Characterizing Booster Seat Children Response in Reclined Seating Configuration During Lateral Oblique Pre-Crash Maneuver

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ABSTRACT

The rise of autonomous vehicles may lead to alternative seating options, including more reclined positions. Belt-positioning booster seats (BPBs) were found to prevent submarining in reclined children when exposed to frontal impacts, but it is unclear if that is the case for lateral-oblique impacts and how pre-crash motion influences the position of reclined children during lateral-oblique impacts. In this study, we examined the effects of BPB type and seatback recline angle on children's responses during a low-acceleration lateral-oblique impact. Five children (6-8 y.o.) seated in two different BPBs with three different seatback recline angles (25°, 45°, and 60°) were exposed to a sled-simulated low-acceleration lateral-oblique pulse (2 g). Human kinematics were recorded with a 10-camera 3D motion-capture system. Seatbelt peak forces were collected with three seatbelt load cells. Lateral and forward peak head and trunk displacements, knee-head forward distance, and seatbelt peak loads (shoulder, left lap, and right lap) were examined. Results showed that lateral peak head and trunk displacement decreased as the seatback recline angle increased (head, 25°: 268 ± 20 mm, 45°: 248 ± 12 mm, 60°: 205 ± 9 mm, $p<0.002$; trunk, 25°: 154 ± 19 mm, 45°: 133 ± 16 mm, 60°: 106 ± 11 mm, $p<0.001$). Shoulder belt peak load also decreased as seatback recline angle increased (25°: 93 ± 6 N, 45°: 65 ± 8 N, 60°: 48 ± 13 N, $p<0.001$). Video analyses confirm that the lap belt did not travel up and over the pelvis. There were no statistically significant differences in forward peak head and trunk displacement, although a trend was observed in which forward peak head displacement slightly increased as recline angle increased (25°: 48 ± 19 mm, 45°: 57 ± 25 mm, 60°: 72 ± 25 mm, $p>0.07$). These results suggest that submarining did not occur in reclined configurations combined with the use of a low-back BPB. The severe reclined configurations with a BPB may reduce out-of-position posture in lateral-oblique pre-crash maneuvers.

INTRODUCTION

With automated vehicles coming to fruition, non-standard seating configurations, such as reclined passengers, may become a reality (Östling et al., 2019; Jorlöv et al., 2017). The introduction of reclined seating postures requires additional research into the protection of occupants as current restraints are designed for upright sitting occupants. Reclined seating positions present additional safety hazards for vehicle occupants since they lead to different lumbar spine and pelvis angles, as well as different contact points between the pelvis and lap belt (Forman et al., 2019). Previous research into reclined seating positions has shown that submarining can be a major issue for occupants in reclined positions during a frontal crash (Rawska et al., 2019, 2020). Submarining refers to the scenario in which the lap belt moves up over the anterior-superior iliac spines of the occupant during a crash, pushing on the abdomen and potentially causing severe injury (Richardson et al., 2020; Thorbole, 2015). Previous studies on reclined vehicle occupants have shown that submarining is more likely for smaller occupants, such as 5th percentile female occupants, and is more likely as the recline angle becomes more severe (Rawska et al., 2020). However, all current published research done on reclined vehicle occupants has examined the effect of the reclined seatback angles on occupant motion in frontal crashes. The effect of reclined seatback angles is unknown in other impact configurations such as lateral or lateral-oblique.

Most of the previous studies performed on reclined occupants have been done on adult occupants, as post-mortem human surrogates (PMHS), Anthropomorphic Test Devices (ATDs), or Finite Element (FE) models. Only two studies have investigated the effects of reclined seating on children (Hauschild et al., 2021; Bohman et al., 2021). It is warranted to examine reclined child occupants as safety solutions designed for reclined adults cannot be simply transferred to children, as they may have different efficacies on different populations of vehicle occupants. Furthermore, the presence of the child restraint systems (CRS), such as the belt positioning booster (BPB), may impact the dynamic between reclined seat, seatbelt, and child's body during an impact. Previous studies on various types of CRS have shown that booster seats may decrease the risk of submarining in children (Beck et al., 2011; Klinich et al., 2014). However, there is little knowledge as to whether a BPB can effectively reduce submarining risk with reclined seatback angles, especially when exposed to lateral-oblique pre-crash maneuvers. A previous study used the Large Omnidirectional Child (LODC) ATD to show that a BPB can prevent submarining for children in moderately reclined (45-degree) seatback angles (Hauschild et al., 2021). Another study found that certain types of low-back boosters lead to a good engagement of the lap belt with the pelvis and contributed to the prevention of submarining in reclined postures when a pretensioner belt was present (Bohman et al., 2021). However, several knowledge gaps in the kinematics of reclined children remain as these above-mentioned child studies did not examine severe reclined seatback angles or lateral-oblique impacts.

Lateral-oblique impacts occur almost as frequently as frontal impacts, and account for a similar number of fatalities and injuries in children (Arbogast et al., 2012). There are two types of lateral-oblique crashes: near-side and far-side. Near-side refers to the occupant being seated on the same side as the crash impact, while far-side is when the occupant is seated on the opposite side of the impact (Mathews, 2015). According to Seacrist et al (2014), far-side impacts can be more prevalent than near-side and can pose an increased risk of injury in child occupants, as there are more countermeasures in place for near-side impacts (i.e., side airbags). Previous studies have investigated the effect of low-acceleration lateral-oblique impacts on children's motion and found that the lateral movement out of the belt from these impacts can be reduced by different countermeasures such as belt-pretensioner (Mathews, 2015; Arbogast et al., 2012; Seacrist et al., 2014). However, it is unknown if this finding can be extended to reclined child occupants in low-acceleration lateral-oblique impacts.

Autonomous vehicles may perform more crash avoidance maneuvers, which are characterized by low acceleration, leading to fewer crash events (Graci et al., 2019). As autonomous vehicles will potentially include reclined seating configurations, low-acceleration events are important to examine as reclined children may be displaced out of the optimal position within the seatbelt during those maneuvers, which leads to an increased risk of injury in potential subsequent crashes. During pre-crash events, reclined seating configurations may displace child occupants differently than the upright postures would. For this reason, the characterization of reclined children's motion during low-acceleration impacts is warranted to design future safety restraints. Another advantage of examining low-acceleration events is the ability to use human volunteers, such as children, and collect biofidelic kinematic data and muscle activation data.

Therefore, the main purpose of this study is to investigate the effects of moderate and severe reclined seatback angles and two types of BPB on the motion of child occupants in low-acceleration far-side lateral-oblique impacts.

METHODS

The study protocol was reviewed and approved by the Institutional Review Board of the Children's Hospital of Philadelphia.

Participants

Five children (ages 6-8 years, standing height 130 ± 5.18 cm, seated height 65 ± 2.92 cm, weight 25.9 ± 2.66 kg) participated in this study. The participants were eligible to participate if they were within the 5th and 95th percentile for height, weight, and BMI, and did not have any musculoskeletal or neuromuscular conditions or fear of amusement park rides.

Sled Apparatus

The participants were seated on two types of low-back BPB that were placed on a vehicle seat and restrained by a 3-point seatbelt on a pneumatically actuated, hydraulically controlled low-speed crash sled (Arbogast et al., 2009) that exposed the participants to a low-speed lateral-oblique pre-crash pulse (Figure 1). The low-speed pulse reached a maximum acceleration of 2 g.

Figure 1: Sled Apparatus

An adjustable fixture was made using slotted aluminum rods (MiniTec, MiniTec Framing Systems LLC, Farmington, NY) to simulate an integrated seatbelt (Figure 2). The seatbelt was equipped with three belt load cells (6200 FL-4130, Denton ATD Inc, Rochester Hills, MI) that were installed on the shoulder belt (between the subject and D-ring) and the lap belt (right side between the BPB and the anchor point, left side between the BPB and the child's lap). The load cell data was sampled at 10,000 Hz using an onboard TDAS Pro data acquisition system (DTS Inc, Seal Beach, CA). The subjects underwent a lateral-oblique (80° from frontal) pulse simulating a far-side low-speed impact.

Figure 2: Simulated Integrated Seatbelt fixture

Three GoPro HERO Session 4 cameras were attached to the framing of the sled apparatus. One camera was placed in the overhead perspective, one was in the frontal perspective, and one was placed for a side view of the subject (left side). These cameras captured 2D video data of each trial at 30 Hz.

Instrumentation

An on-board Optitrack Prime13W 10-camera motion-capture system (200Hz, NaturalPoint Inc., Corvallis, OR) was used to capture kinematic data for each participant. The motion-capture software was calibrated for each camera before each participant to determine the global coordinate system and ensure that every camera had the desired field of view.

Participants wore a tight-fitting athletic shirt with holes cut out for the motion-capture photo-reflective markers to be placed directly on the skin of various skeletal landmarks. The markers were placed on the participants' head using a headband, trunk (suprasternal notch and xiphoid process), and right and left acromia, humeral epicondyles, patellae, and femoral epicondyles. For the suprasternal notch and xiphoid process, an array of 4 markers were placed on a rigid body structure that was then attached to the skeletal landmark. Photo-reflective markers were also placed in two locations on the belt (shoulder belt and lap belt), on the D-ring, and on the seat. The BPBs were also fitted with rigid bodies of four photo-reflective markers on each side to track their movement during each trial.

Testing

Participants were seated in the sled apparatus to undergo a test pulse to ensure they were comfortable with proceeding. Once the participant was comfortable, anthropometric data was recorded for each subject (i.e., weight, standing height, and seated height).

A total of 12 trials were performed for each subject (Table 1). Three seatback recline angles were tested: nominal (25°), moderate (45°), and severely reclined (60°), shown in Figure 3. Each angle was tested with two different booster seats, and each combination was tested twice, totaling 12 trials. The two BPBs tested were a standard booster seat and a lightweight booster (Figure 4). The standard booster was a multi-part construction with various plastic, metal, and fastening pieces, and can weigh approximately 2-5 kg. The standard BPB used in this study weighed 2.3 kg. The lightweight booster was a simple, hollow single-part design that is either blow molded plastic or an inflatable bladder, with approximate weight less than 2 kg. The lightweight BPB used in this study weighed 0.91 kg. The standard booster also had a greater height (21.59 cm) than the lightweight booster (16.51 cm). The trials were completed in a randomized order that was different for each subject.

Table 1: Test Matrix

Booster	**Recline Angle**	**Repetitions**
Lightweight BPB	25°	2
Lightweight BPB	45°	2
Lightweight BPB	60°	2
Standard BPB	25°	2
Standard BPB	45°	2
Standard BPB	60°	2

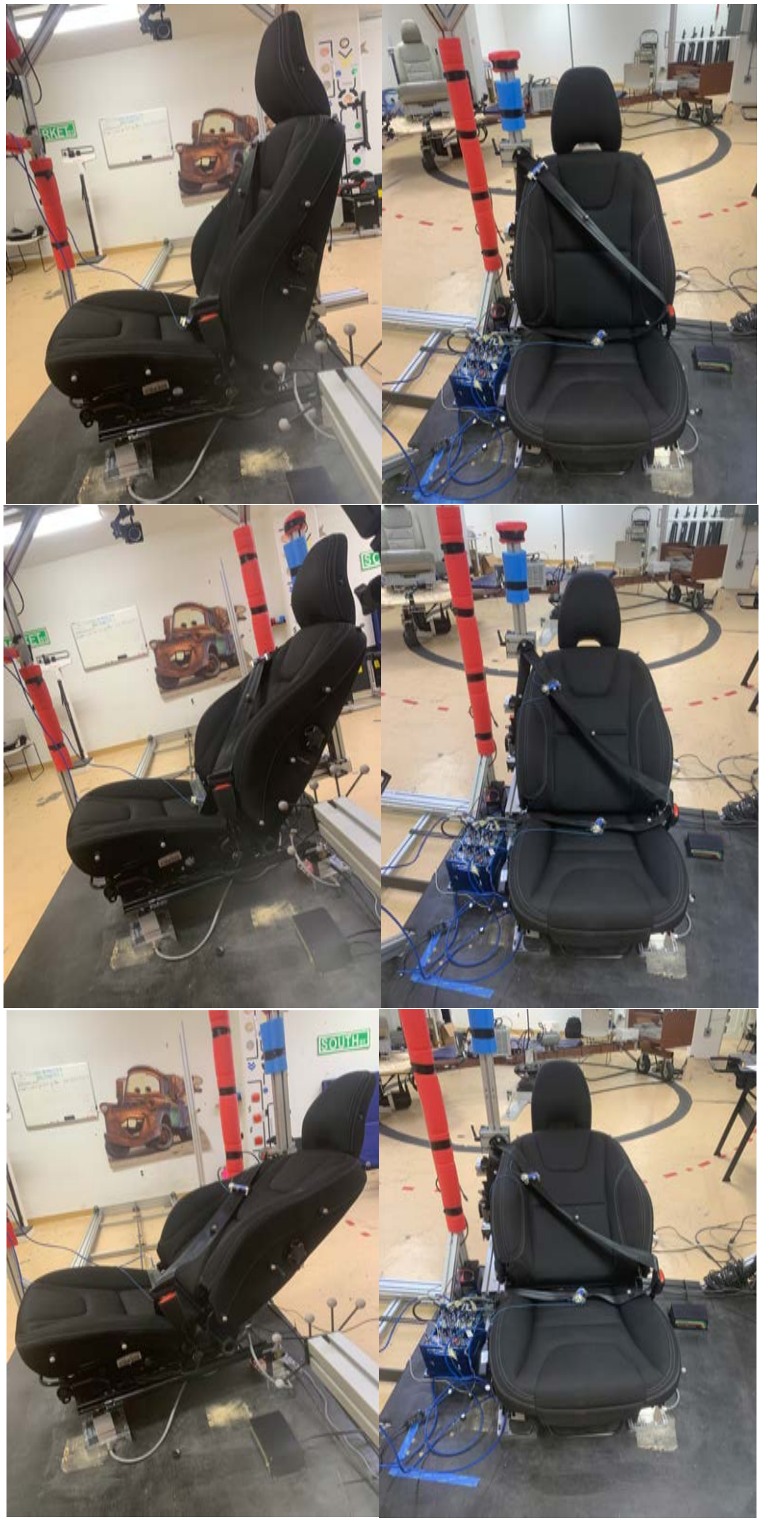

Figure 3: Side and frontal view of various sled recline angles with seatbelt adjusted to each angle (top to bottom: 25°, 45°, 60°)

Figure 4: Lightweight BPB (left) and standard BPB (right)

The subjects were seated on the BPB on the sled apparatus and secured with the integrated seatbelt setup. The subjects were instructed to sit as they normally would on their BPB, while making sure they faced forward and kept their arms and legs uncrossed. Participants were aware that the sled would move but the exact timing of the sled activation was randomized between 1 and 10 seconds to minimize anticipation. Subjects were instructed to stay still until the sled motion began. There was a short break between each trial (5-10 mins) to minimize habituation to the pulse.

Data Analysis

Motive Tracker software (NaturalPoint Inc., Corvallis, OR) was used to process kinematic data. Processed kinematic data and load cell data were exported into custom Matlab (MathWorks 2020, Inc., Natick, MA) codes for extraction of the outcome measures (Table 2).

Table 2: Study outcome measures and descriptions

Dependent Measure	**Description**
Forward peak head displacement	Furthest distance that the participant's head moves in the forward direction
Lateral peak head displacement	Furthest distance that the participant's head moves in the lateral direction
Forward peak trunk displacement	Furthest distance that the participant's suprasternal notch moves in the forward direction
Lateral peak trunk displacement	Furthest distance that the participant's suprasternal notch moves in the lateral direction
Knee-head forward distance	The difference between the knee and head displacement at the time of forward peak head displacement
Shoulder belt peak load	Maximum load on the shoulder belt
Left lap belt peak load	Maximum load on the left lap belt sensor placed by the buckle
Right lap belt peak load	Maximum load on the right lap belt sensor placed by the belt anchor
Time of lateral peak head displacement	The time at which lateral peak head displacement occurred
Time of lateral peak trunk displacement	The time at which lateral peak trunk displacement occurred

The outcome measures were averaged across repetitions. Repeated Measure 2-way ANOVAs were performed to evaluate the effect of recline seatback angle (25°, 45°, 60°) and the different types of BPBs (lightweight BPB versus standard BPB) on the outcome measures in Table 2. Tukey's post-hoc test for pairwise comparisons was used. P-level was set to 0.05.

RESULTS

One subject performed only one repetition of the 60° recline angle with the standard BPB and none of the 60° recline angle lightweight BPB. Another subject only performed one repetition of the 60° recline angle for both standard and lightweight BPBs. Shoulder and lap belt load data is missing for one subject.

Lateral peak head displacement showed a statistically significant main effect of the reclined seatback angle ($p<0.002$): lateral peak head displacement decreased with the increasing seatback recline angle (Table 3, Figure 5a). Tukey's post-hoc test showed that lateral peak head displacement was greater in the 25° compared to 60° condition ($p<0.002$) and in the 45° compared to the 60° condition ($p<0.008$), while the difference in lateral peak head displacement between 25° and 45° was not statistically significant ($p>0.29$; Table 3, Figure 5a). The main effect of BPB was not statistically significant ($p=0.11$), nor was the interaction between BPB and recline angle ($p=0.59$).

Lateral peak trunk displacement showed a statistically significant main effect of the reclined seatback angle ($p<0.001$; Table 3, Figure 5a), and of the BPB ($p<0.02$). Tukey's post-hoc test showed that lateral peak trunk displacement was greater in the 25° than the 45° condition ($p<0.003$) and the 60° condition ($p<0.001$), and in the 45° than the 60° condition ($p<0.001$; Table 3, Figure 5a). No statistically significant interaction between recline angle and BPB was found ($p=0.66$).

Forward peak head displacement showed no statistically significant differences between reclined seatback angles ($p>0.07$; Table 3, Figure 5b). However, the difference between BPB was statistically significant (standard 60 ± 19 mm vs lightweight 58 ± 22 mm, $p<0.02$). The interaction between BPB and recline angle was not statistically significant ($p=0.72$).

The forward peak trunk displacement did not show any statistically significant differences between reclined angles ($p=0.32$, Table 3, Figure 5b), BPB ($p=0.33$), and BPB and recline angle ($p=0.31$).

Knee-head forward distance also increased as recline angle increased, however these differences were not statistically significant ($p=0.24$; Table 3, Figure 5c). The effect of BPB ($p=0.09$) as well as BPB and recline angle ($p=0.89$) were also not statistically significant.

Table 3: Mean (SD) of peak head and trunk displacements, and knee-head forward distance across the seatback angles, $^{*,\%,+}p \leq 0.05$

	Seatback angle	25°	45°	60°
Peak head displacement (mm)	Forward	48 (19)	57 (25)	72 (25)
	Lateral	268 (20)$^{\%}$	248 (12)$^{+}$	205 (9)
Peak trunk displacement (mm)	Forward	42 (8)	37 (11)	43 (12)
	Lateral	154 (19)$^{*,\%}$	133 (16)$^{+}$	106 (11)
Knee-head distance (mm)	Forward	26 (14)	30 (19)	40 (16)

*25°≠45°, $p<0.003$ (trunk)
$^{\%}$25°≠60°, $p<0.002$ (head), $p<0.001$ (trunk)
+45°≠60°, $p<0.008$ (head), $p<0.001$ (trunk)

Table 4 shows the lateral and forward peak head and trunk displacements, as well as knee-head forward distances for the two BPBs across all recline angle conditions.

Table 4: Mean (SD) of peak head and trunk displacements, and knee-head forward distance across different BPBs and seatback angles

	BPB types	Lightweight BPB	Lightweight BPB	Lightweight BPB	Standard BPB	Standard BPB	Standard BPB
	Seatback angle	25°	45°	60°	25°	45°	60°
Peak head displacement (mm)	Forward	48 (22)	56 (24)	69 (29)	49 (19)	57 (27)	74 (27)
	Lateral	264 (27)	241 (13)	202 (21)	271 (15)	256 (17)	206 (13)
Peak trunk displacement (mm)	Forward	37 (12)	39 (15)	41 (17)	47 (15)	35 (9)	44 (11)
	Lateral	150 (22)	127 (17)	100 (13)	158 (18)	139 (17)	109 (10)
Knee-head distance (mm)	Forward	31 (17)	35 (21)	45 (18)	20 (13)	25 (18)	34 (25)

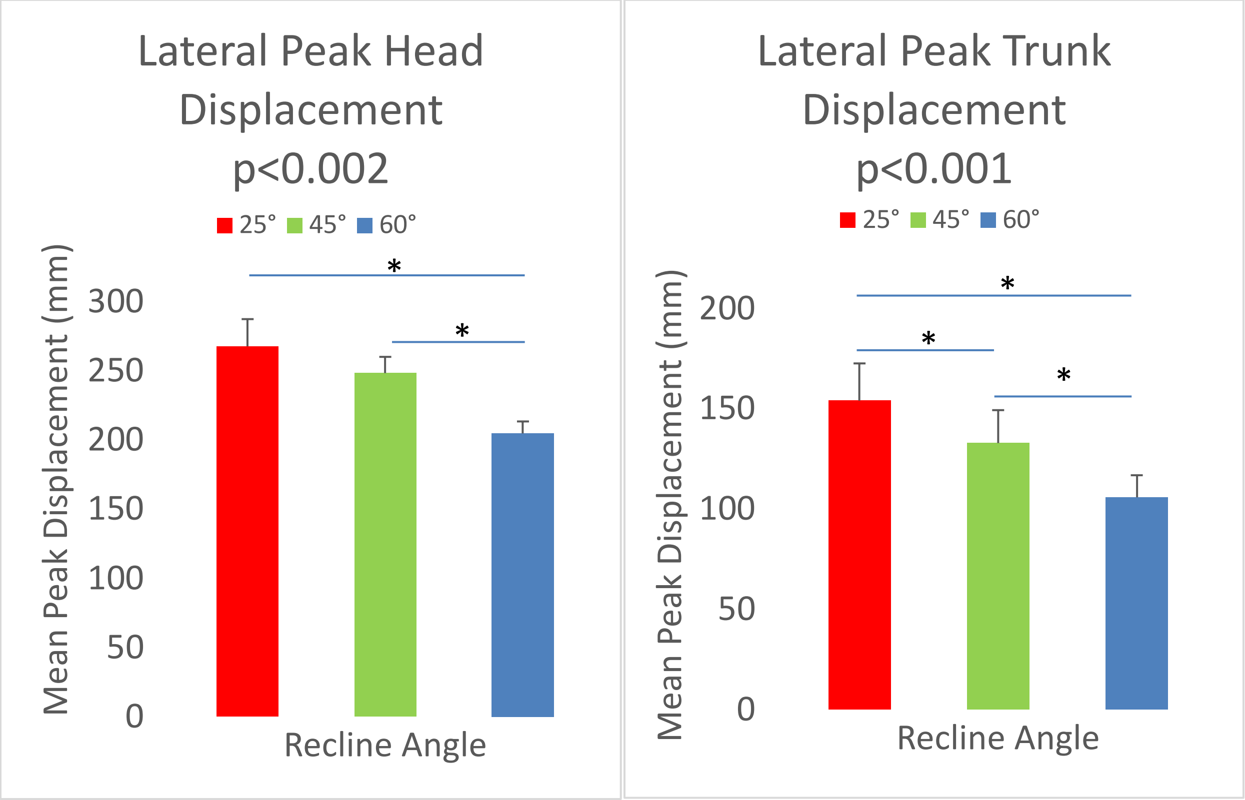

Figure 5a: Mean (SD) of lateral peak head and trunk displacements (mm). *p≤0.05

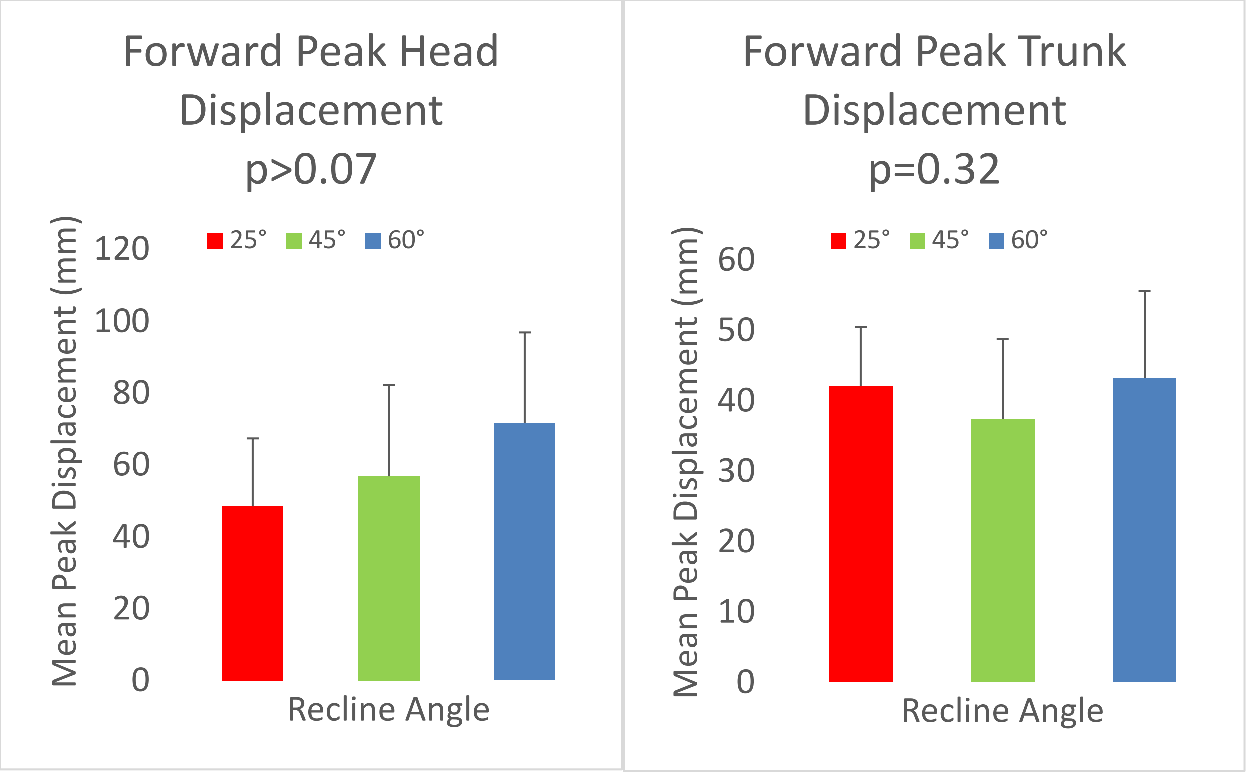

Figure 5b: Mean (SD) of forward peak head and trunk displacements (mm). *p≤0.05

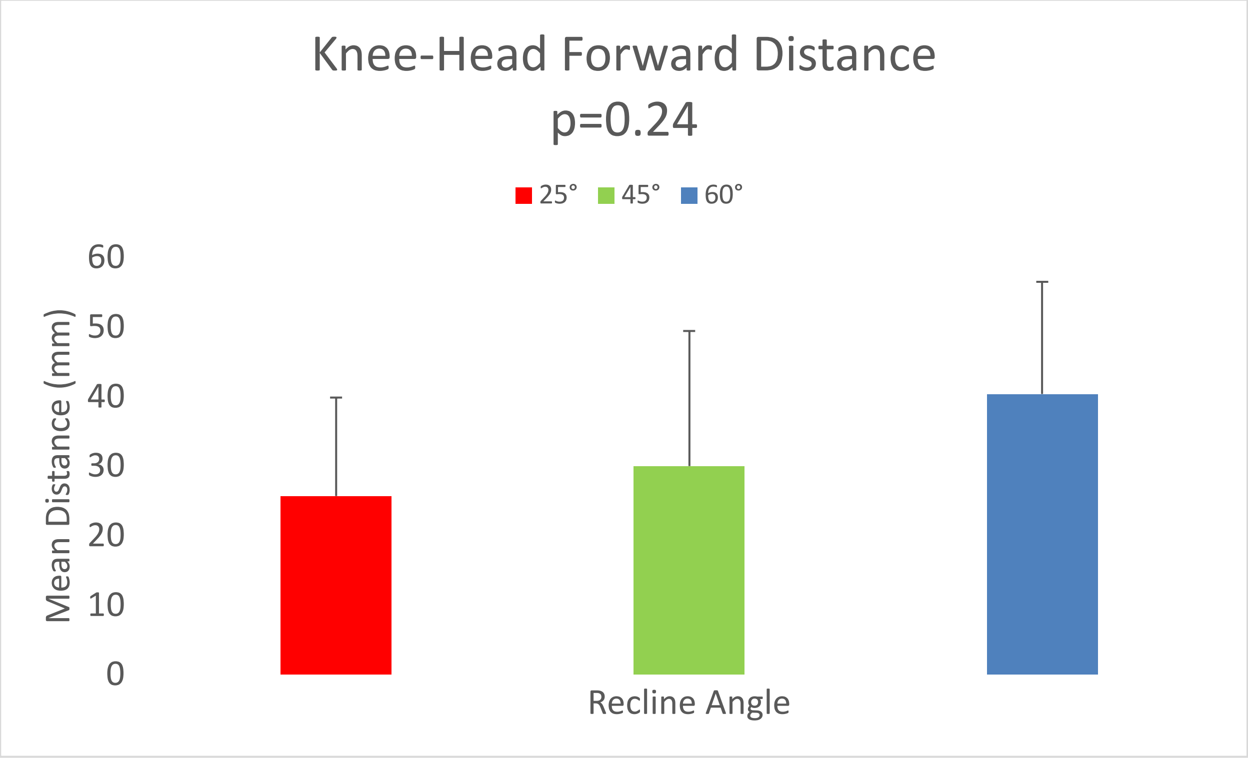

Figure 5c: Mean (SD) of knee-head forward distance (mm). *p≤0.05

Video screenshots at the approximate instant of peak head and trunk displacement for each recline angle are reported in Figure 6, showing that the lateral head and trunk displacements decreased as the recline seatback angle increased.

Figure 6: Side view of head and trunk displacement at seatback recline angles of 25°, 45°, 60° (top to bottom)

Lateral peak head and trunk displacements occurred around the same time. Lateral peak head and trunk displacements occurred only slightly earlier as the recline angle increased (Table 5, Figure 7, Figure 8, Figure 9).

Table 5: Mean (SD) of time of lateral peak head and trunk displacements

BPB Types	Lightweight BPB	Lightweight BPB	Lightweight BPB	Standard BPB	Standard BPB	Standard BPB
Seatback Angle	25°	45°	60°	25°	45°	60°
Lateral Peak Head time (ms)	21 (1)	20 (2)	18 (2)	21 (1)	20 (1)	18 (2)
Lateral Peak Trunk time (ms)	17 (1)	17 (1)	16 (2)	17 (1)	17 (1)	16 (1)

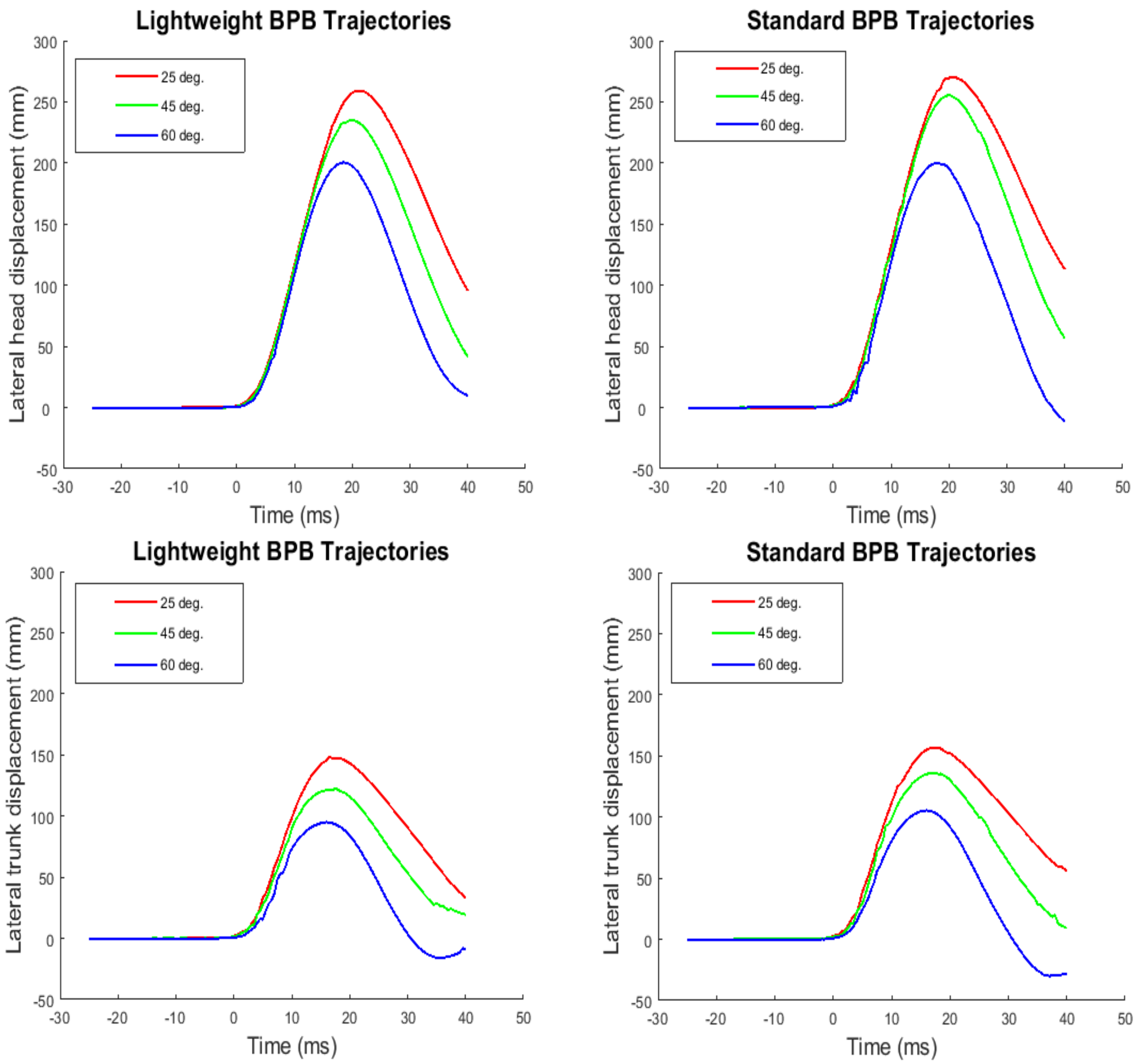

Figure 7: Averaged lateral head and trunk time series for each reclined seatback condition

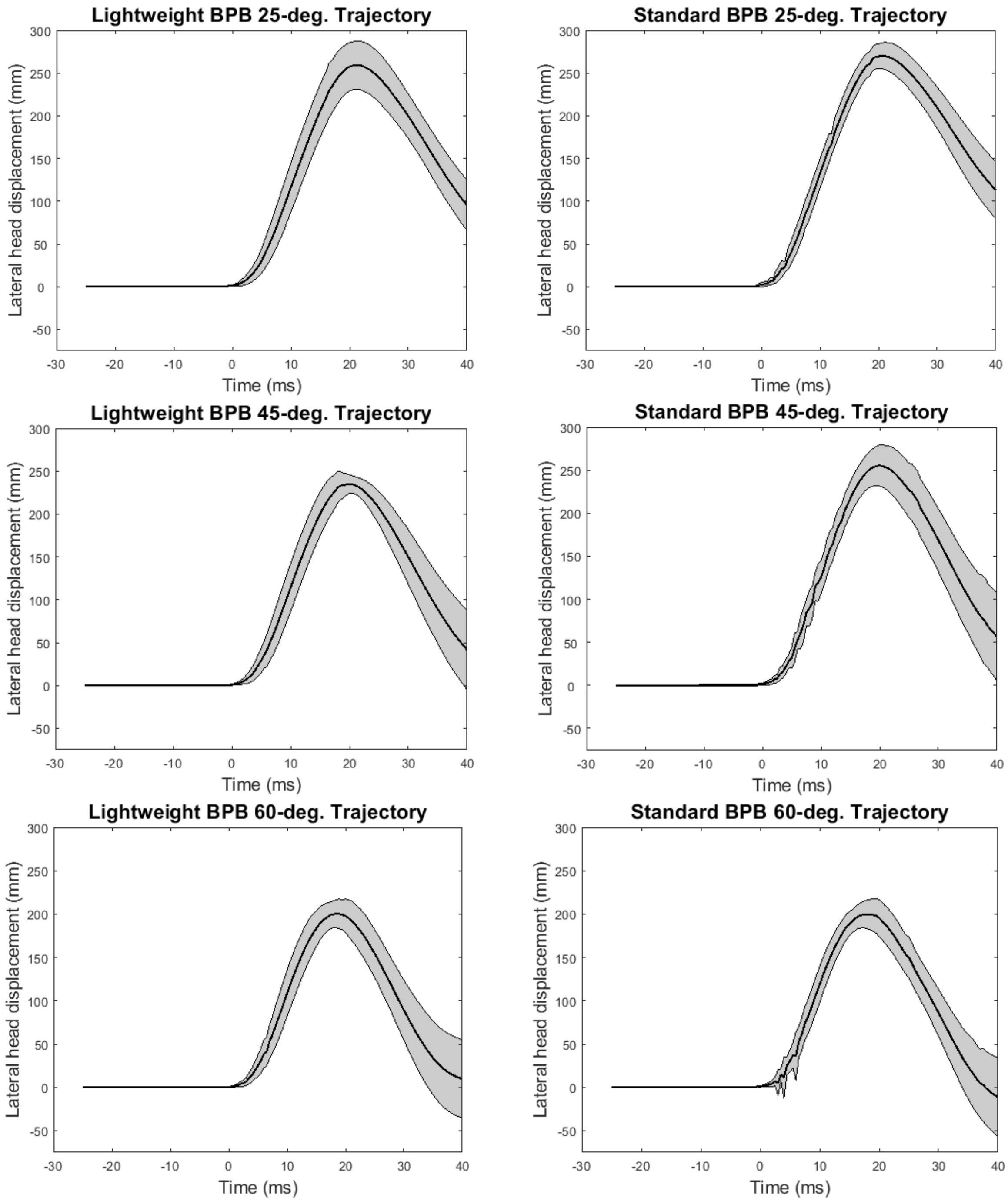

Figure 8: Mean (SD) of the lateral peak head displacement time series for each seatback recline angle and for lightweight & standard BPB

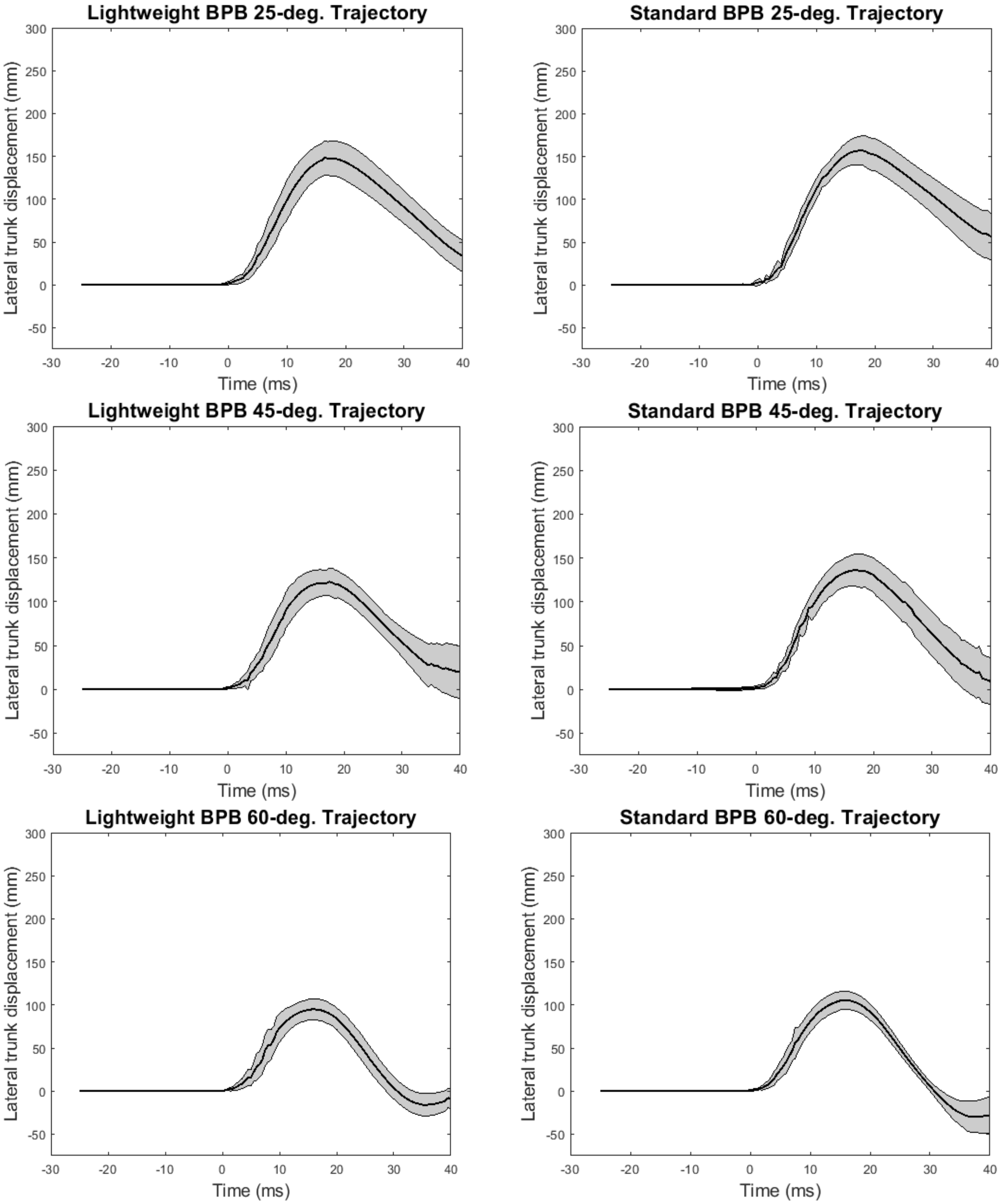

Figure 9: Mean (SD) of the lateral peak trunk displacement time series for each seatback recline angle and for lightweight & standard BPB

Shoulder belt peak loads showed a main effect of reclined seatback angle: shoulder belt peak load decreased as the reclined seatback angle increased (p<0.001; Table 6, Figure 10a). Post-hoc comparisons showed that all the reclined seatback angles were statistically significant from each other (25° vs 45°: p<0.005, 25° vs 60°: p<0.005, 45° vs 60°: p<0.03; Table 6, Figure 10a). The effect of BPB (p=0.11) and BPB and recline angle (p=0.41) were not statistically significant.

Left and right lap belt peak load did not show any statistically significant difference (left, p>0.17; right, p>0.26).

Table 6: Mean (SD) of shoulder belt and left and right lap belt peak loads, $^{*,\%,+}p \leq 0.05$

Seatback Angle	25°	45°	60°
Shoulder belt peak load (N)	93 (6)$^{*,\%}$	65 (8)$^{+}$	48 (13)
Left lap belt peak load (N)	126 (25)	137 (15)	127 (15)
Right lap belt peak load (N)	100 (14)	91 (20)	90 (11)

*25°≠45°, p<0.005
%25°≠60°, p<0.005
+45°≠60°, p<0.03

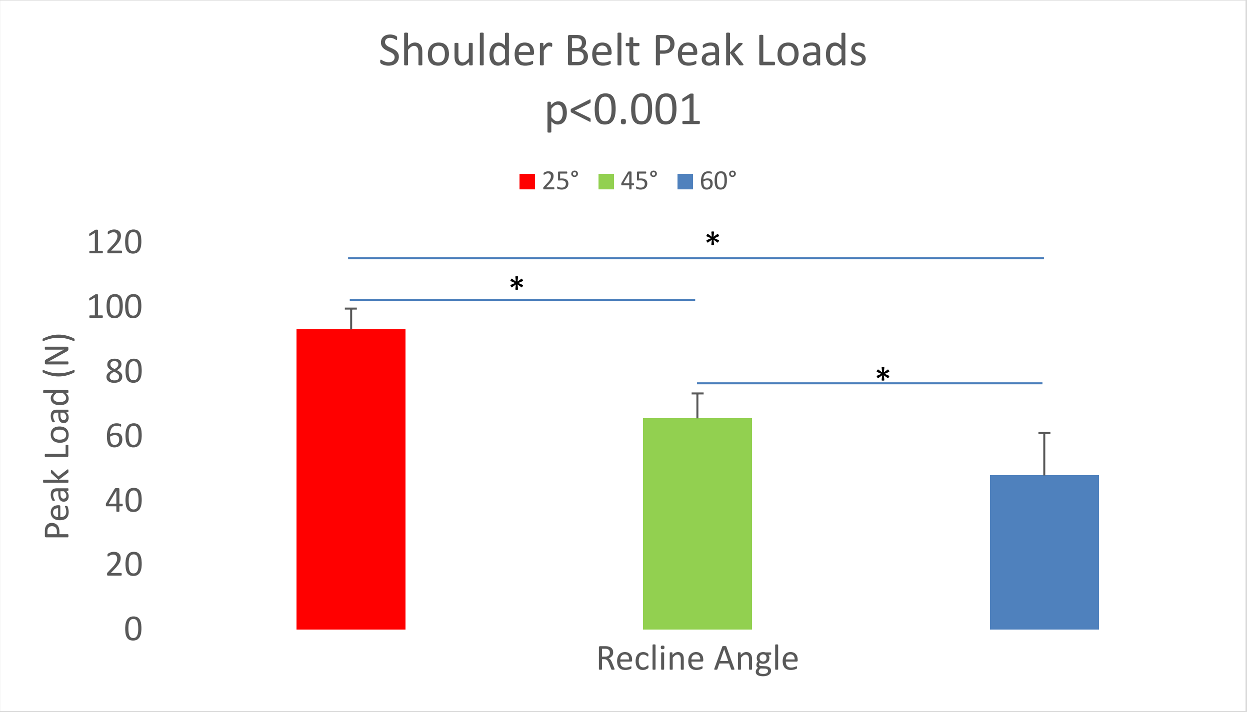

Figure 10a: Mean (SD) of shoulder belt peak loads for each seatback angle (N). *p≤0.05

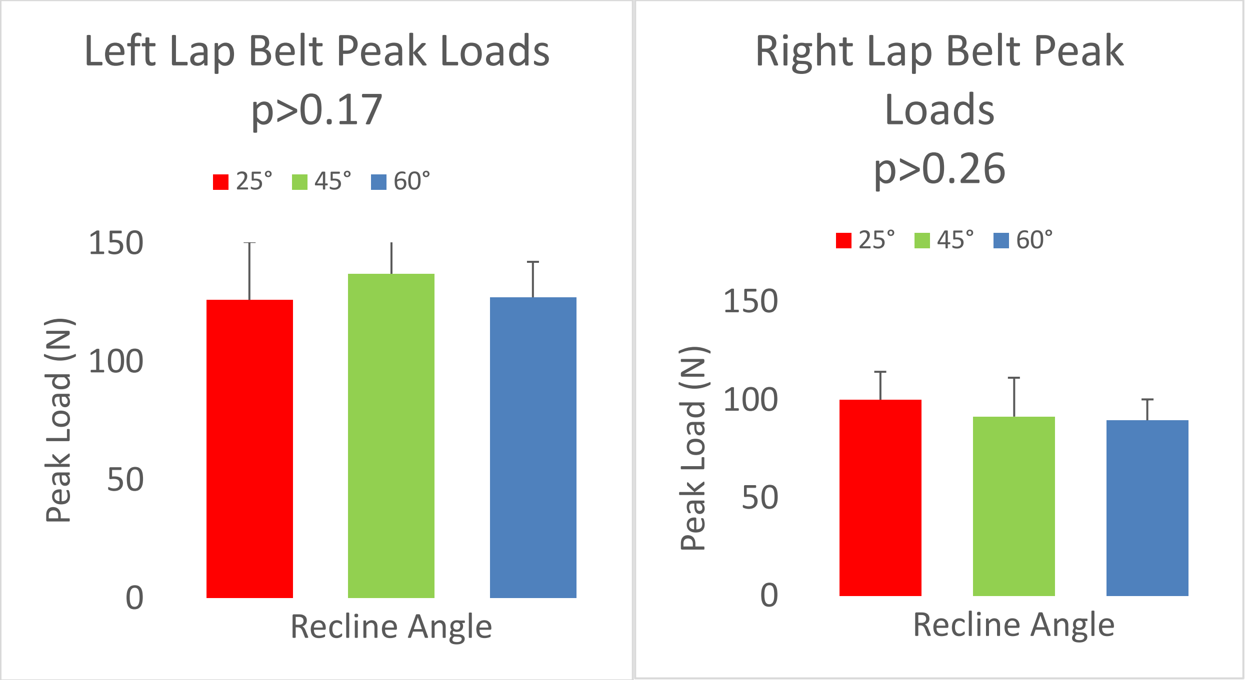

Figure 10b: Mean (SD) of left and right lap belt peak loads for each seatback angle (N). *p≤0.05

DISCUSSION

The aim of this study was to investigate the effects of moderate and severe reclined seatback angles and BPB on child occupants in low-acceleration lateral-oblique impacts.

The findings of this investigation showed that lateral peak head and trunk displacement decreased with the increase of the reclined seatback angle. This was particularly true for the severe reclined condition (60°): lateral peak head displacement was similar between the 25° and 45° condition but differed between the 25° and the 60° condition. This suggests that more severe reclined configurations may show more evident differences in lateral occupant movement compared to the nominal condition in lateral-oblique impacts. Overall, the decrease in lateral head and trunk displacement with the increased reclined seatback angle may lead the booster-seated children to assume a more favorable position within the shoulder seatbelt prior to lateral-oblique impacts compared to the nominal position.

While not statistically significant, there was a slight increase in forward peak head displacement with the increase in recline angle for both types of BPBs, and in forward peak trunk displacement with the lightweight BPB. Furthermore, there was an increase in knee-head forward distance as the seatback recline angle increased. Knee-head forward distances greater than 200 mm are considered to be associated with submarining (Klinich et al., 2010), and displacements over 150 mm are considered to show submarining tendencies (Visvikis et al., 2018). In our study, the knee-head forward distances were small and video analyses showed that the lap belt did not travel over the pelvis. Therefore, in our testing it is unlikely that submarining occurred. On the other hand, from video analyses forward peak head and trunk displacements seemed more related to the child occupants sliding down in the seat (so that the head and trunk would be positioned more forward) rather than being the result of head and trunk flexion (Figure 6, bottom). Overall, video analyses showed that the child occupants tend to roll on the side rather than flex forward and laterally in the moderate and reclined seatback angle conditions during the lateral-oblique sled maneuver. It is unknown if this type of forward peak head and trunk displacement could increase in more severe acceleration pulses and in lateral-oblique crashes. Physical crash testing with child ATDs will need to clarify if that is the case, as this type of motion may result in submarining during crashes.

Minimal differences were found between BPB types. The small differences in lateral peak head and trunk displacement between the two BPB types may have been due to the slight difference in heights of the two BPBs. However, BPBs differ in more ways than just height, so future research comparing multiple types of BPBs with different characteristics in a reclined seating configuration is necessary. One thing to consider is the hollow construction of the lightweight BPB. Since this type of BPB is hollow, it may be more prone to compression when exposed to a more severe pulse, which may potentially increase the risk of submarining. The pulse in this study was mild, so further testing with a more severe pulse may be warranted to confirm this hypothesis.

The shoulder belt peak load decrease with the increase in reclined seatback angle is in line with the decrease in lateral peak head and trunk displacement found with the increase in reclined seatback angle. Due to the decrease in lateral peak trunk displacement with the reclined seatback angle, the child occupants did not load the shoulder belt as much as in the nominal condition. Figure 6 shows the occupant moving less laterally as recline angle increases.

This study had several limitations. Despite the small sample size, we were still able to obtain statistically significant results, and there was very minimal variability between subjects, as shown in Figure 8 and 9 time series. We only used one vehicle seat, therefore it is plausible that different vehicle seat geometries may lead to different results. We only employed low-back BPBs; high-back boosters have different belt routing that may change the children’s kinematics in reclined scenarios compared to low-back BPBs. Bohman et al (2021) found that a high-back booster provided a more stable initial lap belt interaction prior to being exposed to frontal impacts in an upright position, which can potentially improve occupant kinematics. Further research is warranted as to whether this can translate to a reclined seating configuration, and to lateral or lateral-oblique pre-crash events.

CONCLUSIONS

Low-back booster-seated children in reclined seating configurations showed reduced lateral peak head and trunk displacement when exposed to far-side lateral-oblique pre-crash events. Future research with more severe accelerations is needed to better understand reclined children’s motion in far-side lateral-oblique impacts.

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