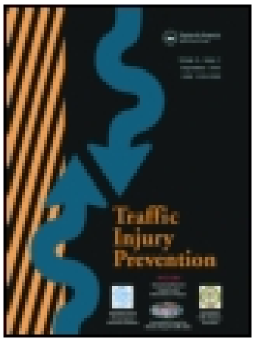

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Characterization of the motion of booster-seated children during simulated in-vehicle precrash maneuvers

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ABSTRACT

Objective: Precrash occupant motion may affect head and trunk position and restraint performance in a subsequent crash, particularly for young children. Others have studied seat belt–restrained adult drivers and adult and adolescent passengers in precrash maneuvers. For younger children, optimal restraint includes a belt-positioning booster seat, which in precrash maneuvers may contribute in unique ways to the overall body motion. Therefore, the objective of this study was to quantify booster-seated child occupant kinematic, kinetic, and muscle responses during precrash maneuvers and characterize booster movement with respect to the overall occupant kinematics.

Methods: Vehicle maneuver tests were conducted with a recent model year sedan at the Transportation Research Center Inc. (TRC, Marysville, Ohio). Three precrash vehicle maneuvers were simulated: Automated and manual emergency braking (AEB and MEB) and oscillatory swerving or slalom (SLA). Each maneuver was repeated twice for each participant. Seven 6- to 8-year-old booster-seated children participated in the study and all subjects were seated in the right rear seat. Vehicle dynamics (i.e., motion, position, and orientation) were measured with an inertial and Global Positioning System navigation system (Oxford RT 3003). Kinematic data from human volunteers were collected with an 8-camera 3D motion capture system (Optitrack Prime 13 200 Hz, NaturalPoint, Inc.). Photoreflective markers were placed on participants' head and trunk. Electromyography (EMG; Trigno EMG Wireless Delsys, Inc., 2,000 Hz) sensors were placed on bilateral muscles predicted to be most likely involved in bracing behaviors.

Results: Children demonstrated greater head and trunk velocity in MEB (head 123.7 ± 13.1 cm/s, trunk 77.6 ± 14.1 cm/s) compared to AEB (head 45.31 ± 11.5 cm/s, trunk 27.1 ± 5.5 cm/s; $P < .001$). Participants also showed greater head motion in MEB (18.9 ± 1.4 cm) vs. AEB (15.1 ± 4.8 cm) but the differences were not statistically significant ($P < .1$). Overall, the booster seats themselves did not move substantially (<3 cm) in the braking maneuvers. During the SLA, however, the booster seat moved laterally up to 5 cm in several subjects, contributing substantially to peak head (6.5–11.5 cm) and trunk (9.0–21.4 cm) excursion during the maneuver. Booster-seated children also exhibited a greater activation of biceps and deltoid muscles and abdominal and middle trapezii muscles than the sternocleidomastoids during these maneuvers.

Conclusions: The quantification of booster seat motion and neuromuscular control and the relationship between kinematics and muscle activation in booster-seated children in precrash maneuvers provides important data on the transition between the precrash and crash phases for this young age group and may help identify opportunities for interventions that integrate active and passive safety.

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Introduction

Child restraint systems (CRS) and, in particular, belt-positioning booster seats (BPBs) have reduced mortality and morbidity associated with motor vehicle crashes for young occupants (Arbogast et al. 2009). However, motor vehicle crashes (MVCs) are still one of the leading causes of death for pediatric passengers (NHTSA 2017) and therefore efforts to further mitigate injuries are valuable.

BPBs represent the transition between harness-based CRS and seat belts for young school-age children. This transition is marked by a notable change in how the child occupant is restrained. Specifically, in a harness-based CRS, the harness restrains the child to the CRS and as long as the harness is tightly fastened per the instructions, the relative movement between the child and the CRS is limited. In contrast, a BPB uses the vehicle seat belt to directly restrain the child; the BPB

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raises the occupant up to help optimize the seat belt geometry for the boney landmarks of the child. Between 60 and 80% of crashes involve some form of precrash maneuver (Seacrist et al. 2018). With the increased availability of automated emergency braking and other automated crash avoidance vehicle technologies, vehicles may crash less often but they may incur more crash avoidance maneuvers, exposing the occupant to a greater variety of emergency maneuver acceleration pulses.

Most previous studies investigating the effect of precrash maneuvers on restrained occupants have focused on seat belt–restrained children, teens, and adults (Osth et al. 2013; Holt et al. 2017, 2018; Graci et al. 2018). There have been limited studies on the kinematic and muscle response of children restrained in BPBs during precrash maneuvers. Previous studies on anthropomorphic test devices (ATDs) cannot provide muscle response information, and ATD kinematics may not be biofidelic in precrash maneuver settings. Young occupants have been previously examined in one maneuver only (Stockman, Bohman, and Jakobsson 2013; Stockman, Bohman, Jakobsson, and Brolin 2013; Stockman et al. 2017). Previous studies on booster-seated children have mainly focused on the interaction between torso and seat belt and have characterized when this interaction would lead to a slip off of the shoulder from the belt (Bohman et al. 2011; Baker et al. 2017, 2018). No previous investigations have examined the diversity of maneuvers, muscle response, and kinematics and focused on the motion of both the child and the booster seat. It is still unclear whether and how the booster seat moves during a precrash maneuver and whether this motion would contribute to or counteract the body motion. These data may help better understand injury risk in younger occupants and direct design interventions to reduce injuries. Hence, the aim of this study was to examine booster-seated child occupant kinematic, kinetic, and muscle responses and booster seat motion during 3 types of precrash vehicle maneuvers (i.e., automated and manual emergency braking and evasive swerving) performed on a test track.

Methods

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

Participants

Seven healthy participants without neuromuscular or musculoskeletal conditions or previous injury were enrolled. Height and weight inclusion criteria were based on ranges related to the Centers for Disease Control and Prevention growth charts (CDC growth charts 2000) and ATD size to capture the range of sizes typical of rear seat child occupants (Table 1). Only male participants were selected to avoid introducing gender differences as a potentially confounding factor (Tierney et al. 2005; Seacrist et al. 2012). This was part of a larger study examining the response of both pediatric and adult occupants (Graci et al. 2018); only the booster-seated occupants' responses are presented herein.

Experimental procedures

The vehicle maneuvers were conducted with a recent model sedan at the Vehicle Dynamics Area of the Transportation Research Center (TRC Inc., Marysville, OH). Three maneuvers were performed: Automated and manual emergency braking (AEB and MEB) and oscillatory swerving or slalom (SLA). The maneuvers' acceleration was based on previous literature (Bohman et al. 2011; Huber et al. 2015; Kim et al. 2013; Osth et al. 2013; Stockman, Bohman, Jakobsson, and Brolin 2013; Kirschbichler et al. 2014) and on preliminary tests performed with a professional driver on the Vehicle Dynamics Area at TRC to ensure repeatability of the maneuvers and appropriateness for human subject testing.

For the MEB maneuver, an average acceleration of $\sim 1\,g$ was achieved by the driver depressing the brake pedal with maximum effort following 120 m of constant velocity at 50 km/h achieved with cruise control. In the AEB trials, the maneuver was initiated by directing the vehicle toward a 3D Guided Soft Target (Dynamic Research, Inc., Torrance, CA) intended to simulate a real vehicle. Similar to MEB, AEB was performed while traveling at 50 km/h constant velocity, achieving an average acceleration of $\sim 0.8\,g$. An auditory warning preceded braking in the AEB maneuver. For the SLA maneuver, an average peak lateral acceleration of $\sim 0.75\,g$ was achieved by having the vehicle move at 65 km/h, set via cruise control, around a set of 8 cones placed at a distance of 20 m apart. The slalom consisted of 4 cycles, where a cycle consisted of a right turn and a left turn. The number of cycles and cones was chosen to match a laboratory study where we simulated 4 cycles of evasive swerving with a low-acceleration sled (Holt et al. 2017) in order to validate laboratory data in the future. The 20-m distance between cones allowed the vehicle to reach the desired peak acceleration of $0.75\,g$ and travel safely through the maneuver.

All participants were seated in the right rear seat of the vehicle on a common model of a backless BPB. The booster was not equipped with the Lower Anchors and Tethers for Children system and a standard 3-point seat belt was used to restrain the subjects. Before performing the maneuvers, a muscle activity baseline was established by a static trial. In the static trial, participants were instructed to sit in the vehicle in a normal nontensed posture, with feet on the floor and hands in their lap looking straight ahead for 5 s. After the static trial, in order to familiarize the participants with the vehicle setting, they remained in the vehicle for a baseline drive where the vehicle was driven on a straight path for approximately 120 m at approximately 50 km/h. After the baseline drive, each maneuver described above was

Table 1. Mean (SD) and range of participants' age, height, and weight.

	Number of subjects	Age (years)	Weight (kg)	Height (cm)	Seated height (cm)
Mean (SD)	7	7.1 (0.9)	27.9 (6.1)	129.4 (6.9)	64.9 (5.1)
Range		6–8	23.1–37.2	119–140	57–72

performed twice for each participant. Each participant was not aware of the exact time at which the maneuver was to occur. Each participant was instructed to sit with hands in his lap in a nontensed posture for the initial position and act spontaneously during the maneuver as one would be expected to do in a real crash avoidance situation. A brief break of approximately 5 min followed each repetition. The maneuvers' order was semi-randomized. However, the 2 AEB maneuvers were restricted to either first or last to minimize the likelihood of human error when configuring the vehicle precollision system during the AEB maneuver. The same professional driver conducted the maneuvers for each participant.

Instrumentation

Vehicle dynamics were measured with an Inertial and Global Positioning System measurement unit (Oxford RT 3003, Oxford Technical Solutions Ltd., Middleton Stoney, Oxfordshire, UK), connected to a data acquisition system (Somat eDAQlite HBM, Inc., Marlborough, MA) placed in the vehicle trunk. The data acquisition system sampled data from the navigation system and the 3 seat belt load cells (shoulder belt, each side of lap belt; Measurement Specialties, TE Connectivity, Inc., Aliso Viejo, CA) at 200 Hz. The right rear seat position was instrumented with an 8-camera infrared 3D motion capture system (Optitrack, NaturalPoint, Inc.) with a sampling frequency of 200 Hz. Photoreflective markers were placed on the participants as described in Graci et al. (2018) and on the booster seat cup holders (nonextended position) in an array of 4 markers placed on a rigid structure (Figure A1, see online supplement). Electromyography (EMG) (Trigno EMG System Delsys Inc., Natick, MA) sensors were placed bilaterally on deltoids, brachioradialis, biceps, rectus femori, rectus abdomini, middle trapezii, and sternocleidomastoids (SCMs; Figure A2, see online supplement). These muscles were selected because they were hypothesized to be most involved in bracing behavior. Muscle activity was collected at 2,000 Hz.

Data processing and analysis

All data processing and analyses were performed with custom Matlab (MathWorks, Inc., Natick, MA) programs. Vehicle acceleration, kinematics, and EMG data were filtered and processed as described in Graci et al. (2018). Occupant and booster seat kinematics were analyzed in relation to the vehicle.

Braking maneuvers analysis: MEB and AEB

The jerk of each braking maneuver was calculated as the average rate of change of vehicle acceleration from onset of maneuver to steady-state acceleration phase (defined below) for AEB and MEB maneuvers. Vehicle mean forward acceleration over 0.5 s before the start of the maneuver was subtracted from the lateral acceleration signal. Three events were defined for analysis (Figure 1):

1. Maneuver start—The first time at which the vehicle's forward acceleration was equal to 5% of the maximum forward acceleration during the maneuver (Osth et al. 2013).

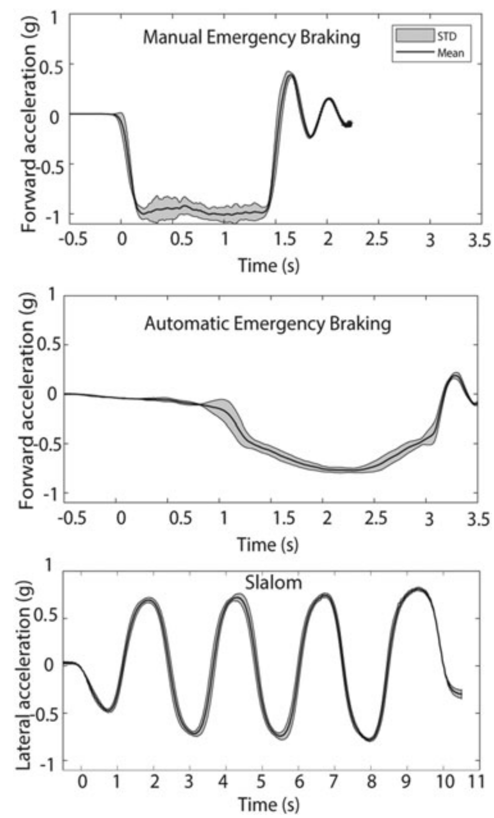

Figure 1. Time series of the vehicle acceleration profiles for all trials of the three maneuvers: MEB (top), AEB (middle), and SLA (bottom).

2. Steady-state acceleration start—The first time at which the vehicle acceleration was above 85% of the peak acceleration.
3. Steady-state acceleration end—The last time at which the vehicle acceleration was above 85% of the peak acceleration.

The following outcome measures were calculated:

1. Mean head, trunk, and booster seat displacements over the duration of the steady-state phase.
2. Head and trunk peak displacement rate of change between maneuver start and the end of the steady-state phase.
3. Mean EMG for the steady-state phase.
4. Peak seat belt forces (shoulder belt, left and right lap belts) within the steady-state phase.

In order to understand the differences in the outcome measures between 2 braking maneuvers, repeated measures 2-way analyses of variance (ANOVAs) were performed to examine the effect of maneuver (MEB vs. AEB) and repetition (first vs. second).

SLA maneuver analysis

Vehicle mean lateral acceleration over 1.0 s before the start of the maneuver was subtracted from the lateral acceleration signal. From the acceleration profile of each trial of the SLA maneuver, the following events were selected:

1. Maneuver start was defined as the first time at which the vehicle's lateral acceleration was equal to 5% of the maximum lateral acceleration during the maneuver.

2. Start and end of each turn were selected by identifying where the acceleration signal crossed zero.

The following kinematic outcome measures were calculated:

1. Mean peak head, trunk, and booster seat displacements for each turn into the belt (outboard) and out of the belt (inboard).
2. Mean EMG over the duration of each turn for each muscle.
3. Peak seat belt forces (shoulder belt, left and right lap belts) were calculated for each turn.

Repeated measures 2-way ANOVAs were performed to examine the influence of cycle (1–4) and repetition (first vs. second) on the kinematic outcome measures. Tukey's post hoc test was used for multiple comparisons. *P* level was set at .05.

Results

Time series of the vehicle acceleration pulses are presented in Figure 1. MEB and AEB forward accelerations were $0.97 \pm 0.06\,g$ and $0.74 \pm 0.02\,g$, and deceleration times were 2.60 ± 0.17 s and 1.48 ± 0.09 s, respectively. The jerk was 4.72 *g*/s (0.05) for MEB and 0.47 *g*/s (0.36) for AEB. SLA peak lateral acceleration was 0.73 ± 0.006 *g* and cycle duration was 2.49 ± 0.04 s.

MEB vs. AEB

All kinematic measures were reduced magnitude in AEB compared to MEB (Table 2); body segment velocities demonstrated statistically significant reductions (head: 64% reduction, $P = .001$; trunk: 65% reduction, $P = .009$), as did booster seat displacement (73% reduction, $P = .04$). Head and trunk displacement showed a nonsignificant trend of reduced displacement in AEB vs. MEB (head: 20% reduction, $P = .11$; trunk: 15% reduction, $P = .06$). The booster seat had small forward movement (Figures A3 and A4, see online supplement) in both braking maneuvers; these represented 6 and 11% of the head and trunk displacement, respectively, in MEB and 2 and 3% of the head and trunk displacement, respectively, in AEB.

Head and trunk velocity and trunk displacement were also greater in the first repetition compared to the second in both maneuvers ($P < .04$). No interaction of maneuver by repetition was found ($P > .09$).

Overall muscle activity was greater during the MEB maneuver than during AEB (Figure A5, see online supplement). Peak shoulder belt loads were significantly greater in MEB (226.9 ± 32.2 N) than in AEB (59.8 ± 23.3 N; $P < .001$). There was no main effect of repetition on shoulder belt loads ($P > .13$). Peak right and left lap belt loads were less than 52 N (Table A.1, see online supplement)

Slalom

Overall, both lateral head and trunk excursion decreased with cycles in both directions; however, only the lateral trunk excursion into the belt showed statistically significant decreased lateral excursion in cycle 3 versus 1, in particular in repetition 2 versus 1, whereas cycle 3 and 4 showed reduced lateral excursion compared to cycle 2 in both repetitions ($P < .02$; Table 3). For out-of-the-belt movement, cycles 3 and 4 showed reduced lateral trunk excursion compared to cycle 2 ($P < .04$).

Booster seat lateral displacement ranged between 1.2 and2.9 cm, representing between 9 and 35% of head and trunk displacement and increased with cycle (Table 3; Figure A6, see online supplement).

Mean EMG showed activation of all muscles during the task; however, the upper limb muscles (deltoids, biceps, and right trapezius) were more active than the SCM (Figure A7, see online supplement). The shoulder belt and right lap belt loads increased with the number of cycles, particularly in the out-of-the-belt direction in the first repetition (Figure A8, see online supplement). However, the average belt loads were not greater than 60 N and they were greater in the out-of-the-belt direction.

Discussion

The aim of this study was to characterize booster-seated children's kinematics, kinetics, and muscle activity during 3 precrash vehicle maneuvers and to examine the motion of the booster seat with the overall movement of the child occupants.

In the 2 braking maneuvers, booster-seated children showed behavior similar to that in previous studies with occupants from other age groups (seat belt–restrained adolescents and adults): They showed greater head and trunk velocities, particularly in the first repetition, and a trend of greater head and trunk excursion in MEB compared to AEB. This was primarily due to the differences in the acceleration profile between the 2 braking maneuvers and illustrated that AEB in this study achieved braking of the vehicle in a more gradual manner that leads to reduced occupant excursion. In line with these results, the motion of the booster seat itself showed greater forward motion in MEB compared to AEB, though the overall magnitude of that movement was small.

Table 2. Mean (SD) MEB and AEB kinematic measures.

Kinematic measures	MEB	AEB	*P* value	Rep 1	Rep 2	*P* value
Head forward displacement (cm)	18.9 (1.4)	15.1 (4.8)	.11	17.9 (2.7)	15.8 (3.4)	.07
Trunk forward displacement (cm)	10.3 (1.7)	8.7 (1.9)	.06	10.3 (1.3)	8.5 (1.8)	.004*
Head forward displacement peak rate of change (cm/s)	123.7 (13.1)	45.3 (11.5)	.001*	89.7 (10.1)	85.9 (19.9)	.02*
Trunk forward displacement peak rate of change (cm/s)	77.6 (14.1)	27.1 (5.5)	.009*	56.2 (9.6)	55.3 (11.1)	.04*
Booster forward displacement (cm)	1.1 (0.6) 5.8% of head motion 10.7% of trunk motion	0.3 (0.1) 2.0% of head motion 3.5% of trunk motion	.04*	0.9 (0.2)	0.7 (0.6)	.48

*$P < .05$.

Table 3. Mean (SD) SLA kinematic measures.

Kinematic measure	Cycle 1	Cycle 2	Cycle 3	Cycle 4	ANOVA Cycle × Rep *P* value	ANOVA Cycle *P* value	Tukey's post hoc *P* value
Peak lateral head excursion **out** of the belt (cm)	7.3 (6.5)	6.9 (5.3)	6.7 (4.5)	6.5 (4.5)	.71	.97	
Peak lateral head excursion **into** the belt (cm)	11.5 (10.4)	10.3(8.9)	9.6 (5.1)	9.9 (6.1)	.64	.70	
Peak lateral trunk excursion **out** of the belt (cm)	12.2 (5.9)	14.0 (6.1)	9.0 (7.0)	10.5 (6.2)	.06	.007*	Cycle 2 > 3, 4 (.04*) Cycle 1 = 2, 3, 4 (.06)
Peak lateral trunk excursion **into** the belt (cm)	17.8 (10.8)	21.4 (9.5)	12.5 (11.2)	14.1 (9.5)	.04*	.003*	Cycle 1 > 3 in Rep 2 (.001*) , not in Rep 1 (.09) Cycle 2 > 3,4 (.02*) in both reps
Peak lateral booster excursion **out** of the belt (cm)	1.2 (0.3) 16.4% of head motion 9. % of trunk motion	2.4 (0.7) 34.8% of head motion 17.1% of trunk motion	2.1 (0.9) 31.3% of head motion 23.3% of trunk motion	2.1 (0.9) 32.3% of head motion 20% of trunk motion	.52	.07	
Peak lateral booster excursion **into** the belt (cm)	1.6 (0.4) 13.9% of head motion 9.0% of trunk motion	1.8 (1.1) 17.5% of head motion 8.4% of trunk motion	2.3 (1.5) 24.0% of head motion 18.4% of trunk motion	2.9 (1.8) 29.3% of head motion 20.6% of trunk motion	.64	.33	

*$P < .05$.

Therefore, in these braking maneuvers the booster seat was quite stable and represented 11% or less of the total occupant motion. This suggested that the booster may have had limited influence on the overall head and trunk excursion, particularly for the AEB test condition where body excursion was less.

In contrast, during the lateral acceleration of the slalom, the booster seat moved laterally up to 5 cm in some subjects, representing up to 35% of the head and trunk motion. This suggested that in this maneuver, the booster motion may have contributed more substantially to the overall kinematics. However, the lateral excursion of the booster seat increased with subsequent cycles of the slalom, whereas lateral head and trunk excursion decreased with each cycle; this suggests that booster motion and occupant motion were not consistently correlated. The trajectories of the booster seats (Figure A6) showed that the booster was displaced laterally in the inboard direction during the first cycle and did not completely return to its initial position as the acceleration was reversed. The booster seat kept sliding inboard incrementally across cycles. Lateral head and trunk excursion instead decreased with subsequent cycles. It is plausible that the occupant counteracted the inboard movement of the booster seated by moving the head and trunk in the opposite direction. This is in part supported by the EMG data, which show that the right biceps and the left deltoid were active during the maneuver, suggesting that occupants used arm muscles to stabilize their upper body and counteract the inboard booster excursion. There is no clear data from naturalistic scenarios as to the number of cycles typically experienced in evasive swerving; however, this investigation may shed light on interaction between booster movement and occupant bracing in a multiswerve event.

In the maneuver characterized by lateral acceleration (slalom), the trunk moved more than the head, whereas the opposite trend was seen in the braking maneuver. It is possible that booster-seated children strive to keep their head stable to preserve their visual and vestibular sensory information (Graci et al. 2018). In the slalom, the movement into the belt was also slightly greater than that out of the belt. The occupants may have felt less supported in the out-of-the-belt direction (inboard) and relied more on voluntary muscle response to control their kinematics. In line with this interpretation, there was greater muscle activation out of the belt. It is possible that a slight inboard rotation of the shoulders to engage the shoulder belt as they moved inboard occurred, and that would explain the greater seat belt load in the out-of-the-belt direction. The increase in seat belt load with number of cycles could also have been due to participant habituation with the maneuver and relying more on the seat belt or on the booster motion, pressing more on the seat belt due to shifted position from original placement.

In all maneuvers, booster-seated children showed a different strategy in muscle activation compared to previous data on older age groups. Biceps, deltoids, abdominal, and middle trapezii muscles were active at similar level of the SCMs during all maneuvers, whereas in older occupants SCMs were more active (Graci et al. 2018). The booster-seated children's muscle strategy could be an attempt to control their overall trunk motion, whereas adolescents and adults may prioritize the control head motion via their neck muscles. Video analysis showed that the children tended to hold onto the booster armrests during the maneuver, providing evidence for the greater arm muscle activation. It is plausible that the greater arm activation in the booster-seated children compared to adolescents and adults in Graci et al. (2018) was also due to the fact that booster-seated children have the booster handles closer to the body than non-booster-seated passengers, who have the door handle.

There are several limitations to this study. First, the maneuvers were performed in a single-vehicle environment and it is unclear whether other vehicles would change participants' responses compared to those reported here. Differences in seat belt geometries, seat contours, and vehicle interior could potentially influence subject response. Because the participants' responses resulted from vehicle kinematic input, it is plausible that our results can be generalizable to other vehicles that perform a similar maneuver with the same target acceleration as used in our investigation. Second, other muscles besides those measured in this study may have contributed to participants' motion. Muscle activity was also not normalized to maximum voluntary isometric contraction (MVIC) but rather to rest to reduce burden on these younger participants. There are several cases in which MVIC cannot be reliably collected (Powell et al. 2017). In these cases, investigators have used other normalization methods that use an EMG established value (e.g., baseline, rest, etc.) that may include greater level of noise of MVIC normalized data but is still informative (Kamen and Gabriel 2010). Last, the testing environment was not completely naturalistic because the participants were aware of the task, they were fully instrumented, and the maneuver was performed on a closed course where no real danger was present. However, our testing environment was more realistic than any laboratory setting in that a full-vehicle environment was studied. Given the placement of the motion capture cameras in the forward sight line of the rear-seated occupants (Graci et al. 2018), they were generally unaware of the specific timing of the maneuvers.

In conclusion, these results show differences in booster-seated occupant response between 2 different braking conditions (MEB and AEB) that mirror that of older occupants; subjects moved slower and experienced less head and trunk excursion in AEB trials than in MEB trials, with small movement of the booster seat in comparison to the overall occupant response. In contrast, in lateral slalom loading, the booster seat moved more substantially, representing up to one-third of the overall occupant movement. The presence of armrests on the booster seat leads to bracing strategies that engage the upper extremities and upper torso, in contrast to previous work that demonstrated that adolescents and adults attempt to control their movement through activation of neck muscles. This study provides novel data on the precrash phase for this young age group and may help identify opportunities for interventions that integrate active and passive safety.

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