

Pediatric and Adult Rear Passenger Kinematics in Manual and Automated Emergency Braking

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ABSTRACT

Up to 80% of crashes are preceded by pre-crash maneuvers such as emergency braking. Pre-crash maneuvers, which may avoid or mitigate crashes, also may influence passenger kinematics and lead to less optimal positioning if a subsequent crash occurs. Previous research has documented driver kinematics during automatic braking. Yet, passenger response to automated emergency braking is less understood. This is also relevant for those in the rear seat who may not anticipate the braking event. Thus, we compared rear passenger kinematics for pediatric and adult human volunteers in driver-applied manual emergency braking (MEB) and automated emergency braking (AEB) via closed track testing. 18 participants (5 adults (age 22.0 \pm 1.9 years), 7 teens (age 14.9 \pm 1.2 years), 6 children (age 10.8 \pm 1.6 years)) were seated in the rear right passenger seat of a modern 4-door sedan. Steady-state head and sternum displacement and peak rate of change of displacement were compared across maneuvers. As a method to compare outcome measures across age groups, displacements were normalized to participant seated height and rate of change in displacement was normalized to participant mass. For MEB an average deceleration of 0.96g was achieved compared to 0.77g for AEB. Mean head and sternum displacement was greater ($p=0.003$, $p=0.006$, respectively) during MEB (15.0 \pm 3.4 cm, 8.1 \pm 1.9 cm, respectively) than AEB (10.9 \pm 4.9 cm, 6.1 \pm 2.4 cm, respectively). Mean head and sternum peak rate of change was greater ($p<0.001$ for both) during MEB (92.2 \pm 11.3 cm/s, 854.6 \pm 10.9 cm/s, respectively) than AEB (37.6 \pm 15.5 cm/s, 20.1 \pm 8.4 cm/s, respectively). Children exhibited greater normalized peak head rate of change ($p=0.03$, 1.43 \pm 0.7) than adults (0.96 \pm 0.50). The reduced excursion and velocity of movement found with the automated emergency braking system demonstrated the potential for AEB to mitigate occupant motion during emergency braking across all age groups.

INTRODUCTION

Despite recent advances in automotive safety, motor vehicle crashes (MVCs) remain the largest cause of death for children and young adults (CDC, 2016). Automotive passive safety research has historically focused on the impact phase of a crash. Current vehicle safety countermeasures are primarily designed to protect occupants from impact forces that result when

the occupant is in a normal seated position, and restraint performance is assessed using Anthropometric Test Devices (ATDs) with standard seating procedures. However, up to 80% of crashes are preceded by an impact avoidance, pre-crash maneuver (Scanlon, 2015; Seacrist, 2018). These pre-crash maneuvers have been defined as low acceleration time extended (LATE) events (Kent, 2016). LATE events have the potential to alter an occupant's posture and position prior to the impending impact. Pre-impact occupant position was a contributing factor in the child fatalities which occurred due to frontal passenger airbag deployments in the early 1990's, as well as for pediatric head injuries in the rear seat (Bohman, 2011; Winston, 1996). Thus, recent research has sought to understand the influence of pre-crash maneuvers on occupant positioning.

Previous analysis of the Strategic Highway Research Program 2 (SHRP2) Naturalistic Driving Study found that braking was the most common evasive maneuver conducted in crash and near-crash scenarios across all age groups (Seacrist, 2018). Additionally, an analysis of the National Automotive Sampling System (NASS) found that a majority (61-79%) of intersection crashes were preceded by braking (Scanlon, 2015). Further, 20% of pediatric head injury cases with AIS 2+ according to the Abbreviated Injury Scale, and 20-35% of all-severity driver injuries from 1993-2003, were sustained during an impact that was preceded by a braking event (Bohman, 2011; Talmor, 2010). Previous literature has investigated the effect of emergency braking on driver and passenger kinematics (Stockman, 2013; Kirschbichler, 2014; Huber, 2014). However, the recent advancement of automated crash avoidance technologies may shift the way emergency braking is achieved – from driver-applied manual braking to vehicle triggered automatic braking. The addition of Automated Emergency Braking (AEB) systems to vehicles have been found to reduce police reported rear-end crash rates by 43% (Cicchino, 2017).

Few studies have investigated the influence of AEB maneuvers on occupant kinematics and whether occupant response in AEB differs from that in manual emergency braking (MEB). One previous study quantified lower extremity kinematics and muscle activity during automated braking; however, sternum and head kinematics were not investigated (Behr, 2010). Osth et al. reported greater occupant head and sternum forward excursions as a result of AEB compared to MEB (2013). However, only adult (age > 23) drivers were considered. Participants were aware of an impending manual braking, but not the automated braking, and thus could exhibit different muscular activation between the two systems - resulting in different kinematics. Carlsson et al. found that front seated passengers exhibit larger forward excursions during AEB than drivers (2011). No previous study was found that compared passenger kinematics between AEB and MEB, especially in children. Additionally, the influence of AEB on rear seated passengers, who may be less aware of the impending impact, is less understood. The increased prevalence of ridesharing services such as Uber and Lyft could lead to an increase in adults seated in the rear seat. Lastly, no previous study was found to examine the effect of AEB in children. Children exhibit altered biomechanics and neuromuscular control strategies than adults, irrespective of body size (Seacrist, 2012; Dotan, 2012). Thus, it is relevant to investigate the influence of AEB on rear seat passenger kinematics across all age groups.

The purpose of this study was to quantify rear passenger head and sternum kinematics in both AEB vs MEB conditions across multiple age groups. We hypothesized that participants would exhibit increased body segment excursions and velocities in the MEB maneuver compared to AEB. This is expected due to the fact that the AEB system detects the object in advance and thus has a

more gradual braking deceleration than MEB. We further hypothesized that child passengers would exhibit increased body segment excursions and velocities compared to adult passengers, due to the aforementioned less developed neuromuscular control in children.

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

Sixteen healthy male participants were selected for this study such that they resembled a broad range of occupant ages and sizes typical of rear seat occupants. Volunteers were categorized into the following age groups: Children age 9-12 ($n=5$, age 10.8 ± 1.8 years, weight 47.8 ± 12.8 kg, height 157.1 ± 9.2 cm), Teens age 13-17 ($n=6$, age 15.0 ± 1.3 years, weight 60.3 ± 8.2 kg, height 173.1 ± 8.2 cm), and Adults ($n=5$, age 22.0 ± 1.9 years, weight 65.2 ± 4.6 kg, height 182.3 ± 2.8 cm). Participants with the following conditions were excluded: fear of amusement park rides; post-traumatic stress disorder due to car crashes; motion sickness; recent concussion; allergies to adhesive tape; history of cervical spine fracture, clavicle fracture, acromial or sternoclavicular or "shoulder" dislocation, or high incidence of other fractures; bone or skeletal conditions (e.g. scoliosis, degenerative bone disease); neuromuscular diseases; bleeding disorders or previous significant thoracic or abdominal surgery.

Experimental Testing

The experimental testing for this study was conducted in two separate phases. First, vehicle dynamics were tested with a professional driver only, to establish the testing sequences and the repeatability of the maneuvers reported in this study. Second, human volunteer testing was performed. The vehicle maneuver tests were performed at the Vehicle Dynamics Area (VDA) of the Transportation Research Center Inc. (TRC, East Liberty, Ohio). The maneuver characteristics were determined based on previous braking literature (Huber, 2014; Kirschbichler, 2014) and the preliminary phase one test maneuvers described previously. All maneuvers were performed in a recent model year 4-door sedan. For the MEB maneuver, an average deceleration of $\sim 1g$ was achieved by the driver pressing the brake pedal with maximum effort while the vehicle was moving at 50km/h with cruise control activated. The AEB maneuver was triggered by the vehicle radar detecting a 3D Guided Soft Target (Dynamic Research, Inc., Torrance, California) representing a real vehicle to the radar and camera sensor. Similar to MEB, this maneuver was performed while travelling at 50 km/h with cruise control active, achieving an average deceleration of $\sim 0.8g$. The jerk of each maneuver, defined as the average rate of change of vehicle acceleration from onset of maneuver to steady-state deceleration phase, was 4.75g/s for MEB and 0.52g/s for AEB.

All participants were seated in the rear right seat of the vehicle. The first test performed for each participant was a baseline trial, in which the participant was instructed to sit relaxed with his hands on his lap looking straight ahead as the vehicle was driven on a straight path for

approximately 120 m at 50 km/hr. This trial served to familiarize the participants with the vehicle environment. Following the baseline trial, the MEB and AEB maneuvers were performed twice for each participant. The order in which MEB and AEB was experienced by each subject varied. The two AEB trials were performed consecutively for logistics of positioning the soft target, while the two MEB trials were randomized among other maneuvers (4 other trials) not reported herein. Each participant was aware of which type of maneuver he was about to experience but was not aware of the specific moment of initiation of each braking event. Participants were instructed to sit with their feet on the floor and hands in their lap in a normal posture with relaxed musculature prior to the maneuver, and to “react naturally” during the maneuver as they would in a real crash-avoidance scenario. A three-minute break was provided between maneuvers so that participant’s well-being and instrumentation could be checked.

Instrumentation

Vehicle dynamics (i.e. motion, position, and orientation) were measured with an Inertial and GPS Navigation system (Oxford RT 3003, Oxford Technical Solutions Ltd.). The Navigation system was connected to a data acquisition system (Somat eDAQlite HBM) and placed in the vehicle trunk. Three seatbelt load cells (Measurement Specialties, TE connectivity, Inc.) collected belt loads on the shoulder belt, and at each side of the lap belt. Data from the Navigation system and seatbelt load cells were sampled at 200 Hz.

Kinematic data was collected with an 8-infrared camera 3D motion capture system (Optitrack, NaturalPoint, Inc.) instrumented in the right rear seat position. The front seat was moved to the furthest forward end of the seat track in order to leave sufficient space for the camera setup (Figure 1a). Seven of the infrared cameras were clamped to a compression pole in front of the participant, and collected kinematic data at a sampling frequency of 200 Hz (Figure 1b). An eighth camera was placed on a post attached to the head restraint of the passenger front seat in order to provide 2D video of the participant’s movement. Participants were provided with a tightly fitted athletic compression shirt and a pair of athletic shorts. Photo-reflective markers were placed on the participant’s head (on a tightly fitted head piece) and suprasternal notch.



Figure 1: a) (Left) Right rear seat position with the 8-camera 3D motion capture system placed behind the front seat pushed fully forward. b) (Right) Frontal view of the 8-camera 3D motion capture setup.

Data Analysis

Data processing and analyses were performed with custom Matlab (MathWorks 2015, Inc., Natick, MA) programs. Vehicle forward acceleration was filtered with a zero-lag 2nd order low pass Butterworth filter with a cut-off frequency set to 6 Hz. For both braking maneuvers, start and end of the steady-state deceleration phase was defined as the first and last point respectively where the vehicle deceleration was above 85% of the peak deceleration (Figure 2a,2b). In order to determine the effect of participant age on kinematics regardless of anthropometric differences, kinematic data were analyzed first as raw values, then excursions were analyzed normalized by participant seated height, while velocity was normalized by participant mass. Mixed three-way Repeated Measure ANOVAs were performed to examine the effect of Age (children vs teen vs adults), Maneuver (MEB vs AEB), and Repetition (2) on a) forward head and sternum displacement during the steady-state vehicle deceleration phase and b) peak rate of change of head and sternum displacement. Tukey's post-hoc test was used for multiple comparisons. P-level was set at 0.05.

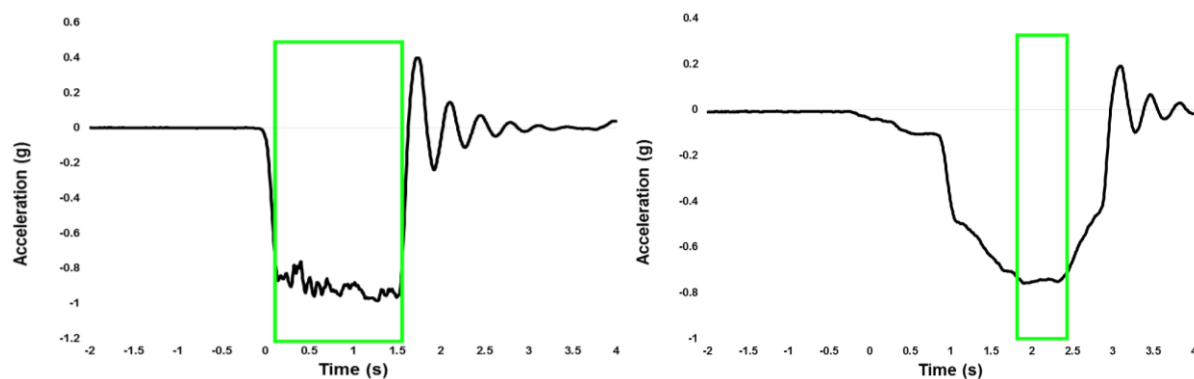


Figure 2: a) (Left) Acceleration time history of the MEB maneuver. b) (Right) Acceleration time history of the AEB maneuver. The green box represents the steady-state deceleration phase.

RESULTS

Primary outcome measures are reported in Table 1. Mean steady-state head and sternum displacement for MEB was greater than mean head and sternum displacement for AEB ($p=0.003$, $p=0.006$, respectively) (Figure 3). Mean head and sternum peak forward displacement rate of change was greater in MEB than in AEB ($p<0.001$ for both) (Figure 4). Normalizing head and sternum displacement and displacement rate of change did not change the relationship between maneuvers.

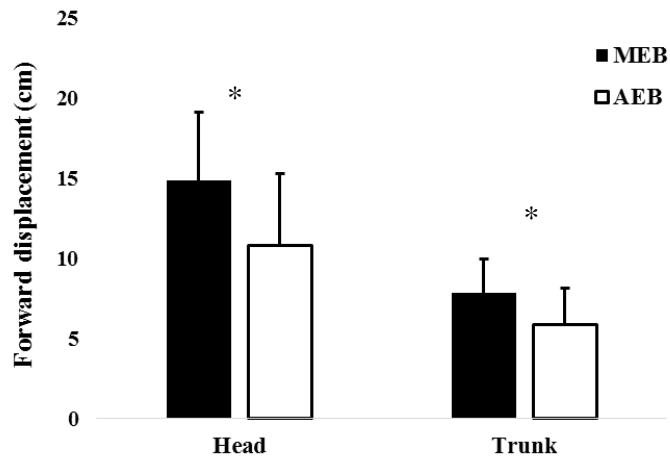


Figure 3. Head and Sternum forward displacement for the MEB and AEB maneuvers. * <0.05

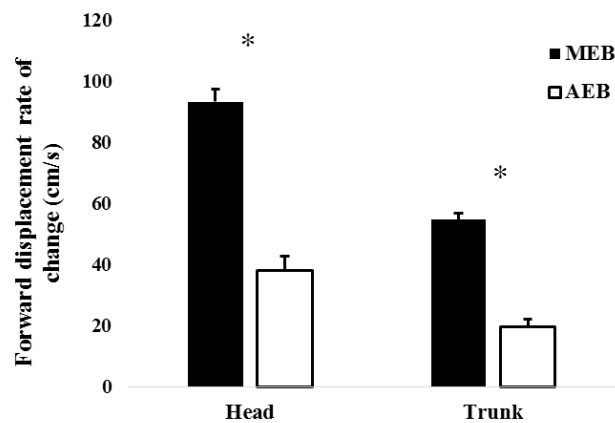


Figure 4. Head and Sternum forward displacement rate of change for the MEB and AEB maneuvers. * <0.05

Mean steady-state head and sternum displacement for repetition one was greater than mean head and sternum displacement for repetition two ($p=0.003$, $p=0.004$ respectively) for both maneuvers. There was a significant interaction effect between repetition and maneuver ($p=0.003$) showing that mean peak rate of change of sternum displacement was greater in repetition one (57.4 ± 13.2 cm/s) than in repetition two (51.8 ± 10.7 cm/s, $p<0.001$) in the MEB but not in the AEB maneuver ($p=0.12$) (Figure 5). Mean peak rate of change of head displacement was greater in repetition one than in repetition two ($p=0.01$) for both maneuvers. Normalizing head and sternum displacements and peak rate of displacement did not change the relationship between repetitions.

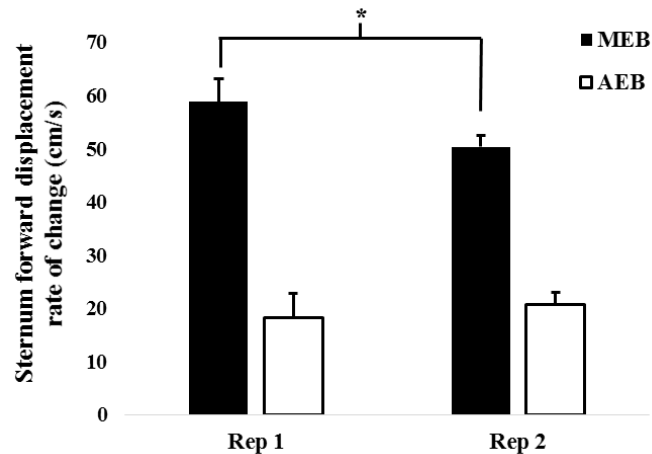


Figure 5. Sternum forward displacement rate of change for the MEB and AEB maneuvers, for both repetitions. $* \leq 0.05$

Mean steady-state head and sternum displacement, peak rate of change of head and sternum displacements, and normalized head and sternum displacements showed no main effect by age. Normalized peak rate of change of head displacement had a significant main effect of age ($p=0.04$). Children aged 9-12 exhibited greater normalized peak rate of change of head displacement than in adults ($p=0.03$) (Figure 6). Teen normalized peak rate of change of head displacement was not significantly different than either the child or adult groups. peak rate of change of sternum displacement showed no main effect of age.

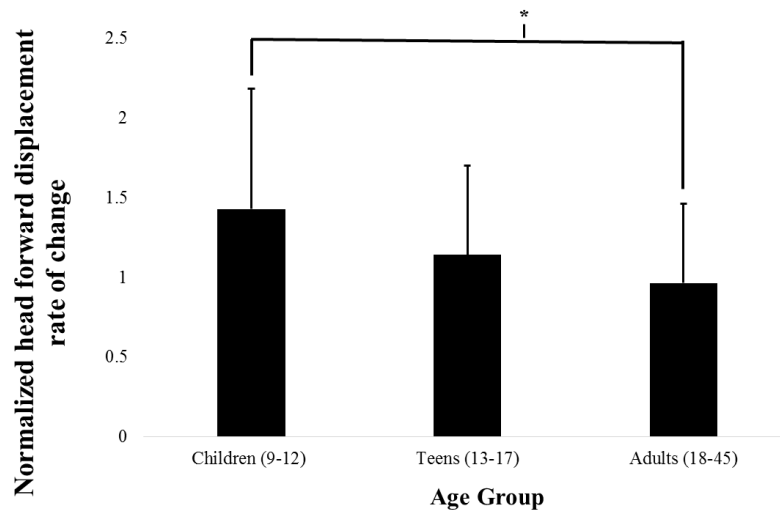


Figure 6. Normalized head forward displacement rate of change by age group. $* < 0.05$.

Table 1. Mean (SD) of Normalized and Non-Normalized Kinematic Outcome Measures

	Condition			
	MEB	AEB	P-Value ($p=<0.05^*$)	
Maneuvers	Head mean displacement (cm)	14.98 (3.38)	10.91 (4.93)	0.003*
	Sternum mean displacement (cm)	8.12 (1.88)	6.05 (2.39)	0.006*
	Head mean displacement <i>normalized</i>	0.18 (0.05)	0.13 (0.06)	0.003*
	Sternum mean displacement <i>normalized</i>	0.10 (0.03)	0.07 (0.03)	0.006*
	Head displacement peak rate of change (cm/s)	92.17 (11.26)	37.63 (15.54)	0.001*
	Sternum displacement peak rate of change (cm/s)	54.57 (10.92)	20.10 (8.38)	0.001*
	Head displacement peak rate of change <i>normalized</i>	1.69 (0.44)	0.69 (0.30)	0.001*
	Sternum displacement peak rate of change <i>normalized</i>	1.02 (0.46)	0.36 (1.88)	0.001*
	Rep 1	Rep 2		
Repetitions	Head mean displacement (cm)	13.63 (4.16)	12.21 (4.38)	0.003*
	Sternum mean displacement (cm)	7.51 (2.13)	6.70 (2.30)	0.004*
	Head mean displacement <i>normalized</i>	0.17 (0.06)	0.15 (0.06)	0.003*
	Sternum mean displacement <i>normalized</i>	0.09 (0.03)	0.08 (0.03)	0.004*
	Head displacement peak rate of change (cm/s)	67.22 (15.27)	62.58 (14.43)	0.01*
	Sternum displacement peak rate of change (cm/s)	11.91 (2.12)	10.45 (0.57)	0.11
	Head displacement peak rate of change <i>normalized</i>	1.25 (0.41)	1.13 (0.38)	0.01*
	Sternum displacement peak rate of change <i>normalized</i>	0.72 (0.34)	0.66 (0.32)	0.16

DISCUSSION

In this study, we examined the influence of AEB vs MEB on rear passenger kinematics across a diverse set of occupant age groups. The results demonstrated that body segment excursions and velocities were greater in the MEB maneuver than the AEB maneuver. Specifically,

head and sternum forward excursion during steady-state braking, and peak rate of change of displacement was greater in the MEB maneuver than the AEB maneuver. Comparisons across the age groups were not consistent. No differences were found with age for the mean steady-state head and sternum displacement, peak rate of change of head and sternum displacements, and normalized head and sternum displacements. However when the head displacement rate of change was normalized by mass, children age 9-12 years demonstrated greater values than adults. No differences existed between the teen and adult or teen and child age group.

The increased head and sternum forward excursion in AEB compared to MEB in our study is likely due to multiple factors. First, despite the same overall change in velocity (50 km/hr) between the two maneuvers, the shape of the two acceleration curves were different. The AEB maneuver exhibited a more gradual curve, with an average jerk of 0.52 g/s for all trials while the MEB maneuver had an average jerk of 4.75 g/s for all trials. This difference in the rate of change of acceleration likely contributed to the reduced excursions and body segment velocities during the AEB maneuver compared to MEB. These results contradict previous findings, in which driver head and sternum excursions were increased during AEB compared to MEB (Osth, 2013). However, while driver kinematics may be influenced by the awareness of the impending maneuver, our study examined rear passengers who were less aware of the specific moment of initiation of either braking maneuver. Future analysis on participant muscle activity will identify the presence of participant bracing and whether bracing response varied between MEB and AEB. These results suggest that AEB potentially may be effective in reducing occupant motion during emergency braking scenarios. Further, this trend remained across all age groups, so these benefits may be applicable for all occupants, not just adults.

Participants experienced greater head and sternum excursions during repetition one compared to repetition two in both maneuvers. This could be an indication of habituation – the participants were more used to the maneuver, or became sensitized to the timing of braking initiation, after completing it the first time. This agrees with previous findings that drivers exhibited altered behavior in successive trials of the same braking maneuver (Osth, 2013), although the role of habituation in pre-crash maneuvers has not been thoroughly investigated. However, peak rate of change of sternum displacement were reduced in repetition two of the MEB maneuver, but not for AEB. This is potentially because trunk excursions in the AEB maneuver were already low, and thus there was little adaptation necessary in order to prevent excessive forward motion. Future work will examine muscle activity between the two repetitions, in order to further investigate altered participant behavior between repetitions.

Head and sternum excursions, even when normalized to seated height, were not significantly different across age groups. Previous research has reported that children exhibit greater normalized head and sternum excursions in response to a low speed frontal loading condition (Arbogast, 2009). However, the frontal pulse experienced by the children in that study was 3.4g compared to 0.8-1.0 g in the current study. It is possible that the lower pulse in our study was not severe enough to elicit a different biomechanical response across age. However, when velocities were normalized to participant mass, children aged 9-12 exhibited greater head velocity than adults. No differences in trunk velocity were observed in the normalized data. This may be because the trunk kinematics were influenced by direct seat belt contact, while head velocity was more removed from belt contact and therefore may more representative of individual

biomechanics. Children have been found to have greater passive cervical flexion range of motion than adults (Seacrist, 2012), which could contribute to the increased head velocities compared to adults. Further, children exhibit altered neuromuscular control strategies than adults (Dotan, 2012). Quantitative analysis of participant muscle activity is ongoing and could help clarify these differences.

This study had several limitations. First, participants were always aware of which maneuver they were about to experience. Information about the type of maneuver was given to enhance comfort for the younger participants. Participants were not informed, however, of the maneuver initiation timing. This potentially allowed for a more natural reaction, despite the knowledge of the specific maneuver being performed. Second, the instrumentation in the vehicle and the location at the testing facility likely limited the naturalistic environment of the experiment. However, instrumentation was carefully placed in a way such that no participant motion was restricted, and pilot testing by experimenters confirmed that rear passengers were not focused on the surroundings.

CONCLUSIONS

Automated emergency braking systems, which may mitigate or prevent crashes, also have potential to reduce occupant motion during emergency braking across a diverse set of age groups, due to the vehicle's ability to detect obstacles in advance and prescribe a more gradual deceleration profile. These differences in pre-crash occupant motion between manual and automated emergency braking systems may guide future research of AEB systems and occupant protection prior to a crash. Children exhibited greater normalized head velocities than adults indicating that pediatric safety may pose unique challenges. Future work will investigate muscle activity differences between the two maneuvers.

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