	12.0	1	1
17	8	32	1.39	13.1	1	1
18	9	31	1.37	13.5	1	1
Average (110-120 cm)	5.2	20	1.14	12.0	--	--
Average (135-145 cm)	8.6	31	1.38	13.4	--	--

° Torso Width defined as lateral distance measured between the two targets placed under the clavicles
*Missing Trials due to data acquisition failure
Gray shading represents SB routed over inboard guiding loop

When the shorter children were tested on the BC, the lap belt and shoulder belt (SB) were routed under the inboard guiding loop (GL). When the taller children were tested on the BC, the lap belt was always routed under the inboard GL. For taller children, the SB was routed either under or above the inboard GL to create the best belt fit for the specific child, which was determined by the test leader. For some taller children, routing the SB under the GL caused the shoulder belt to cross the shoulder in an extremely far or slipped-off position on the shoulder. For these children, routing the SB over the inboard GL created a better belt fit. Three taller children had the SB routed under the inboard GL and the remaining five had the belt routed over the inboard GL (see Table I). The shorter children were tested while seated on the higher stage of the IBC while taller were seated on the lower stage. On the IBC, the lap belt was placed across the lower pelvis and upper portion of the thighs. No SB guide was used and the SB was allowed to assume its natural path across the torso and shoulder after slack was removed.

On both boosters, each child was initially exposed to one trial steering manoeuvre which they were informed would happen. Children were informed they could decide to end the testing at any time. Then each child was exposed to one braking event and two steering events, in a randomised order, on each booster (see appendix, Table A.I). Before each event, the test leader ensured that the child was properly restrained, that the BC was in contact with the seatback and centred in the seat, and that the child was centred on the booster. Correct belt routing was checked and any seatbelt slack was removed. The driver then drove along the test track for approximately 50 seconds before performing the evasive manoeuvre. After the evasive manoeuvre, the vehicle was stopped and the driver drove back to the test leader.

During the braking events, the professional driver applied the brakes quickly to a full stop after reaching a velocity of 70 km/h. The maximum deceleration experienced during any of the braking events was 1.2 g (Fig. 4). The mean (across subjects) peak deceleration was 1 g with a standard deviation of 0.09 g for a period of 1.9 s. The duration of the entire deceleration period was 2.5 s.

Method of Analysis

Posture and Restraint Interaction

A series of parameters were defined to describe the child's initial seated posture, shoulder belt position, behaviour and body-motions. For all events, these parameters were evaluated and crosschecked manually by two experienced researchers. Lateral posture was defined according to a previous study [14] as upright, slightly tilted, or substantially tilted. Lateral seated position was defined as centred, slightly shifted, or shifted [14]. In addition, it was noted if the tilt or shift was inboard or outboard. Initial sagittal torso position was defined according to a previous study [15] as having the entire back against the seat, the entire back but not the shoulders against the seat, the child being upright but no part of the back in contact with the seat, or the torso leaning forward without contact with the seatback. Initial sagittal head position [15] was defined as having the head against the seatback, the head upright relative to the torso, or the head leaning forward relative to the torso. The child's hand position at the beginning of the event was recorded, noting if they were grabbing the booster, car interior, or had their hands resting on their lap. Characteristics of child motion were also described.

Fig. 2. Shoulder belt position on torso: (left to right) low, mid, and high.

Initial SB position on the inboard side of the lower torso was defined as high, mid, or low, describing its position as it crossed the lower torso (Fig 2). In addition, it was noted if a gap were present between the SB and the front of the inboard side lower torso, near the belt anchorage (Fig. 3).

Fig. 3. Comparison of front and lateral views for an exemplar shorter child on the BC with gap (left) and on the IBC (right) without gap.

SB position on the shoulder was analysed according to [16] as close to neck, mid-shoulder, far out, or slip-off (Fig. 4). The SB position on the shoulder was evaluated at the first image of the event, at the image immediately preceding the end of the child's forward motion due to the increase in longitudinal acceleration, and the end of any secondary motion phases of the child, i.e., when the child moved backward at the end of the braking event, or the end of the event. For each event, the image corresponding to the child's maximum forward position was imported into MATLAB (version R2014b; The Mathworks Inc., Natick, MA, USA), and the contour of the thoracic spine, head, neck, and upper torso was tracked using custom MATLAB software.

Fig. 4. Shoulder belt position on shoulder: (left to right) close to neck, mid-shoulder, and far out.

Kinematic Response

Video (50 Hz camera images) and acceleration (2000 Hz accelerometer) data were analysed using custom MATLAB software. The beginning of the braking event was defined as 0.5 s before the time when the longitudinal acceleration first exceeded 0.1 g to ensure that the event captured images prior to the commencement of braking. The end of the braking event was defined as the average time the children had begun to rebound, approximately three seconds, ensuring that the maximum forward position was captured in the extracted images for analysis.The corresponding images (0-3 seconds) of the lateral view of the child's head and torso were imported into TEMA to track the motion of the nasion and EAM targets and to determine head rotation angle throughout the braking event. Head rotation angle was defined as the angle, relative to the horizontal plane, of the line connecting the EAM and the nasion targets. A positive angle represents the nasion/EAM line inclined higher than horizontal, and negative angles represent lower than horizontal (see appendix, Fig, A.1). Change in head rotation angle was defined as the initial head rotation angle subtracted from maximum forward head rotation angle. The nasion was assumed to move in the sagittal plane aligned with the centreline of the seat while the tracking plane for the EAM was offset toward the lateral view camera by a distance corresponding to half of each child's measured head width. Head width was measured using TEMA and the anthropometry images taken of the children prior to the event. In five cases, the child was shifted laterally at the beginning of the braking event. In these cases, both the nasion and EAM tracking planes were offset by the distance of the lateral shift of the child, measured in TEMA using the first image of the event from the front view camera (50 Hz). The maximum lateral shifts of the nasion from the centreline plane were 100 mm outboard and 60 mm inboard from the centreline. The distortion effect due to the wide-angle lenses was less than 6% (an average of 3 mm) in the area where the children's motion occurred.

The forward and downward motion of the nasion and EAM were tracked using TEMA for the duration of the braking event. Maximum forward displacement was defined as the point of the greatest forward change from initial lateral position during the first one second of the braking event. Maximum downward displacement was defined as the point of the greatest downward change from initial position during the first one second of the braking event. These points were chosen as they describe the maximum forward and downward displacement caused by the ramping phase of the longitudinal acceleration due to braking, not by any secondary motions that may occur during the plateau phase of the longitudinal acceleration that could be influenced by voluntary movement of the head. Furthermore, to study effects of booster and stature group, the motion of the nasion and EAM were normalised to have common initial starting positions. The mean initial vertical position of the nasion and EAM were calculated for each stature group on each booster, and this was used as the common initial vertical position. All initial lateral positions were set to zero in the normalised results.

III. RESULTS

All children completed two braking events, for a total of 36 braking events. All 36 events were included in analysis of posture and restraint interaction. A total of 32 events were included in kinematic results (for exceptions, see Table I) as four events had unsynchronised video and accelerometer data. In their initial positions, 67% of children had an upright lateral posture, centred pelvis and torso, sagittal head position of upright relative to torso or in contact with the seatback, and back and shoulders in contact with the seatback. The remaining 14% were shifted in pelvis and torso and tilted laterally, 11% were tilted laterally, and 8% were shifted in the pelvis or torso.

Shoulder Belt Position

Clear trends in initial SB position were seen for the shorter and taller children. A summary of initial SB position can be seen below in Table II. Children had an initial SB position close to the neck during 50% of events on the IBC as compared to during 22% of events on the BC. This trend was seen especially for shorter children, whose SB position was evenly distributed on the BC while on the IBC 60% of children had the SB close to the neck. Children generally had higher SB positions on the torso on the IBC than the BC. Shorter children had the SB position low on the torso in 90% of events on the BC compared to mid on the torso in 70% on the IBC. For taller children on the BC, in 50% of the events they had the SB high on the torso, and on the IBC this increased to 75%. Shorter children also displayed a gap between the SB and the lower torso in 90% of events on the BC. Taller children displayed a small gap in 20% of events while seated on the BC. There were no gaps between SB and the lower torso for taller children seated on the IBC, and for shorter children, 80% percent had no gap. Children were observed grabbing the booster or car interior prior to the event in 42% of braking events.

TABLE II
INITIAL SHOULDER BELT POSITION

		Shorter BC	Shorter IBC	Taller BC	Taller IBC
SB on shoulder	*Close to neck*	3	6	1	3
	Mid-shoulder	4	3	5	3
	Far out	3	1	2	2
SB on lower torso	*Low*	9	1	2	0
	Mid	1	7	2	2
	High	0	2	4	6
Gap	*Small Gap*	2	1	2	0
	Gap	7	1	0	0

Shorter: number out of 10 total braking events
Taller: number out of 8 total braking events

Fig. 5 shows the evaluation of the SB position on the shoulder for the duration of the event, relative to the mean longitudinal acceleration of all the braking events. Child motion began during the ramping phase of the longitudinal acceleration (average of 0.55 s from the beginning of the event). During the ramping phase of the longitudinal acceleration, the torso moved forward until stopped by the seatbelt. Forward motion of the child's torso ended at approximately the plateau of the mean longitudinal acceleration (an average of 0.9 s after event start). During the period of forward child motion due to braking, the SB did not move on the shoulder except during three events, one event for one taller child on the BC when the SB moved inboard and two events for shorter children on the BC, one when the SB moved inboard and one when the SB moved outboard. Slip-off of the SB only occurred during one event, a shorter child seated on the BC. The SB started and ended in the far out (or slip-off) position for five events on the BC and for three events on the IBC.

Silhouettes at Maximum Forward Displacement

Fig. 6 shows silhouettes of the lateral view of the child's head, thoracic spine, and torso at the point of maximum forward displacement relative to the vehicle reference system. Regardless of booster, the shorter children displayed greater variety of head positions and tended to have head positions that were further forward and more rotated downward relative to the vehicle reference system than the taller children. The taller children had a more upright head posture at the point of maximum forward displacement. The taller children also had a greater variety of forward positions while seated on the BC compared to the IBC.

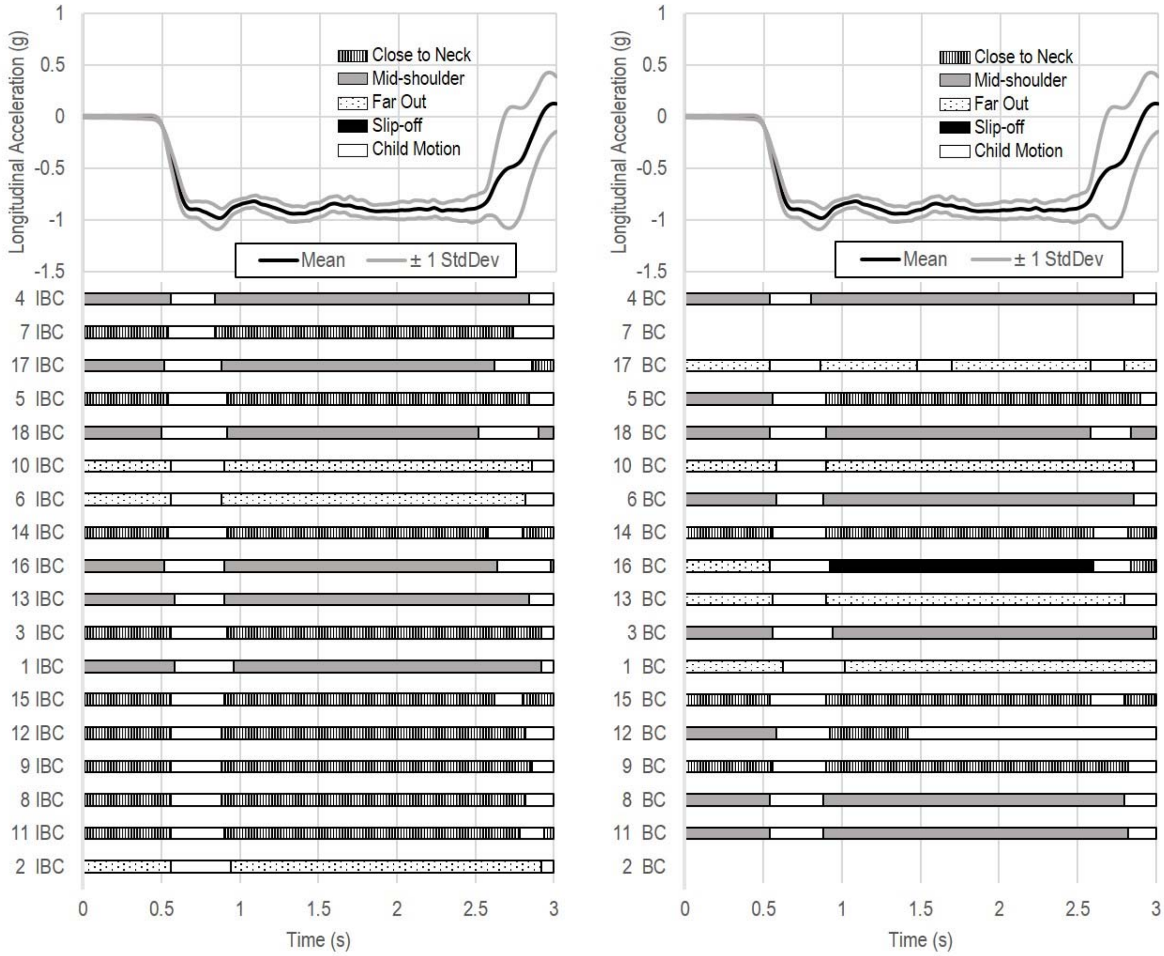

Fig. 5. Average longitudinal acceleration and shoulder belt position on shoulder during braking on the BC (left) and IBC (right), plotted for each child from tallest (top bar) to shortest (bottom bar) in order of decreasing stature.

Fig. 6. Lateral silhouettes at maximum forward displacement for Shorter BC, Shorter IBC, Taller BC, and Taller IBC compared to common vertical reference line in the vehicle reference system. Plotted in the X (longitudinal) and Z (vertical) plane.

Head Trajectories

Fig. 7 and 8 show the trajectories of the nasion and EAM for all children from initial starting position to the point of maximum forward displacement. For both shorter and taller children, the nasion had a more forward and downward trajectory than the EAM. Shorter children had more flexion of the head about the neck compared to taller children, with greater forward and downward trajectories.

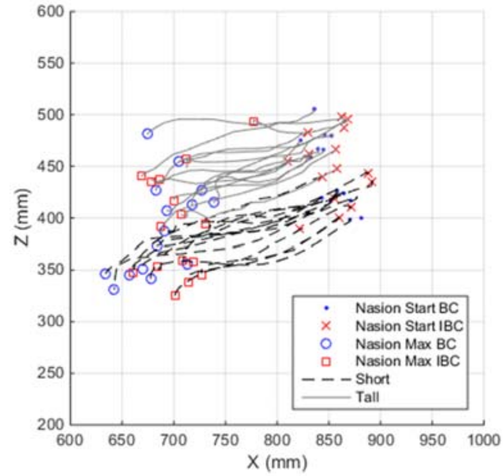

Fig. 7. Nasion trajectories.

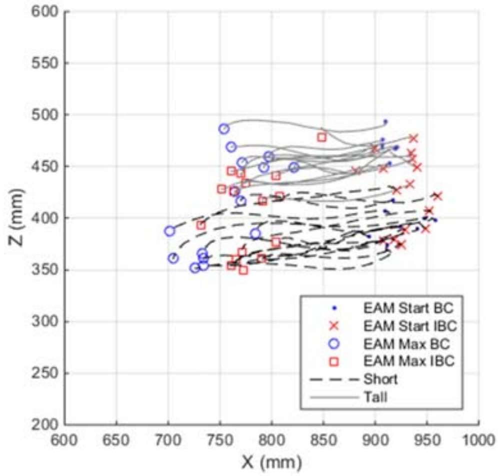

Fig. 8. EAM trajectories.

Fig. 9 and 10 show the trajectories of the nasion and EAM for shorter and taller children that have been normalised to a common initial starting position. The taller children had a higher initial vertical position of the EAM on the BC compared to the IBC with an average difference of approximately 16 mm. The average initial vertical positions of the EAM for shorter children were approximately the same on the BC and IBC. Considering the normalised data, a difference in maximum displacement can be seen for shorter children between the BC and IBC. For taller children, maximum displacement were more similar between the BC and IBC, with a small vertical separation occurring for the EAM, due to the difference in initial height between the BC and IBC.

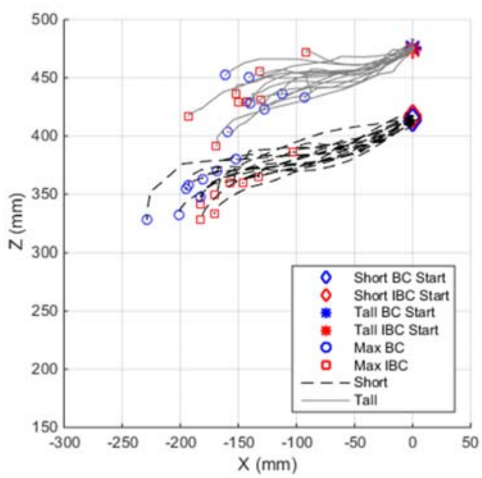

Fig. 9. Normalised nasion trajectories.

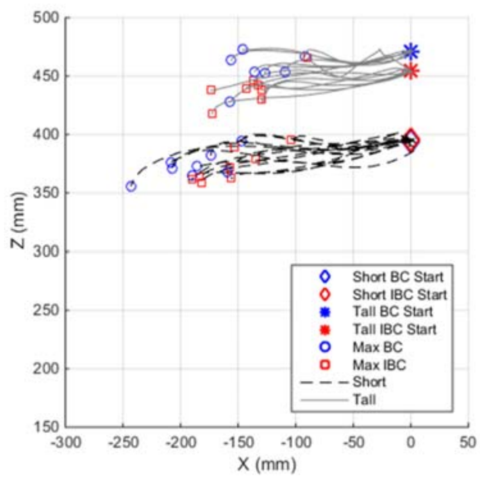

Fig. 10. Normalised EAM trajectories.

Head Displacement and Rotation

Table III shows the average displacements (with one standard deviation) of both stature groups on the BC and the IBC. The shorter children on the BC had the greatest average forward displacement of the EAM (190 mm) and the nasion (185 mm) while taller children on the BC had the lowest average forward displacement of the EAM (130 mm) and the nasion (135 mm). Shorter children on the IBC had the greatest average downward displacement of the nasion (65 mm) and the EAM (25 mm). Taller children on the BC and IBC had the lowest average downward displacement of the nasion (45 mm) and of the EAM (20 mm).

TABLE III

AVERAGE AND ONE STANDARD DEVIATION HEAD DISPLACEMENT DURING BRAKING

		Shorter BC	Shorter IBC	Taller BC	Taller IBC
Average X displacement	*EAM*	190 ± 30 mm	160 ± 25 mm	130 ± 25 mm	140 ± 30 mm
	Nasion	185 ± 25 mm	160 ± 25 mm	135 ± 25 mm	145 ± 30 mm
Average Z displacement	*EAM*	25 ± 15 mm	25 ± 15 mm	20 ± 10 mm	20 ± 10 mm
	Nasion	65 ± 20 mm	65 ± 20 mm	45 ± 25 mm	45 ± 20 mm

Table IV includes the average change in head rotation angle of both stature groups on the BC and IBC. On average, shorter children displayed greater change in head rotation angle during the braking events on both the BC (35°) and the IBC (34°) than the taller children on the BC (22°) and the IBC (22°). Table IV summarises the maximum head rotation angle achieved during the braking event. Shorter children on the BC, shorter children on the IBC, and taller children on the BC all had similar average maximum head rotation angles (-18°, -17°, and -18°, respectively) while taller children on the IBC displayed a lower average (-8°).

TABLE IV
AVERAGE AND ONE STANDARD DEVIATION HEAD ROTATION DURING BRAKING

	Shorter BC	Shorter IBC	Taller BC	Taller IBC
Average maximum head rotation angle	- 18 ± 12°	- 17 ± 10°	- 18 ± 11°	- 8 ± 11°
Average change in head rotation angle	35 ± 9°	34 ± 7°	22 ± 9°	22 ± 10°

IV. DISCUSSION

This study was designed to safely expose child volunteers to braking events and to evaluate their resulting kinematic responses and restraint interaction when restrained by the seatbelt and two different belt-positioning boosters. This is the first study to evaluate children seated on an IBC during braking events, providing insight on the effect of different booster designs, i.e., the presence or absence of guiding loops, on initial SB position and motion of the SB during braking. The selection of the BC in this study was made to limit the variety of influencing factors, hence a backless booster was used. In analogy, the positioning of the shoulder belt (above or below the GL) was made to enable as good belt fit as possible for the individual. The height of the BC was in between the height of the two stages for the IBC. Braking events placed the head of children approximately 150-190 mm more forward than the initial position, and the degree of forward and downward displacement was influenced by child stature and booster type. Vehicle manoeuvres (including emergency braking) prior to crash have been identified as contributing factors to restrained children sustaining head injuries in real-world frontal impacts due to contact with the vehicle interior [10]. The present study found that braking events placed the head of children approximately 150-190 mm more forward than the initial position. If a subsequent crash was to occur, these children may be more likely to sustain head impact with the seatback or side interior due to their pre-crash forward position.

The nasion and EAM had similar average forward displacements, but the nasion displaced further downward than the EAM. Shorter children had greater average forward displacements than taller children. This supports previous findings where greater forward displacements were observed for shorter children than taller children due to 1 g braking events when restrained in the same BC as the present study [12]. Reference [18] also found that forward head excursion decreased with age during low-speed frontal sled tests of children aged 6-14 years. In the present study, shorter (younger) children also had greater head downward displacement than taller (older) children, resulting in more head rotation. The taller (older) children tended to move forward with an upright head orientation, with less change in head rotation angle than shorter (younger) children. This is in line with the results from Reference [12] where shorter (younger) children were observed to have greater flexion of the head while taller (older) children had a more upright head position during the maximum forward position due to braking.

Shorter children seated on the BC had a larger average forward displacement of the nasion and EAM compared to the IBC, by an average of 30 mm. Contrastingly, taller children seated on the IBC had slightly greater forward displacement than when seated on the BC, by an average of 10 mm. Average forward displacement was found to differ by only 5 mm between taller children on the BC with the SB routed over (135 mm) and those with the SB routed under (130 mm) the inboard guiding loop.

The amount of forward displacement during braking may have been influenced by the initial position of the SB and the amount of contact between SB and torso prior to the event. The BC and IBC produced different initial SB positions and contact with the torso prior to braking. When seated on the IBC, the SB was closer to the neck and crossed the torso higher than on the BC. Shorter children on the BC had a gap between the SB and lower torso prior to almost every braking event while only in two cases on the IBC. These differences in initial SB position are likely due in part to the difference in design between the BC and IBC. When the SB is routed under the guiding loop on the BC, the belt is pulled forward away from the body, creating a gap. Because of this, the SB path was more horizontal and crossed the inboard torso in a lower position, causing the belt to cross the shoulder at a more outboard lateral position. The gap between the belt and the lower torso meant that, for shorter children, often only the upper inboard portion of the torso was fully in contact with the SB prior to the braking event. As the IBC has no GLs, the SB was not forced away from the torso, which resulted in more of the SB wrapping with full contact against the child's hip, torso, and shoulder. As a result, both shorter and taller children on the IBC had the SB in contact with almost the entire torso. On the IBC, the SB also created a more vertical line from outlet to buckle, resulting in the SB crossing the shoulder closer to the neck than on the BC.

In addition, differences in anthropometry between the shorter and taller groups also influenced SB position on the body. The taller group was older and had a greater seated height and larger torso depth, which contributed to more of the SB being directly in contact with the torso. The IBC included in this study also produced different seated heights for the shorter and taller children, influencing their interaction with the SB. Taller children on the BC had a slightly higher seated height than on the IBC, which could also have influenced the initial position of the SB.

Analysis of the SB position on the shoulder was conducted for all children before and after the period of forward motion due to braking (Fig. 5). The SB stayed in its initial position on the shoulder for all but three events. One of these instances was for a taller child seated on the BC where the SB moved from mid-shoulder to close to neck during the braking event. Another case was a shorter child seated on the BC where the SB moved from mid-shoulder to close to neck. In this case, the child raised their arms just prior to the ramping phase of the longitudinal acceleration, causing the shoulders to rise slightly and move the SB closer to the neck. The last case was a shorter child on the BC where the SB moved from far out on the shoulder to slip-off. Prior to the event, the torso of this child was slightly tilted inboard, causing the SB not to *grab* the shoulder as the child moved forward which resulted in SB slip-off.

The braking events where the SB position is far out or slipped-off the shoulder represent potentially unstable restraint conditions if a subsequent crash was to occur. In this analysis of braking events, more instances of the SB far out or slip-off occurred while children were seated on the BC (five) than the IBC (three). In these cases (excepting one where SB slip-off occurred), the SB did not move on the shoulder during the braking event. This suggests that if the initial position of the SB had been mid-shoulder or close to neck for these children, they would have maintained a more optimal belt position during the braking event, which points to the importance of maintaining optimal SB position on the shoulder prior to and during pre-crash emergency braking. During the one instance of slip-off, initial posture of the child contributed to an initially suboptimal SB position on the shoulder, which points to the importance of designing boosters that promote an upright posture through their design.

Children behaved and moved their bodies in different ways prior to the braking manoeuvres; however, the majority of children maintained a centred and upright position, looking forward, with their hands resting on their thighs. There were some exceptions to this *standard* initial position. Forty-five percent of the shorter children grabbed on to the vehicle door or booster cushions. Shorter children who were grabbing on to the car interior or booster had approximately 15 mm *more* forward displacement than those who began the braking manoeuvre with their hands in their lap. This may be due to the fact that the shorter children who displayed *nonstandard* hand positions were also likely to display *nonstandard* initial positions, which may have contributed to less optimal initial postures or SB positioning on the body. While seated on the IBC, some children were able to support themselves with their feet by placing them on the space created on the rear seat in front of the raised portion of the IBC. This differed from the previous study of children during braking events [12], as the children were not able to support themselves while tested on a high-back booster and BC. If children are able to support themselves with their feet, they are more likely to be able to brace themselves prior to or during braking, possibly decreasing the amount of forward displacement they exhibit. In this study, three of the shorter children were observed to place their feet on the rear seat while on the IBC. Two out of these three children were included in kinematic analysis and had the smallest forward displacements of all shorter children on the IBC (approximately 10 mm and 15 mm less than the next smallest displacements). However, many of the shorter children on the IBC were grabbing the vehicle interior or booster prior to the event and/or were not in a centred, upright initial position which may also influence their degree of forward displacement.

During the braking manoeuvres, children moved forward only in the longitudinal direction, with the exception of four events where some *nonstandard* body motions were observed. Of the exceptions, one taller child (7) on the IBC exhibited a small amount of axial rotation in its torso during the forward motion. After the SB stopped the torso forward motion, the inboard shoulder continued its forward motion, creating a small axial rotation. Another shorter child (2) on the BC exhibited out of plane motion of the head during braking. Prior to the braking event, this child turned its head 90° outboard to look out the window, and during the braking event they rotated the head back to forward. A taller child (4) on the BC exhibited a small out of plane motion of the head during braking. After achieving maximum forward displacement in its torso, this child bent its neck so the head moved inboard. Another shorter child (15) seated on the BC exhibited out of plane motion of its head and torso. This child had an initial head position rotated 45° outboard in addition to its pelvis shifted inboard. During the event, this child rotated its head inboard back to forward. This child also moved its torso laterally inboard after reaching maximum forward displacement, aligning its torso centrally on top of its inboard-shifted pelvis.

Repeatable test performance (see acceleration, Fig. 5) during the braking events was achieved by placing cones along the test track to indicate when the evasive manoeuvre should commence. The braking pulse was also chosen to replicate that of the prior study of children during emergency braking events by [12] and was determined as safe deceleration that would not expose the children to any risk of contact with the front passenger seat, which was placed in an upright, far-forward position to increase the distance from the child. Children were not given any specific instructions on how to behave in the test vehicle, which influenced their initial position at the beginning of the braking events. This helped the children to be relaxed and behave more normally during the testing and did produce some variation in initial posture and SB position. However, clear trends were still observed between children on the BC and IBC and between shorter and taller children. The test matrix included a randomised order of braking events and steering manoeuvres which helped the children be less aware of what type of event would take place and less likely to engage their muscles prior to the event.

In this study, one booster cushion was tested. This BC is similar to other booster cushions on the market but not representative of all belt-positioning boosters. Other boosters have been shown to produce a variety of initial seatbelt positions for children of different sizes [5], which may also influence kinematic response and seatbelt engagement during emergency braking. In a prior study of booster-restrained children tested during braking events, a high-back booster was tested in addition to the same backless BC and resulted in slightly lower forward displacement of the forehead of shorter children when the backrest was included as compared to when they were seated on a backless BC, probably due to the influence of the backrest [12]. The interaction between the BC and the rear seat of the test vehicle may also influence the kinematic response and restraint interaction. Booster and seatbelt misuse is also known to influence restraint and seatbelt interaction and kinematic response during braking. These aspects are not directly addressed in this study.

In an analysis of real world crashes, the rear half of the window (from the sill to the centre of the window vertically) was identified as an area of head/face contact points in nearside side impacts of seatbelt-restrained children (4-15 years) [17]. This area of contact points was described as adjacent to an initial position of a centred and upright child and slightly shifted forward due to a frontal component in the included crashes [17]. This suggests that in crashes with emergency braking prior to a lateral impact, a greater area of the rear window and sill should be considered as a potential impact zone for children in the rear seat, even when restrained by a BC or IBC, as their initial position could be 150-190 mm more forward due to emergency braking. Reference [11] compared paediatric dummy kinematics, seatbelt motion, and injury outcomes using laboratory sled test reconstructions of real-world crashes where children sustained significant injuries due to improper restraint scenarios, in addition to testing corresponding optimal restraint scenarios. The authors found that the optimal restraint scenarios helped to reduce upper body motion, proposing that the injuries in the real-world crashes may have been avoided if optimal restraint conditions had been maintained prior to crash [11]. Understanding how emergency braking potentially affects the position of the SB on the body of children is essential to maintaining optimal restraint scenarios, with the goal of minimising head and body displacement to prevent contact with the vehicle interior. Differences between boosters and children of different stature groups were also observed in SB position and head kinematics during braking events in this study. In order to protect children of all ages and statures, understanding how their specific anthropometry influences initial positioning of the seatbelt and degree of forward displacement on different belt-positioning boosters is imperative. Understanding the position of the head and the interaction between the body and seatbelt, as a result of emergency braking prior to crash, provides essential information on the likelihood of sustaining impact with the vehicle interior or achieving suboptimal seatbelt positions, ultimately helping to better protect restrained children, especially their head.

V. CONCLUSIONS

During the braking events, all children moved forward, and the degree of forward and downward displacement was influenced by child stature and booster type. Braking events placed the head of children approximately 150-190 mm more forward than the initial position, which may increase the risk of impacting the vehicle interior. Initial shoulder belt position on the body likely influenced the amount of forward displacement, with greater initial contact between the torso and belt resulting in less forward displacement. The BC resulted in initial shoulder belt positions further out on the shoulder and often with a gap between the belt and lower torso, especially for shorter children. Children on the IBC generally had the seatbelt closer to the neck with more direct contact between the belt and torso. For all but three braking events, the SB did not move from its original position relative to the shoulder after the forward motion of the child stopped. SB slip-off only occurred for one event, a shorter child seated on the BC, and approximately half of the children on the BC ended with the SB far out on the shoulder, potentially unstable restraint conditions if a subsequent crash was to occur.

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VIII. Appendix

TABLE A.I
Number and Type of Events Included in Testing

Child	Booster 1	Trial Steering	Steering	Braking	Booster 2	Trial Steering	Steering	Braking
1-10	BC	1	2	1	IBC	1	2	1
11-18	IBC	1	2	1	IBC	1	2	1

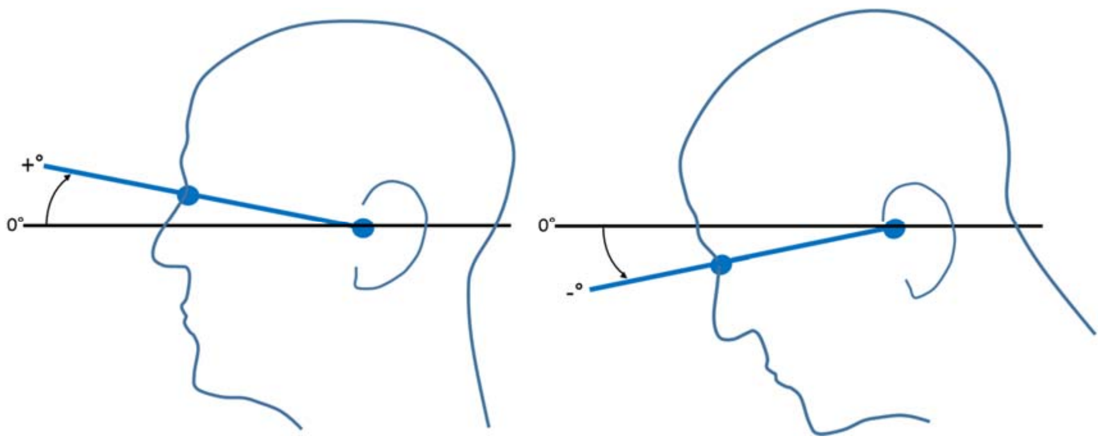

Fig. A.1. Definition of head rotation angle where positive angles represent angles above horizontal and negative angles represent angles below horizontal.