Reclined seating in frontal impacts – a simulation study using PIPER 6y

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Abstract:

Reclined seating poses challenges for protection of adults in case of a frontal impact, while less attention has been given to child occupant protection. The overall purpose of this study is to contribute to the understanding of what challenges there are for child occupant protection when traveling in reclined seating position, applying the protection systems as of today. The specific aims are to compare reclined seating position to upright seating position in a standardized front passenger vehicle environment by investigating the influence of booster type and shoulder belt geometry in a simulation model, as well as studying the effect of seatbelt pretensioning and attachment to the ISOFIX anchorages, using one child size exposed to frontal impacts.

Five parameters were varied in the simulation study using the PIPER 6y human body model (HBM). The parameters include two different boosters (booster cushion and booster seat), two vehicle seat positions (‘upright position’ and ‘reclined position’), two shoulder belt geometries (‘nominal D-ring position’ and ‘rearward D-ring position’), in addition to with or without pretensioner activation and with and without attachment to the ISOFIX anchorages. In total 20 simulations were conducted using a full-frontal crash pulse of 56 km/h.

Submarining occurred when seated on the booster cushion in ‘reclined position’ without pretensioner. In all other simulations the booster combined with the pretensioner helped keep the lap belt on the pelvis and avoid submarining. Hence, submarining can be addressed in reclined seating using current booster design in combination with a vehicle seatbelt pretensioner.

The shoulder belt remained on the shoulder in all configurations with pretensioners. While a late belt slip-off (just before rebound) was seen for several configurations without pretensioner. Configurations with pretensioner resulted in lower head and neck loadings, in addition to reduced head excursion, as compared to the configuration without pretensioners. Furthermore, the initial shoulder belt geometry was important for enabling good restraint of the torso. The more rearward position of the shoulder belt D-ring improved initial shoulder belt contact for both seating positions when using the booster cushion.

This study provides evidence of the importance of including the whole context of child occupant protection when investigating novel seating. The interaction and compatibility of the booster, the vehicle seat and seatbelt are essential. This is exemplified by the importance of the pretensioner and the static incompatibility of the booster seat’s backrest and the vehicle seat back.

Introduction

As highly automatic vehicles are being developed, studies have shown that new seating configurations are desired by the consumer (Jorlöv et al. 2019, Östling et al. 2019). As occupants want to relax and sleep in vehicles, a reclined seating position is one desired seating position. Several studies have shown possible countermeasures to reduce the risk of submarining in reclined seating position for adults (Östling et al. 2021, Richardsson et al. 2020, Rawska et al. 2019).

It is known that children are at risk of submarining in current vehicles if they are seated directly on the vehicle seat. Boosters are designed to help provide children proper overall beltfit, including lap belt position on the pelvis. Real world crash data has shown that boosters nearly eliminate the risk of abdominal injuries compared to travelling without boosters, in the age group 4-7 years (Durbin et al. 2003).

However, there are limited studies addressing upcoming challenges with new seating configurations and seating positions. Tremoulet et al. (2021) explored the preferences among parents and their children between different types of face-to-face seating configurations. Levallois et al. (2019) highlighted challenges with compatibility between booster seats and reclined vehicle seat backs. In that user study, the booster seat could not reach similar reclined angle as the vehicle seat back, resulting in a wide gap behind the booster back. Masheshwari et al. (2020a) conducted a CAE study using PIPER 6y in a rearward facing seating position exposed to a frontal impact pulse, in both upright and reclined seating positions. In a study of various initial sitting postures using PIPER 6y and 10y HBMs, submarining was found when the HBM was pre-positioned in slouched sitting posture and the seat back was in upright position (Masheshwari et al. 2020b). Miller et al. (2021) presented a method to prepare a large simulation matrix with the PIPER 6y, in which various degrees of slouched posture will be investigated. The results are yet to be published. To the authors' knowledge, there are no studies exploring the consequences and potential need of restraint modifications addressing child occupant protection in reclined seating positions when facing forward in frontal impacts.

The overall purpose of the current study is to contribute to the understanding of what challenges there are for child occupant protection when traveling in reclined seating position, applying the protection systems as of today. Using the 6-year-old PIPER HBM, the specific aims are to compare reclined seating position to upright seating position, in a standardized front passenger vehicle environment, investigating the influence of booster type and shoulder belt geometry, in addition to study the effect of seatbelt pretensioning and attachment to the ISOFIX anchorages.

Methods

Twenty simulations were executed using the PIPER 6-year-old human body model (PIPER 6yHBM) v1.0.2 (Giordano et al. 2017, http://www.piper-project.org/), positioned as a front seat passenger in a mid-sized SUV in a sled environment with deformable interior. The sled was exposed to a full-frontal pulse of 56km/h (see Figure A1 in Appendix) and was executed using LS-DYNA MPP version R9.3.1 with 240 CPUs (LSTC, Livermore.).

Five different parameters were varied, including booster type, seating position, shoulder belt geometry (D-ring position), use of the ISOFIX anchorages, and with or without seatbelt pretensioner. In total 20 simulations were conducted, see Table 1.

Table 1 Test matrix including information on booster type, seating position, pretensioner, attachment to ISOFIX anchorages and shoulder belt geometry (D-ring position).

Simulation No.	***Booster***	***Seating Position***	***Pretensioner***	***ISOFIX***	***D-ring position***
1	*Booster Seat*	*Upright*	*Yes*	*No*	*Nominal*
2	*Booster Seat*	*Upright*	*Yes*	*Yes*	*Nominal*
3	*Booster Seat*	*Reclined*	*Yes*	*No*	*Nominal*
4	*Booster Seat*	*Reclined*	*Yes*	*Yes*	*Nominal*
5	*Booster Seat*	*Upright*	*No*	*No*	*Nominal*
6	*Booster Seat*	*Upright*	*No*	*Yes*	*Nominal*
7	*Booster Seat*	*Reclined*	*No*	*No*	*Nominal*
8	*Booster Seat*	*Reclined*	*No*	*Yes*	*Nominal*
9	*Booster Cushion*	*Upright*	*Yes*	*No*	*Nominal*
10	*Booster Cushion*	*Upright*	*Yes*	*Yes*	*Nominal*
11	*Booster Cushion*	*Reclined*	*Yes*	*No*	*Nominal*
12	*Booster Cushion*	*Reclined*	*Yes*	*Yes*	*Nominal*
13	*Booster Cushion*	*Upright*	*No*	*No*	*Nominal*
14	*Booster Cushion*	*Upright*	*No*	*Yes*	*Nominal*
15	*Booster Cushion*	*Reclined*	*No*	*No*	*Nominal*
16	*Booster Cushion*	*Reclined*	*No*	*Yes*	*Nominal*
17	*Booster Seat*	*Upright*	*Yes*	*No*	*Rearward*
18	*Booster Seat*	*Reclined*	*Yes*	*No*	*Rearward*
19	*Booster Cushion*	*Upright*	*Yes*	*No*	*Rearward*
20	*Booster Cushion*	*Reclined*	*Yes*	*No*	*Rearward*

Two different boosters were used, one booster seat (BS) and one booster cushion (BC) (Figure A2 in Appendix). The four configurations of seating positions and shoulder belt geometries are shown in Figure 1, for the BC and BS, respectively. The seating position was achieved by adjusting the seatback angle; 25° for the 'upright position' and 40° for the 'reclined position'. The shoulder belt geometry was varied by moving the D-ring position achieving an alternate 'rearward D-ring position' in addition to the 'nominal D-ring position'. The 'rearward D-ring position' was translated 250 mm rearwards and 120 mm downwards from 'nominal D-ring position', with the purpose to obtain full contact of the belt to shoulder in all seating positions. The attachment of the boosters to the ISOFIX anchorages was modeled by rigid constraints between the booster and the ISOFIX anchorages.

The seatbelt was routed using the pre-processor PRIMER v18.0 (Oasys Ltd, Solihull, UK), with a load limiter level of 4.2kN and a pretensioner time to fire of 10ms when activated. The seatbelt was the only vehicle restraint activated during the crash event. The PIPER 6y HBM was positioned using LS-DYNA. The BS was modelled as an inflexible inner structure surrounded by a solid meshed foam surface, while the BC was modeled with materials of high stiffness, with a solid meshed foam surface. The Boosters are shown in Figure A2 in Appendix. The lap belt and shoulder belt were routed under the belt guides of the boosters in all simulations, according to the manufacturers' guidelines.

Analyses

The effect of the seatbelt pretensioning and attachment to the ISOFIX anchorages were investigated on the subset of simulations with 'nominal D-ring position' (simulations 1-16).

When investigating the two shoulder belt geometries ('nominal D-ring' versus 'rearward D-ring') for the boosters and seating positions, the subset of simulations with activated seatbelt pretensioner and no attachment to the ISOFIX anchorages was used (simulations 1, 3, 9, 11 and 17-20). The focus was on lap and shoulder belt interaction, kinematics and loadings comparing 'upright position' and 'reclined position'.

The initial lap belt position was defined as the longitudinal (x-distance) and vertical (z-distance) distance between the anterior superior iliac spine (ASIS) and the upper edge of the lap belt. The paper presents the average of left and right ASIS to lap belt. The shoulder belt interaction analyses were done by lateral measurements of the acromion, and the edge of the shoulder belt. The x-distance between the PIPER 6y and the shoulder belt, defined as the gap, was measured by a defining a longitudinal distance between the skin, at the mid clavicle, to the shoulder belt.

Results

Initial posture and beltfit

In the 'upright position', PIPER 6y had an initial torso angle of 40˚, which was the same for both types of boosters. While in the 'reclined position', the initial torso angle was influenced by the booster seat's backrest position and its interaction with the vehicle seat back. This resulted in a less reclined torso angle of 47˚ when seated in BS, as compared to 55˚ for the BC, see Figure 1.

The BS positions the pelvis more forward than the BC in relation to the vehicle seat, irrespective seating position; 113 mm in 'upright position' and 144 mm in 'reclined position'. The 'upright position' positions the pelvis more rearward compared to 'reclined position', irrespective of booster (31 mm for BS and 62 mm for BC).

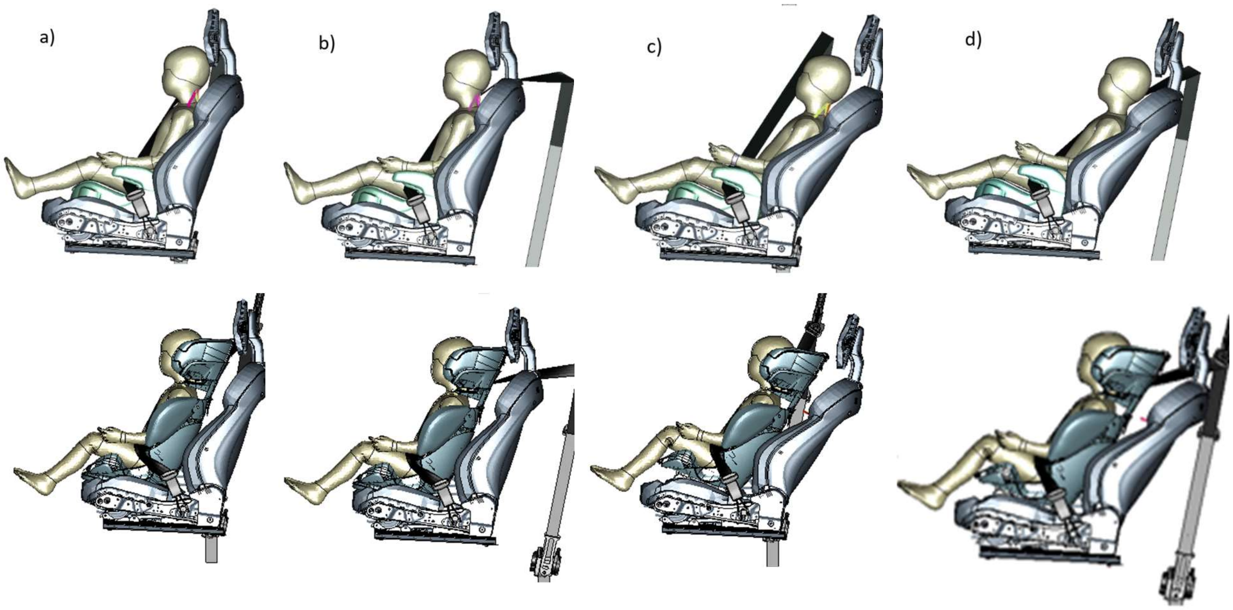

Figure 1 Side views of PIPER's initial posture when using BC (top row) and BS (bottom row). From left to right; a) 'upright position' and 'nominal D-ring positions', b) 'upright position' and 'rearward D-ring position', c) 'reclined position' and 'nominal D-ring position', d) 'reclined position' and 'rearward D-ring position'.

The initial lap belt position was more forward and lower on the thighs when in the BC, as compared to the BS. In 'reclined position', the x-distance from lap belt to left ASIS was 35 mm longer than when in 'nominal position' (65 mm and 30 mm, respectively), when using the BC, while no major difference was seen when using the BS. The lap belt was kept below the ASIS for all configurations.

When using the BS (and the shoulder belt geometry was in 'nominal D-ring position'), the shoulder belt attained a mid-shoulder position for both 'upright position' and 'reclined position', and the shoulder belt was in initial contact with the shoulder (no gap) in both positions. When using the BC in 'upright position', the shoulder belt was in contact with the shoulder, but with an initial position slightly further out on the shoulder than for the BS (see Figure 3). On the BC in 'reclined position', there was an initial gap of 69 mm between the shoulder belt and shoulder.

With 'rearward D-ring position', the shoulder belt had contact with the shoulder for BC in both 'upright position' and 'reclined position' (Figure 1). The shoulder belt kept a similar mid-shoulder position for both boosters, in both seating positions.

Shoulder and lap belt interaction

When using the BS no submarining occurred in any of the configurations. The shoulder belt stayed on the shoulder for all configurations with activated pretensioner, while late shoulder belt slip-off occurred in some configurations without pretensioner, see Table 2. When using the BC, submarining occurred when in 'reclined position' with no activation of the pretensioner. The lap belt slipped off both ASIS when ISOFIX anchorages was used, and left side only when no ISOFIX anchorage was used. When using BC, the shoulder belt stayed on the shoulder for all the configurations with the BC, except 'upright position' without pretensioner. Overall, the pretensioner helped to provide robust lap and shoulder belt interaction in the simulation model, with no submarining or shoulder belt slip-off in any of the configurations with activated pretensioner. In addition, the pretensioners helped to reduce the influence seen by the attachment to the ISOFIX anchorages in the configuration of 'reclined position'.

When comparing the simulations without submarining, there were still differences for the lap belt interaction with ASIS (see Figure 2). Focusing on the simulations with pretensioner and no attachment to the ISOFIX anchorages in 'upright position' ,the lap belt was positioned on the thigh 28 mm in front of the ASIS (the average of left and right ASIS) when using the BC, while the corresponding position was 10 mm in front of the ASIS for the BS. During the impact, this distance decreased on the BC to approximately 10 mm, while the x-distance on the BS was kept constant. The x-distance between lap belt and ASIS was up to 62 mm when using the BC in 'reclined position', and 28 mm in the 'upright position'. During the crash, this distance decrease to around 10 mm.

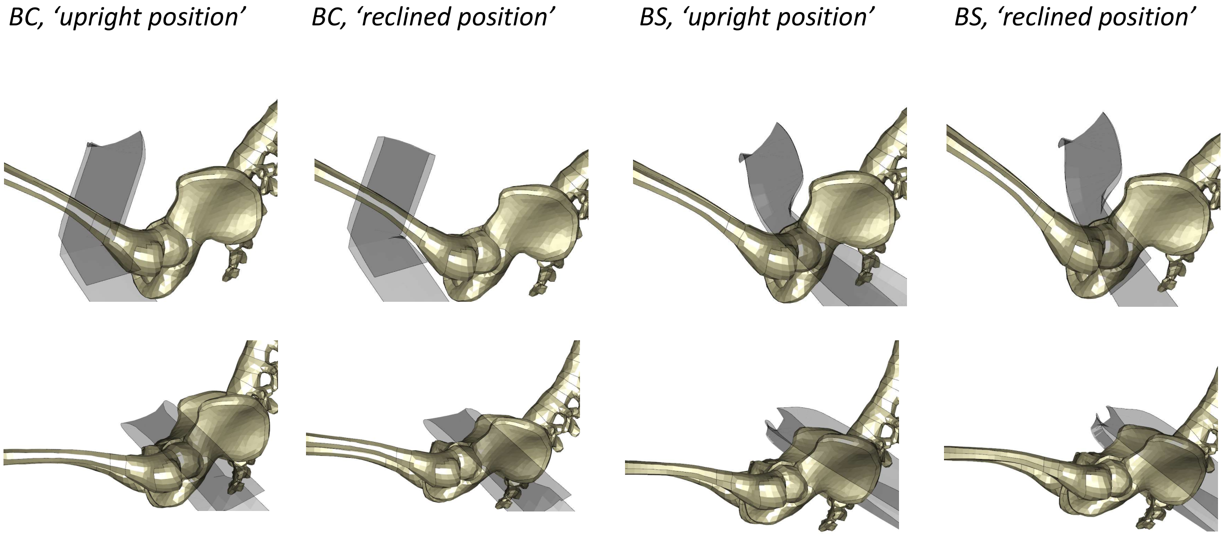

Figure 2 Initial lap belt positions (top row) and lap belt positions at 85ms (bottom row) for the following configurations (left to right): BC, 'upright position', BC, 'reclined position', BS, 'upright position', BS, 'reclined position'. The shoulder belt is removed from the picture, to give full overview of the lap belt. 'Nominal D-ring position' for all configurations.

Using the same subset of simulations with pretensioner and no attachment to the ISOFIX anchorages, the lap belt was initially positioned approximately 25 mm below the ASIS (z-distance) when using the BS. This applied to both seating positions. During the crash, the lap belt stayed in approximately the same place. When using the BC, the corresponding initial lap belt positions were 23 mm below ASIS, when in the 'upright position'. While in the 'reclined position', the initial lap belt position was 30 mm below the ASIS. During the crash, the lap belt moved up the pelvis, and in some configurations the lap belt even passed above the ASIS, with a few millimeters. Even though, no submarining occurred, although the lap belt moved slightly above the ASIS.

Although no shoulder belt slip-off occurred in any of the simulations for these configurations with pretensioner, the shoulder belt interaction varied between the configurations. The shoulder belt moved more inboard in the 'reclined position' during the crash as compared to when in 'upright position', see Figure 3. This applied for both boosters.

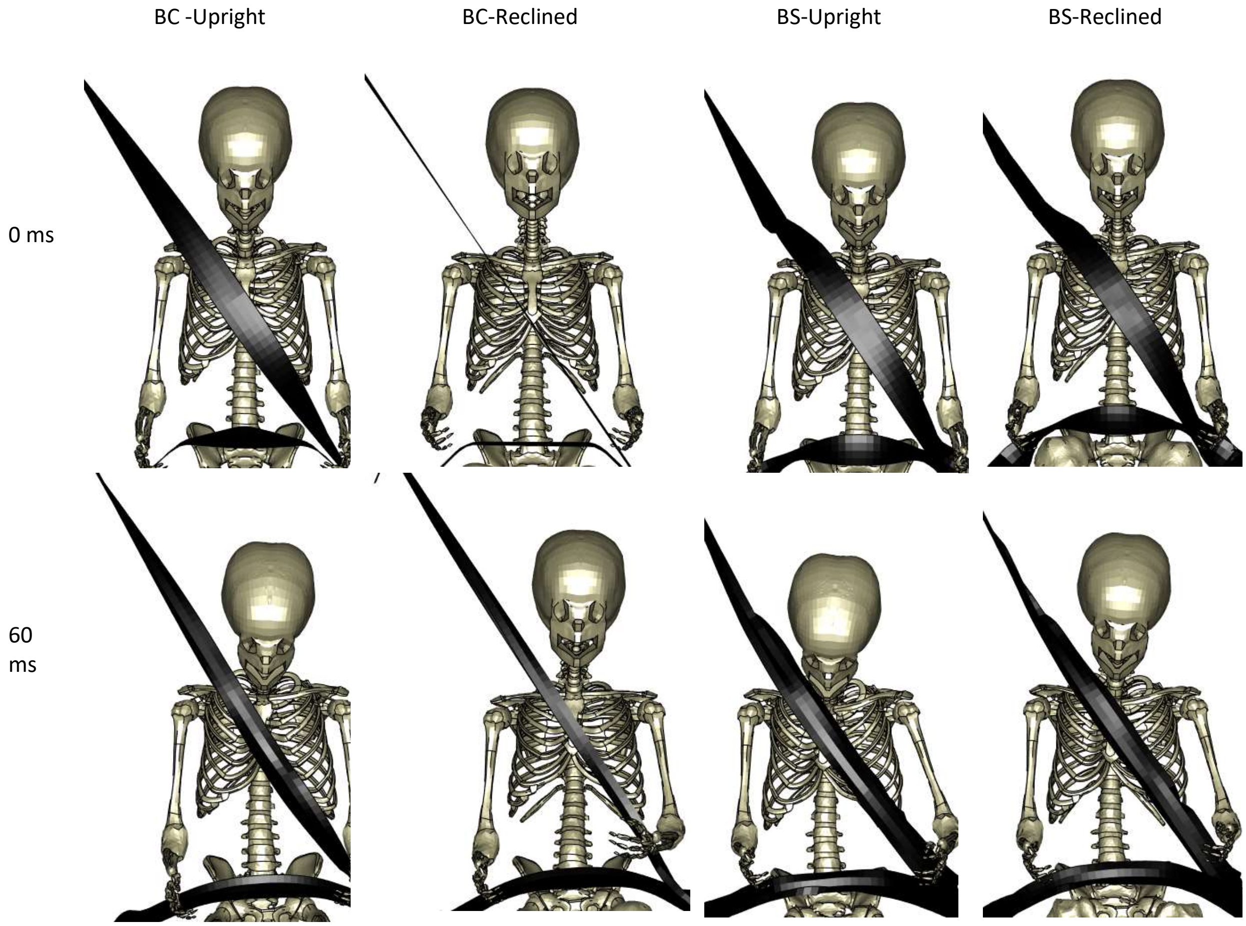

Figure 3 Initial seatbelt positions (top row) and shoulder belt positions at 60 ms (bottom row) for the following configurations (left to right): BC, 'upright position', BC, 'reclined position', BS, 'upright position', BS, 'reclined position. 'Nominal D-ring position' for all configurations.

Kinematics

In all the configurations with ‘nominal D-ring position, the head, chest and pelvis maximum displacements of the PIPER model were more forward when without pretensioner than when the pretensioner was activated (Figure 4). It can also be seen that irrespective of booster and seating position, given the pretensioner was activated, there were only minor differences in kinematics whether the attachment to the ISOFIX anchorages were used or not.

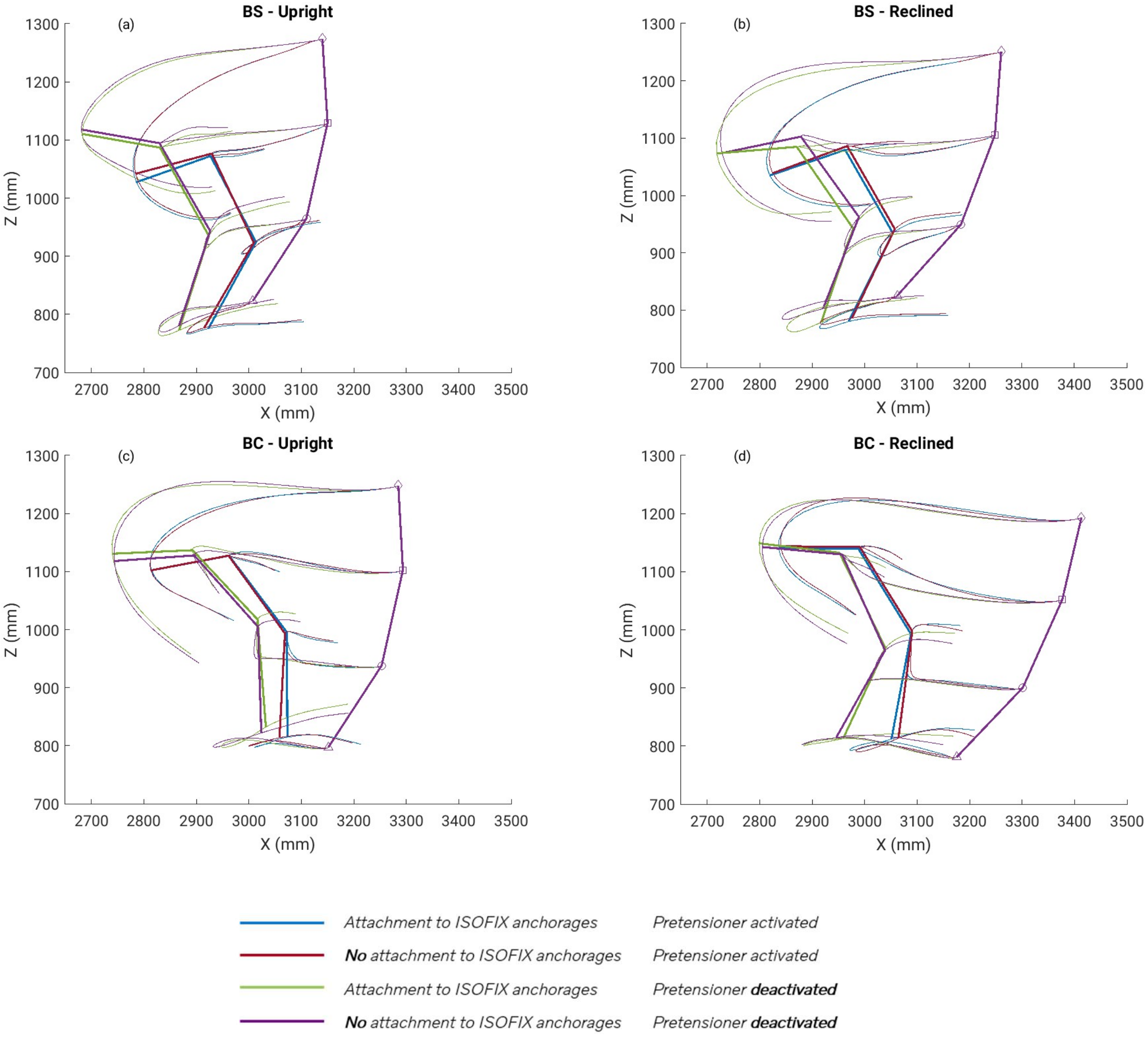

Figure 4 Stick figures illustrating initial position, position at time of maximum forward head position and trajectories in x and z for pelvis, chest (T1), T12 and head, for simulations with ‘nominal D-ring position’: a) BS, ‘upright position’, b) BS, ‘reclined position’, c) BC, ‘upright position’, d) BC, ‘reclined position’. The coordinate system is related to the seat reference point (SRP) in the vehicle.

Figure 5 shows the pelvis, chest and head trajectories in x and z, for simulations with activated pretensioner and no attachment to ISOFIX anchorages. See Figure 6 for whole body kinematics. The pelvis forward displacement was higher in BC than in BS for all configurations. In 'reclined position' with pretensioner, the BS configuration resulted in a pelvis displacement of 147 mm, while 203 mm for the BC configuration. When in 'reclined position', a 63 mm longer pelvis forward displacement compared to 'upright position' was seen when using the BC; while only 21 mm when using the BS. There was minor influence on the forward pelvis displacement depending on the shoulder belt geometry.

A greater head displacement was seen in 'reclined position' as compared to 'upright position', irrespective of type of booster. The 'rearward D-ring position' resulted in shorter head forward displacement, in comparison to 'nominal D-ring position' but was slightly higher in head downward movement.

In general, a shorter head displacement was seen using the BS as compared to the BC, but since the starting position of the head was 150 mm more forward for the BS, due to the seat back, the absolute value of the maximum displacement was larger for the BS compared to the BC. The largest maximum head displacement occurred when using the BS in 'upright position' with 'nominal shoulder belt'.

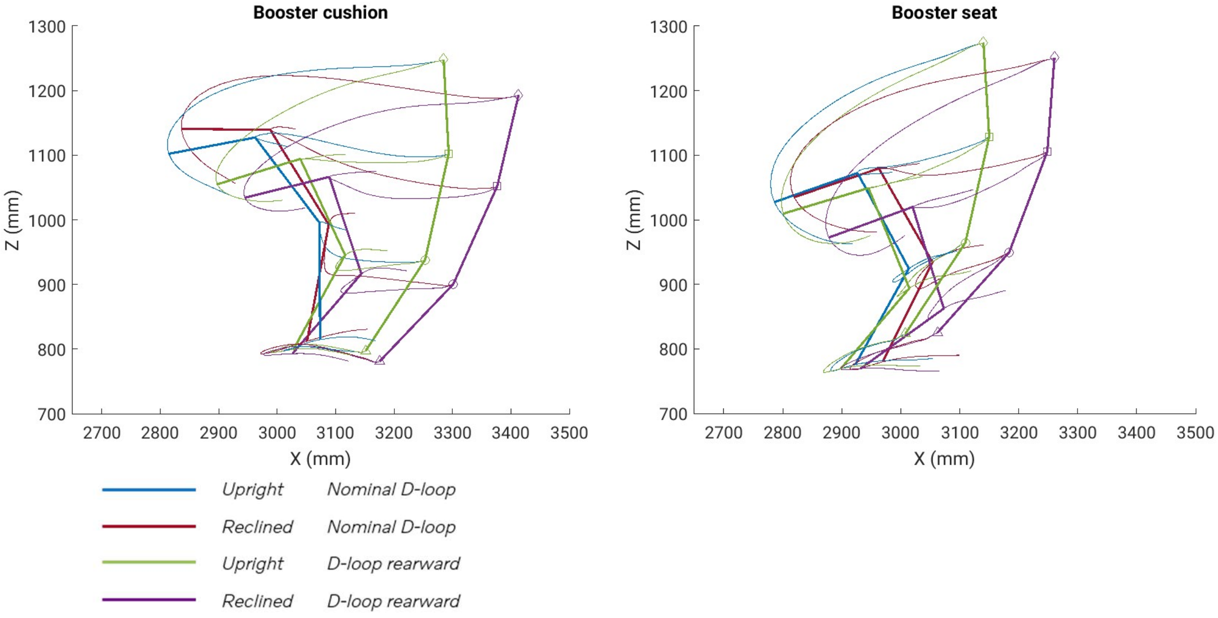

Figure 5 Stick figures illustrating initial position, position at time of maximum forward head positions and trajectories in x and z, for pelvis, chest (T1), T12 and head, for simulations with activated pretensioner and no attachment to ISOFIX anchorages. Left: BC, 'upright position' and 'reclined position''. Right: BS, 'upright position' and 'reclined position'. The coordinate system is related to the seat reference point (SRP) in the vehicle.

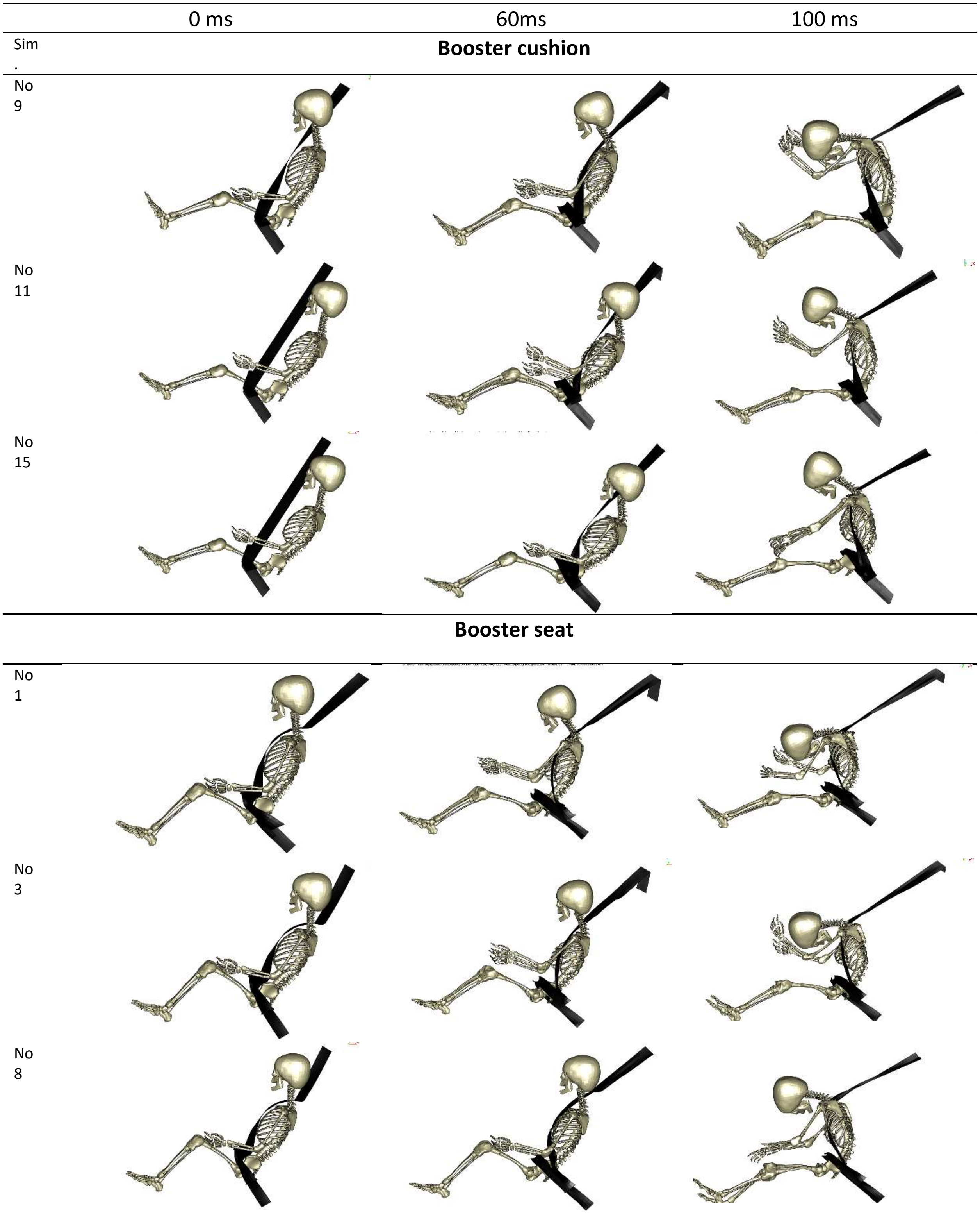

Figure 6 Side views of PIPER 6y HBM at 0 ms, 60 ms and 100 ms (left to right). First row: BC, 'upright position' with pretensioner. Second row: BC, 'reclined position' with pretensioner. Third row: BC, 'reclined position' without pretensioner. Fourth row: BS, 'upright position' with pretensioner. Fifth row: BS, 'reclined position' with pretensioner. Sixth row: BS, 'reclined position' without pretensioner.

Loading

As can be seen in Table 2, the head, neck and chest responses showed small differences if the attachment to the ISOFIX anchorages was used or not. With one exception, this observation applies for both boosters and irrespective seating position.

When using the BS, the activation of the pretensioner resulted in overall lower head, chest and pelvis accelerations and neck tension, as compared to corresponding configuration without pretensioner, see Table 2. When using the BC, lower responses were seen for all body parts except the head, when comparing activated pretensioner to without. The head acceleration was influence by differences in impact object (knee versus booster guide). Lower head acceleration was seen in 'upright position', but not in 'reclined position' when comparing with and without pretensioner.

Table 2 The maximum responses of the loadings in the head, neck, chest and pelvis of PIPER 6y, in addition to information on submarining and shoulder belt slip off.

No	Booster	ISOFIX	Preten-sioner	Position	D-ring	Head Res. Acc. g	Neck Fz (tension) kN	Chest Res. Acc. g	Pelvis Res. Acc. g	Chest Defl. Lower mm	Chest Defl. Mid mm	Chest Defl. Upper mm	Submarining	Shoulder belt slip off
1	BS	no	yes	upright	Nominal	63	-1,5	40	54	-39	-46	-38	No	No
2	BS	yes	yes	upright	Nominal	62	-1,5	37	49	-38	-46	-38	No	No
3	BS	no	yes	reclined	Nominal	76	-1,6	43	62	-32	-40	-36	No	No
4	BS	yes	yes	reclined	Nominal	75	-1,6	40	67	-30	-38	-35	No	No
5	BS	no	no	upright	Nominal	128	-1,6	53	75	-44	-45	-37	No	Yes
6	BS	yes	no	upright	Nominal	141	-1,6	65	63	-45	-45	-37	No	Yes
7	BS	no	no	reclined	Nominal	104	-2,0	54	78	-37	-41	-37	No	Yes
8	BS	yes	no	reclined	Nominal	79	-1,9	65	80	-39	-44	-38	No	Yes
9	BC	no	yes	upright	Nominal	84	-1,4	35	49	-40	-40	-35	No	No
10	BC	yes	yes	upright	Nominal	79	-1,3	34	51	-38	-38	-33	No	No
11	BC	no	yes	reclined	Nominal	94	-1,7	50	58	-37	-37	-34	No	No
12	BC	yes	yes	reclined	Nominal	106	-1,6	49	63	-35	-35	-32	No	No
13	BC	no	no	upright	Nominal	88	-1,8	51	67	-37	-39	-35	No	Yes
14	BC	yes	no	upright	Nominal	92	-1,7	64	70	-37	-39	-35	No	Yes
15	BC	no	no	reclined	Nominal	87	-1,9	87	83	-24	-35	-36	Left side	No
16	BC	yes	no	reclined	Nominal	83	-1,8	89	99	-24	-33	-35	Left & right side	No
17	BS	no	yes	upright	Rearward	65	-1,3	35	61	-39	-44	-36	No	No
18	BS	no	yes	reclined	Rearward	75	-1,4	42	60	-40	-43	-35	No	No
19	BC	no	yes	upright	Rearward	57	-1,2	33	64	-33	-37	-34	No	No
20	BC	no	yes	reclined	Rearward	78	-1,2	47	60	-24	-30	-29	No	No

When activating the pretensioner without attachment to the ISOFIX anchorages, both boosters showed similar trends for both head acceleration and the neck tension, which was higher in 'reclined position' compared to 'upright position'. Head acceleration and neck tension were lower with 'rearward D-ring position', compared to 'nominal D-ring position'. This was seen for both boosters and in both seating positions, further details, see Table 2.

When using the BC, the sternum deflections (upper, mid, and lower) were lower in 'reclined position' compared to 'upright position'. The sternum deflections were also lower with 'rearward D-ring position' compared to 'nominal D-ring position'. Lower sternum deflection was slightly more sensitive to the shoulder belt geometry changes than upper sternum deflection.

When using the BS, lower sternum deflection was seen in the ‘reclined position’, compared to the ‘upright position’, with ‘nominal D-ring position’. However, with ‘rearward D-ring position’ there was hardly any difference in deflection for any of the upper, mid or lower sternum deflection points in the model.

Discussion

This study explores the influence of reclined seating in frontal impacts using simulations with a PIPER 6y human body model, restrained using two different boosters and varying two different shoulder belt geometries. Overall, the protection was good, given a seatbelt with activated pretensioner was used. Together with the pretensioner, the booster helped to keep the lap belt on the pelvis and the shoulder belt on the shoulder in 14 of the 20 configurations explored.

Neither of the two boosters included in the study are specifically designed to be used in reclined vehicle seats. Still, no submarining for either booster occurred when used together with a pretensioner. In studies with adult occupants in reclined seats submarining has been shown to occur if no specific countermeasures are added to the restraint system (Gepner et al. 2019a, Gepner et al. 2019b, Rawska et al. 2019, Ji et al. 2017). The present study indicates that the belt guides of the booster help to maintain the lap belt on the pelvis during a frontal impact, even when the seat back is reclined. The two boosters differed both with respect to having a backrest or not, and by different designs of the lap belt guides. These two parameters cannot be separated clearly in this study, due to the 8 degrees more upright posture of the PIPER model because of the booster seat backrest’s interaction with the vehicle seat back, when in the ‘reclined position’. The lap belt interaction was more stable between the seating positions when PIPER 6y was using the BS and more efficient overall. The BS offered an initially more rearward position of the lap belt, as compared to the BC, resulting in an earlier coupling of the pelvis and thereby less pelvis movement during the simulated crash. This influenced both kinematics and loading favorably. When using the BC, submarining occurred when no pretensioner was activated. Hence, the activation of the pretensioner removed the potential critical situation of lap belt slip-off, which was more pronounced when the BC was attached to the ISOFIX anchorages.

The head displacement was reduced with activated pretensioner, as compared to without, for both boosters. Late shoulder belt slip-off occurred for some configurations without pretensioner for both boosters, contributing to the head displacement. The largest head displacement for the PIPER 6y HBM-model was seen on the booster cushion in the ‘reclined position’ and with ‘nominal D-ring position’. However, the largest head excursion relative the vehicle seat was seen when in ‘upright position’ using the BS. This can be explained by the more forward initial position relative to the vehicle seat, which was due to the static incompatibility of the booster’s backrest and the vehicle seat back, which limited the booster seat’s possibility to recline to the same extent as the vehicle seat back. This incompatibility together with the thickness of the booster’s backrest, positioned the pelvis initially 144 mm more forward than the booster cushion in reclined position.

When comparing the influence of the shoulder belt geometries, the greatest effect was seen when PIPER 6y used the BC. This is because of that the gap between the shoulder and the shoulder belt, as seen in ‘nominal D-ring position’, was eliminated in ‘rearward D-ring position’. This enabled an earlier coupling to the torso, resulting in lower loadings to the head and neck, as well as shorter head displacement. When using the BS, these differences were less, due to initial shoulder belt contact (i.e., no gap) in both shoulder belt geometries. A future restraint system for reclined seating position should target to enable a tight shoulder belt position on the shoulder irrespective of seating position, allowing the desired early shoulder belt engagement.

In this study, attaching the booster to the ISOFIX anchorages had limited influence on kinematics as well as loadings, in both seating positions. In a previous study by Tylko et al. (2016), the LATCH attachment resulted in submarining in some vehicle environments with soft rear seat benches, since the LATCH did not stop the motion of the crash test dummy relative to the booster cushion, resulting in a downward rotation of the booster cushion, whereby the crash test dummy slid off the booster. Although not as dramatic in the current study, the trend of reduced protection by the additional attachment of the booster to the vehicle was seen in the combination of ‘reclined position’ and no seatbelt pretensioner. In this combination, submarining occurred when the PIPER 6y HBM-model was using the BC when attached to the ISOFIX anchorages, while submarining occurs only on one side without this attachment. This adds to highlight the importance of the pretensioner; tightening the seatbelt which restrains the child together with booster and thereby reducing the sensitivity of additional attachment of the booster.

This study included two different boosters, which provided different initial beltfit and dynamic behavior. Baker et al. (2021) studied static beltfit of ten different boosters, both with and without backrest, showing a range of different lap and shoulder beltfit. Bohman et al. (2020) exposed three types of booster cushions to frontal impacts, showing poorer shoulder belt interaction with boosters with deformable characteristics. Hence, there is a need to study a greater variation of boosters, and to further identify boosters design features which are relevant for occupant protection in reclined seating positions, while monitoring the potential effect when used in upright seating positions.

In the current study, the PIPER 6y was positioned based on engineering judgement. There is a need to quantify the initial posture in reclined seating for real children, especially the ranges of pelvis positions and orientation, since pelvis orientation and position is essential when evaluating risk of submarining. Furthermore, there were technical challenges when positioning the PIPER 6y model. Due to lack of an LS-Dyna positioning tree in PIPER, difficulties in orienting the pelvis angle were experienced. Additional work is also encouraged in this area to enable positioning of the PIPER 6y in other software environments.

The two booster and the two seating positions exposed the PIPER 6y HBM-model to different postures and beltfit, resulting in different kinematics and loadings during the crash. The PIPER 6y HBM-model has not been developed for reclined sitting posture, nor is there any available data on child sitting postures in reclined posture, at this stage. For adult occupants, there are ongoing efforts worldwide to develop and validate tools (crash test dummies and HBM) for reclined seating (Richardson et al. 2020, Östling et al. 2021, Gepner et al. 2019b). Similar activities are encouraged for the pediatric tools too, to better address the future challenges with reclined seating for child occupants as well.

As child occupant protection is being developed to meet future challenges, this includes good protection in reclined as well as upright seating positions. This means that the protection principles in addition to compatibility, should be addressed, irrespective of seat back angle. The protection principles include an early and tight contact between the pelvis and the lap belt and to keep the lap belt on the pelvis during the whole crash (Adomeit 1975, 1977). The booster design serves an important role to help provide this, together with the seatbelt design. The current study provides insight into a more challenging initial pelvis position when the vehicle seat was reclined. The more rearward initial pelvis position increased the distance between the lap belt and ASIS, reducing the potential efficiency of the pelvis restraint in frontal impacts, as compared to when in ‘upright position’. The protection principles also include an initial tight connection of the torso by the shoulder belt. As seen in the current study, a close contact between the shoulder belt and the shoulder was more efficient than when an initial gap was seen. Reduction of the gap is addressed by the seatbelt position in relation to the vehicle seat. In this study a more rearward position of the shoulder belt D-ring reduced the gap that occurred when reclining the seat. Today, compatibility issues are seen for some combinations of booster seats and current vehicle seats, even in upright seating position. Levallois et al. (2019) highlighted this issue by performing static testing with child seats in reclined vehicle seats. In the context of child occupant protection, the interaction of the booster, the vehicle seat and the seatbelt are essential. This applies for current seating positions (Jakobsson et al. 2017) as well as when addressing new seating configurations in future vehicles.

Conclusions

This study shows that submarining can be addressed in reclined seating using current booster design in combination with a vehicle seatbelt pretensioner.

It also shows that the booster design, with respect to lap belt guiding, can be further developed to ensure a tight and early coupling of the pelvis. The specific challenge includes an initially more rearward positioned pelvis as the vehicle seat back is reclined and the booster’s design needs to enable an early coupling of pelvis in both upright and reclined seating position.

The pretensioner and the initial shoulder belt geometry is important for enabling good restraint of the torso. The more rearward position of the shoulder belt D-ring improves initial shoulder belt contact, for both seating positions when using the booster cushion. This also results in lower head and neck loadings, in addition to reduced head excursion, as compared to nominal shoulder belt geometry.

This study provides evidence of the importance of including the whole context of child occupant protection when investigating novel seating. The interaction and compatibility of the booster, the vehicle seat and the seatbelt are essential. This is exemplified by the positive effect of the pretensioner and the static incompatibility of the booster seat’s backrest and the vehicle seat back rest. The latter is also an example of how compatibility issues will influence fit and stability, in addition to achieve desired posture, in reclined seating.

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References

Adomeit D. Motion sequence criteria and design proposals for restraint devices in order to avoid unfavorable biomechanics conditions and submarining, Proc. of *19th Car Crash Conference*, SAE, Warrendale, USA, 1975:139–165. Adomeit D. Evaluation methods for the biomechanical quality of restraint systems during frontal impact, Proc. of *21st Stapp Car Crash Conference*, SAE, Warrendale, USA, 1977:911–932.

Baker G, Mansfield J, Hunter R, Bolte J. Evaluation of static belt fit and belt torso contact for children on belt-positioning booster seats, *Traffic Inj Prev*, 2021:16:1-6.

Bohman K, Östh J, Jakobsson L, Stockman I, Wimmerstedt M, Walling H. Booster cushion design effects on child occupant kinematics and loading assessed using the PIPER 6-year-old HBM and the Q10 ATD in frontal impacts, *Traffic Inj Prev*, 2020, Aug 24:1-6.

Bohman K, Arbogast KA, Boström O. Head injury causation scenarios for belted, rear-seated children in frontal impact, *Traffic Inj Prev*, 2011 Feb;12(1):62-70.

Durbin DR, Elliott MR, Winston FK. Belt-positioning booster seats and reduction in risk of injury among children in vehicle crashes. *JAMA*, 2003;289:2835–2840.

Gepner B, Rawska K, Richardson R, Kulkarni S, Chastain K, Zhu J, Forman J, Kerrigan J. Challenges for Occupant Safety in Highly Automated Vehicles Across Various Anthropometries. Paper No 19-0335, *Proc of 26th Int. ESV Conf.*, Eindhoven, Netherlands, 2019a.

Gepner B, Draper D, Mroz K, Richardson R, Ostling M, Pipkorn B, Forman JL, Kerrigan JR. Comparison of Human Body Models in Frontal Crashes with Reclined Seatback. IRC-19-44, *IRCOBI Conference*, Florence, Italy, 2019b.

Giordano C, Li X, Kleiven S. Performance of the PIPER scalable child human body model in accident reconstruction, *PLoS ONE*, 2017:12(11).

Ji P, Huang Y, Zhou Q. Mechanisms of using knee bolster to control kinematical motion of occupant in reclined posture for lowering injury risk. *International journal of crashworthiness*, 2017:22(4), 415-424.

Jakobsson L, Bohman K, Svensson M, Wimmerstedt M. Rear seat safety for children aged 4-12: Identifying the real-world needs towards development of countermeasures, Paper no. 17-0088, *Proc of 25th Int. ESV Conf.,* Detroit, USA, 2017

Jorlöv S, Bohman K, Larsson A. Seating positions and activities in highly automated cars – A qualitative study of future automated driving scenarios. IRC-17-11, *IRCOBI Conference*, Antwerp, Belgium, 2017

Koppel S, Jiménez-Octavio J, Bohman K, Logan D, Raphael W, Quintana Jimenez L, and Lopez-Valdes F. Seating configuration and position preferences in highly automated vehicles. *Traffic Inj Prev*. Jun 2019:27:1-7.

Levallois I, Recko P, Bohman K, Renaudin F. Novel seating configurations in automated vehicles: opportunities and challenges for child seats, *17th Int. Conf. Protection of Children in Cars*, Munich, Germany, 2019.

Maheshwari J, Belwadi A. Biomechanics in Autonomous Vehicles: A Pilot Study to Explore Responses of Pediatric Occupants in Non-Traditional Seating Conditions, *18th Int. Conf. Protection of Children in Cars*, 2020a.

Maheshwari J. Pediatric Occupant Human Body Model Kinematic and Kinetic Response Variation to Changes in Seating Posture in Simulated Frontal Impacts - With and Without Automatic Emergency Braking, *Traffic Inj Prev*, 2020b;12;21(sup1):S49-S53.

Miller M, Perez-Rapela D, Gepner B, Edwards M, Jermakian J, Forman J. A methodology for large-scale parametric evaluation of child booster seats, IRC-21-62, *IRCOBI Conference*, Online, 2021.

Rawska K, Gepner B, Kulkarni S, Chastain K, Zhu J, Richardson R, Perez-Rapela D, Forman J, Kerrigan J. Submarining Sensitivity across Varied Anthropometry in Autonomous Driving System Environment. *Traffic Inj Prev*. 2019;20(sup2):S123-S127.

Richardson R, Jayathirtha M, Donlon JP, Forman JL, Gepner B, Ostling M, Mroz K, Pipkorn B, Kerrigan JR. Pelvis Kinematics and Injuries of Reclined Occupants in Frontal Impacts. IRC-20-60, *IRCOBI Conference*, Munich, Germany, 2020.

Tremoulet P, Belwadi A, Corr B, Sarfare S, Seacrist T, Tushakd S. How do novel seat positions impact usability of child restraints? Transportation Research Interdisciplinary Perspectives, Volume 10, June 2021.

Tylko S, Bussieres A, Starr A. Evaluating child safety innovations: Have we got the right tools and the right test methodologies? *14th Int. Conf. Protection of Children in Cars*, Munich, Germany, 2016.

Östling M, Larsson A. Occupant activities and sitting positions in automated vehicles in China and Sweden. Paper no. 19-0083, *Proc. of 26th Int. ESV Conf.,* Eindhoven, Netherlands, 2019.

Östling M, Lundgren C, Lubbe N, Huf A, Wernicke P, Pipkorn B. The Influence of a Seat Track Load Limiter on Lumbar Spine Compression Forces in Relaxed, Reclined, and Upright Seating Positions: A Sled Test Study using THOR-50M, IRC-21-46, *IRCOBI Conference,* online, 2021.

Appendix A

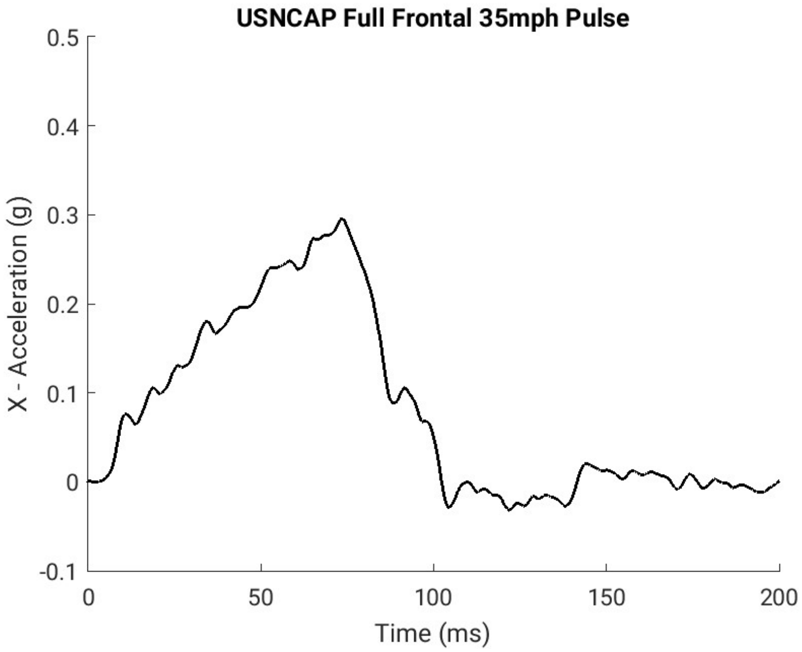

Figure A1 The generic full frontal crash pulse.

Figure A2. Booster seat (left) and booster cushion (right)