Evaluating Occupant Kinematic Responses to Low Acceleration Time-Extended Evasive Swerving Events

Christine Holt [1,2] Thomas Seacrist [2] Kristy B. Arbogast [2] Sriram Balasubramanian [1,2] Jason Kerrigan [3] Richard Kent[3]

1) School of Biomedical Engineering, Science, and Health Systems, Drexel University,
3141 Chestnut St., Philadelphia, PA USA 19104 (E-mail: cmh439@drexel.edu)
2) Center for Injury Research and Prevention, Children's Hospital of Philadelphia, Philadelphia, PA, USA
3) Center for Applied Biomechanics, University of Virginia, Charlottesville, VA USA

Abstract

Low-acceleration time-extended (LATE) events often precede a crash event. The inertial forces, during such events have the potential to cause changes to the occupant's "state", which may result in profound consequences in restraint performance. To quantify these effects, a customized laboratory test fixture was constriucted to mimic oscillatory swerving for a restrained occupant. Healthy adult male volunteers (*n*=7) were exposed to a series of 4 complete oscillatory cycles with peak lateral accelerations of approximately 0.75 g. Kinematics of key skeletal landmarks of the head and torso were quantified.

Introduction

Motor vehicle crashes (MVCs) continue to be a prime contributor to mortality and morbidity for children and young adults worldwide [(6)]. Head injuries, specifically, are the most common serious injury sustained by children in MVCs [(2-4)], with head contact to the vehicle interior being the primary causation scenario for injury[(3)]. Most previous automotive safety research has emphasized the impact phase of MVC and current automotive safety countermeasures, such as airbags and seatbelts, are designed primarily to minimize the adverse events resulting from crash forces during impact, often neglecting the precursors of the event. However, it is also necessary to study the pre-crash maneuvers preceding impact, such as evasive swerving. Previous research has shown 60% of crashes involve some form of pre-crash maneuvers [(1)]. These maneuvers have been defined as low acceleration, time extended (LATE) events. LATE events are a spectrum of dynamic emergency, impact avoidance maneuvers that are exhibited in critical driving situations [(5)]. The inertial forces, during this pre-crash phase, have the potential to cause alterations to the occupant's "state" (initial posture, position, muscle tension), which could lead to decreased effectiveness of the restraint system and increased likelihood of head contact with the vehicle interior. Prior analysis of the National Highway Traffic Safety Administration (NHTSA) databases identified pre-crash maneuvres as a contributing factor to head impact with the vehicle interior [(3)]. Pre-impact occupant position was a key component of the primary injury mechanism to children killed by frontal passenger airbag deployments in the early 1990s [(7)]. Additionally, as active safety technologies (AST) come to fruition, automated vehicle maneuvres that occur prior to a crash may result in increased frequency and magnitude of displacement of the occupant state. In turn, the occupant's state may result in profound consequences for the restraint system's performance. Hence, it is paramount to study the motion of the occupant during LATE events because the optimal performance of restraint systems requires an accurate assessment of the pre-impact position of the occupant. Currently, there is limited understanding of occupant kinematic activity during pre-crash maneuvers and how this activity contributes to protection. Evasive swerving was identified as a vital LATE event that is currently understudied. Evasive swerving is exhibited when a vehicle generates a sinusoidal or oscillating path. Some potential causes of this maneuver include: heavy or unbalanced loading, wet or icy pavement, and swift lane changes in an attempt to avoid an object. The objective of this study, in its entirety, is to quantify kinematic responses of adult and pediatric restrained human volunteers during simulated evasive swerving maneuvers. A safe and repeatable test fixture, custom constructed for this study exposes volunteers to low, non-injurious loading conditions that are relevant to the pre-crash event. This paper describes the methodology of evaluating occupant response in LATE oscillatory or swerving events and preliminary results.

Methods

Safe Volunteer Pulse: The focus of this laboratory test method was to provide the oscillatory loading experienced by an occupant during pre-crash emergency swerving. A meta-analysis of previous laboratory and on-road studies as well as consumer information programs and safety standards were compiled. This analysis was conducted to determine the appropriate oscillatory acceleration and magnitude that is safe for human volunteer testing and also representative of dynamic pre-crash field data (Table 1). To define parameters that are relevant to real world evasive swerving scenarios, five specific vehicle-handling tests were studied. These tests include the resonant steer, slalom, fishhook, moose test, and verband der deutschen automobilindustrie (VDA) test. The geometric dimensions of one cycle (both forward and lateral), time to achieve one cycle, magnitude of peak acceleration and testing population from each of the maneuvers were compiled and quantitative values averaged to create a relevant testing envelope.

Table 1. Previous Pre-Crash Swerving Maneuver Studies

Reference	Peak Lateral Acceleration	Population	Maneuver	Primary Metric
Laboratory Testing				
Ejima et al, 2012	0.6 *g*	Adult (n=3)	Pure Lateral	Kinematics, EMG
Kirschbichler et al, 2011	0.5 *g*	Adult (n=11)	Pure Lateral	Kinematics, EMG
Parenteau et al, 2006	0.9 *g*	Adult (n=3)	Fishhook	Kinematics
Van Rooji et al, 2013	0.7 *g*	Adult (n=10)	Pure Lateral, Lane Change	Kinematics, EMG
Closed Track / On Road Testing				
Bohman et al, 2011	0.91 *g*	Pediatric (n=16)	Sharp Turn/Curve	Kinematics
Howe et al, 2002	0.53, 0.74 *g*	N/A	Fishhook, Resonant Steer	Vehicle Dynamics
Huber et al, 2013	1.0 *g*	Adult (n=21)	VDA	Kinematics, EMG
Kirschbichler et al, 2014	1.02 *g*	Adult (n=57)	VDA	Kinematics
Breuer et al,1998	1.23 *g*	N/A	Moose Test	Vehicle Dynamics
Kim et al, 2013	0.87 *g*	N/A	Slalom	Vehicle Dynamics
Stockman et al, 2013	0.84 *g*	Pediatric ATD	Sharp Turn/Curve	Kinematics

Table 1. Results of the meta-analysis are listed. Previous pre-crash swerving loading conditions ranged from 0.5 – 1.2 g's. Based on these data, the sled apparatus was developed to mimic pre-crash swerving. The sled apparatus is capable of delivering up to 1 g of sinusoidal oscillatory acceleration. This loading environment was determined to be safe for the study population based on review of the literature above and amusement park standards (ASTM F2291).

Based on this analysis, a novel, non-injurious, repeatable test fixture, was designed to mimic pre-crash swerving. An occupant compartment capable of mimicking various automotive seating environments was also designed (Fig. 1). The study protocol was approved by the Institutional Review Board at the Children's Hospital of Philadelphia. Healthy volunteers (9–40 yrs) are exposed to a series of oscillatory accelerations with varying parameters while restrained with a standard three-point belt.

Sled Apparatus: The LATE device consists of a 1.5 m x 0.9 m cart (Fig. 1) that slides along two parallel 3 m steel rails via near-frictionless Teflon shoes. The cart is actuated via a Scotch yoke mechanism consisting of a sprocket, driven by two WEG W21 5 HP motors, which is coupled to a sliding yoke on the bottom of the cart. An occupant compartment consisting of a second row captain's chair, three-point belt and 3-degree of freedom adjustable B/C-pillar and D-ring structure was designed to mimic various front and rear passenger seating environments. An automotive three point-belt system with three seat belt load cells was used, along with a pre-pretensioner integrated into the shoulder belt.

Figure 1 Sled Apparatus with Seating Compartment

A 1.5 m x 1.5 m occupant compartment is mounted to the cart such that the motion is perpendicular to the occupant. The compartment includes two onboard GoPro HERO Session 4 cameras oriented in the overhead and frontal perspective of the volunteers. High speed 2D video data from these cameras were captured at 60 Hz. An accelerometer (Endevco 7290a-10) was affixed to the frame of the compartment. A triaxial force plate was mounted to the footrest to obtain loads exerted from the lower extremities. The accelerometer and force plate data were sampled at 10,000 Hz using an onboard T-DAS data acquisition system (Model T-DAS Pro, DTS Inc, Seal Beach, CA).

Volunteers: Healthy male volunteers whose weight and BMI were within 5th and 95th percentile for the subject's age (based upon CDC growth charts for children and CDC NHANES data for subjects 18+ years) and who had a stature between 144.8 cm to 185.4 cm were included in the study. The volunteers were selected such that they resembled the broad range of occupant ages and sizes found in a motor vehicle. Subjects with a proclivity to motion sickness, existing neurologic, orthopedic, genetic, or neuromuscular conditions, any previous injury or abnormal pathology relating to the head, neck or spine were excluded from the study. Subjects for the study, in its entirety, are categorized into the following age groups: 9 to 11, 12 to 14, 15 to 17 and 18-40 years old. For the analysis presented herein, a total of 7 male subjects within the 18-40 y/o age range were evaluated

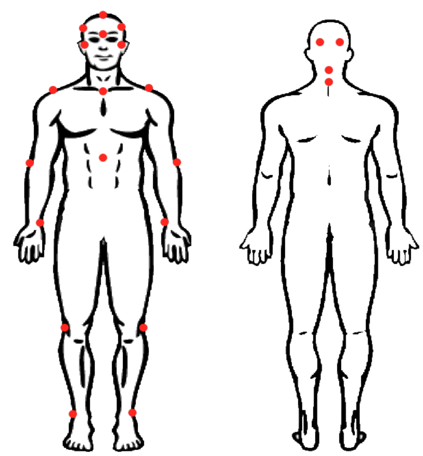

Figure 2 Motion Capture Marker Placement

Volunteer kinematic data were captured using an on board Optitrack Flex 13 motion−capturing system featuring eight infrared cameras (NaturalPoint, Inc., Corvallis, OR). Spherical photo-reflective markers were placed on key anatomical landmarks, shoulder belt and various locations on the seating compartment. A calibration process was performed prior to each test session, where the spatial configuration of a known object was recorded by all cameras. Thereby the the relative position and field of view of each camera was determined. The markers were recorded at a sampling frequency of 120 Hz and reconstructed to give their 3D positions.

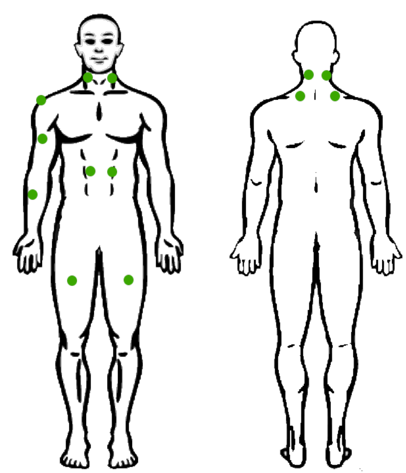

Figure 3 EMG Sensor Placement

Volunteers were provided with an athletic compression shirt and pair of atletic shorts. Once in proper attire photo-refeltive markers were adhered to the head, torso and extremities (Fig. 2). For the head markers volunteers wore a tightly fitted headpiece with five head markers (top, bilateraly on the front and back). In total 8 markers were placed on the head (bilateral: Front of the head, back of the head, external auditory meatus; central: top of head, C4, Nasion). 13 markers were placed on the torso and extremities (bilateral: acromion, humeral epicondyle, ulnar styloid process, femoral epicondyle, lateral malleolus; central: suprasternal notch, T1, xiphoid process).

Wireless surface electromyography (EMG) electrodes were placed on the musculature of the neck, torso, abdomen and extremities and will later be quantified to characterize volunteer muscle response (Fig. 3).

Experimental Conditions: While restrained in a production vehicle bucket seat, volunteers were exposed to a unique series of testing conditions all with oscillatory peak lateral accelerations of approximately 0.75 g. The effect of bracing and two countermeasures, a pre-pretensioner and a more sculpted vehicle seat with inflatable torso bolsters, were assessed. In total, each volunteer participated in five randomized testing conditions:

1. relaxed posture-standard seat
2. braced posture-standard seat
3. relaxed posture-seatbelt pre-pretensioner-standard seat
4. relaxed posture-sculpted seat (un-inflated torso bolsters),
5. relaxed posture-sculpted seat (inflated torso bolsters).

Figure 4 Adult Volunteer Before Start of Baseline Condition

The first condition served as the baseline condition. To assess bracing, a removable bracing structure was attached to the outboard (right) side of the compartment in immediate reach of subject. The structure was designed to accommodate a wide range of subject arm-forearm lengths and allow the subject to brace comfortably. Volunteers were informed to brace with their maximum muscle strength to resist the motion prior to the test impulse. In the third condition the pre-pretensioner was powered by a 12V-20A electrical output and was integrated into the sled trigger enalbling it to be fired simultaneously at the start of the test. It achieved a pre-tensioning load of approximately 200N. The restraint system was designed such that the pre-pretensioner could be inactive during subsequent tests. Condition four, with the bolsters of the sculpted seat unfilled constitutes as the baseline condition for the sculpted seat. Condition five inflated both left and right torso bolsters with 13.8 kPa, respectively. Inflation was achieved with a regulated air compresser. One complete cycle of oscillation requires the seating compartment to travel 1.8 m laterally, in the +y direction (towards the volunteer's right such that they move away from the shoulder belt) and then return 1.8 m back to the starting position. Each trial includes 4 cycles with a frequency of 2 Hz and each condition was repeated once for a total of 10 trials per subject. Subjects were unaware of test start to capture the response of a naïve occupant.

Data Analysis: The Motion Analysis data acquired at 120 fps were analyzed using Motive:Tracker software (NaturalPoint, Inc., Corvallis, OR). The accelerometer was filtered with a 1 Hz 4-pole Butterworth filter. The time series motion analysis and T-DAS data were imported into MATLAB (Mathworks, Inc., Natick, MA) for data analysis using a custom program.

The parameters of interest for this preliminary analysis were the kinematics of the head top and left and right acromion. Displacement was measured by quantifying the motion of the markers in the lateral (y) and (z) vertical direction, relative to initial position (t = event onset). Positive y corresponds to the right side of the volunteer and negative to the left. In addition, +y correlates the volunteer moving into the belt and outboard and –y is inboard and out of the belt. Marker trajectories were normalized by the initial position of the subject's head top marker. Mean values of the outboard and inboard maximum lateral head top displacement were calculated separately for each direction. In the subsequent statistical analysis to evaluate the effect of the 4 cycles and direction (outboard versus inboard) a Two-ways Repeated Measure ANOVA was performed on the maximum lateral head top displacement. Post-hoc tests were performed using Tukey's HSD. Level of significance was set to p=0.05.

Results

The following data represents the baseline test (relaxed posture-standard seat) of 7 healthy adult males (height: 179.0 ± 5.5 cm, weight: 80.6 kg ± 12.6 kg, age: 27.3 ± 5.6 years) that were evaluated. One complete cycle of oscillation requires the seating compartment to travel six feet, laterally, in the +y direction (towards the volunteer's right) and then return six feet back to the starting position. Each trial includes 4 cycles with a frequency of 2 Hz. The device is capable of producing accelerations up to 1 g; however, for volunteer testing purposes peak lateral accelerations are maintained at 0.75 g's.

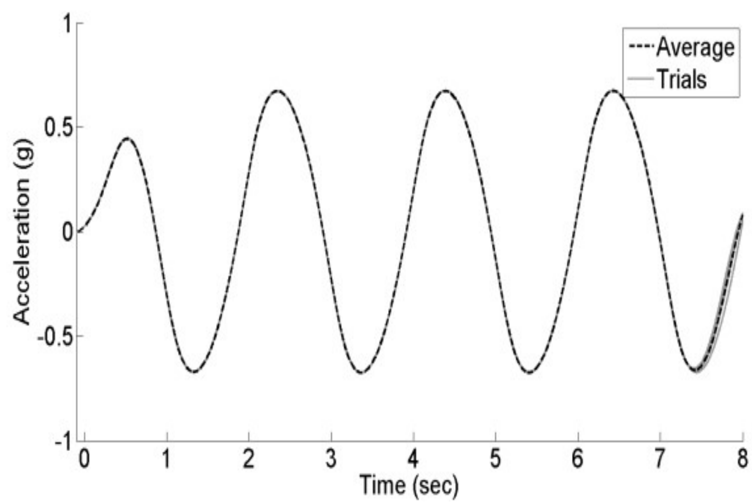

Figure 5 Seating Compartment Acceleration Profile

The time histories of the resultant sled accelerations were measured for all test conditions (Fig. 5). Acceleration from separate trials are depicted in gray and the black line represents the average. The consistency in the resultant sled accelerations indicates that the sled pulse is repeatable. All data motion capture data sets were synchronized with time zero as the onset of the compartment accerleration.

Head Top Kinematics

Figure 6 depicts the lateral motion, relative to the moving compartment, of the head top marker across the 4 cycles, averaged across trials and subjects (n=14 trials). The first oscillation demonstrates the greatest magnitude of outboard head excursion likely due to the unaware nature of the test start. Once the first cycle is complete, the remainder of the test shows reduced outboard excursion across the other 3 cycles (Fig. 7).

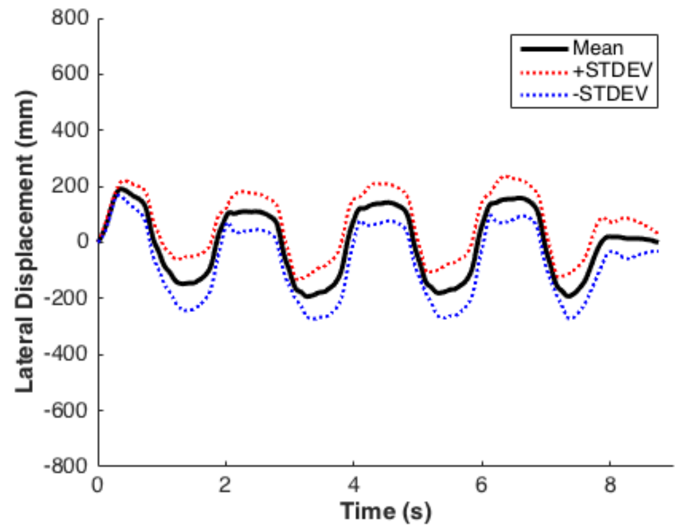

Figure 6 Time Series of Head Top Marker

During the first cycle, the inboard and outboard motion of the head is very similar. However for the second and subsequent cycles, the inboard excursion is much greater (40-80%) than outboard excursion.

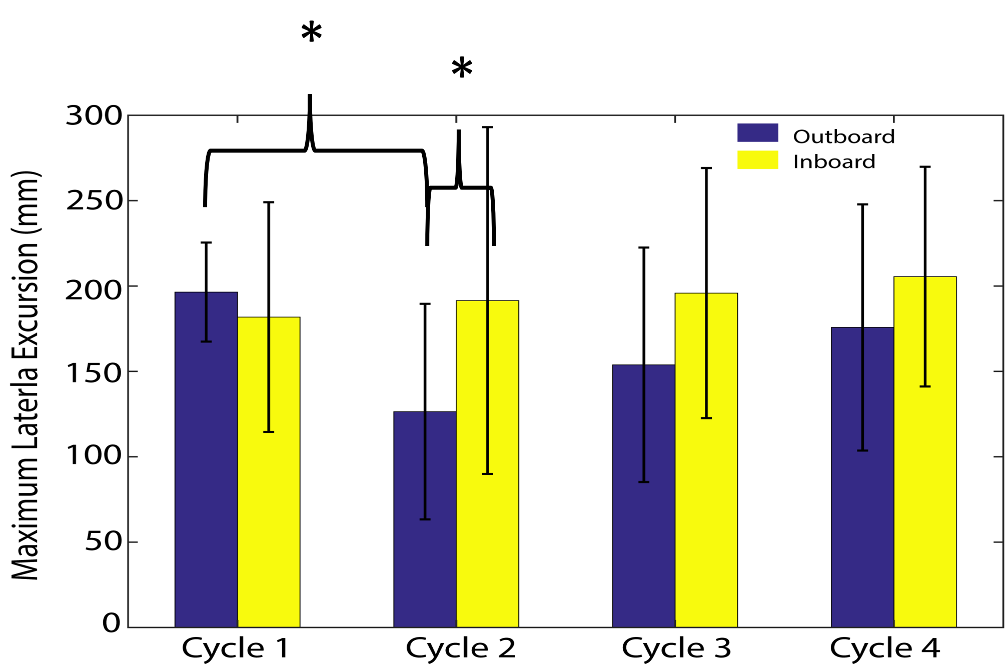

Figure 7 Head Top Maximum Lateral Excursion *p<0.05

An average (n=14) maximum outboard displacement of 196.5 mm (±29.0mm) occurring during cycle one. An overall average maximum displacement of 205.5 mm (±64.3mm) occurred during the inboard direction of cycle 4.

The two way interaction between cycle number and direction was statistically significant ($p=0.004$). Post-hoc comparisons revealed that, in the outboard direction, the maximum lateral displacement of the head in the first cycle was greater than the maximum lateral displacement of the second cycle ($p=0.003$). In addition, in the second cycle the maximum lateral displacement of the head was greater in the inboard direction compared to the outboard direction ($p=0.007$).

Shoulder Kinematics

Figure 8 depicts the frontal plane, outboard and inboard, peak lateral shoulder kinematics for the first three cycles of the baseline condition. Each graph represents a single subject and the various lines are the peak lateral accelerations as the volunteer deviates from their distinct initial positions. This initial position is displayed in black. There is substantial subject to subject variation – particularly in the inboard direction such that one of the subjects assumes a close to vertical orientation of his shoulders.

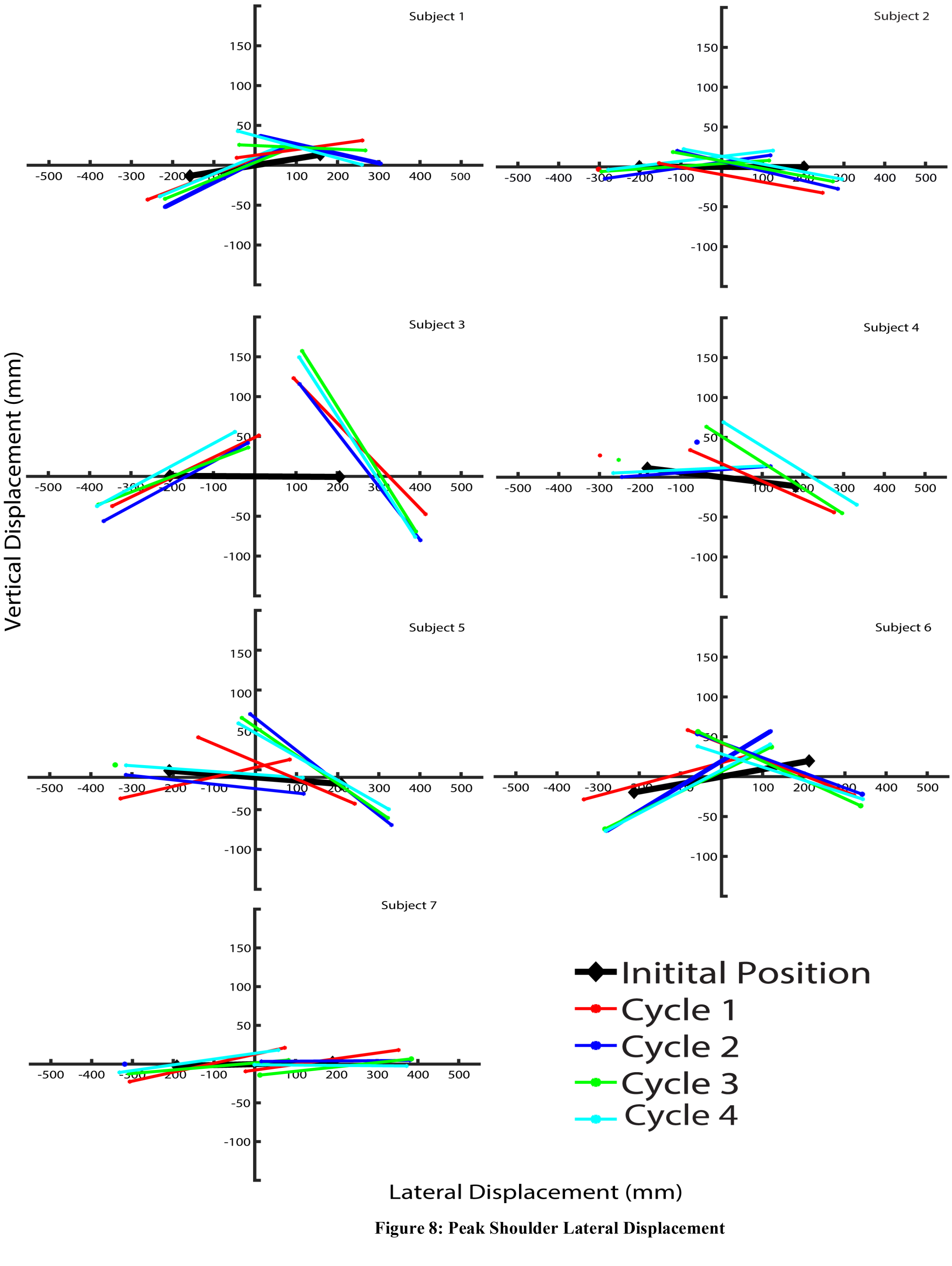

Figure 8: Peak Shoulder Lateral Displacement

Discussion

A novel laboratory device has been constructed to evaluate subject kinematics in the oscillatory swerving that accompanies emergency maneuvers pre-crash. Preliminary data analysis of 7 adult subjects shows the head top excursion follows the acceleration profile. The first cycle caused greater lateral displacement in the outboard direction than subsequent cycles, indicating the potential for a startle effect. Overall, greater excursions were observed when traveling inboard as many subjects slipped out of the belt. The motion of the shoulders confirms these kinematics. Some volunteers reacted to the motion by elevating their shoulders combined with a substantial lateral lean of the torso. However, some demonstrated relatively small magnitude, controlled movement of the torso. The difference in maximum lateral displacement between inboard and outboard may reveal a volunteers' strategy to counteract the perturbation: in the first cycle the greater maximum lateral displacement of the head in the outboard direction may be governed by the passive reliance of the volunteers on the seatbelt in addition to the naive start (Fig. 7). The second cycle may represent an overcompensation of muscle contraction to restrict the movement. While in the third and fourth cycle volunteer may have employed a compromise between passive reliance on the seatbelt and muscle contraction to counteract the perturbation (Fig. 7). Future analysis of the seatbelt load cell signal and EMG data is warranted to corroborate this interpretation.

Furthermore, investigation of EMG responses will provide insight into whether variability in muscle reaction governs these kinematics or these subject to subject differences represent varied lateral flexibility of the torso. Recruitment and testing of volunteers is underway; a total of 40 subjects from age 9-40 years is targeted. It is vital to investigate this broad range of subject ages and sizes because they are representative of the motor vehical occupant population. In addition, future restraint design must robustly accomodate various occupant sizes while similtaneously providing the appropiate level of protection. Thus, a greater understanding of these findings, including exploring the effect of age, will occur when a larger sample size is reached.

Conclusion

This study represents the first step in a broader line of research aimed at quantifying and mitigating occupant pre-crash motion. Whereas previous research has focused on vehicle dynamics or limited age ranges, this line of research represents the first effort at evaluating LATE events in a controlled laboratory environment using human volunteers across a range of occupant ages. Future analysis will evaluate the kinematic response of novel countermeasures used to mitigate pre-crash motion and quantify muscle response as a result of the varying conditions.

These data will provide restraint manufacturers with fundamental biomechanics data of occupant motion and positioning prior to impact in order to: 1. provide fundamental validation data for advanced computational human body models that incorporate muscle activity; 2. guide design of AST to minimize occupant motion during these maneuvers; and 3. influence restraint design to ensure that restraints can accommodate variations in occupant state and maximize protection offered

Acknowledgements

The authors would like to thank Acen Jordan for his efforts in designing the LATE device, the human volunteers who participated in this study and Valentina Graci for her assistance with the study. We would also like to acknowledge Takata Corporation for their financial support and Mike Scavnicky and Kirk Morris for their collaboration.

References

1) Accident Analysis Report (JAPAN) Institute for Traffic Accident Research and Data Analysis (ITARDA) 2007

2) Arbogast, K. B., et al. "Predictors and patterns of paediatric head injury in motor vehicle crashes." IRCOBI Conference 2005

3) Bohman, Katarina, Kristy B. Arbogast, and Ola Boström. "Head injury causation scenarios for belted, rear-seated children in frontal impacts." Traffic injury prevention 12.1 (2011): 62-70.

4) Scanlon JM, Kusano KD, Gabler HC. Analysis of Driver Evasive Maneuvering Prior to Intersection Crashes Using Event Data Recorders. Traffic Injury Prevention 16 (2015): S182-S189.

5) Kent, Richard et al (2014). The Interface of Active and Passive Safety: Low- Acceleration, Time-Extended Events (LATEs). JSAE 2014 Conference, Tokyo, Japan

6) WHO, Global Status Report on World Safety, 2009.

7) Winston, F. K., & Reed, R. (1996). *Air bags and children: results of a National Highway Traffic Safety Administration special investigation into actual crashes* (No. 962438). SAE Technical Paper.