Influence of support leg for booster seats

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Abstract:

Currently, support legs are only allowed for integral child restraints systems in UN ECE R129. Discussions are ongoing to include support legs for booster seats as well. With the overall purpose to understand potential real-world safety benefits, this study aimed at exploring the effect of a support leg on the protection of a booster-seated child. This was done by simulations, comparing booster seats with and without a support leg in a vehicle like interior model using the PIPER6y human body model (HBM) and the Q6 Anthropomorphic Test Device (ATD), exposed to two different frontal impact crash types. The influence of seatbelt pretensioner in this context was also explored.

With activated seatbelt pretensioner, the simulation series resulted in minor and non-consistent differences when adding a support leg to the booster seat in a modern vehicle environment model. Without the seatbelt pretensioner, somewhat larger differences between the two configurations were seen. Most importantly, neither aspects of kinematics nor responses provided evidence of enhanced real-world protective benefits from adding a support leg to the booster seat. With increasing degree of car sharing and ride sharing, ensuring access to easy-to-use, portable and low complexity booster seats is increasingly important to ensure that children 4 to 10-12 years keep using boosters. Considering both performance and user aspects, the overall real-world safety benefit of allowing a support leg for booster seats is not evident.

Introduction

Children aged 4 to 10-12 years old are well protected if using boosters that elevate them, shorten the seat cushion length, position the lap belt in contact with the pelvis, and position the shoulder belt across the chest and shoulder. Their protection in case of a crash is a combination of the vehicle design, the booster design and how the child is using the restraints. Boosters have shown to help reduce injury risks, and almost eliminated the risk of abdominal injury (Arbogast et al., 2009, Durbin et al., 2003). There are three main types of boosters: booster seat (with a backrest), booster cushion (without backrest) and integrated (built-in) booster. This study is about booster seats (with backrests).

Driven by sustainability goals, shared mobility services are increasing worldwide, which also includes families with children (Ehsani et al., 2021). Studies indicate an overall lower child restraint usage in ride-sharing trips compared to when travelling in privately owned vehicle (Reed et al., 2022, Koppel et al., 2021). Convenience is a major factor when families choose not to use ride-share services (Owen et al., 2019). A portable, light weight and safe solutions is essential to facilitate child restraint usage in shared mobility services (Jakobsson et al., 2020).

Support legs have been used for rearward facing child restraint systems for decades, decreasing forward seat rotation in frontal impacts and followed by implementation in forward-facing integral child restraint systems. In UN ECE R129, a support leg is allowed to be used as an anti-rotation device for these two seat categories (referred to as integral child restraint systems), while not for booster seats. Recently, the question on allowing a support leg for the booster seat category was raised at GRSP (2022). The main argument, addressing the convertible or multi-purpose type of child restraints, was to enable the use of the support leg also when in a booster seat mode. Currently, the booster seat envelope in UN ECE R16 does not allow for a support leg. If including the possibility of a support leg for a booster seat, there is an obvious risk this may become popular when designing pure booster seats as well. Hence, driving the already large booster seats to become more complex, heavier and bulky.

With the overall purpose to understand potential real-world safety benefits this study aimed at exploring the effect of a support leg on the protection of a booster-seated child. Specifically, the aim is to compare booster seats with and without a support leg in a vehicle like interior model using the PIPER6y human body model (HBM) and the Q6 ATD, exposed to frontal impact simulations. The influence of seatbelt pretensioner functionality in this context is also investigated.

Methods

Simulations were executed using the PIPER 6-year-old HBM (PIPER6y) v1.0.2 (Giordano et al., 2017) and Q6 ATD model v1.2 positioned in a concept booster seat model with (Figure 1) and without support leg. A representative vehicle rear seat interior was used, including floor, seat structure with cushion and seatback, in addition to a state-of-the art seatbelt model. The concept booster was attached to the ISOFIX anchorages by connectors modeled as non-deformable. The support leg was modeled as non-deformable beam elements, attached to the front of the concept booster and in contact with the floor structure. The PIPER6y and the Q6 models, restrained on the concept booster model, were positioned on left rear seat and settled with gravity over a duration of 600ms. The nodal coordinates of the PIPER6y and Q6 models and concept booster model were extracted from the final timestep of the pre-simulation. PRIMER v18 (Oasys Ltd, Solihull, UK) was used to route the seatbelt. The shoulder belt was routed under the belt guide. The seatbelt had a pretensioner and a load limiter function.

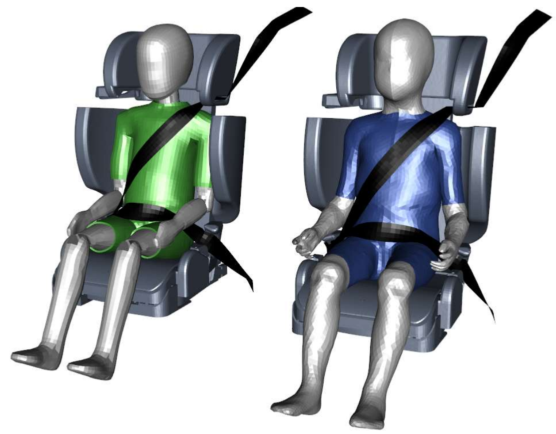

Figure 1. PIPER6y (blue) and Q6 (green) models positioned in a concept booster seat model.

Two different frontal impact simulations were included, representing a full-frontal rigid barrier impact in 64km/h (FF) and a frontal offset, with 50% overlap at the left-hand side in 50km/h (FO). The simulations were executed using LS-DYNA MPP version R9.3.1 with 240 CPUs (ANSYS/LSTC, Livermore, CA.) for a simulation time of 120ms. In total 16 simulations were conducted, see Table 1. In addition to the two frontal impact crash types and the two child occupant models, the parameters varied were with and without support leg, and with and without seatbelt pretensioner.

Table 1. Simulation matrix

SIMULATION N0.	MODEL	CRASH TYPE	SUPPORT LEG (with/without)	PRETENSIONER (with/without)
1	Q6	FF	without	with
2	Q6	FF	with	with
3	Q6	FF	without	without
4	Q6	FF	with	without
5	Q6	FO	without	with
6	Q6	FO	with	with
7	Q6	FO	without	without
8	Q6	FO	with	without
9	PIPER6y	FF	without	with
10	PIPER6y	FF	with	with
11	PIPER6y	FF	without	without
12	PIPER6y	FF	with	without
13	PIPER6y	FO	without	with
14	PIPER6y	FO	with	with
15	PIPER6y	FO	without	without
16	PIPER6y	FO	with	without

Analyses

Trajectories and accelerations were extracted from the accelerometers provided in the child occupant models. Head, T1 and pelvis kinematics were analyzed by horizontal (x) and vertical (z) trajectories over time and by maximum displacement. The neck force (tension and compression) was measured by a local cross-section in the child occupant models, at the C2-C3 region of the cervical spine for PIPER6y, and at the upper neck load cell for Q6. The lumbar spine forces were extracted from the lumar load cell for Q6.

Submarining was defined as when the lap belt moved above both the left and right anterior superior iliac spine (ASIS) landmarks. Belt slip-off was defined as when the shoulder belt completely slipped-off the shoulder of the child occupant models, during the forward motion of the child occupant model.

Results

Kinematics

No submarining occurred in any of the 16 simulations. Without pretensioner in crash type FF, the shoulder belt slipped-off the shoulder of PIPER6y close to the start of the rebound, regardless of the use of the support leg (Sim No. 11 and 12).

For Q6, the pelvis x-displacement was similar for both crash types and ranged from 108 to 198 mm (Figure 2). There was a somewhat shorter pelvis x-displacement with support leg, by 20 respective 42 mm in FO and FF. In simulations with support leg, the pelvis moved up to 38 mm upwards, while pelvis had a more horizontal trajectory or a slightly downward motion without support leg (Figure 3). The support leg provided an extra support to the front of the booster, reducing the downward rotation of the cushion part of the booster. These somewhat higher upward pelvis z-trajectories also influenced the head trajectories, with a slightly upward z-trajectories (Figure 3).

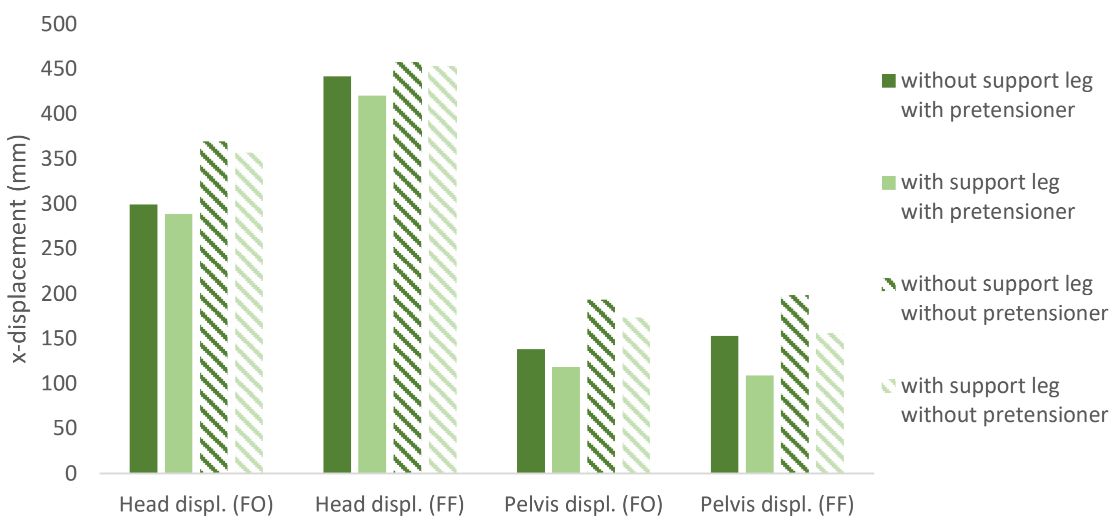

Figure 2 Head and pelvis maximum x-displacements for Q6 in FO and FF simulations.

For Q6, the head displacement ranged from 289 to 457 mm with the highest displacement in FF (Figure 2). The support leg resulted in 4 to 12 mm shorter head displacement in FF respective FO, compared without support leg. The shortest head x-displacements were seen with pretensioner, resulting in up to

70 mm shorter head x-displacement, compared to no pretensioner, irrespective if the support leg was present or not.

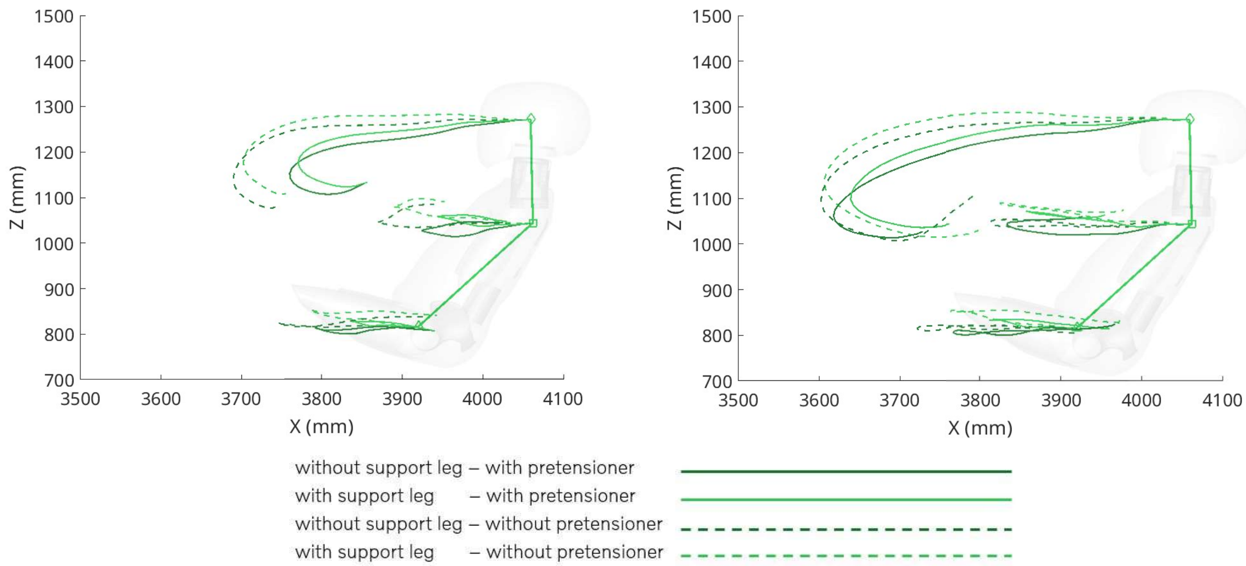

Figure 3 Head, T1 and pelvis trajectories for Q6 in FO (left) and FF (right) simulations.

For PIPER6y, pelvis displacement ranged from 62 to 162 mm, which was somewhat shorter compared to Q6. Pelvis displacement was relatively shorter with support leg, by 58 respective 71 mm in FO and FF. Similar trend was observed for PIPER6y as seen with Q6 of pelvis more upwards trajectories with the support leg, as well as the influence on T1 and head trajectories (Figure 5).

Head displacement ranged from 321 to 512 mm. The PIPER6y had similar kinematics as Q6, with slightly shorter head displacement when support leg was present compared to no support leg (Figure 4).

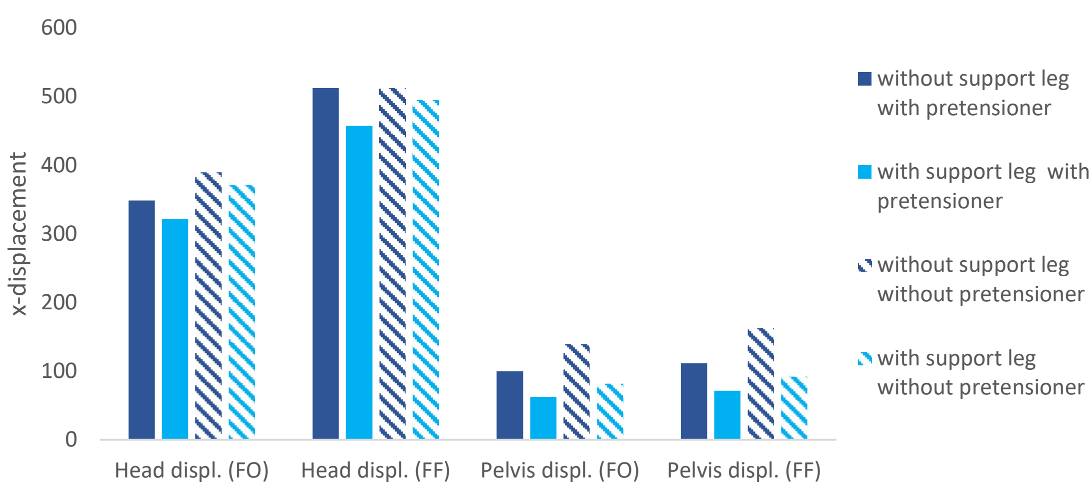

Figure 4 Head and pelvis maximum x-displacements for PIPER6y in FO and FF simulations.

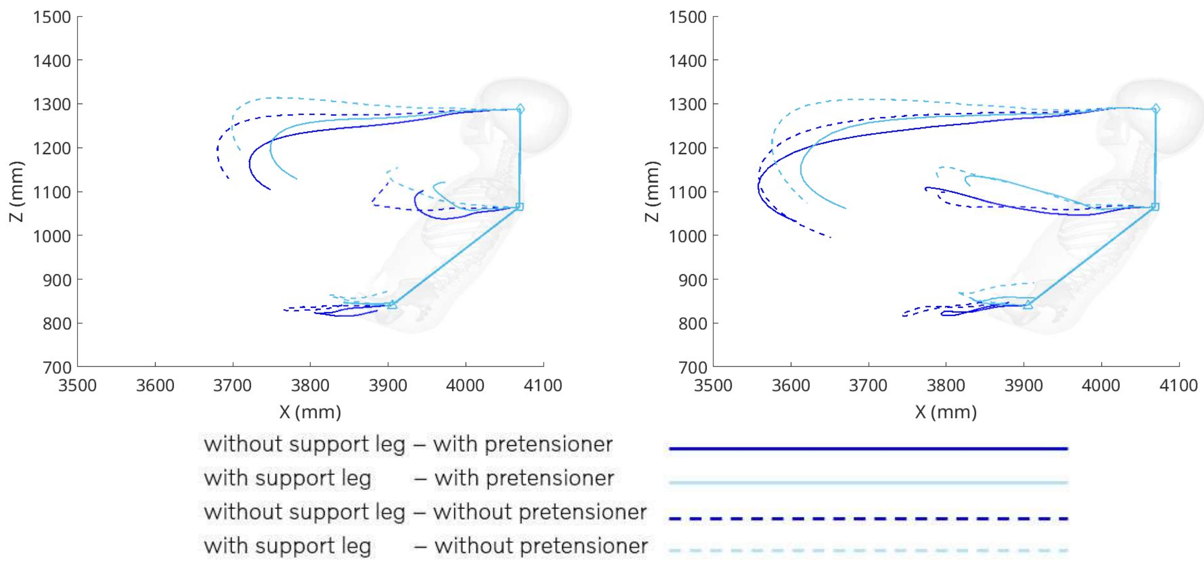

Figure 5 Head, T1 and pelvis trajectories for PIPER6y in FO (left) and FF (right) simulations.

Both Q6 and PIPER6y had similar kinematics trends with some exception. Both occupant models had shorter displacement with activated pretensioner. This was also valid for the support leg, but not to the same extent as the pretensioner. In all simulations the pelvis displacement was shorter for PIPER6y compared to Q6, while the opposite was found for the head displacement.

Figure 6 shows side views of the two child models at time of maximum head displacement in the FO crash type. This also corresponds to approximately the time of maximum neck tension (Table 2). The difference in spine shape in Figure 6 provides insight into different curvature of the spines of the two child models. PIPER6y has a more continuous curvature over the whole spine, enabled by its detailed modelled spine, including segments for each vertebra in the lumbar, thoracic and cervical spine. Q6 is modelled with a rigid thoracic spine box and flexible rubber sections for the cervical and lumbar spine, respectively. This influenced the overall curvature, resulting in a more pronounced flexion of the cervical spine at the junction of the rigid thoracic spine box. See Appendix for side views for all simulations.

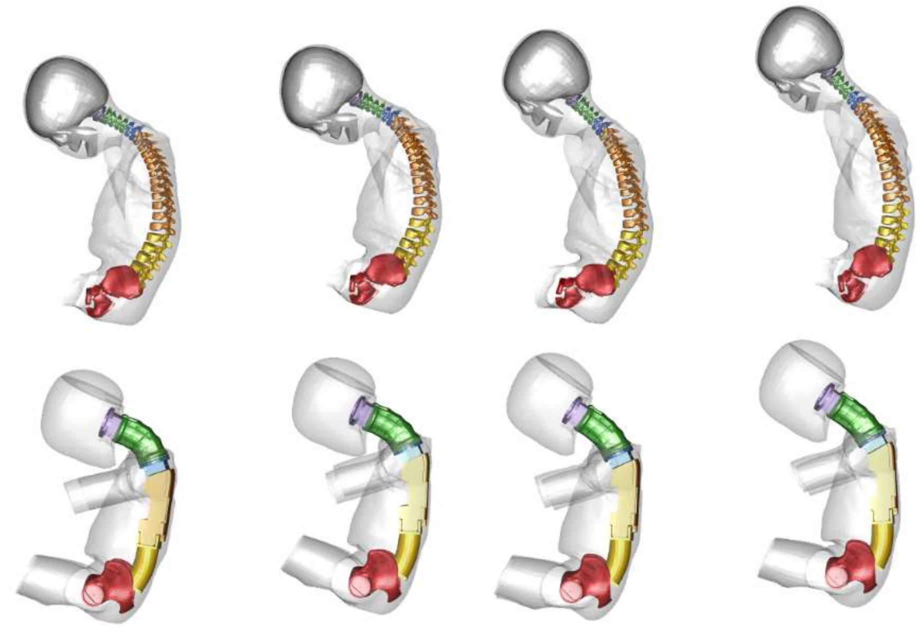

Figure 6 Side views of PIPER6y (top row) and Q6 (bottom row) at 80 ms in FO, approximately the time for maximum neck tension force. Simulation No. for PIPER6y left to right: 13, 14, 15, 16 and for Q6 left to right: 5, 6, 7, 8.

Responses

In FO, Q6 simulations with support leg resulted in 18% lower head acceleration, 13% lower chest accelerations and 18% lower pelvis acceleration, as compared to without support leg, when without pretensioner. With pretensioner, the support leg resulted in 6% lower head acceleration, 6% higher chest acceleration and 28% lower pelvis acceleration. In FF, similar trends were seen as in FO, but with higher magnitudes due to the increased crash severity in the FF crash type (Table 2).

In FO, 10% higher head acceleration, 16% lower chest acceleration and 23% lower pelvis acceleration was observed with PIPER6y with support leg as compared to without support leg, when without pretensioner. With pretensioner, only minor differences in head, chest and pelvis acceleration comparing with/without support leg were seen.

The effect of the pretensioner function was overall superior as compared to the support leg effect. Similar or lower accelerations for head, chest and pelvis were found in simulations with pretensioner compared to simulations with support leg, for both child models in both crash types, with exception for pelvis acceleration for PIPER6y in FO.

Table 2 Head, neck, chest and pelvis responses of Q6 and PIPER6.

Max responses		**Model**	**Crash type**	**with pretensioner**		**without pretensioner**	
				without support leg	**with support leg**	**without support leg**	**with support leg**
Head acc. resultant	g	Q6	FF	89	86	129	110
Upper neck tension	kN	Q6	FF	2.7	2.6	3.7	3.3
Chest acc. resultant	g	Q6	FF	59	63	78	73
Pelvis acc. resultant	g	Q6	FF	86	70	104	90
Lumbar spine compression	kN	Q6	FF	0.9	1.1	1.1	0.9
Lumbar spine tension	kN	Q6	FF	1.3	1.7	1.9	1.7
Head acc. resultant	g	Q6	FO	58	55	67	55
Upper neck tension	kN	Q6	FO	1.8	1.7	2.0	1.7
Chest acc. resultant	g	Q6	FO	42	45	51	44
Pelvis acc. resultant	g	Q6	FO	54	39	75	62
Lumbar spine compression	kN	Q6	FO	1.1	0.8	1.0	0.7
Lumbar spine tension	kN	Q6	FO	0.4	0.5	0.5	0.7
Head acc. resultant	g	PIPER6y	FF	103	100	128	139
Upper neck tension	kN	PIPER6y	FF	2.2	2.2	2.7	2.8
Chest acc. resultant	g	PIPER6y	FF	55	48	71	58
Pelvis acc. resultant	g	PIPER6y	FF	73	68	92	83
Head acc. resultant	g	PIPER6y	FO	61	64	68	75
Upper neck tension	kN	PIPER6y	FO	1.6	1.7	1.9	2.0
Chest acc. resultant	g	PIPER6y	FO	42	40	58	48
Pelvis acc. resultant	g	PIPER6y	FO	59	51	66	51

No clear trend was observed for Q6 lumbar spine forces. In FF, the lumbar spine compression (occurring during the first 50 ms) was higher when a support leg was included, with activated pretensioner. The opposite was seen in FO, with lower lumbar spine compression with support leg. Lumbar spine tension (occurring later in the sequence) was at lower levels in FO for all combinations of support leg and pretensioner, while the lumbar spine tension was up to 1.9 kN in FF, due to more pronounced torso pitch in this relatively higher crash severity. The combination with support leg and pretensioner resulted in higher lumbar tension (1.7 kN) compared to the simulation without support leg and with pretensioner.

In FO and without pretensioner, the Q6 neck tension load was 16% lower with the support leg as compared without. In the configuration with pretensioner, the effect of the support leg was neglectable. The opposite trend was observed for PIPER6y, with a 4% higher neck tension with the support leg as compared to without, in the configuration without pretensioner. In comparison, irrespective of support leg, PIPER6y had up to 15% lower upper neck tension with pretensioner as compared to without pretensioner (Figure 7).

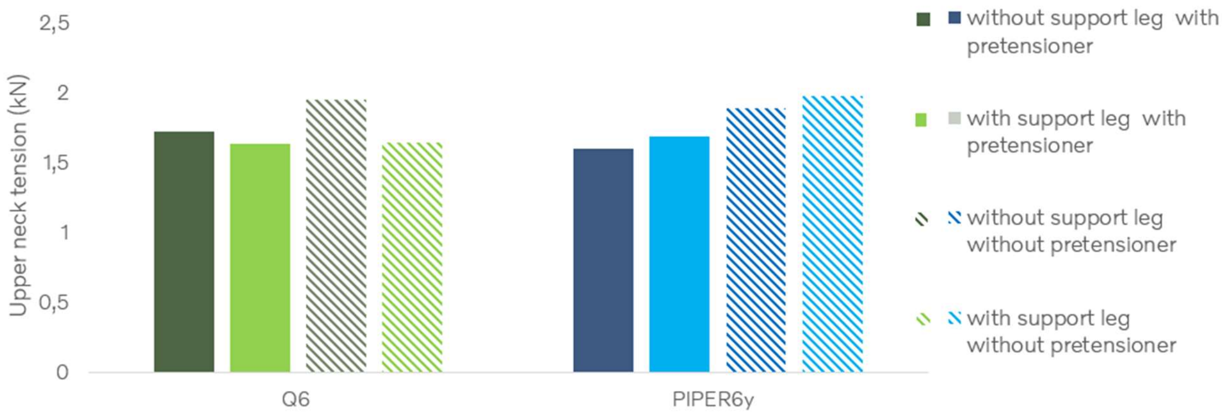

Figure 7 Maximum upper neck tension force in FO simulations, Q6 (left) and PIPER6y (right).

Discussion

This study explored influence on child occupant protection using a booster seat with and without a support leg, by varying crash type, child model and seatbelt pretensioner. The support leg helped reduce forward rotation of the booster, since it provided a stable attachment together with the attachments to the ISOFIX anchorages. As a result, differences were seen in the simulations with a support leg in relation to without, in terms of shorter displacements and lower responses to most body regions. While, in the configurations with seatbelt pretensioner, only minor effect was seen with the support leg.

Consistently, the pretensioner contributed to higher performance in both kinematics and responses, as compared to without pretensioner. Furthermore, the effect of the pretensioner function was overall superior as compared to the support leg.

Neck tension load was lower in the simulations with the support leg in comparison to without. This was most pronounced for Q6, while less for PIPER6y. The Q6, due to its rigid thoracis spine design, has limited capability of humanlike spine motion. PIPER6y has a more humanlike spine design, including vertebrae throughout the spine, allowing a flexible spine motion when exposed to a frontal impact (see Figure 6 and Appendix). When compared to PIPER6y, the real-world relevance of the Q6 neck loadings can therefore be questioned. In a previous study, Sherwood et al. (2003) showed that the rigid thoracic spine in the child ATD results in high upper neck loads that are not representative of the true injury potential. In the same study, they executed simulations using a model of the child ATD, in which the stiffness to the thoracic spine was reduced. This resulted in a dramatic reduction to the neck loading and also provided a more humanlike curvature of the spine. With this knowledge, it is essential to understand that the neck loads measured in the Q6 in the current study are likely also influenced by this ATD spine artefact, restricting the humanlike spine motion, whereby the relative difference in neck loads should be interpreted with care. Furthermore, cervical spine injuries to booster-seated children are rare (Sherwood et al., 2003, Durbin et al., 2003). Durbin et al. noted that there were no neck injuries to booster-seated children in their study, while injuries to the head, face and chest were seen. The ATD's limited measurement sensitivity is necessary to take into consideration when assessing child restraints. Therefore it is essential for consumer information tests and similar, to understand the ATD measurement capabilities, when assessing complex restraint solutions and to balance this result together with the risk of misuse and limited real-life benefit.

The support leg's influence on the booster rotation could impose additional loads through the spine. However, no clear trend for the effect of the support leg was seen in the lumbar spine loads. Lumbar spine compression loads occurred within the first 50ms of the crash, during the initial lap belt to pelvis interaction, prior to the torso forward motion (torso pitch) was initiated. As the torso pitch occurred, the lumbar spine loading transferred into tension. Further work is needed, to understand the possible consequences to the lumbar spine when the booster seat movement is restricted both vertically and horizontally, being rigidly attached between the support leg and the ISOFIX anchorages. Another aspect, in need of further investigation, is the comfort experience for the child, as the booster is so rigidly attached.

As shared mobility services increase over the world, the demand of easy to use and portable boosters intensifies. Already with current booster designs, despite the boosters' fairly simple design compared to child restraint systems with integral harness, studies have shown a high prevalence of misuse of boosters as well (O'Neil et al., 2009, Koppel et al., 2013, Fastenmeier et al., 2006). Misuse may diminish its injury reducing effect in case of a crash (Bilston et al., 2007). Adding a support leg introduces an additional feature for potential misuse and drives booster design in the opposite direction of the users' demands of usability. For real-world safety effect, any potential safety benefit should be put in relation to the consequences of added weight and complexity, and the fact that conventional boosters have shown to provide excellent real-world protection over the years (Durbin et al., 2003, Arbogast et al., 2009, Anderson et al., 2017). Besides, already today there is a challenge to avoid a premature transition from booster to seatbelt only, among 4 to 7 year old children (Enriquez, 2021). Ensuring ease-of-use and keeping complexity down is important to ensure children keep using boosters until they can travel safely without.

Today, there is a clear trend towards complex and bulky booster seats, driven by consumer information tests. Trends have also driven booster designs to include questionable features, that are not proven to contribute to occupant safety. Examples of such features are; shoulder belt pads, designed for the ATDs in the crash test; lap belt crotch routers, designed based on a perception of need to position the lap belt, while instead potentially adding slack to the seatbelt; rigid attachments to the ISOFIX anchorages, while the booster also is restrained by the seatbelt; and large lateral side structures, including "external side impact devices" optimized for test rigs not cars. Efficient communication of consumer information test results to the consumer has resulted in acceptance and even a demand for these features. If GRSP allows for inclusion of a support leg for booster seats, and those seats then provide somewhat improved ATD responses in consumer information tests, there is a significant risk that the support leg may be perceived as an essential part of a booster seat. Thereby, it might also add to the list of the other questionable features. This would increase the booster's complexity, weight and size and may pose issues for booster usage, especially in shared mobility, and thereby influence overall real-world protection.

The most pronounced child occupant protection effect seen in this study was that of the seatbelt pretensioner. Consistently, the simulations with pretensioner resulted in shorter head and pelvis forward displacements and lower head, chest and pelvis accelerations, as compared to simulations without pretensioner. Hence, the focus should be on increasing the availability of pretensioners in cars, instead of adding complexity to the boosters. In 2017, Euro NCAP introduced an upgraded rear seat rating program resulting in an increase of pretensioner and load limiters from 10% to be included in almost all cars within a year (Barry, 2020). C-NCAP has also included similar consumer rating program in China, driving implementation of advanced restraints in the rear seat. The US consumer rating program by IIHS is about to introduce a rear seat rating in frontal impacts, which will likely drive the rear seatbelts to include pretensioner and load limiter functions as well. The rear seats of cars are constantly improving; therefore there is a need to investigate how booster seat certification/consumer information test set-ups can be further developed, to improve the representation of modern vehicles. The booster seat is just one part of the real-world child occupant protection, the vehicle interior and the seatbelt are just as important. To capture the full protective effect of new design features of booster seats, such as a support leg, the context should be as realistic as possible.

Conclusions

This simulation study shows that minor and non-consistent differences in displacements and responses were seen by adding a support leg to the booster seat when exposed to frontal impacts in a modern vehicle interior model, including activated seatbelt pretensioner. Somewhat larger differences were seen in the configurations without pretensioner. Most importantly, including two different child occupant models and two different frontal impact crash types, neither aspects of kinematics nor responses provided evidence of enhanced real-world protective needs from adding a support leg to the booster seat in a modern vehicle. Put in a context of the importance of portability and ease-of-use to ensure usage at all trips, the real-world benefit of a support leg on booster seats is questionable.

The seatbelt pretensioner was the overall most influencing parameter, having impact on kinematics as well as responses. With the increasing availability of pretensioners in current cars, this study indicates a need to investigate how booster seat certification/consumer information test set-ups can be further developed, to improve the representation of cars on the road. This is needed in order to capture the full protective effect if adding new design features to booster seats, such as support legs.

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Appendix

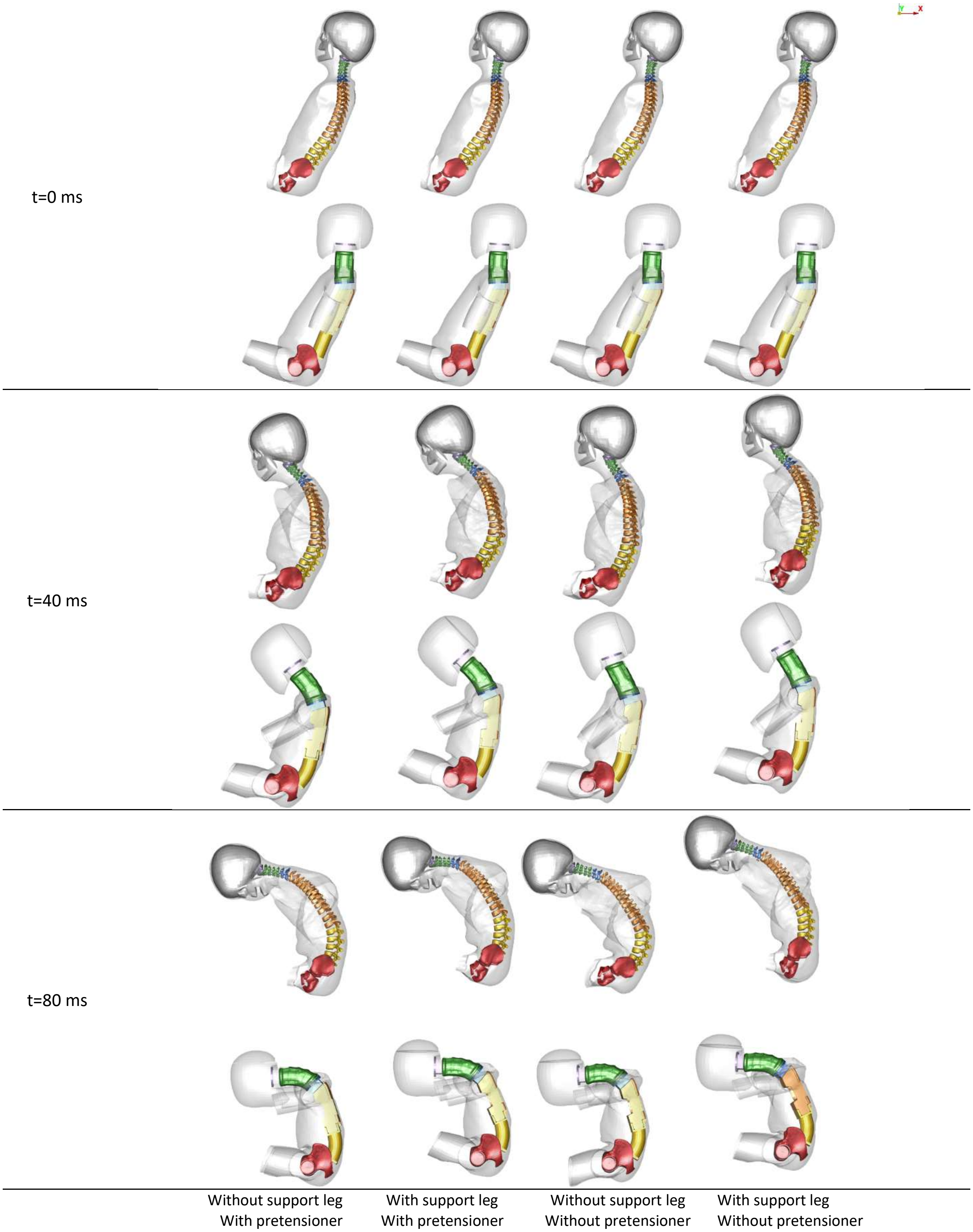

*Figure 8. Side views of PIPER6y (top row) and Q6 (bottom row) in **full frontal (FF) crash type**, at timesteps 0ms, 40ms and 80ms. Simulation No. for PIPER6y left to right: 9, 10, 11, 12 and for Q6 left to right: 1, 2, 3, 4.*

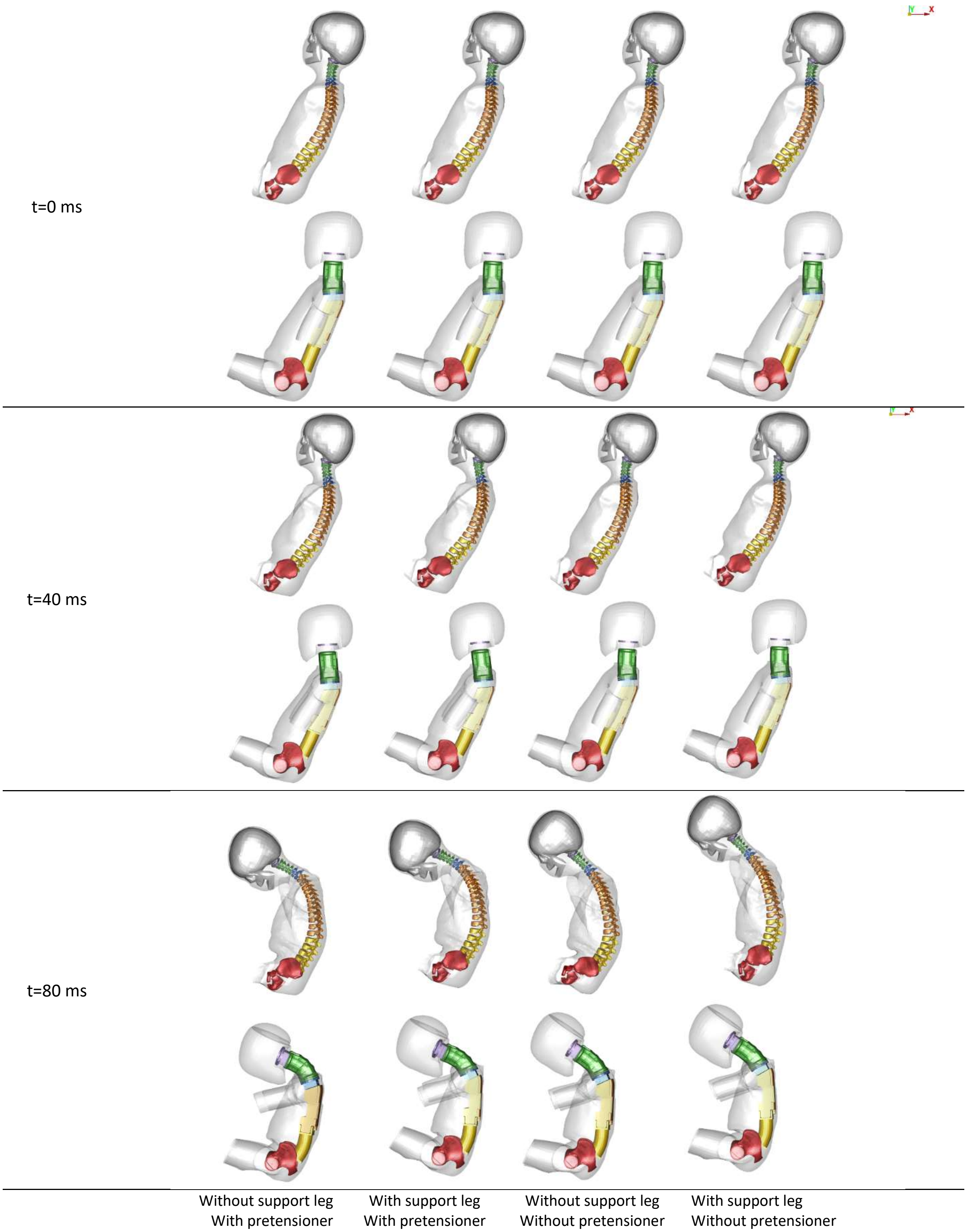

*Figure 9. Side views of PIPER6y (top row) and Q6 (bottom row) in **frontal offset (FO) crash type**, at timesteps 0ms, 40ms and 80ms. Simulation No. for PIPER6y left to right: 13, 14, 15, 16 and for Q6 left to right: 5, 6, 7, 8.*