Evaluation of Pediatric ATD Biofidelity as Compared to Child Volunteers in Low-Speed Far-Side Oblique and Lateral Impacts

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ABSTRACT

Motor vehicle crashes are a leading cause of injury and mortality for children. Mitigation of these injuries requires a biofidelic anthropomorphic test devices (ATD) to design and evaluate automotive safety systems. Far-side impacts represent increased injury and mortality rates compared to frontal impacts. The objective of this study was to evaluate the biofidelity of the 6-year-old ATDs in low-speed far-side impacts, with and without shoulder belt pre-tightening. Low-speed (2g), far-side oblique (60º) and lateral (90º) sled tests were conducted using the Hybrid III and Q-series 6 year old ATDs. ATDs were restrained by a lap and shoulder belt equipped with a pre-crash belt pre-tightener. Photo-reflective targets were attached to the head, spine, shoulders, and sternum. ATDs were exposed to low-speed sled tests with and without pre-tightening. Age-matched volunteer cohorts consisting of 6-8 year olds (n=7) corresponding to the 6 year old were tested with similar methods. Kinematic data from ATD and human volunteers were collected from a 3-D target tracking system. Metrics of comparison included maximum excursionout of the head top, C4, and T1 landmarks. The ATDs exhibited increased lateral excursion of the head top, C4, and T1 as well as increased downward excursion of the head top compared to the volunteers. Volunteers exhibited greater forward excursion than the ATDs In pre-tightened impacts, the ATDs exhibited reduced excursions than the volunteers. In general, the ATDs overestimated lateral excursion, while underestimating forward excursion of the head and neck compared to the pediatric volunteers. These analyses provide insight into aspects of ATD biofidelity in far-side impacts.

INTRODUCTION

Traumatic brain injuries are the most common serious injury children sustained in motor vehicle crashes (MVC) [CDC 2011]. Due to the use of anthropomorphic test device (ATD) motion in developing preventative features in motor vehicles, it is vital that ATDs accurately mimic the kinematics of pediatric occupants in MVCs.

In the past, adult ATDs have been validated by using post-mortem human subjects (PMHS). However, due to the lack of specimen supply to be used for pediatric PMHS testing, pediatric data has been scaled from the adult PMHS [Irwin and Mertz 1997]. Scaling of data from adult PMHS response does not take into account the morphological and tissue changes that transpire due to aging. Because of the absence of pediatric PMHS testing, human volunteer testing in low-speed crashes as shown to be a promising route to better evaluate the biofidelity of pediatric ATDs [Begeman et al. 1980; Beeman et al. 2012].

Our lab has previously reported the dynamic response of pediatric volunteers (6-14 years) in low-speed (<4 g) *frontal* crash conditions [Arbogast et al. 2009; Seacrist et al. 2012a]. The human subject response has also been compared to Hybrid III and Q-Series 6 and 10 year-old ATDs; significant differences have been noted in the head and spine kinematics. These results provide a good indication of the biofidelity of pediatric ATDs; however, frontal collisions are only a subset of MVCs. Hence, it is important to evaluate ATD biofidelity in other crash directions, including side impacts.

In addition, it is important to evaluate ATD response to novel safety systems such as active pre-crash devices. One such device is a novel belt pre-tightener. Similar in function to pre-tensioners, pre-tighteners are designed to pull the slack from the seat belt bringing the occupant into proper posture at the moment of vehicle collision, but provide this assistance prior to a collision at at relatively low loads compared to pre-tensioners. It is important that the pediatrics ATDs accurately predict a child's response to these novel pre-tighteners.

The first goal of this study was to evaluate the biofidelity of pediatric ATDs in low-speed lateral and oblique-side impacts by comparing kinematic motion to pediatric volunteers. The second goal of the study was to analyze the effectiveness of preventative measures in cars such as pre-tighteners.

METHODS

This study protocol was reviewed and proved by the Institutional Review Boards at The Children's Hospital of Philadelphia, Philadelphia, PA and Rowan University, Glassboro, NJ (the testing site).

Experimental Testing

A comprehensive description of the human volunteer testing can be found in Arbogast et al. (2012). A safe, low-speed, non-injurious far-side oblique (60°) and lateral (90°) sled tests were conducted on healthy male pediatric volunteers between the ages of 6-8 years (n = 7). Informed consent was obtained from a parent/guardian and informed assent was obtained from the child. Subjects were seated in a pneumatically-actuated, hydraulically-controlled low-speed deceleration sled equipped with an onboard accelerometer. A safe, non-injurious crash pulse applicable to the pediatric population was derived from an amusement park bumper car impact. The peak sled acceleration and rise time were 1.88 *g* in 52.7 ms for oblique impacts, and 1.91 *g* in 54.3 ms for lateral impacts. Subjects were restrained using a standard automotive three-point belt system (Takata Corp., Tokyo, Japan) equipped with a pre-tightener capable of applying a

250 N pre-tightening force to the occupant. The belt geometry was such that the D-ring is located 296 mm rearward of the H-point, falling within the measured range of 2001-2008 US based vehicles (Reed et al. 2008). Lightweight belt webbing load cells (Model 6200FL-41-30, Denton ATD Inc, Rochester Hills, MI) were attached to the shoulder belt and on the right and left locations on the lap belt. The initial position of the torso and knee angles was set to 110°. The height of the shoulder belt anchor was adjusted to provide similar fit across subjects. The lap belt anchor locations were fixed throughout the test series. Photo-reflective markers were placed on anatomical landmarks of interest including the head top, C4, T1, and were tracked using a 3D near-infrared video target tracking system (Model Eagle 4 Motion Analysis Corporation, Santa Rosa, CA). A high-speed video camera (MotionXtra HGTH, Redlake, San Diego, CA) focused on the coronal plane of the occupant recorded the qualitative relative movement of the torso and the shoulder belt. Volunteers were assigned to either the oblique or lateral test conditions. Two repetitive trials were conducted for both the non-tightened and pre-tightened conditions such that each volunteer experienced 4 trials.

These pediatric volunteer data were compared with the Hybrid III and Q-series 6-year-old ATDs. ATD marker placement, initial position, and test matrix mimicked the methodology used for the pediatric subjects (Figure 1). Mean (±SE) age, mass, and erect seated height for the ATDs and matched volunteer cohorts are listed in Table 1.

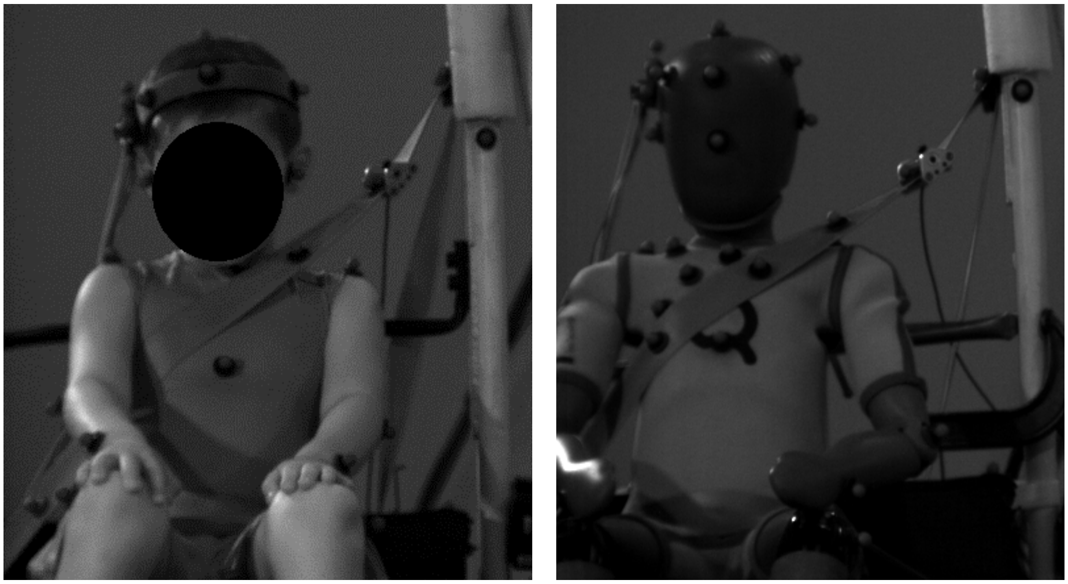
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Figure 1. Instrumentation and initial position comparison of a pediatric volunteer (left) and ATD (right).

Table 1. Volunteer and ATD Anthropometry and Scale Factors

Group	**Impact Angle**	**Age** (years)	**Mass** (kg)	**Erect Seated Height** (cm)	λ_L	λ_F
6-Year-Old Cohort						
Hybrid III	60º/90º	6	23.4	63.5	1.00	1.00

Q/Qs	60º/90º	6	22.9	60.1	1.06	1.01
Volunteers (n = 3)	60º	7.4 ± 0.7	25.3 ± 2.5	66.4 ± 1.1	0.96 ± 0.02	0.96 ± 0.07
Volunteers (n = 4)	90º	7.8 ± 0.4	32.0 ± 1.8	69.7 ± 1.4	0.91 ± 0.02	0.81 ± 0.03
10-Year-Old Cohort						
Hybrid III	60º/90º	10	35.3	72.4	1.00	1.00
Q	60º/90º	10.5	38.5	77.8	0.93	0.94
Volunteers (n = 5)	60º	10.7 ± 0.4	37.0 ± 4.1	74.7 ± 1.8	0.97 ± 0.02	1.00 ± 0.07
Volunteers (n = 5)	90º	10.8 ± 0.5	34.8 ± 0.9	74.8 ± 1.5	0.97 ± 0.02	1.01 ± 0.02

Data Acquisition and Processing

Motion analysis data were acquired at 100 Hz and analyzed using Motion Analysis software (Motion Analysis Corporation, Santa Rosa, CA). High speed video was collected at 1000 Hz.

Data Reduction

The time series motion analysis and T-DAS data were imported into MATLAB (Mathworks, Inc., Natick, MA) for data analysis using a custom algorithm. The right rear seat pan marker was designated as the origin for the local (sled) coordinate system.

To account for variations in stature and mass within the age groups, trajectories and seat environment reaction loads of the volunteers and Q-series ATDs were scaled to the anthropometry of the corresponding Hybrid III ATD according to length scaling (Eq. 1) (Langhaar 1951) and force scaling (Eq. 2) (Eppinger et al. 1984), respectively:

$$\lambda_L = \frac{L_{Hybrid\,III}}{L_{subject}} \tag{1}$$

$$\lambda_F = \lambda_m^{2/3} = \left(\frac{m_{Hybrid\,III}}{m_{subject}}\right)^{2/3} \tag{2}$$

where λ_L is the ratio of seated height, λ_F is the force scaling factor, and λ_m is the ratio of body mass. Mean (±SE) scale factors for the volunteers and ATDs are listed in Table 1.

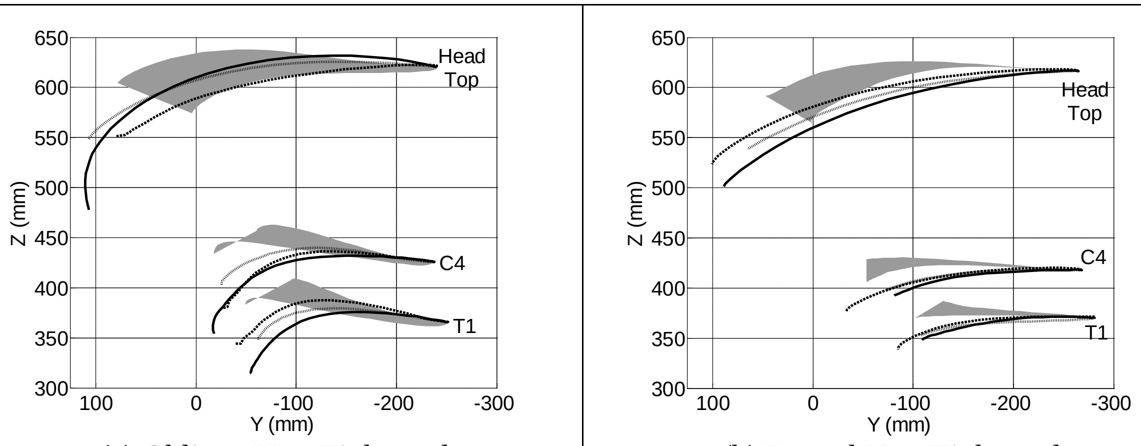
Peak excursion of the head and neck markers was calculated as the difference between initial position at event onset (onset of sled acceleration) and maximum change in position. Pediatric volunteer trajectory corridors were developed based on the mean response and one standard deviation in the *x*, *y* and *z* directions.

Statistical Analysis

Data were imported into Statistical Analysis System (SAS) 9.3 for statistical analysis and analyzed using both descriptive and inferential statistical techniques. The experiment wise error rate was held at the 0.05 level. To account for clustering of trials due to the multiple trials of each pediatric volunteer, robust variances were computed by using the Taylor series linearization method and 95% confidence intervals (CI) were estimated for all parameters. Differences between the ATDs and the pediatric volunteers were assessed by comparing the ATD mean value to the corresponding pediatric volunteer 95% CI.

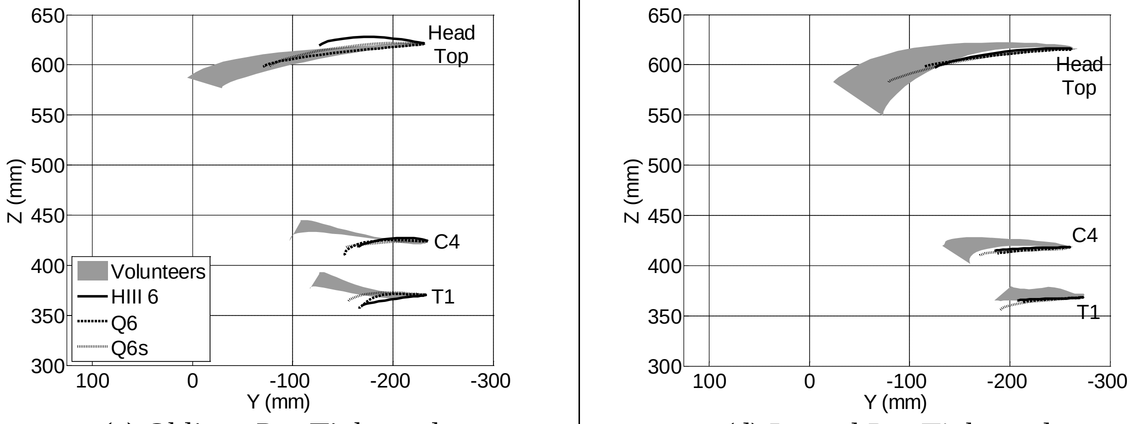
RESULTS

Head and neck transverse plane (*x*-*y*) ATD trajectories and volunteer corridors are included in the Figures 3 and 4. Peak ATD response and pediatric volunteer 95% CIs for the 6-year-old comparison in oblique and lateral impacts are listed in Tables 2-3, respectively.



(a) Oblique Non-Tightened

(b) Lateral Non-Tightened



(c) Oblique Pre-Tightened

(d) Lateral Pre-Tightened

Figure 2. Head and neck coronal plane trajectories for the Hybrid III 6, Q6, and Q6s ATDs as well as trajectory corridors for the 6-8 year old volunteers in oblique (60°) non-tightened (a), lateral (90°) non-tightened (b), oblique (60°) pre-tightened (c), and lateral (90°) pre-tightened (d) impacts. All trajectories were scaled to the seated height of the Hybrid III 6 and aligned to the initial position of the Hybrid III 6 landmarks.

Table 2. Volunteer and ATD Anthropometry and Scale Factors

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				(cm)		
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Volunteers (n = 4)	90º	7.8 ± 0.4	32.0 ± 1.8	69.7 ± 1.4	0.91 ± 0.02	0.81 ± 0.03

Table 3. Comparison of Peak Responses: 6-Year-Old ATDs (Oblique)

	Non-Tightened				**Pre-Tightened**			
	HIII 6	**Q6**	**Q6s**	**6-8 Yrs** (95% CI)	**HIII 6**	**Q6**	**Q6s**	**6-8 Yrs** (95% CI)
Head Top ΔX (mm)	107*	63*	76*	120 – 132	36*	33*	15*	57 – 97
Head Top ΔY (mm)	350*	321	348*	241 – 324	107*	160*	154*	204 – 239
Head Top ΔZ (mm)	-143*	-72*	-76*	-23 – -52	-26*	-24*	-24*	-51 – -38
C4 ΔX (mm)	47*	36*	44*	68 – 74	2*	10*	4*	15 –24
C4 ΔY (mm)	220	214	212	181 – 221	69*	83*	82*	126 – 139
C4 ΔZ (mm)	-74*	-49*	-27*	28 – 31	-8	-16	-7	-7 – 27
T1 ΔX (mm)	31*	24*	38*	56 – 59	1*	3*	4*	7 – 11
T1 ΔY (mm)	197	214*	189	163 – 203	63*	66*	77*	106 – 116
T1 ΔZ (mm)	-53*	-4*	-23*	30 – 39	-11*	-14*	-9*	-1 – 26

* = Significant differences between the ATD and the human volunteers at $p < 0.05$ level.

The 6-year-old ATDs overestimated lateral (ΔY) excursion and downward (ΔZ) excursion of the head compared to the corresponding volunteer cohorts in non-tightened oblique and lateral impacts. Interestingly, the ATDs underestimated or exhibited similar forward (ΔX) excursion compared to the volunteers in oblique impacts. Similarly, with the exception of the Q6 lateral impact, the ATDs overestimated head rotation compared to the pediatric volunteers. Contrary to the volunteers who exhibited upward excursion of the C4 and T1, the ATDs exhibited downward excursions of these landmarks. The Hybrid III 6 and Q6 exhibited increased torso rollout compared to the volunteers in non-tightened oblique and lateral impacts, whereas the Q6s exhibited similar torso rollout to the volunteers. Also, the ATDs exhibited similar or reduced head rotation compared to the volunteers.

DISCUSSION

From the results above, the ATDs overestimated lateral and downward motion of the head and neck in low-speed far-side impacts. This is contrary to our previous findings (Arbogast et al 2012) and also to adult human volunteer findings (Beeman et al. 2012) where the ATDs slightly underestimated motion of the head and neck compared to the human volunteers. In oblique impacts, out-of-plane motion of the head and neck most likely contribute to the difference. Pre-tightening resulted in a major decrease in both lateral and downward excursions of the head and neck for both the ATDs and pediatric volunteers. This phenomenon was significantly more prevalent in the ATDs excursion compared to the pediatric volunteers excursion. A possible explanation for this is the joining of the lower and upper thorax, causing an increase effect of the pre-tightener.

This is the first study that evaluates the biofidelity of the 6-year old ATDs in low-speed far-side and oblique impacts by comparing their response with pediatric volunteers. In addition to overestimated lateral excursions and head rotation, pediatric ATDs also exhibited lateral bending in the coronal plane compared to translation of the thorax relative to the abdomen followed by lateral torso rotation in the volunteers. These differences lead to increased shoulder belt slip-out in the ATDs compared to the volunteers. Belt pre-tightening had a great effect on ATD performance and appears to be a promising preventive measure for pediatric occupants. These data provides an insight into the pediatric ATD biofidelity in low-speed far-side impacts and have important implications in future design and construction of preventative measures in vehicles today.

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