Effect of Age on Kinematics during Pre-crash Vehicle Manoeuvres with Sustained Lateral Acceleration

Valentina Graci, Ethan C Douglas, Thomas Seacrist, Jason Kerrigan, Julie Mansfield, John Bolte,

Rini Sherony, Jason J Hallman, Kristy B Arbogast

Abstract Pre-crash occupant motion has the potential to influence restraint performance, particularly for children. We examined kinematics of adults versus children in a vehicle subjected to a constant radius manoeuvre designed to produce sustained lateral acceleration via closed-course testing. Nine adults and six children were seated in the right rear seat of a late-model year 4-door sedan. A constant radius manoeuvre was conducted with an average lateral acceleration of ~0.5 g for ~30 seconds.
Vehicle dynamics were measured with an Inertial and GPS Navigation system. Head and trunk displacement were collected with an eight-camera 3D motion capture system. Electromyography sensors were placed on the upper body and lower limbs and load cells were placed on the seat belt to characterise bracing behaviours. Head and trunk displacement and their variability were compared between age groups. Results showed that in the first four seconds of the manoeuvre, children had less head and trunk lateral displacement than adults even when data were normalised by seated height. Neck muscle activation was greater in children compared to adults. These findings suggest children may brace more and with a different neuromuscular strategy than adults to control motion.

Keywords between-trial variability, constant radius turn, low-acceleration time extended event, occupant kinematics, restraints.

I. INTRODUCTION

Although recent research has found that motor vehicle crash deaths in children younger than 13 years old have declined since 1975, motor vehicle crashes (MVCs) remain the leading cause of fatal injury for children and young adults ages 5 to 24 years in the United States [1]. In 2016 it was found that 71% of paediatric motor vehicle crash deaths were passenger vehicle occupants [2]. Therefore, we are continuing to investigate child passenger safety in vehicles and the efficacy of current safety restraints.

In recent years, crash avoidance manoeuvres have been a topic of focus. It is during the pre-crash phase that passenger vehicle occupants may move outside of a nominal seated position, potentially changing the effectiveness of the restraint system during a subsequent crash. Between 60% and 80% of crashes involve some form of pre-crash manoeuvre [3, 4]. Previous research has identified that during pre-crash occupant manoeuvres, some smaller children slipped out of the shoulder belt, potentially reducing the effectiveness of the belt in restraining the torso and mitigating head excursion [5].

Advanced automated crash avoidance technologies and the future deployment of automated vehicles may further alter occupant pre-crash kinematics. Active safety and automated vehicle features are anticipated to decrease the number of crashes by monitoring the road when the driver’s attention is diverted. These features, however, may result in additional instances of vehicle motion that is unanticipated by the occupants.

Pre-crash manoeuvres are characterised by low-acceleration, time extended events (LATE) such as swerving, emergency braking, and sustained lateral accelerations that emerge in critical driving situations [6]. LATE events are characterised by inertial forces that alter the occupant’s *state* (initial posture, position, muscle tension) and may influence the performance of the restraint system. LATE events generated by lateral vehicle acceleration (e.g. the oscillatory movement of evasive swerving or sustained lateral accelerations, simulating lateral vehicle skidding) have been studied in less detail [7] than LATE events generated by emergency braking. Therefore, in the present study we focused our investigation on a constant radius turn that generated sustained lateral

V. Graci PhD (graciv@email.chop.edu, +1 267 425 0333) is a post-doctoral fellow, T. Seacrist MBE is a Project Manager, and K. Arbogast PhD is Research Professor at the Center for Injury Research and Prevention, at the Children’s Hospital of Philadelphia, USA. E. Douglas is a Master’s student at the Department of Bioengineering at University of Pennsylvania, USA. J. Mansfield is a Research Engineer, and J. Bolte PhD is Associate Professor at the Injury Biomechanics Research Center, Ohio State University. J Kerrigan PhD is Assistant Professor at the Center for Applied Biomechanics, University of Virginia. R. Sherony is Sr. Principal Engineer and J. Hallman PhD is Principal Engineer at the Collaborative Safety Research Center, Toyota Motor North America.

accelerations on vehicle occupants that may precede either a planar or rollover crash [8, 9].

The effect of LATE events on occupant displacement may vary depending on the age of the occupant due to factors that are beyond the geometry of the body. Children are not simply small adults: biomechanical differences across the age span have been well-established. In addition, children differ in how they use their visual and vestibular systems, and also employ different neuromuscular strategies to control movement [10]. These differences could lead to altered body motion and bracing behaviour compared to adults. The possible differences between adult and paediatric population in bracing behaviour constitute the rationale for investigating head and trunk kinematics and muscle activation in both children and adults in this study.

Therefore, the objective of this study was to characterise key occupant kinematic, kinetic, and muscular responses in children and adults when experiencing sustained lateral accelerations in a constant radius turn in closed-course testing. Investigating the effect of pre-crash occupant manoeuvres on vehicle rear seat passengers using human volunteers may help identify novel strategies to enhance safety restraints and mitigate injuries.

II. 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, USA.

Participants

Children and adults were selected based on specific height and weight ranges in an attempt to capture the range of adult and children sizes typical of rear seat occupants. Only male participants were selected since gender differences in neck flexion in children were observed in a previous study [11]. Gender differences were not a topic of investigation of the present study and would have represented a confounding factor in the data. Table I reports the participants' selection criteria.

TABLE I
INCLUSION CRITERIA

Participants	Age (years)	Height Range (cm)	Basis for Minimum height	Basis for Maximum height	Weight Range (kg)	Basis for Minimum weight	Basis for Maximum weight
Children	9-12	145-169	Above booster seat height requirement	+30% Hybrid III 10 Year Old Child ATD height	28.2-52.5	-20% Hybrid III 10 Year Old Child ATD weight	75th percentile Individual Growth Chart CDC [12]
Adults	18-45	157-183	-10% Hybrid III 50th Male ATD Height	Limited by the vehicle ceiling height with head instrumentation	62.2-101.4	-30% Hybrid III 50th Male ATD weight	10th percentile NHANES [13]

Experimental Testing

The experimental testing consisted of two phases. In the first phase the vehicle dynamics were tested with a professional driver only, to establish the appropriateness of the test sequences for human volunteers and the repeatability of the manoeuvre examined in this study. In the second phase the human subjects testing was performed.

The vehicle manoeuvre tests were conducted with a recent model year sedan at the Vehicle Dynamics Area (VDA) of the Transportation Research Center Inc. (TRC, East Liberty, Ohio, USA). The manoeuvre characteristics were based on previous literature [5], [14] and on preliminary tests performed with a professional driver on the VDA at TRC. A target lateral acceleration of 0.5 g was found to be repeatable for the constant radius turn and was achieved by having the vehicle circulate twice in a circle of 30 meters in diameter with a speed of 50 km/h. The driver drove clockwise, i.e., turned right, around the circle, such that the subject in the right rear seat would naturally lean inboard. The duration of the manoeuvre was approximately 30 seconds.

All participants were seated in the right rear seat of the vehicle. We chose to focus on the rear seat environment for several reasons. First, children and teens utilise the rear seat position more often and, may be less aware of impending manoeuvres. Therefore, resulting vehicle dynamics may have a greater influence on their kinematics. Second, adult rear seating may become more common because of the popularity of rideshare services and may continue to become more common in the future as driverless technologies are introduced.

Before performing the manoeuvre, a static trial was collected in order to establish a baseline of muscle activity. In the static trial, participants were instructed to sit in the vehicle in a normal non-tensed posture, with feet on the floor and hands in their lap looking straight ahead for five seconds. These data were used to normalise muscle activity during the manoeuvre. After the static trial, each participant 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/hr. This baseline drive was performed so that participants, in particular the children, could become familiarised with the vehicle setting. After the baseline drive, the constant radius turn described above was performed twice for each participant. Each participant was aware of the type of manoeuvre he was about to experience. They were instructed to sit with feet on the floor and hands in their lap in a relaxed posture for their initial position. They were also asked to act spontaneously during the manoeuvre as they would do in a real crash-avoidance situation. A brief break of few minutes followed each repetition so that participants' well-being and data recording could be checked.

The same professional driver conducted the manoeuvre for each participant. Data were always collected in daylight. In case of rain, cold temperature, or wet pavement, several trials of the manoeuvre were conducted a few minutes before subjects' testing to ensure repeatability of vehicle dynamics.

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, UK). The Navigation system was placed in the vehicle trunk and was connected to a data acquisition system (Somat eDAQlite HBM, Inc., USA) also placed in the vehicle trunk. Measurements of the centre of gravity of the vehicle were input in the GPS Navigation system so that that the vehicle acceleration was referenced to the location of the centre of gravity. The data acquisition system sampled data from the navigation system and the three seat belt load cells (Measurement Specialties, TE connectivity, Inc., USA) at 200 Hz. The seat belt load cells were placed on the shoulder belt and at each side of the lap belt to characterise belt loads.

The right rear seat position was instrumented with an 8-infrared camera 3D motion capture system (Optitrack, NaturalPoint, Inc.) with sampling frequency of 200Hz. The front seat was moved fully forward on the seat track to leave sufficient space for a compression pole on which the cameras were mounted. The compression pole was placed so that it would not interfere with the subjects' feet (Fig. 1a). The 7-infrared cameras clamped to the compression pole were used for data collection. These were placed on the same pole so that any potential vibration noise from the manoeuvre of the car would affect the cameras equally minimising possible influence on the data. The eighth camera was placed on a post attached to the head restraint of the passenger front seat (Fig. 1b) and was used to provide 2D video of the subject's movement for qualitative assessment. The motion capture system was powered with a 12 volt Ethernet Switch (Antaira Technologies LLC.) connected to the vehicle cigarette 12 volt lighter.

Photo-reflective markers were placed on participants' head (on a tightly fitted head piece) and trunk (bilateral acromion, suprasternal notch, and xiphoid process), on the vehicle (on the ceiling and rear seat head restraint), and on the shoulder seat belt. In order to minimise motion artefact and best approximate skeletal movement, the markers on the participants were placed directly on the skin by cutting holes into the provided compression shirt (Fig 1.c). For the two seat belt markers, the suprasternal notch, and the xiphoid process, an array of four markers were placed on rigid structures that were then attached to the skeletal landmark/belt.

Electromyography (EMG) (Delsys Inc.,) sensors were placed bilaterally on: deltoids, brachioradialis, biceps, rectus femori, rectus abdomini, middle trapezii, and sternocleidomastoids. These muscles were selected as they are most likely to be involved in bracing behaviour. Muscle activity was collected at 2000Hz.

a) b) c)

Fig. 1. a) 8-camera 3D motion capture system placed behind the front seat pushed forward. b) One camera of the 3D motion capture system was placed on a post clamped to the head rest on the front seat. c) Subject instrumentation.

Data analysis

All data processing and analyses were performed with custom Matlab (MathWorks 2015, Inc., Natick, MA) programmes. Vehicle lateral acceleration was filtered with a zero-lag 2nd order low pass Butterworth filter with the cut-off frequency set to 6 Hz. From the acceleration profile of each trial three events were selected:

1) *Manoeuvre start* – defined as the first time at which the vehicle's lateral acceleration was equal to 5% of the maximum lateral acceleration during the manoeuvre [15];
2) *Steady-state acceleration start* – defined as the time at which the vehicle reached a steady-state lateral acceleration phase within the constant radius, where acceleration was equal to 95% of the target lateral acceleration (0.5 g);
3) *Steady-state acceleration end* – defined as the time at which the vehicle exited the constant radius, where lateral acceleration was below 95% of the target lateral acceleration (Fig 3a).

Vehicle acceleration profiles from each trial of the human subjects' testing phase of the study were averaged and standard deviation was calculated to examine repeatability of the manoeuvre.

Head and trunk positions were defined as the geometric centre of the group of markers placed on the head and the suprasternal notch rigid bodies, and the rigid bodies' orientation axis was aligned with the global coordinate axis trajectories (Motive 2.0, Natural Point Inc., Corvalis OR). For the head, the rigid body centre approximated the geometric centre of the head. Head and trunk positions were filtered with a moving average method spanning five frames. The initial positions of head and trunk were defined as the position of each of those segments averaged over the one second before the vehicle enters the constant radius turn. The initial position was subtracted from head and trunk displacements during the manoeuvre.

Head and trunk positions were first analysed non-normalised, and then normalised by seated height. Rate of change of position was also calculated from head and trunk displacements in order to understand if there were differences by age in the rate at which a subject achieved maximum excursion.

Data analysis was conducted for two phases of the vehicle manoeuvre (Fig.2):

1) *Transient phase:* From manoeuvre start to four seconds into the manoeuvre. This was chosen as being representative of the duration of lateral furrowing preceding a rollover [8, 9].
2) *Steady-state phase: From steady state start to steady state end.* The steady-state phase was of interest to understand what happens to the body when a constant acceleration is sustained for a longer period.

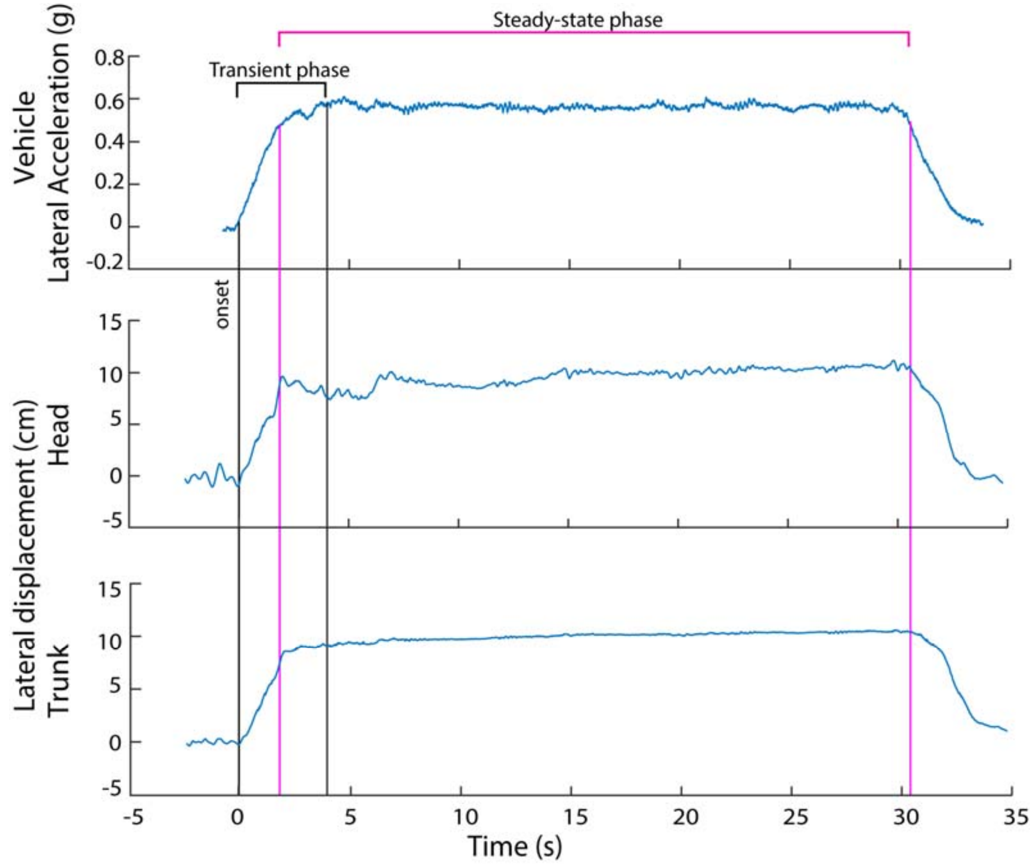

Fig. 2. Exemplar vehicle acceleration (top graph), head (middle graph) and trunk (bottom graph) kinematic time series from a single trial. Transient and Steady-state phases were based on the vehicle acceleration profile. The two black lines define the boundaries of the transient phase while the two pink lines represent the boundaries of the steady-state phase.

In order to understand head and trunk kinematics during the transient and steady-state phases of the manoeuvre, mean head and trunk displacements over the duration of each phase were calculated. For the transient phase, head and trunk displacement maximum rate of change were also calculated to examine the velocity of the head and trunk during the first phase of the manoeuvre.

In order to understand the repeatability of the two trials per subject, between-trial variabilities of head and trunk motion were calculated and compared between age groups. Between-trial variability of head and trunk motion was defined as the standard deviation of mean head and trunk displacement between the two repetitions. This measure was calculated for both the transient and steady-state phase.

Secondary outcome measures were extracted from EMG and load cell data to characterise muscle activity and load distribution. The raw EMG signals were filtered with a Band-pass filter (20–500 Hz, filter order: 558) based on the Finite Impulse Response (Kaiser Window method) filter [16]. A root-mean-squared (RMS) method with a 200 ms moving average smoothing window was applied. EMG signals during the manoeuvre were normalised by the average EMG signal during the static trial. Therefore, muscle activity during the manoeuvre was expressed as a percentage of rest, with rest defined as the muscle activity during the static trial. The mean of the normalised EMG signals (mean EMG) were calculated for both the transient and steady state phases for each left and right muscle and for each trial. Once mean EMG was calculated for each trial and each manoeuvre phase, data were checked for the presence of outliers and any mean EMG greater than three standard deviations above the mean was removed.

Seat belt load cells signals were filtered by an eighth poll Butterworth filter (Somat TCE, HBM, Inc., USA) and the mean load over one second before the start of the manoeuvre was subtracted from the load signal. The load applied on the shoulder belt was averaged for both the transient and steady-state phase for each trial and was normalised by the subject's weight.

Repeated Measures Mixed 2-ways ANOVAs were performed to examine the influence of age (children vs. adults) and repetition (first vs. second) on the primary outcome measures of displacement (normalized and non-normalized) and rate of change of displacement. Repeated Measures Mixed 2-ways ANOVAs were performed to examine the influence of age (children vs. adults) and body segment (head vs. trunk) on the normalised and non-normalised between-trials variability. P-level was set at 0.05.

III. RESULTS

Nine adults and six children participated in the study. Data from one of the children were excluded from the analysis since he did not follow study instructions to begin upright and relaxed and behave normally throughout the manoeuvre. This was quantitatively assessed by values of his head and trunk displacement that had two sudden changes in value of >5 cm, indicating voluntary movement not in response to the vehicle dynamics. In one adult, the second trial could not be analysed because of some of the relevant markers were obscured for the duration of the trial. Therefore, this participant's data were excluded from the calculation of the between trial variability. In Table II, the remaining participants' anthropometrics are reported.

TABLE II
MEAN (SD) OF PARTICIPANTS DEMOGRAPHIC AND ANTHROPOMETRIC PARAMETERS

Participants	Sample used for analysis	Age Range (years)	Weight (Kg)	Height (cm)	Seated Height (cm)
Children	5	11.6 (0.9)	47.3 (11.8)	154.4 (11.1)	75.0 (7.2)
Adults	9	22.8 (3.9)	61.2 (17.3)	182.6 (2.8)	88.3 (3.1)

The averaged lateral acceleration from all tests (n=27) show that the vehicle reached the target acceleration (mean: 0.55g) and the manoeuvre was repeatable (SD: 0.003 g) (Fig. 3).

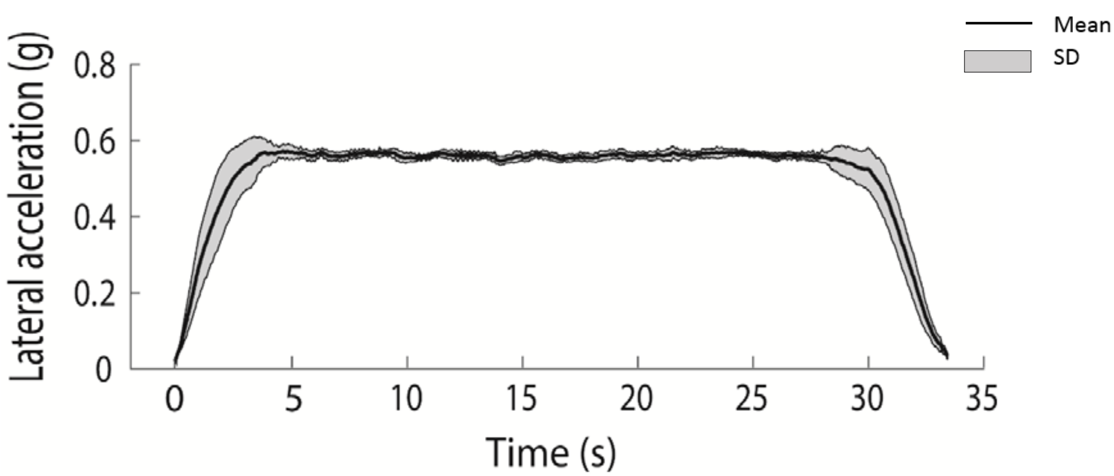

Fig. 3. Time series of the vehicle lateral acceleration averaged for all trials.

The primary outcome measures are reported in Table III and IV. During the transient phase of the manoeuvre, compared to adults, children showed reduced non-normalised head (2.8 vs. 4.3 cm, p=0.01) and trunk (2.7 vs. 4.9 cm, p=0.002) displacement (Fig 4). When normalised by seated height, statistically significant differences remained between the age groups only for the trunk (0.04 vs. 0.06, p=0.029). No differences between the age groups were detected for the displacement maximum rate of change of the head or the trunk, despite the differences in body mass between children and adults. During the steady-state phase of the manoeuvre, differences in head and trunk excursions were not statistically different between children and adults in either the non-normalised or normalised data (p>0.41).

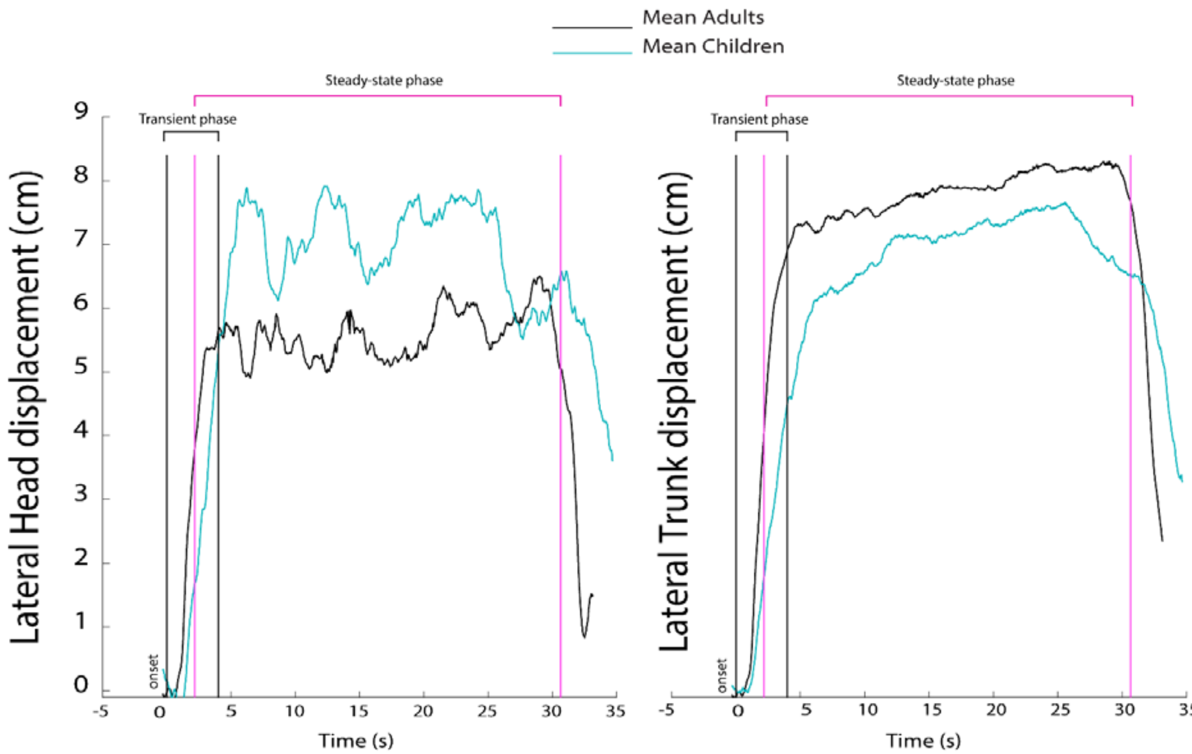

Fig 4. Time series of head and trunk displacement averaged for each age group. Standard deviation are reported in Table III but not on the graph for visual clarity.

TABLE III
MEAN (SD) OF NORMALISED AND NON-NORMALISED KINEMATIC OUTCOME MEASURES

		Age Groups		
		Children	Adults	P-Value (*p=<0.05**)
Transient phase	Head mean displacement (cm)	2.82 (0.38)	4.28 (0.32)	*0.01**
	Trunk mean displacement (cm)	2.66 (0.41)	4.86 (0.19)	*0.002**
	Head mean displacement *normalised*	0.04 (0.01)	0.05 (0.01)	0.45
	Trunk mean displacement *normalised*	0.04 (0.01)	0.06 (0.01)	*0.03**
	Head displacement max rate of change (cm/s)	14.85 (1.93)	13.97 (1.09)	0.74
	Trunk displacement max rate of change (cm/s)	11.91 (2.12)	10.45 (0.57)	0.66
Steady-state phase	Head mean displacement (cm)	6.96 (0.77)	5.58 (0.06)	0.68
	Trunk mean displacement (cm)	6.92 (0.21)	7.66 (0.39)	0.61
	Head mean displacement *normalised*	0.11 (0.01)	0.07 (0.01)	0.41
	Trunk mean displacement *normalised*	0.09 (0.01)	0.09 (0.01)	0.82

No statistically significant effect of repetition and no significant interaction of age with repetition was found on all outcome measures ($p>0.09$).

Children showed greater between-trial variability than adults in both the transient and steady-state phase when displacement were normalised to seated height ($p<0.038$). Across age groups, head motion showed greater variability between trials than the trunk for both normalised and non-normalised data in the transient phase ($p<0.007$) while the same differences between body segments were borderline statistically significant in the steady-state phase of the manoeuvre ($p<0.06$, Table IV). No statistically significant interaction of age with body segment was found with the between-trial variability of displacement ($p>0.05$).

TABLE IV
MEAN (SD) OF NORMALISED AND NON-NORMALISED BETWEEN-TRIAL VARIABILITY OF HEAD AND TRUNK DISPLACEMENT

		Age Group			Body Segment		
		Children	Adults	P-value (p<0.05*)	Head	Trunk	P-value (p<0.05*)
Transient phase	Between-trial variability (cm)	2.07 (0.35)	1.01 (0.67)	*0.04**	1.80 (1.03)	1.01 (0.95)	*0.007**
	Between-trial variability *normalised*	0.03 (0.01)	0.01 (0.01)	*0.01**	0.02 (0.01)	0.01 (0.01)	*0.006**
Steady-state phase	Between-trial variability (cm)	2.19 (0.38)	1.56 (0.88)	0.16	2.29 (1.07)	1.31 (1.03)	0.06
	Between-trial variability *normalised*	0.03 (0.01)	0.02 (0.01)	0.04*	0.03 (0.01)	0.02 (0.01)	0.06

Both age groups showed greater mean EMG in the right bicep compared to other muscles in both phases of the manoeuvre. Of note, the bilateral sternocleidomastoids showed greater muscle activation in children versus adults in both the transient and steady-state phase (Fig 5). All other muscles showed similar activation between age groups. One participant among the children showed a particularly high muscle activity in the right sternocleidomastoid (10,105% of the muscle activity in the static trial) in the attempt to resist the lateral inboard movement of the head. For graphing purposes this particular muscle (right sternocleidomastoid) for this subject was removed from Fig. 5 because it would have masked the overall muscle activity differences between groups.

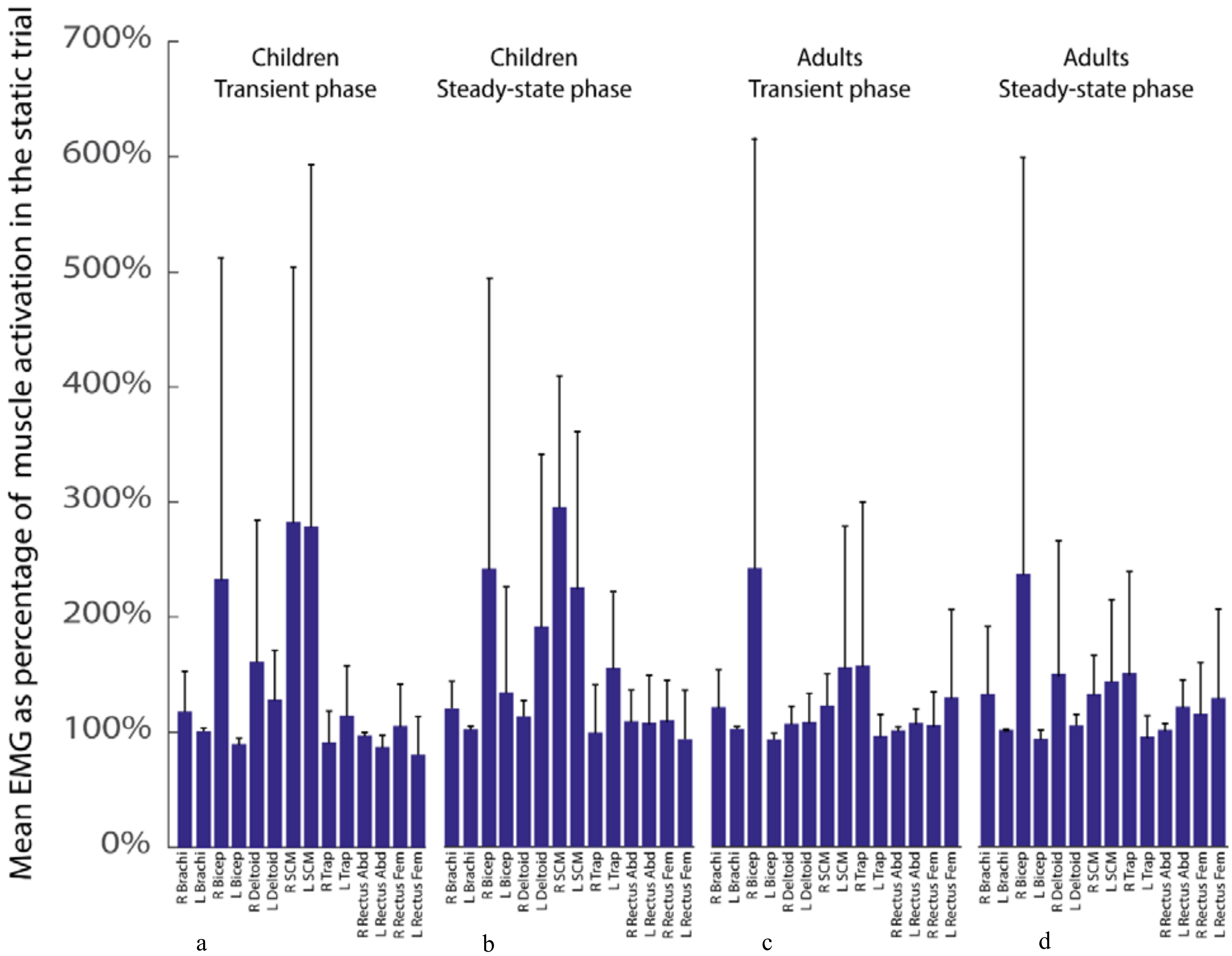

Fig. 5. Mean and SD of Mean EMG calculated for the transient and steady-state phases for each age group and expressed as a percentage of muscle activation from static trial

Shoulder belt load was lower than 25 N across the entire manoeuvre therefore differences between age groups were negligible as the subjects did not load the belt in the primarily lateral motion.

IV. DISCUSSION

This study provided, to our knowledge, the first integrated human volunteer kinematic and muscle activity data for a vehicle manoeuvre with sustained lateral acceleration that may precede a crash. Results demonstrated differences in kinematics and muscle activity between children and adults. The vehicle dynamics showed great repeatability between trials; therefore, these results suggest that observed differences in kinematics and muscle activity may have resulted from biomechanics and neuromuscular differences across the age groups rather than differences in vehicle acceleration during the manoeuvre.

Transient phase

In the transient phase children showed smaller trunk displacement than adults, however this difference might not simply be due to the differences in body geometry between children and adults since trunk displacement was significantly different between age groups when normalised by seated height. These results are in disagreement with previous in-laboratory studies that showed greater normalised spinal displacement in children in lateral loading conditions due to suspected greater spinal flexibility [17]. However, those tests were conducted at higher lateral accelerations (~2.5g maximum) and not in a vehicle environment where opportunities to brace are more accessible. This study also demonstrated that in the transient phase, head displacement was smaller in children than in adults, but this difference was not statistically significant in normalised data, suggesting that the greater head displacement in adults may have simply been influenced by height differences.

Our findings suggest that during the transient phase of the constant radius manoeuvre, the children may have employed a neuromuscular strategy that decreased motion. Both children and adults demonstrated elevated muscle activity in the right bicep, suggesting that they used the right arm to restrict the upper body lateral inboard motion. In addition to their activity in the right arm, children showed elevated bilateral activity of the sternocleidomastoid (SCM), suggesting they also engage their neck muscles to control movement in addition to their upper extremity. The engagement of the SCM was not as apparent in the adult subjects. It is plausible that children's greater activation of the SCM might have been an attempt to stabilise the neck joint to minimise both head and upper trunk motion. This interpretation agrees with previous literature on locomotion reporting that children adopt a stiff head-neck posture while walking to improve head stabilisation and compensate for a less developed vestibular system [18, 19]. However, although beneficial while walking, this stabilisation strategy may expose children to increased neck muscle strain and potential injury during a motor vehicle crash [20].

There were no statistically significant differences in kinematics between the two repetitions of the manoeuvre, showing that the subjects' kinematics in response to the vehicle manoeuvre was consistent between different trials. However, small variability between the two repetitions existed. In the transient phase, the between-trial variability showed that children have more variable head and trunk position than adults between repetitions. Since children seemed to brace more to prevent the lateral inboard motion of their upper body, their position was dependent on their active neuromuscular strategies and therefore more variable between trials compared to the adults. On the other hand, adults used a less active strategy to brace the head and trunk motion, so that their kinematics were more influenced by the vehicle dynamics, which was very consistent between trials. It is plausible that adults showed smaller between-trial variability of displacement compared to children because their mature neuromuscular system might have been able to accommodate to the manoeuvre better. In both groups the head had more variability in position than the trunk between trials. This was likely due to the fact that the trunk was restrained by the seat belt while the head position was more influenced by subject-related factors such as for example the subject gaze direction.

Steady-state phase

During the steady-state phase, no significant differences in head and trunk motion with age were found, however similar to the transient phase, children showed greater activation of their SCM muscles than adults. In this longer phase the right SCM was more active than the left SCM (Fig. 5 b), possibly because the children tended to tilt their head to the right to counteract the lateral inboard motion. The 2D videos of the participant trials confirm this interpretation. In the steady-state phase both age groups showed similar muscle activation strategy to the one employed in the transient phase: by engaging the right bicep muscle to brace. For children however, the SCM bilateral activity was greater than the right bicep. This suggests that children continued to prefer to engage their neck muscle to control motion even during this longer and more stable phase of the manoeuvre.

Similar to the transient phase, children showed greater between-trial variability in head position compared to adults. Furthermore, during this phase of the manoeuvre the head showed more between-trial variability then trunk (these differences were borderline statistically significant). This phase of the manoeuvre had a duration of ~30s so the participants may have had opportunities to adjust their upper body position several times. It was noted that all subjects in this study remained engaged with the shoulder belt.

Limitations

The manoeuvre was performed in a single vehicle environment and it is unclear if vehicles of bigger size, such as SUVs, would change participants' responses from those reported here. Differences in seat belt geometries, seat contours, and vehicle interior could potentially influence subject response. On the other hand, it seems that participants' motion resulted from the acceleration they were subjected to, therefore, it is plausible that our results can be generalisable to other vehicles that perform a similar manoeuvre with the same target acceleration as used in our investigation.

Other muscles besides those measured in this study may have contributed to participants' motion. The muscles analysed were chosen based on previous literature. We did not place EMG sensors on other muscle groups likely involved in bracing behaviour such as the lower trapezii because the interactions between EMG sensor and back of the seat would have created electrical artefacts in the EMG signal. Furthermore deep muscles such as the paraspinals might have played a role in neck kinematics however we only used surface EMG because of the challenges to use subcutaneous EMG on paediatric volunteers. Muscle activity was also not normalized to maximum voluntary isometric contraction but rather to rest.

The testing environment was not completely naturalistic since the participants were aware of the task and they were fully instrumented, and the manoeuvre was performed on a closed-course where no real danger was present. However, our testing environment was more realistic than any laboratory setting. Additionally, participants were instructed to relax and react naturally to the manoeuvre and baseline tests were conducted to help acclimate the subjects to the vehicle and driver. The duration of the constant radius turn was approximately 30 seconds. A 30 second pre-crash manoeuvre is likely longer than lateral accelerations experienced in a crash avoidance setting. However, considering that crash-avoidance scenarios in automated driving are still being investigated, the duration of the manoeuvre was selected to understand what happens to the body when a constant acceleration is sustained for a longer period.

V. CONCLUSIONS

The findings of this study quantified for the first time in-vehicle human volunteer kinematics and muscle activity during a pre-crash manoeuvre with sustained lateral acceleration that may precede a crash event. During the initial transient phase of the manoeuvre, children demonstrated reduced lateral excursion compared to adults in both the normalised (trunk only) and non-normalised (head and trunk) data. The data suggest that children may brace more than adults to control their upper body motion particularly during the transient phase of the manoeuvre. Children in this research study employed a different neuromuscular strategy compared to adults; specifically children display greater neck muscle activity in addition to bracing from the upper extremity to prevent lateral displacement of the body. Although similar trends in muscle activity were noted in the steady-state phase of the manoeuvre, age differences in kinematics were not present. This is the first study showing that age may influence bracing strategies and overall kinematics in pre-crash vehicle manoeuvre.

VI. ACKNOWLEDGEMENT

The authors would like to thank: the Toyota Collaborative Safety Research Center (CSRC) Ann Arbor (MI) for funding of this work, and the Transportation Research Center Inc. (East Liberty, OH, USA).

VII. REFERENCES

[1] Murphy SL, Xu J, Kochanek KD, Curtin SD. National Vital Statistics Reports Deaths : Final Data for 2015. *National Vital Statistics Report from the Center for Disease Control & Prevention*, 2017, 66(6):1–75.

[2] National Highway Traffic Safety Administration (NHTSA): USDOT Releases 2016 Fatal Traffic Crash Data https://www.nhtsa.gov/press-releases/usdot-releases-2016-fatal-traffic-crash-data, 2017.

[3] Institute for Traffic Accident Research and Data Analysis (ITARDA): Accident Analysis Report (JAPAN). 2007.

[4] Seacrist T, Douglas E, et al. Analysis of near crashes among teen, young adult, and experienced adult drivers using the SHRP2 naturalistic driving study. *Traffic Injury Prevention, 2018*, 19(1):S89–S96.

[5] Bohman K, Stockman I, Jakobsson L, Osvalder A-L, Bostrom O, Arbogast KB. Kinematics and shoulder belt position of child rear seat passengers during vehicle maneuvers. *Proceeding of the Association for the Advancement of Automotive Medicine Conference*, 2011, Paris, France.

[6] Kent R, Kerrigan J, Forman J, Arbogast K. The interface of active and passive safety: low- acceleration, time-extended events (LATEs). *Proceeding of the JSAE Conference*, 2014, Tokyo, Japan.

[7] Holt C, Seacrist T, et al. Occupant torso kinematics in low acceleration time-extended evasive swerving events. *Proceeding of the Stapp Car Crash Conference, 2*017, Charleston, South Carolina.

[8] Asay AF, Woolley RL. Rollover testing on an actual highway. *SAE International Journal of Passenger Cars-Mechanical Systems, 2009,* 2(1):1237–1267.

[9] Kim T, Bollapragada V, Kerrigan J, Crandall J, Clauser M. Effects of types of vehicles and maneuvers on vehcile kinematics during steering-induced soil-trip rollovers. *Proceeding of the 23rd International Conference on the Enhanced Safey of Vehicle*, 2013, Seoul, South Korea.

[10] Dotan R, Mitchell C, Cohen R, Klentrou P, Gabriel D, Falk B. Child—Adult Differences in Muscle Activation — A Review. *Pediatric Exercise Science, 2012*, 24(1):2–21.

[11] Seacrist T, Saffioti J, et al. Passive cervical spine flexion: The effect of age and gender. *Clinical Biomechanics*, 2012, 27(4):326-333.

[12] Centers for Disease Control and Prevention: Individual Growth Chart. https://www.cdc.gov/growthcharts/charts.htm. 2009

[13] National Health and Nutristion Examination Survey (NHANES): Clinical Growth Charts. http://163.178.103.176/Fisiologia/Integra/Objetivo4/clinical_charts.htm. 2008

[14] Kirschbichler S, Huber P, et al. Factors influencing occupant kinematics during braking and lane change maneuvers in a passenger vehicle. *Proceeding of IRCOBI Conference,* 2014, Berlin, Germany.

[15] Osth J, Olafsdóttir M, Davidsson J, Brolin K. Driver kinematic and muscle responses in braking events with standard and reversible pre-tensioned restraints: validation data for human models. *Stapp Car Crash Journal*, 2013, 57(11):1–41.

[16] De Luca CJ, Gilmore LD, Kuznetsov M, Roy SH. Filtering the surface EMG signal: Movement artifact and baseline noise contamination. *Journal Biomechanics*, 2010, 43(8):1573–1579.

[17] Arbogast K, Matthews E, et al. The Effect of Pretensioning and Age on Torso Rollout in Restrained Human Volunteers in Far-Side Lateral and Oblique Loading. *Stapp Car Crash Journal*, 2012, 56(10):443-467.

[18] Assaiante C, Mallau S, Viel S, Jover M, Schmitz C. Development of Postural Control in Healthy Children : A Functional Approach. *Neural Plasticity*, 2005, 12(2-3):109-118.

[19] Assaiante C, Amblard B. An ontogenetic model for the sensorimotor organization of balance control in humans. *Human Movement Science, 1995,* 14(1):13–43.

[20] Mang DWH, Siegmund GP, Inglis JT, Blouin J-S. The startle response during whiplash: a protective or harmful response? *Journal of Applied Physiology*, 2012, 113(4):532-540.