Highback-To-Backless Booster Seat and Child Head Motion in Frontal Oblique Impacts with and without the Lower Anchor

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ABSTRACT

Backless belt-positioning boosters (BPB) without lower anchors (LA) showed increased BPB tipping and rotation. It is unclear if we can extend these findings to highback-to-backless BPBs. In highback-to-backless BPBs, the backless mode's static lap belt positions lands across the child's femurs rather than the pelvis. This study explores child motion in highback-to-backless BPBs in the context of LA or no LA during far-side frontal oblique impacts. The Q6 Anthropomorphic Test Device (ATD) was restrained with a 3-point seatbelt in 8 far-side frontal-oblique impacts (30° from frontal) sled tests (32 km/h, duration 55 ms, peak acceleration 25 g, FMVSS 213a pulse) repeated twice. Two types of highback-to-backless BPBs were tested in highback and backless modes. BPB 2 had a more forward static lap belt position. In both modes, BPB 1 had a greater forward rotation with LA than without LA, while BPB 2 had a smaller forward rotation with LA than without LA. BPB 1 had greater head forward rotation without LA and vice versa for BPB 2. In all modes, both BPBs showed greater lateral rotation towards the far-side direction without LA (12.5 ± 3.1°) than with LA (8.2 ± 1.7°). Both backless BPBs led to greater head lateral rotation inboard relative to its initial position (147.4 ± 10.3°) compared to the highback mode (119.5 ± 17.7°), with the highest head lateral rotation in backless mode without LA (154.0 ± 4.4°). BPB 2 without LA had greater BPB forward rotation as the child ATD femurs slid under the belt reducing head forward motion. No LA led to greater lateral BPBs' rotation and overall greater lateral head rotation particularly in the backless mode, suggesting no LA and BPB seatback influenced the lateral rotation of BPB and head rather than the lap belt position.

INTRODUCTION

Lower Anchor (LA) usage on Belt-Positioning Boosters (BPB) in the US is relatively low at 50% (Jermakian et al., 2011, O'Neil et al., 2010), although BPB manufacturers indicate these connectors are designed to prevent the BPB from becoming a projectile in the vehicle during a crash. Previous investigations on the impact of LA on child kinematics show conflicting results for frontal impacts due to different BPB and varied pulse severity. For example, a previous study investigated the influence of a fixed rigid LA system (ISOFIX) on highback BPBs in 50 kph frontal impact conditions on three Q-series Anthropomorphic Test Devices (ATDs): a Q3, Q6, and Q10 (Visvikis et al., 2017). The authors found greater pelvis displacement while the BPB had fixed

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ISOFIX attachments, which prevented BPB translation. Greater pelvis displacement for BPB with fixed ISOFIX was attributed to the lack of coupling between the ATD and BPB's forward motion, as the BPB was unable to translate forward in the fixed condition, primarily with the Q6 and Q10 (Visvikis et al., 2017). However, overall, there were minimal differences between LA and non-LA conditions for injury metrics such as head loading, chest acceleration, or abdomen pressure, indicating low risk of submarining (i.e., risk of the lap belt sliding onto the abdomen) during frontal impacts (Visvikis et al., 2017).

Another study has also shown reduced head and BPB forward movement in frontal impacts for highback and backless BPB with LA compared to non-LA installations (Mansfield et al., 2021). Specifically, the authors found that the BPBs with rigid LA had the least forward movement compared to flexible webbing LA connectors. Minimal differences were found between LA and non-LA installations in kinematics and injury metrics, similarly to Visvikis et al. (2017). Previous research on backless BPB with and without ISOFIX in frontal impacts has shown the Q6 ATD sliding off the front edge of the BPB and submarining, where the lap belt penetrated the abdomen. This study utilized a full vehicle frontal crash test with a higher impact pulse (56 kph), which introduced pitch to the ATD kinematics compared to traditional sled tests (Tylko et al., 2016).

The impact of LA on BPBs in lateral impacts has also been investigated. As mentioned previously, LA are available in several different styles for BPB including rigid ISOFIX, flexible single-loop webbing, and flexible dual-loop webbing. Hauschild et al., (2018) investigated the impact of these various LA attachments on highback BPBs with the Q3s in oblique near-side impacts (80º from frontal, 35 km/h impact pulse). The study found reduced BPB tipping and rotation and ATD injury measures, such as lateral head excursion and neck tension, with rigid and dual-loop webbing LA compared to single-loop LA. Another previous study by Hauschild et al., (2016) also evaluated the role of LA on center-seated highback BPB for the Q3 ATD in two oblique lateral side impacts (60º and 80º from frontal). For all non-LA conditions at 80º, the Q3 ATD made head contact with the simulated door and had increased HIC15 values compared to LA conditions, where head injury values were reduced and the impact with the simulated door was less forceful.

Overall, previous studies on the impact of LA on BPBs for frontal impact have shown reduced BPB rotation, but minimal differences on child kinematics between LA and non-LA conditions due to variations between BPB type and pulse severity. Previous studies in lateral-oblique impacts have shown reduced tipping and rotation for BPBs with LA, but vary depending on LA attachment style. However, as previously mentioned, Hauschild et al., (2016) primarily focused on the near-side 80º impact with a Q3 ATD, while Visvikis et al., (2017) and Mansfield et al., (2021) examined pure frontal impacts. Therefore, it is unknown the influence of LA on BPB for an older child, which can be seen with a Q6 ATD, in other oblique angles such as 30º from frontal. Previous studies have also not investigated the role of LA in far-side lateral-oblique impacts, which may more clearly demonstrate the influence of LA on BPB performance without a simulated door to stop the child's excursion. The child moving towards the inboard side of the vehicle (in far-side impacts) is also too far from the vehicle countermeasures such as the curtain airbag and may contact other rear-seated occupants. Furthermore, it is unclear if we can extend these findings to highback-to-backless BPBs, which are a popular option among caregivers as it

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provides flexibility to adapt to their vehicle and child's growth. Highback-to-backless BPBs have a removable seatback that allows the BPB to be utilized in both highback and backless mode. In highback-to-backless BPBs, the backless mode's lap belt positions lands forward on the pelvis and in some models across the child's femurs rather than the pelvis, which is considered a less ideal belt fit.

Therefore, the aim of this study is to investigate child motion in two types of highback-to-backless BPBs in both highback and backless modes in the context of LA or no LA during far-side frontal oblique impacts.

METHODS

Sled Apparatus

The Q6 Anthropomorphic Test Device (ATD) was seated on two types of highback-to-backless Belt-Positioning Boosters (BPB) tested in two modes, highback and backless, that were placed on a rigidized seat frame with production vehicle seat foams and covers and restrained by a 3-point seatbelt that exposed them to frontal-oblique impacts, 30º from frontal (Figure 1). The 32 km/h pulse (FMVSS 213a) had a duration of 55 ms and peak acceleration of 25 g.

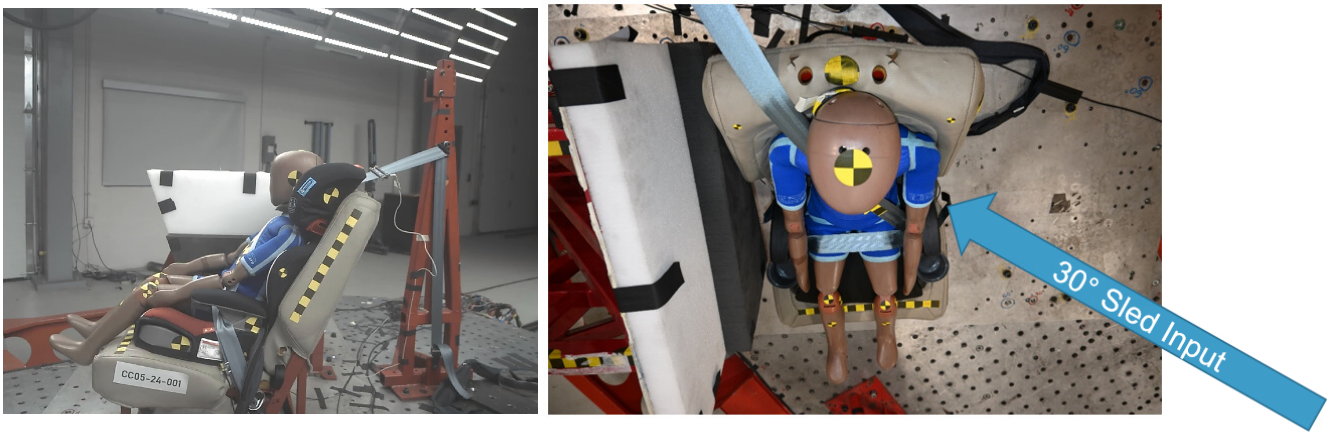

Figure 1: Sled Apparatus

The seat buck did not have a simulated front seatback. During the simulated frontal-oblique impact pulse, the Q6 moved out of the belt, towards the buckle side.

Instrumentation

25 measurements were taken from the Q6 ATD. These included head accelerometers, head angular rate sensors, upper neck load cell, chest deflection sensor, chest accelerometers, left and right abdomen pressure sensors, pelvis accelerometer, and left and right iliac/ASIS load cells. Seat belt loads were also measured on the left and right lap belt and shoulder belt. A tri-axis accelerometer on the BPB measured the rate of change of velocity of the BPB during simulated impacts.

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Testing

Eight trial conditions were examined with the Q6 ATD, each repeated twice for a total of 16 trials (Table 1). The two conditions included two types of highback-to-backless BPB tested in two modes: highback and backless. BPB 1 had a double loop, flexible LA connector, and BPB 2 had a single loop, flexible LA connector. BPB 2 in backless mode had a more forward static lap belt position across the femur compared to BPB 1, as shown in Figure 2.

Table 1: Test Matrix

BPB Mode and Type	Lower Anchor	Repetitions
Highback 1	Y	2
Highback 1	N	2
Backless 1	Y	2
Backless 1	N	2
Highback 2	Y	2
Highback 2	N	2
Backless 2	Y	2
Backless 2	N	2

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Figure 2: BPB 1 (left) and BPB 2 (right)

Data Analysis

For the scope of this study, only the head and BPB angular rate sensor data were considered. Head and BPB angular velocities were filtered with a CFC60 filter and then imported into a custom-made MATLAB (MathWorks 2020, Inc., Natick, MA) program. Angular velocities were integrated to obtain angular kinematics, including head and BPB forward and lateral peak angular displacement within the 100 ms window of interest were extracted (Table 2). The outcome measures were averaged, and the standard deviation was taken across repetitions to evaluate variation between repetitions and exclude outliers.

RESULTS

Peak forward and lateral angular displacements for BPB 1 and 2 in highback and backless modes with and without LA from the simulated frontal impact are shown in Table 2**.** Overall, head forward displacements were much greater in magnitude than BPB displacements. In both highback and backless mode, BPB 1 had a greater forward rotation with (double loop, flexible) LA (19.25° ± 4.1°) than without LA (11.76° ± 5.2°), while BPB 2 had a smaller forward rotation with (single loop, flexible) LA (8.81° ± 1.2°) than without LA (15.35° ± 1.7°), as visualized in Figure 3a. Head forward rotation showed the opposite trend compared to BPB, where BPB 1 had a greater head forward rotation without the LA (132.05° ± 5.9°) and vice versa for BPB 2 (Figure 3b).

For all modes, there was greater BPB lateral angular displacement towards the buckle side (i.e., inboard motion) without LA (12.5° ± 3.1°) than with LA (8.2° ± 1.7°) (Figure 4a). For lateral angular displacement, the greatest difference between LA and non-LA conditions was in BPB 1 in backless mode (68.4%, Table 3) and the smallest difference was in BPB 1 in highback mode (9.3%, Table 3) as visualized in Figure 4a.

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Table 2. Mean ± SD of peak BPB and head forward and lateral angular displacement for BPB 1 and 2 in highback and backless modes

Outcome measures	BPB 1 highback		BPB 2 highback		BPB 1 backless		BPB 2 backless	
	LA	No LA	LA	No LA	LA	No LA	LA	No LA
Peak BPB forward angular disp (°)	21.33 ± 3.6	13.38 ± 0.4	8.37 ± 1.5	16.28 ± 0.5	17.16 ± 4.5	10.14 ± 9.9	9.25 ± 0.8	14.41 ± 2.9
Peak head forward angular disp (°)	123.60 ± 18.0	129.98 ± 2.3	108.39 ± 6.6	97.71 ± 3.3	127.48 ± 0.1	134.12 ± 9.4	99.87 ± 0.5	84.54 ± 3.5
Peak BPB lateral angular disp (°)	10.53 ± 0.5	11.56 ± 1.8	7.39 ± 0.0	11.07 ± 2.5	7.48 ± 0.6	15.26 ± 5.5	7.41 ± 2.2	12.20 ± 2.2
Peak head lateral angular disp (°)	96.46 ± 12.3	117.29 ± 1.5	136.75 ± 14.9	127.74 ± 5.0	145.68 ± 13.8	152.74 ± 5.5	136.15 ± 7.6	155.18 ± 4.7

Table 3. BPB kinematics in LA vs. non-LA installations, where a (+) difference indicates greater displacment without LA than with LA and a (-) difference is a greater displacement with LA than without LA.

	BPB Mode	BPB Type	LA	Non-LA	Difference	Percent Difference
BPB forward angular displacement, x-direction (°)	Highback	1	21.33	13.38	-7.95	-45.8%
		2	8.37	16.28	7.91	64.2%
	Backless	1	17.16	10.14	-7.02	-51.4%
		2	9.25	14.41	5.16	43.6%
BPB lateral angular displacement, y-direction (°)	Highback	1	10.53	11.56	1.03	9.3%
		2	7.39	11.07	3.68	39.9%
	Backless	1	7.48	15.26	7.78	68.4%
		2	7.41	12.2	4.79	48.9%

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Table 4. Head kinematics in LA vs. non-LA installations, where a (+) difference indicates greater displacment without LA than with LA and a (-) difference is a greater displacement with LA than without LA.

	BPB Mode	BPB Type	LA	Non-LA	Difference	Percent Difference
Head forward angular displacement, x-direction (°)	Highback	1	123.60	129.98	6.38	5.0%
		2	108.39	97.71	-10.68	-10.4%
	Backless	1	127.48	134.12	6.64	5.1%
		2	99.87	84.54	-15.33	-16.6%
Head lateral angular displacement, y-direction (°)	Highback	1	96.46	117.29	20.83	19.5%
		2	136.75	127.74	-9.01	-6.8%
	Backless	1	145.68	152.74	7.06	4.7%
		2	136.15	155.18	19.03	13.1%

Both backless BPBs led to greater head lateral rotation towards the buckle side (147.4º ± 10.3º) compared to the highback mode (119.5º ± 17.7º), with the highest head lateral rotation in backless mode without LA (154.0º ± 4.4º) (Figure 4b).

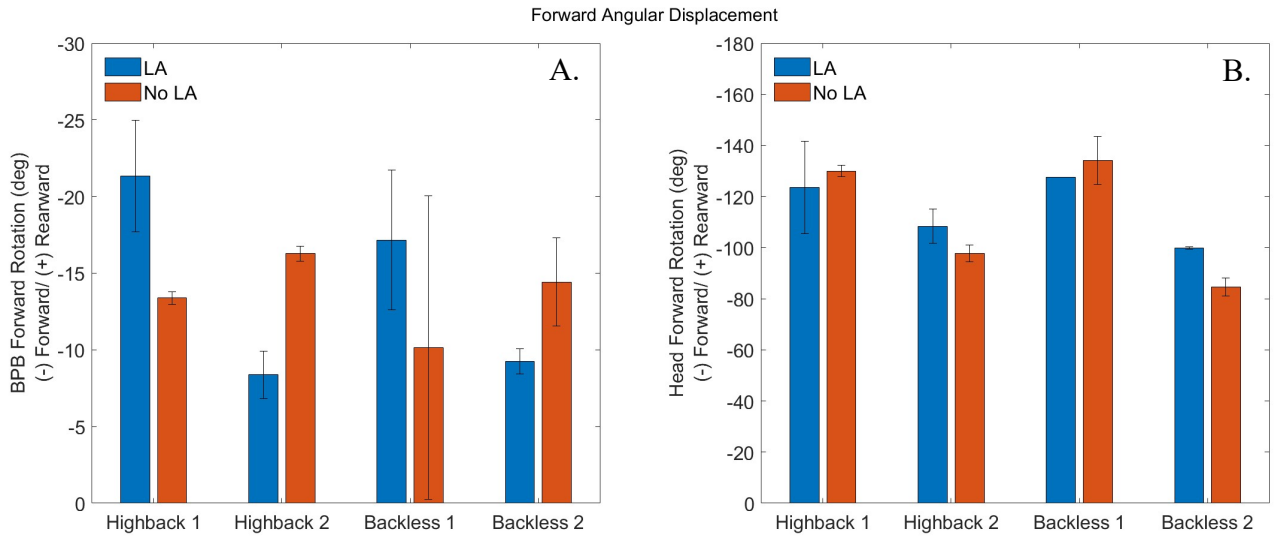

Figure 3. A) Head and B) BPB Forward Angular Rotation

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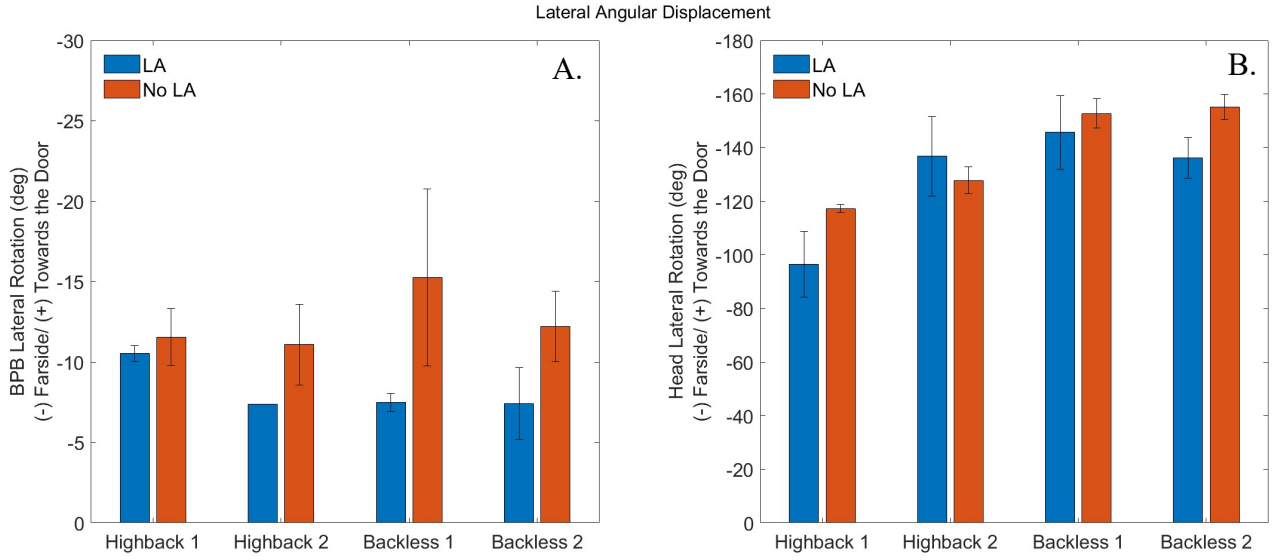

Figure 4. A) Head and B) BPB Lateral Angular Displacement

Time-history of BPB forward rotation over 100 ms generally showed motion differences between no LA and LA for both types of BPB. In both modes, BPB 1 without LA initially moved rearward whereas with LA, the BPB initially moved forward around 30 ms. This was reversed in BPB 2 at the same time point, where BPB 2 initially moved forward without LA and rearward with LA. BPB 1 in highback mode had a significant negative peak forward without LA around 55 ms, compared to a significant rearward peak for BPB 1 in backless mode with LA. Unlike BPB 1, peak forward rotation for BPB 2 in all modes were in the same direction throughout the window of interest, with BPB 2 in backless mode without LA having an overall higher magnitude than with LA.

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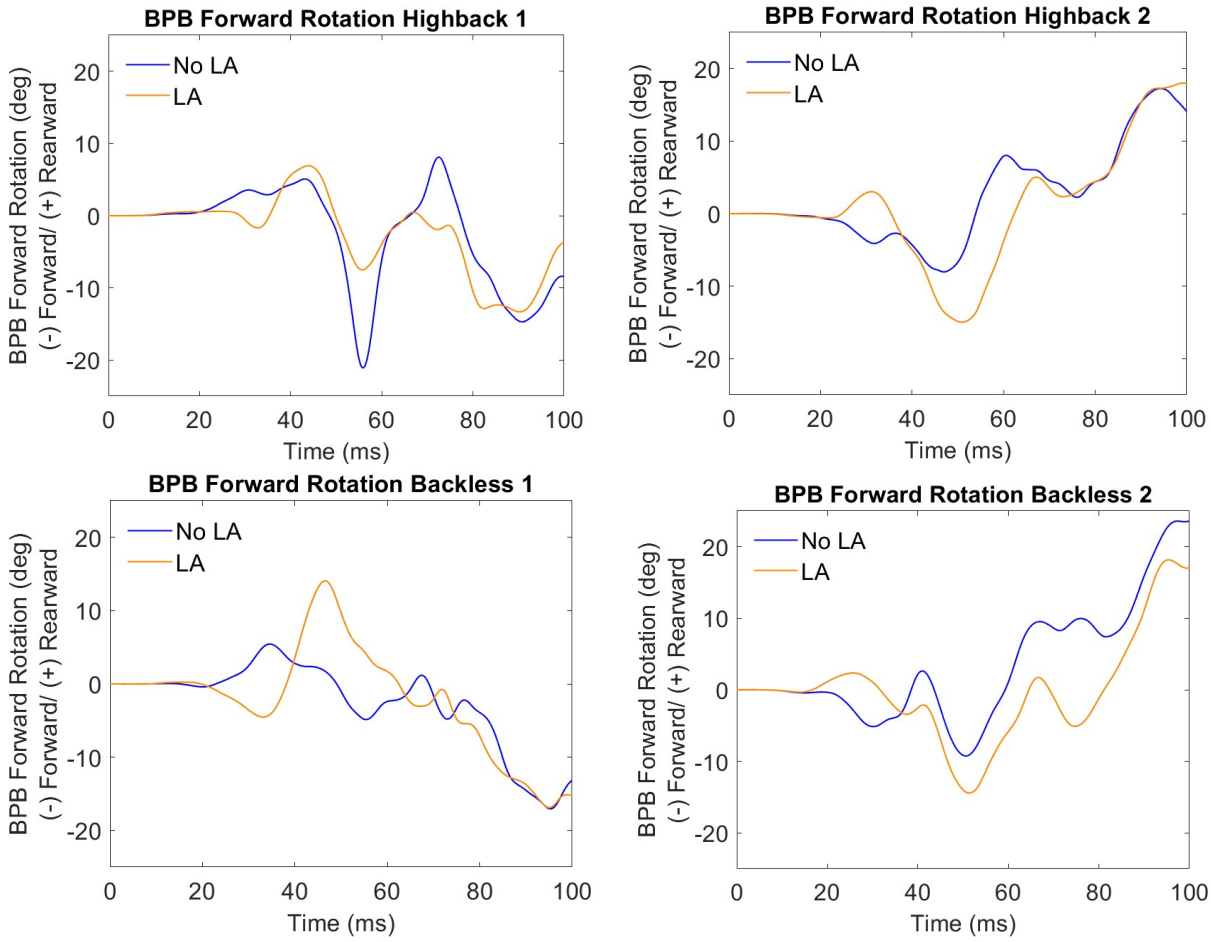

Figure 5. BPB Forward Rotation over 100 ms for BPB 1 and 2 in highback and backless modes

For all modes, there was a greater BPB lateral rotation peak towards the door with LA than without LA around 40 ms (Figure 6). Additionally, all BPB conditions with no LA initially rotated towards the far-side direction compared to with LA, where the BPB initially rotated towards the door. Notably, BPB 2 in backless mode had an earlier peak rotation (40 ms) towards the door with LA and a later peak rotation (80 ms) without LA.

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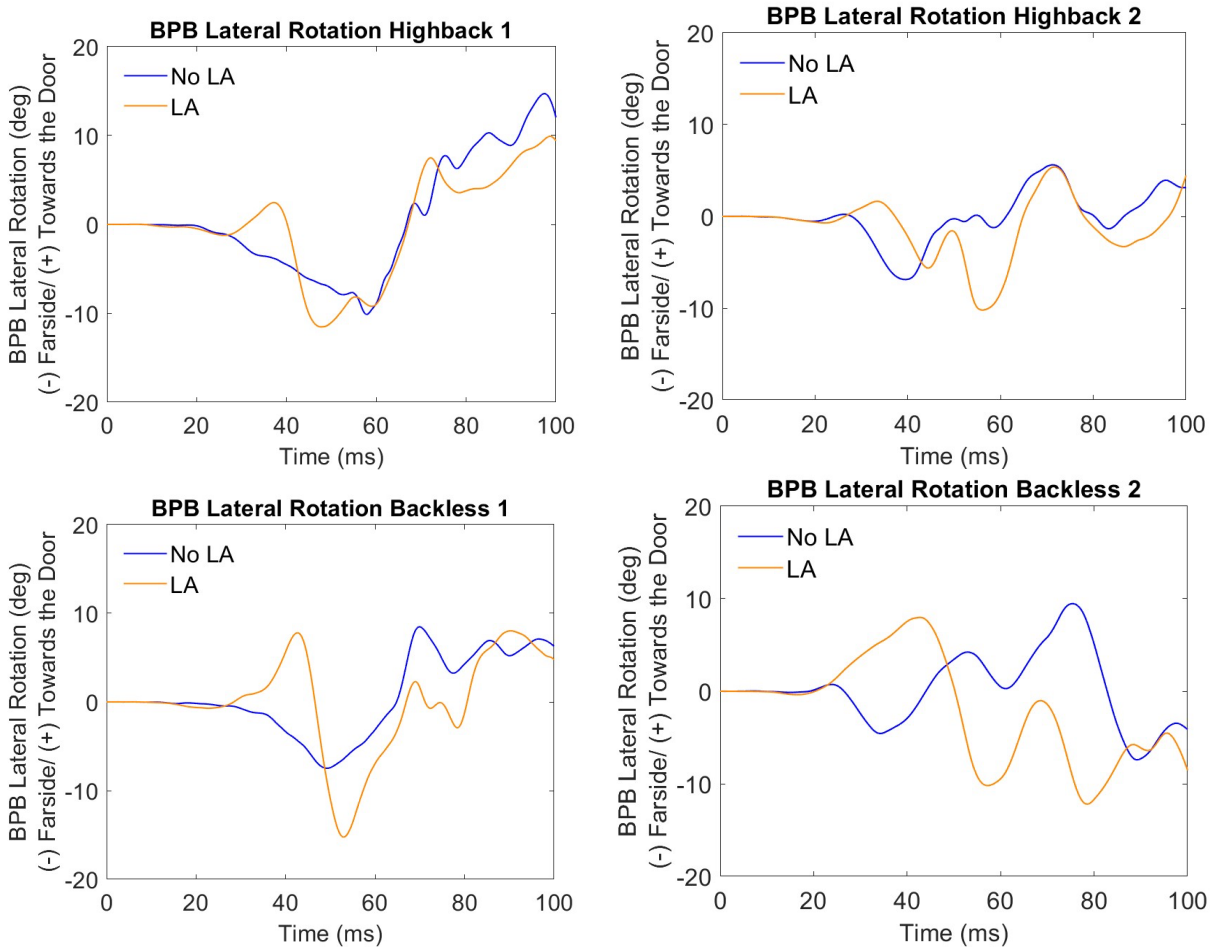

Figure 6. BPB Lateral Rotation over 100 ms for BPB 1 and 2 in highback and backless modes

Overall motion of the BPB over the 100 ms window of interest of the pulse is relatively small within less than 40° range. Laterally both backless BPB show greater motion than all other BPB conditions and compared to frontal motion.

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DISCUSSION

The aim of this study was to examine child kinematics in two types of highback-to-backless BPB in highback and backless modes when the BPB is or is not secured via LA during 30° frontal-oblique impacts.

The findings of this investigation found that in the BPB type with a more forward lap belt position (BPB 2), the absence of LA led to greater BPB forward rotation, but reduced head forward rotation compared to BPB 1 (Figure 3). Time-history of BPB forward motion showed that the BPB with a more forward lap belt position initially rotated forward in non-LA conditions compared to with LA conditions, where the BPB initially moved rearward. The opposite trend was observed with the other BPB type. These findings were potentially due to the child ATD femurs sliding under the belt reducing head forward motion while the opposite was true for the other BPB type, with a more engaged lap belt on the pelvis at the Anterior Superior Iliac Spine (ASIS). These findings do not align with the ones from previous studies in frontal impacts that showed reduced head and BPB forward movement for highback and backless BPB with LA compared to non-LA conditions (Mansfield et al., 2021). The reason for these differences between our study and Mansfield's study may likely be due to the fact that highback-to-backless BPBs (particularly type 2) have a more forward lap belt position on the femur rather than on the pelvis in backless mode. Furthermore, as previously mentioned, our study found opposing results between two BPB types in both highback and backless mode with flexible webbing LA connectors, which may have caused increased BPB forward movement compared to rigid LA connectors, which Mansfield et al. (2021) utilized for their study.

The absence of LA led to greater lateral BPB and head rotation (Figure 4), particularly in the backless mode, where there was the greatest difference between LA and non-LA conditions compared to highback mode of the same BPB type. These findings aligned with previous studies also showing reduced BPB tipping and rotation with LA in lateral impacts (Hauschild et al., 2016). This suggests that the absence of both LA and the BPB seatback influenced lateral rotation of the BPB and head rather than the lap belt position, which instead had greater influence on the forward rotation of the BPB and head as mentioned above.

Generally, small differences were found between LA and non-LA in the BPB (<8°, Table 3) and head (<21°, Table 4) kinematics for far-side frontal oblique impacts (30º from frontal), which was also previously found by Mansfield et al. 2021 and Visvikis et al. 2017 in pure frontal impacts. There was a drastic difference between BPB and head displacement magnitudes with the BPB rotation being smaller than the head rotation (BPB rotation <22°, Table 3 vs Head rotation >85°, Table 4). This suggests that the BPB rotation and the presence and absence of the LA were not the only contributing factor to head rotation. The lap belt position was another contributing factor to the head motion particularly in highback-to backless BPB styles where the lap belt is forward on the femur in backless mode. In those cases, the decrease in head motion may suggest potential ATD motion under the lap belt leading to submarining in more severe crash conditions.

While it was found that with LA reduces BPB lateral rotation in far-side frontal oblique impacts, further research is warranted to understand how LA influences BPB forward rotation and ATD kinematics with various types of LA connectors for highback-to-backless BPBs.

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This study had several limitations. The number of repetitions per condition (n=2) was small, which did not allow for statistical testing. Only one vehicle seat model was investigated so it is unclear how different vehicle seat geometries influences BPB and ATD motion. However, it is plausible that the differences between the BPBs and LA conditions are analogous when using another vehicle seat. Our sled seat buck did not include a head restraint, which may have influenced the ATD lateral motion and therefore the shoulder belt lateral position during the sled impact, however our impact angle was only 30° from frontal reducing the lateral motion of the ATD in any case.

CONCLUSIONS

In the BPB type with the more forward lap belt position in the backless mode, the absence of LA led to greater BPB forward rotation potentially because the child ATD femurs slid under the lap belt thereby reducing head forward motion while the opposite was true for the other BPB type that has a less forward lap belt position. For both types, the absence of LA led to greater lateral BPB rotation and overall greater lateral head rotation particularly in the backless mode, suggesting that the absence of both LA and the BPB seatback influenced the lateral rotation of BPB and head. The lateral head motion was overall reduced in highback mode across both BPB types and LA conditions suggesting there is some advantages in keeping highback-to-backless BPBs in highback mode, particularly in lateral loading conditions when seated on the far-side, as that may reduce the likelihood to contact another rear-seated occupant.

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