The influence of Booster Cushion design on child kinematics and loading, using the PIPER model and the Q10 in frontal impacts

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ABSTRACT

Booster cushions are used to adapt children's height to the vehicle restraint systems, and additionally allowing the children to comfortably bend their knees to help avoid a slouched sitting posture. There is a need to understand how different booster designs may influence the restraint performance in case of a crash, especially when placed on a vehicle seat. The aim of this study was to compare different booster designs and their effect on child kinematics and loading using the Q10 in frontal impact sled tests and the PIPER 6y in computer simulations. Two different vehicle interiors were used, and three different booster cushion designs (A, B, and C) were evaluated in the 50km/h Euro NCAP MPDB impact configuration.

Booster B with delayed pelvis restraint, resulted in reduced torso pitch and increased neck loading, compared to booster A for both the Q10 and the PIPER 6y. The shoulder belt slipped off the shoulder of the Q10, when restrained on Booster C with shoulder belt routed under the guiding loop. The shoulder belt stayed on the shoulder for both Q10 and PIPER 6y, when restrained on both Booster A and Booster B.

This study shows that boosters with similar initial static belt fit can result in differences in dynamic performance during crash, due to the design of the boosters. The option to allow the shoulder belt to be placed above the guiding loop (in addition to under), provides a more stable shoulder belt position, especially for the taller children. This mitigates the risk of shoulder belt slip off. Such flexibility of the booster cushion, allowing shoulder belt being guided both above or under the guiding loops, could accommodate a larger size span of children.

INTRODUCTION

Booster cushions are essential to raise the children's height in position to the vehicle restraint systems, ensuring the seat belts to engage with the bony structures such as pelvis, ribcage and shoulder. In addition, the booster cushions allow the children to comfortably bend their knees to help avoid a slouched sitting posture. Several studies have shown a great injury reducing effect of booster cushions compared to children being restrained by seat belt without boosters (Warren Bidez and Syson 2001, Arbogast et al. 2009, Durbin et al. 2003). Especially, the risk of abdominal injury is almost eliminated when using a booster cushion (Durbin et al. 2003).

While most boosters provide an increase in height, there are several design variations (e.g. angle of seat cushion, height of guiding loops, belt routing options) among different booster designs. Tylko et al. (2016) conducted tests with novel unconventional 'booster cushions', such as foldable and inflatable booster cushion designs. The tests showed an increased risk of abdominal interaction when the lap belt was not kept on the pelvis or the booster cushion deformed in such a way that the pelvis was no longer supported efficiently. Further understanding how variations in booster cushion designs may influence performance in case of a crash, especially when placed in a vehicle seat, is essential to ensure the development of real-world safe booster cushions. Hence, the aim of the study was to compare different booster cushion designs and their effect on child kinematics and loading using the Q10 and the PIPER 6y in frontal impact sled tests and computer simulations, respectively.

METHODS

Two methods were used in this study; frontal impact sled tests conducted with a physical Q10 and frontal impact simulations with the PIPER 6y Human Body Model (HBM) (Giordano et al., 2017). Two different vehicle interiors were used, one for each test series. Both test series were run in the 50km/h EuroNCAP Moveable Progressive Deformable Barrier (MPDB) impact configuration. The dummy and the HBM were positioned in the right rear seat position, using a seatbelt with pretensioner and load limiter of similar specification in both test series.

Three different Booster Cushion designs (A, B, and C) were included in the study. See measurements in Table 1 and Figure 1. Booster B and Booster C were chosen based on their differences in size, shape, stiffness and guiding loop user specification and design. Booster C has adaptive height of the guide, depending on size of the child, with a relative difference of 70 mm between high and low position of the guide. Booster C has the largest width (from outside guide to outside guide) as well as the highest height of the guide (Measure 2 and Measure 3, Table 1) even when the guide was put in its lowest position. Booster A and Booster C have the highest sitting height, while Booster B has the lowest.

		Booster A	Booster B	Booster C
1 Width	mm	330	360	390
2 Height, below guide	mm	120	130	145/165*
3 Height, top of guide	mm	170	195	215/235*
4 Height of seat cushion	mm	80	60	80
5 x-poisition of guide	mm	140	130	155
6 Femur angle on Piper 6y	degrees	16	15	16
7 Femur angle on Q10	degrees	10	3	9
8 Contact surface to seat bench	cm^2	980	680	1280

*Table 1 Measurements of Booster A, Booster B and Booster C. Measurements description in Figure 1. * Booster C had high position on guides for Q10 and low position for Piper 6y.*

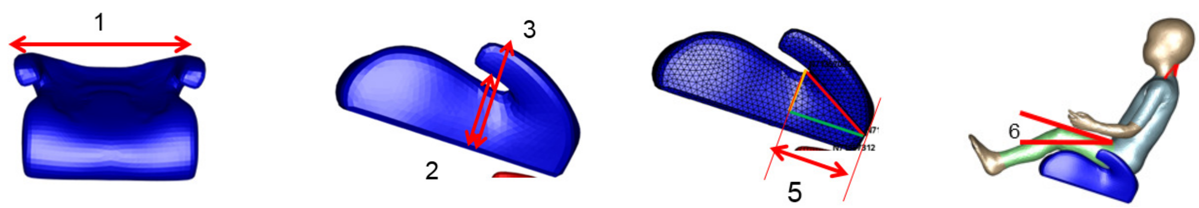

Figure 1 The measurements that was taken to distinguish between the boosters.

Booster A is made of a solid EPP foam and Booster C of solid plastic, and they only experienced limited deformation during the crash. Booster B consists of a plastic shell and deforms substantially more than the other two during the crash.

All three boosters have different manufacturer user guidelines regarding shoulder belt routing above or under the guiding loop. Booster A allows alternative shoulder belt routing above or below the guide depending on the size of the child occupant, while Booster B allows shoulder belt guiding above the guide and Booster C allows shoulder belt guiding under the guide. For the present study, belt routings in accordance with the manufacturer recommendations, Table 2, were used.

Table 2 The shoulder belt routing according to the manufacturer recommendation for the two different sizes of child occupants.

	Booster A	**Booster B**	**Booster C**
Piper 6y	under guide	above guide	under guide
Q10	above guide	above guide	under guide

Occupant kinematics, head accelerations, neck forces and chest deflections were recorded and analyzed.

Sled tests

Three tests were conducted with the Q10, seated on the three different booster cushions, in a reinforced sled body of a car mounted on a linear accelerator sled. The sled body was rotated 14°. A Humanetics Q10 with Cellbond update kit and suit was used in the tests.

High-speed cameras captured a front view and right side views of the dummy. Dummy kinematics, loadings and seatbelt-to-body interactions during the forward motion of the dummy were analyzed and compared for the different boosters.

Simulations

In total three simulations were made using the PIPER child HBM v1.0.2 in its baseline geometry representing a six-year-old (Giordano et al. 2017). The HBM was seated on the three different booster cushions, respectively, in the rear right position of a car. All simulations were run for 150 ms using MPP LS-DYNA R9.3.1 on 240 CPUs.

RESULTS

Kinematics and shoulder belt interaction for the Q10 in the sled tests

Similar initial shoulder belt position was seen when seated on Booster A and Booster B, while on Booster C the shoulder belt was further out, positioned on the edge of the shoulder (Figure 2, first column). During pretensioning, the shoulder belt moved inboard somewhat, due to a moveable shoulder belt guide (Figure 2, second column). As can be seen in Figure 2, during the crash, the shoulder belt stayed on the mid-shoulder for Booster A, the shoulder belt slipped to the neck and up the armpit when on Booster B and the shoulder belt slipped off the shoulder when on Booster C.

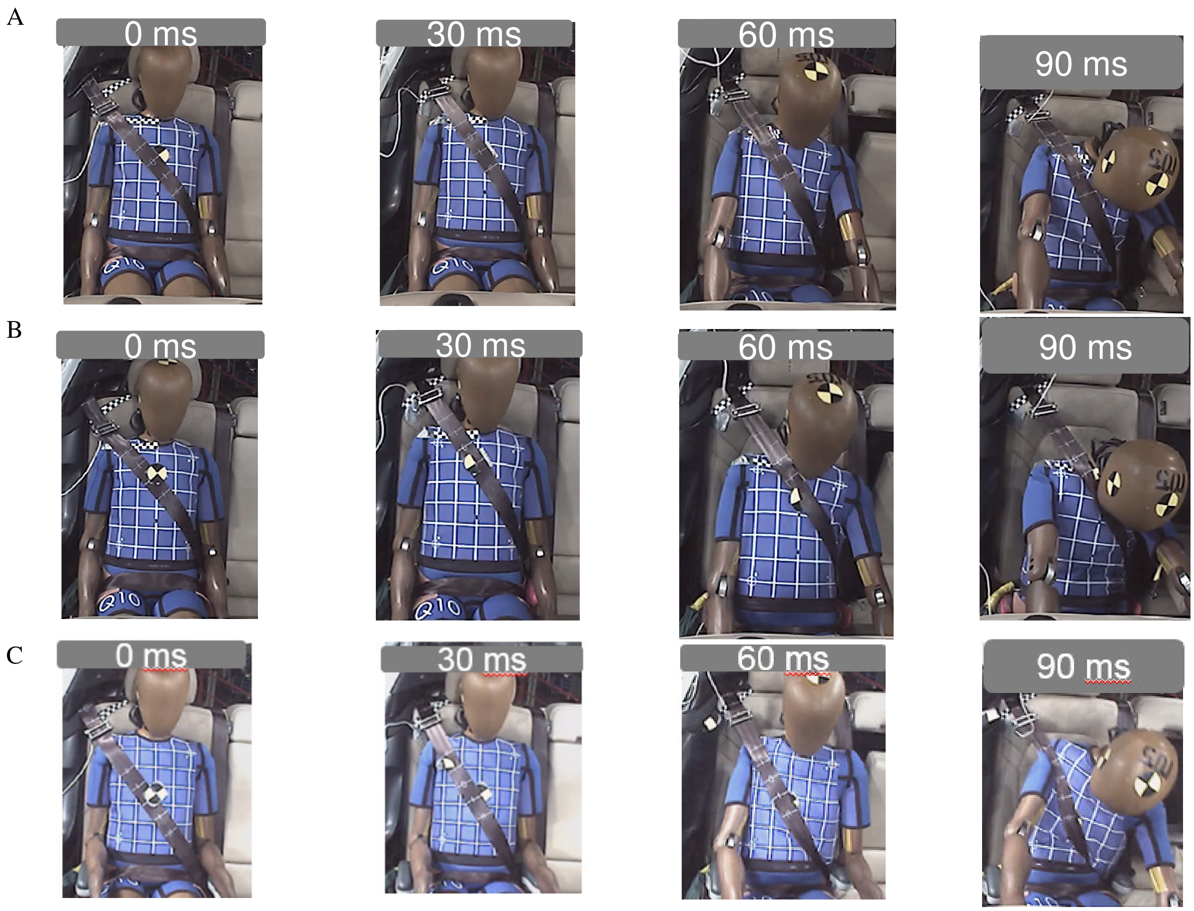

Figure 2 Front view Q10 for the three different boosters at 0, 30, 60 and 90 ms.

The side view (Figure 3), shows that the Q10 restrained on Booster B had a more forward and downward motion of the pelvis, compared to the other two boosters. The head reached most forward when restrained on Booster C, where the shoulder belt slipped off the shoulder. A difference in neck kinematics was seen for Booster A, with the neck more stretched out compared to Booster B, which gave more flexion motion in the neck.

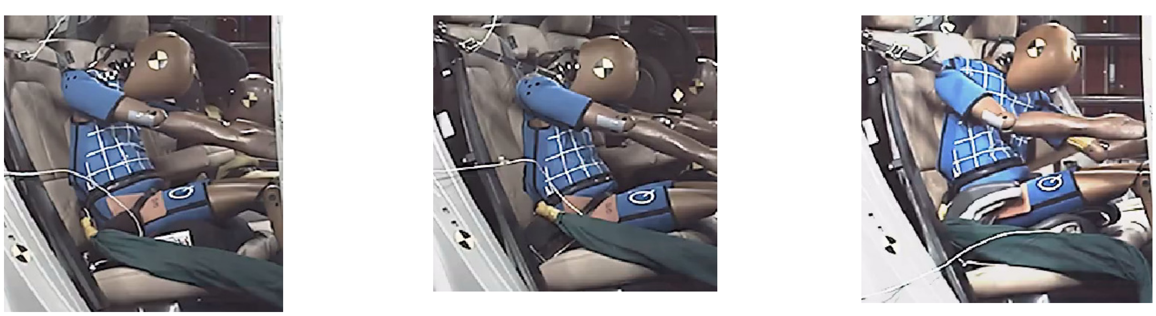

Figure 3 Side view of Q10 for the three different boosters at the time of maximum excursion.

<u>Loading for the Q10 in the sled tests</u>

The loading in the Q10 is shown in Figure 4. The lowest head acceleration was seen when on Booster C. The upper neck tension was highest when restrained on Booster B. Chest deflection was highest for Booster C and lowest for Booster B.

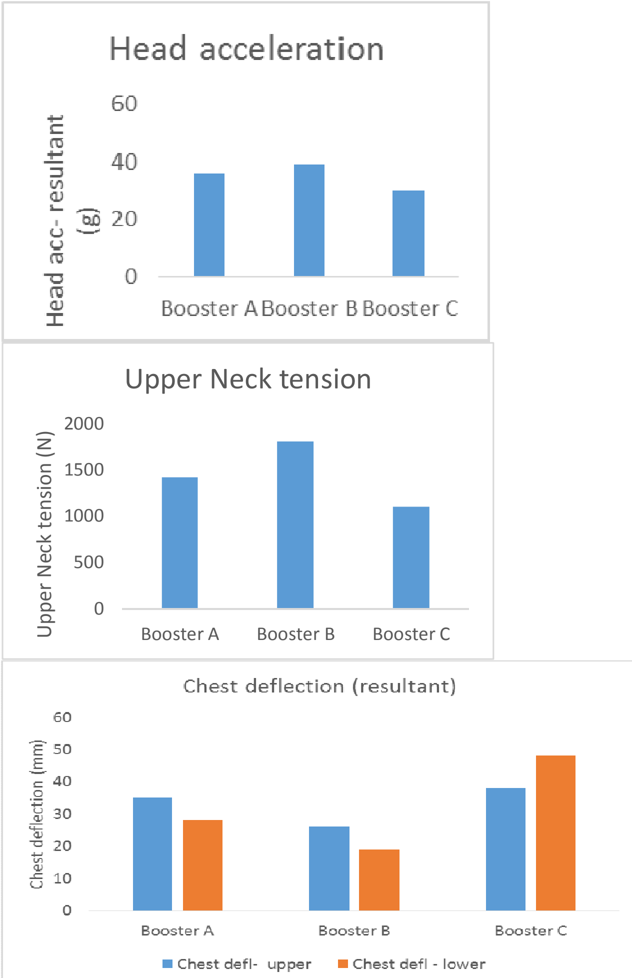

Figure 4 Q10 loading: resultant head acceleration, upper neck tension and chest deflection resultants (upper and lower).

<u>Kinematics and shoulder belt interaction for the PIPER 6y in the simulation series</u>

Overall, Booster A and Booster C showed similar kinematics, with a more efficient engagement of the pelvis resulting in less pelvis forward and downwards movement, compared to Booster B (Figure 5). The delay in pelvis restraint in Booster B resulted in a delayed torso pitch.

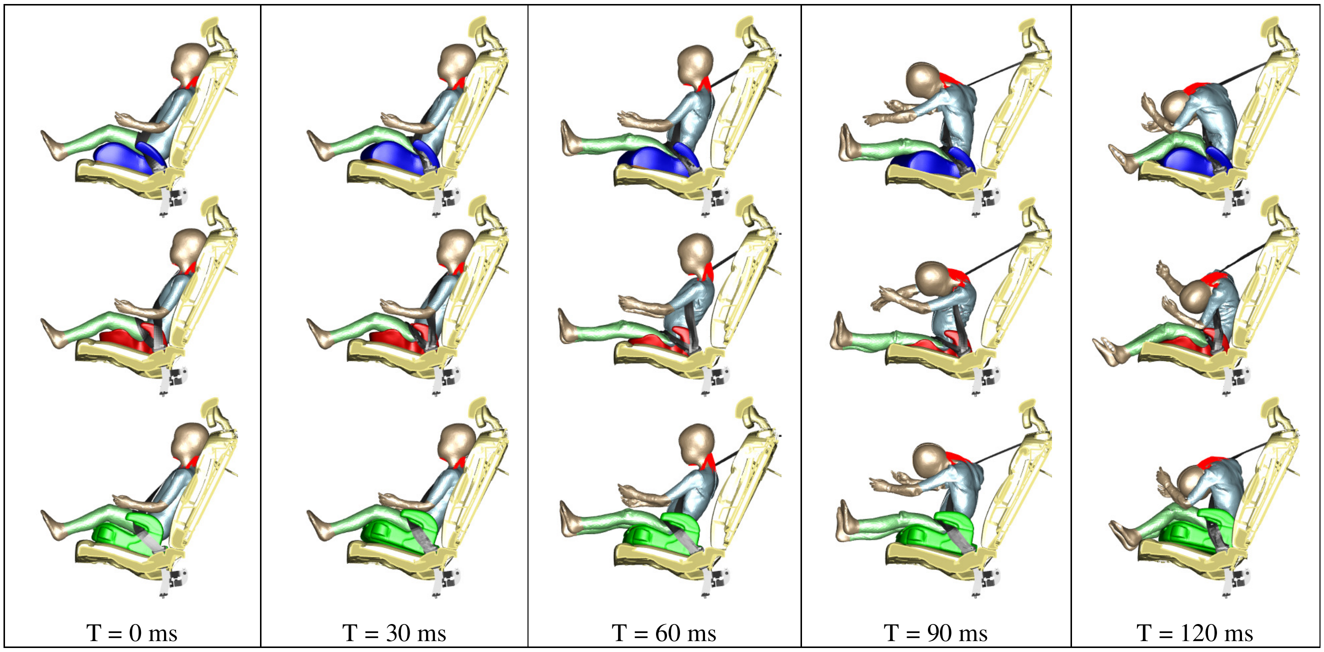

Figure 5. Lateral view time series with the PIPER 6ywith the Booster A (blue) on top, Booster B (red) in the middle, and Booster C at the bottom (green), at 0, 30, 60 , 90 and 120 ms.

Figure 6 displays the frontal view time series corresponding to Figure 5, showing that the seat belt loaded into the neck for Booster B, while the belt stayed in a mid-shoulder position for Booster A and Booster C.

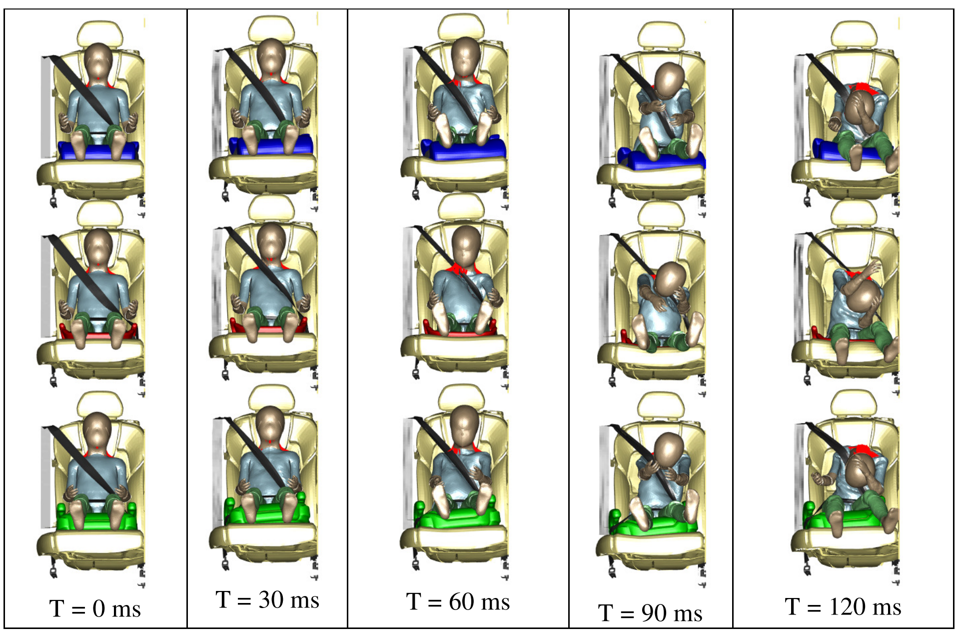

Figure 6. Front view time series with the PIPER 6y with the Booster A (blue) on top, Booster B (red) in the middle, and Booster C at the bottom (green).

The forward and downward displacement of the pelvis was largest when on Booster B, while the lowest forward displacement was found for Booster A, see (Figure 7). Booster C contributed to an upward movement of the pelvis. This was an effect of its bottom surface area being the largest so the booster slid on top of the vehicle seat, but also likely to some extent that its base was modelled as rigid and it couldn't deform. Booster B dug into the vehicle seat while Booster A and C more slid on top of the vehicle seat. The peak deformation of Booster B occurred at 70 ms and it was then compressed 24 mm at the center. While for Booster A, the peak compression was 6 mm, also at 70 ms.

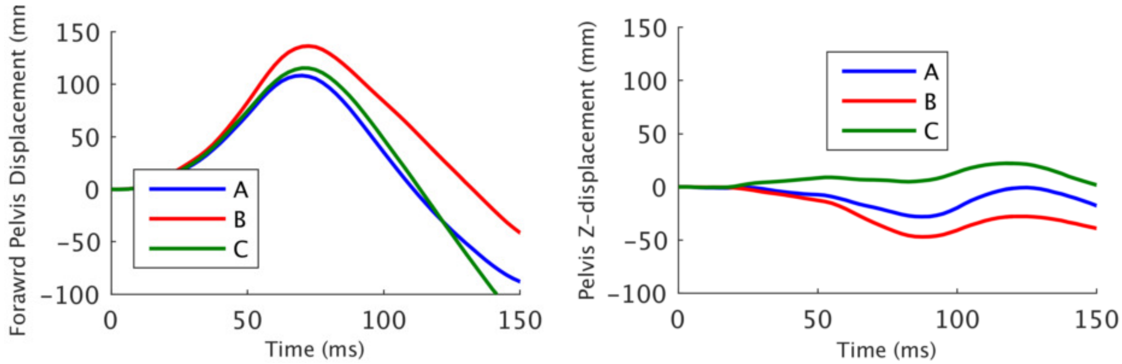

Figure 7. Displacement of the pelvis measured at the pelvis accelerometer node in the HBM. Left: Forward displacement. Right: Z-Displacement.

While Booster B gave the largest forward pelvis displacement, the opposite trends was seen for the forward head displacement for which Booster A resulted in 58 mm larger peak head displacement as compared to Booster B, see Figure 8.

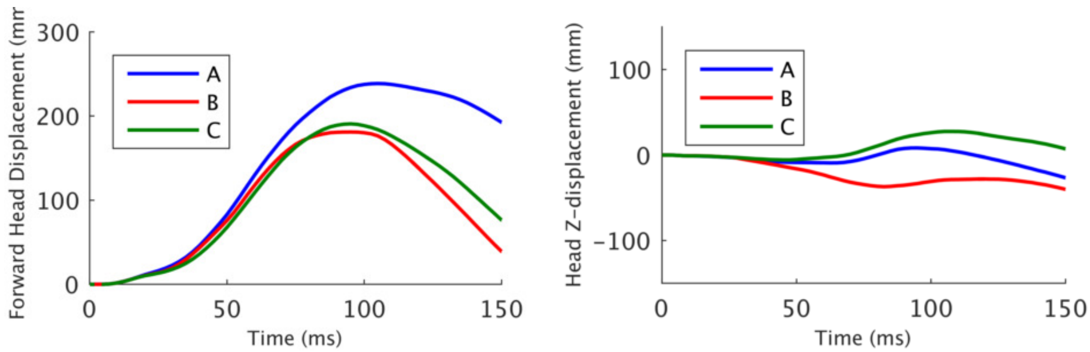

Figure 8. Displacement of the head measured at the head accelerometer node in the HBM. Left: Forward displacement. Right: Z-displacement.

Displacement data in the form of trajectories is shown in Figure 9, complemented with a trajectory figure connecting the trajectories at time of peak T1 forward displacement which was 75 ms for Booster A and Booster C and 80 ms for Booster B.

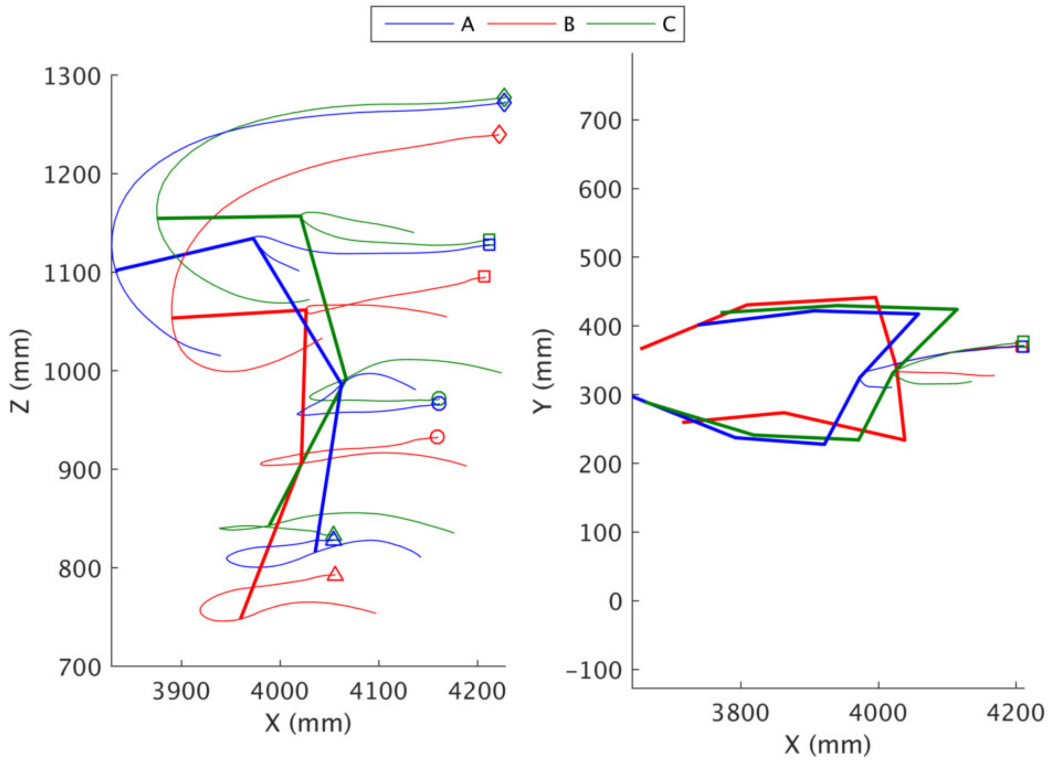

Figure 9. Head (diamond), T1 (square), T12 (circle), and pelvis displacement (triangle) trajectories. The markers show the origin of the trajectories. The thicker lines connecting the trajectories and creates a stick figure at the peak T1 forward displacement which occurs at 75 ms for Booster A and Booster C, and 80 ms for Booster B. Left: Lateral view. Right: Top view showing the T1 trajectory and the arms connected to the T1 vertebra via nodes on the acromion process.

Loadings for the PIPER 6y in the simulation series

The resulting anterior-posterior (AP) chest deflections, measured at the lower, mid, and upper end of the sternum of the HBM in a local coordinate system located at the T9 vertebra (Giordano et al. 2017) are shown in Figure 10. Booster A and Booster C produced a similar deflection pattern with peak AP deflection at 80 ms, with the highest deflections at the low- and mid-level, while the Booster B gave lower deflection values at the low and mid level, and the highest at the upper sternum, due to the belt loading the neck rather than the chest of the HBM. The deformation pattern of the ribcage at peak deflection timing of 80 ms is shown in Figure 11.

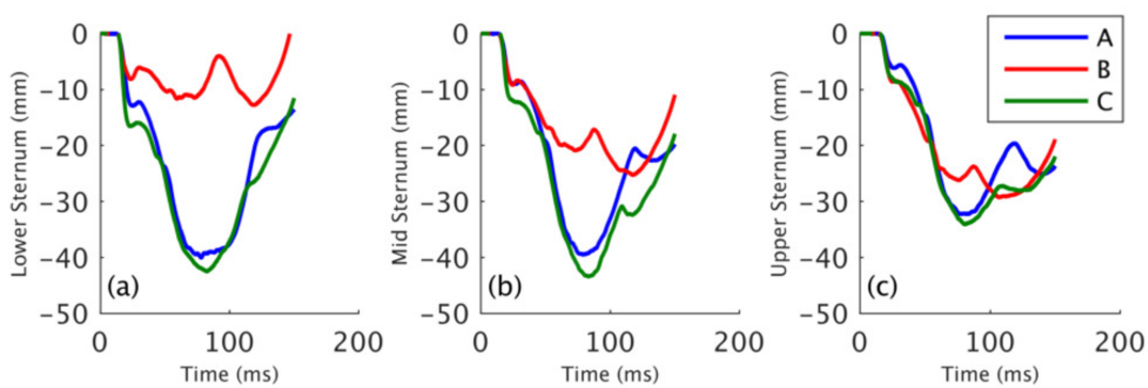

Figure 10. Anterior-posterior sternum deflections of the HBM for three points on the sternum relative to a local coordinate system at the T9 vertebra. (a) Lower sternum. (b) Mid sternum. (c) Upper sternum.

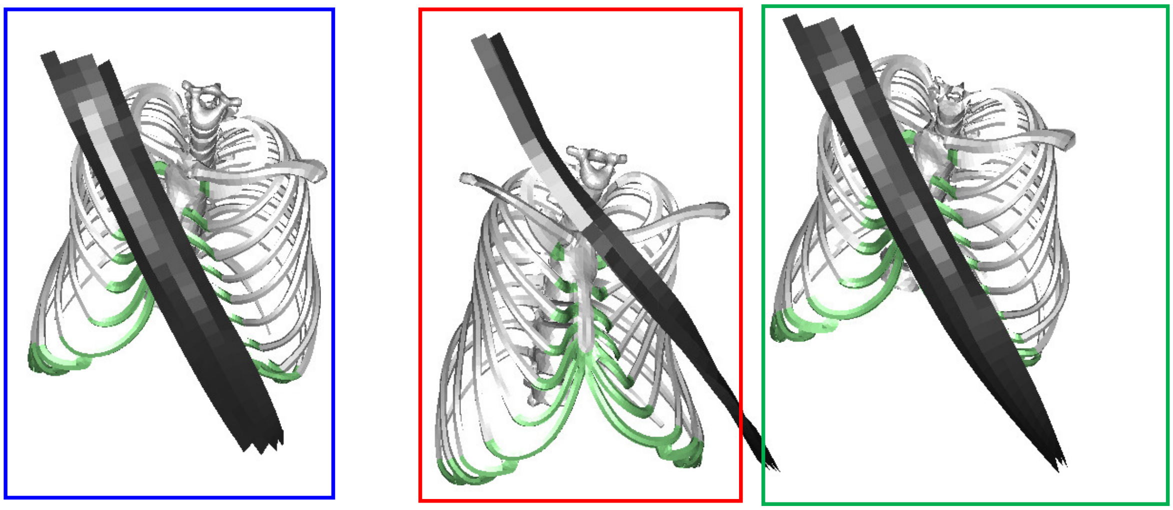

Figure 11. Chest deformation due to belt loading at 80 ms for Booster A (blue frame, to the left), Booster B (red frame, middle), and Booster C (green frame, to the right).

Cross-sectional forces through the ligamentous cervical spine at C2-C3 level are shown in Figure 12. A small effect of the high belt position for Booster B can be seen as the peak shearing (Fx) force was highest for this simulation, while the other components were similar for all simulations.

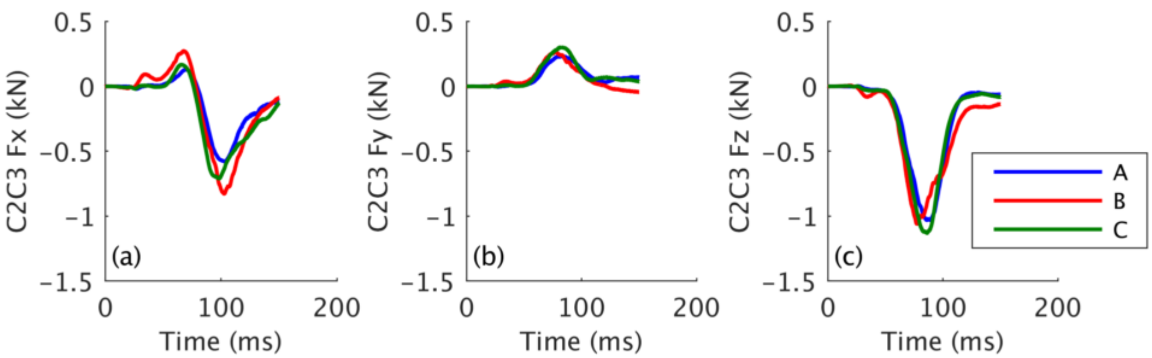

Figure 12. Cross-sectional forces through the ligamentous cervical spine at C2-C3 level.

The head acceleration of the HBM in the simulation with Booster B had a peak at 105 ms, see Figure 13. This was due to an impact between the mandible and sternum of the HBM at this time. This peak was likely over-exaggerated in the simulation as the mandible connected directly to the cranium, omitting the mandibular joint.

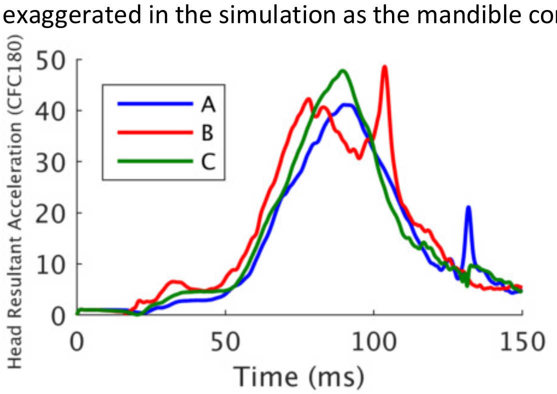

Figure 13. Head acceleration filtered with a CFC180 filter according to SAE J211.

DISCUSSION

Three booster cushions with different size, shape, stiffness and guiding loop user specification and design were exposed to frontal impacts using the Q10 in physical sled tests and the PIPER 6y in a simulation series. In summary, the Q10 and PIPER 6y both showed desirable kinematics and loadings when restrained on Booster A, while not when restrained on Booster B. When restrained on Booster C, the PIPER 6y showed good kinematics, while Q10 experienced shoulder belt slipping off the shoulder.

As for adults, optimal protection of child occupants is achieved when fulfilling two main restraint principles. Most importantly, the pelvis must be restrained. An early and tight coupling to the pelvic bones is desired and maintaining it throughout the whole event is prioritized (Adomeit 1975 and 1977). The restraint of the pelvis is also a prerequisite to initiate an essential torso pitch (Kent and Forman, 2015, Adomeit 1975). By keeping the shoulder belt on the shoulder, a controlled forward torso and head movement is achieved. Boosters serve the main purpose to raise the child to enable the pelvis restraint, and to help keep the shoulder belt over the shoulder in an adult seat and seatbelt environment. Hence, for optimal child protection it is essential to consider the whole system of the seat belt, the vehicle seat, the booster and other vehicle interior structure, which may contribute. Although a limited number of booster designs and child occupant sizes evaluated in this study, it nevertheless provides some interesting insights on these interactions.

With respect to kinematics and pelvis interaction, several factors were observed contributing to delayed pelvis restraint. The relatively more forward and downwards movement by Booster B, as shown in Figure 9, is influenced by substantial booster deformation (20 mm) and less surface in contact with the vehicle seat. The digging into the seat by Booster B, due smaller contact surface, resulted in a more downward angle of the booster, delaying the pelvis restraint.

The desired torso pitch is influenced by the pelvis restraint as well as the shoulder belt interaction. The occupant response on Booster B is an example of these two factors and their inter-relation (see Figure 3 and Figure 5). The phenomenon of shoulder belt moving into the neck and the lower portion of the shoulder belt moving up the lower torso towards the axilla, was seen for both the Q10 and the PIPER 6y when on Booster B, but not on Booster A and Booster C. Investigating in detail for the PIPER 6y, it is seen that the shoulder belt moved above the upper sternum, influencing the chest deflection measurements available in the HBM. This is the reason behind the substantial lower chest deflections for Booster B than the other two boosters (see Figure 10). For efficient torso restraint, it is essential that the shoulder belt loads the strong parts of the chest and that it does not move above the sternum (Adomeit, 1977).

The shoulder belt interaction with the torso is important for a good occupant restraint during crash. The shoulder belt should remain on the shoulder during the whole impact in order to control the upper torso and head kinematics. Booster A illustrates such a favorable shoulder belt interaction, for both sizes of child occupants, see Figure 2 and Figure 6. With Booster C however, during the crash, the shoulder belt slip-off was seen with the Q10. Booster A and Booster B allow shoulder belt routing above the guide for older/larger children, which helps the shoulder belt remain on the shoulder of the Q10. The option to allow the shoulder belt to be placed above the guiding loop or under the guiding loop, depending on the size of the child, provides a more stable shoulder belt position, and mitigates the risk of shoulder belt slip-off.

The different designs and instructions for the shoulder belt guiding influence the shoulder belt interaction with the torso. By keeping the shoulder belt under the guide, it can help to keep the lower portion of the shoulder belt from moving up towards the axilla. This reduces the likelihood of the shoulder belt getting close to the neck and high on or above the sternum. Nevertheless, in Booster A with shoulder belt routing above the guide for the Q10, it was still possible to keep the shoulder belt over the rib cage and on mid shoulder. For this, the design of the guides is important, and should be studied further.

With respect to loading and occupant responses some general trends can be noted. The neck loading was influenced by a delay in the torso pitch (exemplified by Booster B) as well as the extent of torso pitch. Torso pitch also results in increased head excursion. This kinematic response is preferred to help reducing the neck loading, but it is important to control head excursion to limit risk of head impacts. Both the Q10 and the PIPER 6y were sensitive to delayed pelvis restraint, resulting in delayed and limited torso pitch, followed by increased neck loading.

The challenge of designing seat belt geometry in a vehicle to accommodate all sizes of occupants is mainly a balance between the small adults and the larger children requiring boosters. To accommodate the protection needs for the larger children (ensuring mid-shoulder position), the small adults may get the shoulder belt close to the neck, causing discomfort from chafing against the neck. Such discomfort may result in unsafe solutions such as placing the shoulder belt under the arm or off the shoulder. This challenge can be overcome by the design and user specification of the booster. Booster A, which allows the choice of shoulder belt routing above or under the guide, is an example of how the comfort as well as the protection needs for a larger span of sizes of children is accommodated, without compromising the comfort for smaller adults. Today, none of the boosters in the EuroNCAP prescribed booster list (EuroNCAP, 2019) allows more than one shoulder belt routing. In addition, the UN ECE R129 puts restrictions on this aspect too, since only one safety-belt route and one main load-bearing contact point is allowed (UN ECE R129, 2013). This study provides insights on the importance of booster design and the benefits of allowing booster designs with flexible shoulder belt routing, contributing to real world protection of small adults as well as large children on boosters.

CONCLUSIONS

This study shows that booster shape and deformability influence the dynamic restraint performance, even though the initial belt fit was similar. When restrained on Booster A, both the Q10 and the PIPER 6y showed desirable kinematics and loadings, while not when restrained on Booster B. The Q10 experienced shoulder belt slipping off the shoulder when restrained on booster C.

The tested boosters' shape as well as the design of the guiding loops influenced the overall kinematics as well as the occupant loading.

Q10 and PIPER 6y responded similarly to the different booster designs in terms of pelvis restraints.

The option to allow to the shoulder belt to be placed above the guiding loop (in addition to under), provides a more stable shoulder belt position, especially for the taller children. This mitigates the risk of shoulder belt slip off. Such flexibility of the booster cushion, allowing shoulder belt being guided both above or under the guiding loops, could accommodate a larger size span of children.

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