RECONSTRUCTION OF A REAL WORLD CRASH INVOLVING A CHILD USING HYBRID III 10-YEAR OLD AND 5TH PERCENTILE ADULT FEMALE ATDS

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ABSTRACT

Validation data for child anthropomorphic test devices (ATDs) are scarce, making it difficult to assess their biofidelity. The goal of this study was to use previously collected real-world data involving a frontal crash with a child occupant to assess the biofidelity of current child dummies. The 9-year old child's anthropometry placed him between the size of the Hybrid III 10-year old and 5th-percentile Adult Female (AF5) dummies. Though injuries on the child indicated that he was properly belted, there were contact points on the vehicle interior and the exact position of the child before the accident could not be definitively determined from the crash investigation. Sled tests with identical seat belts and bench seat were conducted with the HIII-10 year old (n=9) and AF5 (n=6) in various seating configurations to explore the possible posture of the child before the accident. The tests were designed to reproduce the predicted Delta-V of 51 km/h with a smaller subset of the tests performed at 59 km/h to assess the implications of a higher speed on occupant contacts. Video analysis was performed to determine trajectories of the dummy head, chest, pelvis, and extremities. Despite the variation in speed, neither dummy was able to achieve the maximum head excursion necessary to make contact with the dash board. The results suggest that the dummies may underestimate the magnitude of excursion experienced by the child involved in the actual crash. To further investigate this finding, a sensitivity study was carried out using MADYMO Hybrid III 5th percentile female model. In addition to making use of existing data to further the investigation of child dummies, this study examines the biofidelity of two dummies used in child response approximation.

INTRODUCTION

The design of safety equipment for children relies on accurate biomechanical information about their response in crashes. Given the paucity of validation data for child ATDs used in the development and evaluation of safety equipment, efforts must be made to use all available sources. The source of additional data examined in this study is the reconstruction of an automobile crash involving a child. Information about the characteristics of the crash will be used to attempt to recreate the outcome of the crash in laboratory conditions. In the actual crash, the child appeared to be correctly belted in a three point belt when the vehicle had a severe frontal crash with a tree. It is likely that the child was leaning in some fashion to the left in an attempt to help steer the vehicle due to the fact that the driver had lost consciousness while driving. This hypothesis stems from the fact that the child had a head contact closer to the centerline of the vehicle.

This case was chosen for reconstruction because the child seemed to be belted properly (lung contusions, chest contusions, right clavicle fracture all consistent with good shoulder belt placement), did not show signs of submarining (no abdominal injuries, presence of contusions from lap belt low on pelvis), and had a definitive head contact in the vehicle (severe head injury and definite head loading marks on dash). The only criteria which were not ideal were that the child had some degree of non-optimal initial positioning leading to the head contacting the dash approximately 40 cm left of his centerline seating position.

METHODS

Real World Crash

The case was drawn from the Partners for Child Passenger Safety (PCPS) Crash Investigation database. The PCPS Crash Investigation database, from a collaboration between Children's Hospital of Philadelphia and State Farm Insurance Companies, consists of crashes involving child passengers reported to a US auto-insurance company and selected for detailed crash investigation.

The case vehicle was a 1998 Chevrolet W/T 1500 pick-up truck. The W/T stands for "work truck" and indicates the trim level of the vehicle. The work truck is the most basic model of the 1500 series. The work truck trim level differs in several ways from the other trim packages offered in the 1998 model year selection of 1500 series truck with one of the most important differences being the vinyl bench seat as opposed to a cloth bench or cloth captain's chairs that were offered in other levels. The vehicle was also equipped with an after-market seat covering resembling a cotton blanket. The vehicle had cargo in the bed of the truck that increased the overall mass of the vehicle by 159 kg which included the following: camping equipment, 3 bicycles, and tents. With cargo and occupants included the total mass of the vehicle was 2141 kg.

The vehicle was traveling on a tortuous, wooded road when the driver, an adult male, lost consciousness, veered off the road and struck a tree. The driver was restrained with a three point belt and airbag while the child passenger, a 9-year old male, was only restrained with a three point belt. The passenger airbag had been turned off due to the age of the child according to current recommendations. Based on the crash reconstruction, the vehicle had a Delta V of 51.4 km/h and an impact speed of 55.6 km/h. The vehicle made impact with the tree near the centerline of the vehicle causing the crash to be a directly frontal crash with no rotation. The principal direction of force was approximately 360 degrees and the maximum crush depth was 78.4 cm located 7 cm right of the vehicle center line. The child showed injury signs consistent with belt loading on his pelvis and right shoulder indicating proper belt use. The vehicle interior contact locations suggested that the child was out of position at the time of the crash. It was speculated that the child was attempting to either assist the driver or steer the vehicle before the tree impact occurred.

The injuries to the child were severe and caused the child to remain deeply comatose for 12 days after the accident. His head impact was attributed to contact with the displaced vent cover. Heavy scuffing and residual epidermis deposits were found on the vent cover located on the dashboard near the centerline of the vehicle (Figure 1).

Figure 1. Interior of vehicle with contact locations identified.

The case occupant's severe head injuries consisted of a cerebral edema (AIS-3), left medial temporal/posterior basal gangliar hemorrhagic contusions (AIS-5), a diffuse subarachnoid hemorrhage and a diffuse axonal injury with a white matter injury (AIS-5). He also sustained soft tissue ecchymosis areas above each eye (AIS-1). The proper use of belts was determined by injuries sustained to the child's torso and pelvis. His lower torso loaded the lap belt webbing which resulted in ecchymotic lesions over his pelvis (AIS-1). His interaction with the shoulder belt webbing resulted in a right chest contusion (AIS-1), a complete fracture through the mid-shaft of the right clavicle (AIS-2) and a right lung contusion (AIS-3) with residual atelectases. Though other injuries occurred, these injuries were the most pertinent to crash reconstruction and the severity of the crash.

Crash Reconstruction

The child's anthropometry placed him between the size, stature and approximated seated height, of the Hybrid III 10 year old and Hybrid III 5th percentile female dummies (Table 1). Both dummies were tested, and due to the relatively small differences between the child and each dummy size, no scaling was performed on the dummy injury metrics or kinematic trajectories.

Table 1.
Anthropometric data for 9-year old involved in crash

Measurement	Unit	Value
Shoulder to Hip	cm	41
Elbow to Beginning of Hand	cm	20
Hip to knee	cm	37
Knee to ankle	cm	33
Seat to Shoulder	cm	50
Bottom of Neck to Top of Head	cm	20
Head Circumference	cm	51
Neck Length	cm	5
Chest Circumference	cm	76
Height	cm	145
Weight	kg	34
Percentile based on Height	%	95
Percentile based on Weight	%	85

The sled tests were conducted using the UVA sled system (Via Systems Model 713). The test fixture, or "buck," utilized in this test series consisted of the front bench seat of a 1998 Chevrolet 1500 W/T with correct anchorage locations for the vehicle seatbelts. The anchorage locations were determined from measurements of a similar vehicle using a portable measurement device (Platinum FARO Arm, FARO Technologies Inc.). The seat-adjustment mechanism was removed to make it more durable for repeated testing, and both the seat pan and seat back were rigidly fixed to the buck. One test was conducted with the standard seat fixture to determine the effect of rigidizing the seat.

The tests were recorded using three high-speed (1000 frames/s) digital video imagers. The color imagers (Redlake HG-TH) were positioned to provide a perpendicular view from each side of the sled track, and an overhead view. These imagers were used to capture complete video records of the entire deceleration phase of the test event. Numerous photo targets were placed on the occupant and vehicle buck. Photos documenting both pre- and post-test conditions were taken with a digital still camera.

Sled deceleration and restraint belt loads were recorded for all of the tests. The ATD was instrumented to record accelerations, forces, and moments. Triaxial accelerometers were mounted at the head center of gravity (CG), at the chest CG, and at the pelvis CG. Load cells were located at the upper neck, lower neck, and lumbar spine and captured F_x, F_y, F_z, M_x, and M_y forces and moments. Load cells were also located at the left and right iliac spines, capturing F_x and M_y data. Chest displacement was also measured. Appendix C contains complete instrument descriptions.

Electronic data was acquired at 10,000 samples/sec using TRAQ-P, a DSP Technology Transient Acquisition and Processing System. The data was collected using IMPAX (DSP Technology) a PC-based data acquisition program. Data associated with a time domain from the beginning of the test event (T_0) until 150 ms after T_0 were selected for post-processing. Raw force and acceleration data were processed by subtracting small initial offset values, filtering to SAE J211-prescribed filter classes, and calculating resultants and injury criteria parameters.

Several parameters were included in the test matrix. The original case analysis predicted a Delta-V of 51 km/h, and the majority of the sled tests were performed at this speed. A subset of test conditions was repeated at 59 km/h to test the effect of speed. One final test was also performed in which the vehicle bench seat was tested without the rigidized base which was used for every other test. Replacing the seat support system with a rigid component is common in sled tests to create a more consistent, durable testing environment. For this final test, however, the original seat support system was installed.

The most important parameter varied, however, was the initial position of the dummy. The baseline tests positioned the dummies as specified by FMVSS 213, except for modifications suggested by Reed (2006) (Figure 2 and Figure 3).

Figure 2. View of baseline ATD positioning in reconstruction tests with Hybrid III 10-year old.

Figure 3. Oblique view of baseline ATD positioning in reconstruction tests with Hybrid III 10-year old.

The dummy was calibrated prior to the baseline testing, and all joints were adjusted to the relevant specification (1 g). For the Hybrid III 10-year old the lumbar joint was adjusted to a zero degree angle (most upright), while the adjustable neck was located in the 8 degree position. In addition, a 20 mm pad was placed behind the pelvis so that the dummy more accurately matched the sitting position of real children (Reed, 2006). To attempt to account for the unknown position of the child before the crash began, each dummy was moved in a variety of possible postures that the child could have been in before the crash. One position, "Torso," was based on the possibility that the child was leaning forward (sitting more upright) without moving his lower body (Figure 4).

The dummy was also positioned to simulate the situation in which the child may have been slouched significantly forward (possibly sleeping) and then sat straight up. For this condition "Body," the entire dummy was translated forward, which provided a good comparison with the baseline tests with no significant change in dummy orientation (Figure 5).

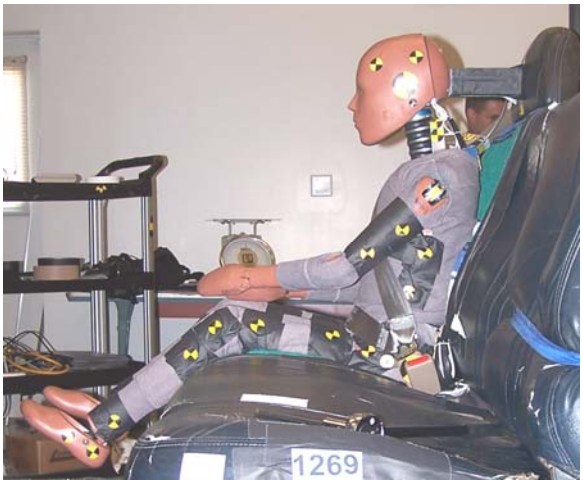

Figure 4. View of "Torso" adjusted position of ATD in reconstruction test with Hybrid III 10-year old.

Figure 5. View of "Body" adjusted position of ATD in reconstruction test with Hybrid III 10-year old.

Since there was strong evidence that the child had moved to the left prior to the crash, possibly while shaking the driver or attempting to steer the truck, the next dummy position, "Lean," involved leaning the dummy to the left with no other rotation along the Z axis, although there was some forward movement of the upper body (Figure 6).

Figure 6. View of "Lean" adjusted position of ATD in reconstruction test with Hybrid III 10-yeal old.

Finally, the most extreme position, "Lean-Rotate," involved both leaning the dummy to the left and rotating the dummy to the left along the Z axis (Figure 7 and Figure 8).

Figure 7. Frontal view of "Lean-Rotate" adjusted position of ATD in reconstruction test with Hybrid III 10-yeal old.

Figure 8. Side view of "Lean-Rotate" adjusted position of ATD in reconstruction test with Hybrid III 10-yeal old.

Both of the ATDs were tested in each of the adjusted positions with the Hybrid III 10-year old tested at the higher speed as well. The 5th percentile female was not tested at the higher speed but was tested with the standard, non-rigidized, seat support (Table 2).

Table 2.
Test matrix for reconstruction tests involving the Hybrid III 10-year old and 5th percentile female ATDs

9-Year Old Real World Reconstruction Tests		
	HIII 10yo	**AF5**
Baseline	X	X
Baseline, higher speed	X	
Baseline, non-rigidized seat		X
Torso leaning forward ("Torso")	X	
Whole body shifted forward ("Body")	X	X
Whole body shifted forward ("Body"), higher speed	X	
Leaning left ("Lean")	X	X
Leaning left/whole body rotated ("Lean-Rotate")	X	X
Leaning left/whole body rotated ("Lean-Rotate"), higher speed	X	

For use in the sled testing, a crash pulse was developed that represented the unknown crash pulse of the case vehicle. Using Insurance Institute for

Highway Safety (IIHS) event data recorder (ERD) pulse information for totally frontal pole crashes it was found that the velocity-time curves were similar between crashes with an 80 ms duration for several crash events. The shape of the known velocity-time curves was used along with the 80 ms duration to develop the crash pulse that would be used in our test series (Figure 9).

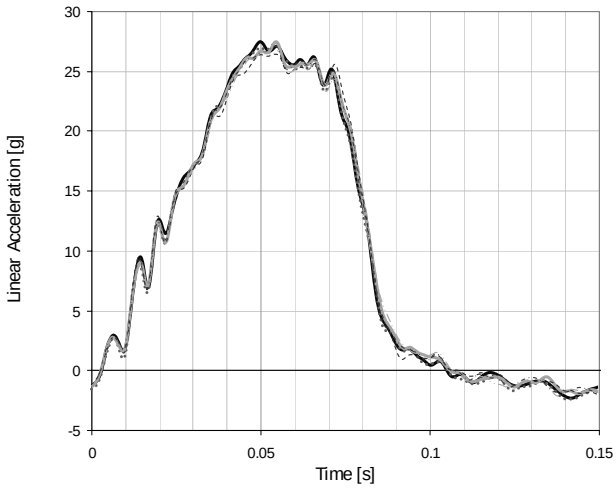

Figure 9. Example crash pulse from reconstruction tests developed from ERD pulse information involving totally frontal pole crashes.

Video Analysis

Markers for post test video analysis were placed on the ATDs. The markers were placed on tape that was directly attached to the outer skin of the dummy. Holes were cut in the clothing covering the ATDs to allow for direct attachment of the tape markers to dummy skin. This direct attachment was done to prevent any introduction of error in the video analysis from marker movement during testing. A coordinate system was established for the kinematics of the ATDs with the origin at the junction of the top surface of the seat cushion and the rear surface of the backrest.

Sensitivity Study

In order to assess the sensitivity of subject response to various conditions, a series of computer simulations were conducted using the MADYMO 6.4.1 solver (MADYMO, 2008).

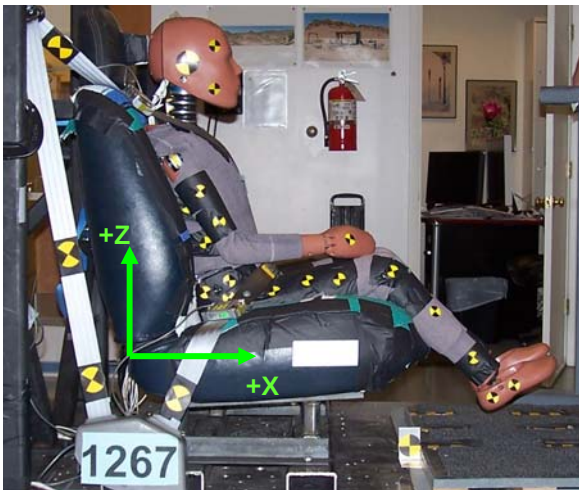

Figure 10. Origin of coordinate system for ATD kinematics.

A baseline simulation mirroring the initial sled test of the Hybrid III 5th percentile small female test dummy (Figure 11) was refined to within 10% of the measured response for shoulder belt tension, head excursion, head acceleration, chest acceleration, and chest deflection. Before conducting a parameter sensitivity study, the MADYMO model of the Hybrid III 5th percentile female was modified to include joint in the thoracic spine, similar to a previous study using the Hybrid III six-year-old test dummy (Sherwood, 2003). However, instead of a revolute joint, a free joint was added with restraints in all six degrees of freedom: longitudinal shear, lateral shear, tension/compression, flexion/extension, lateral bending, and torsion. The baseline restraint functions for each of these degrees of freedom were set to be twice as stiff as those of the modified Hybrid III six-year-old dummy, though the initial magnitude was not expected to influence the parameter sensitivity study.

A total of nineteen parameters were included in the parameter sensitivity study (Table 3). The first eighteen parameters represent a scale factor applied to the force or moment component of the force-deflection or moment-rotation restraint characteristics of the lumbar spine, thoracic spine, and the neck. Changes to the neck joint restraints are applied to each of the five neck joints. The final parameter describes the orientation of the subject about the longitudinal axis of the vehicle, expressed in radians.

Figure 11. Comparison of the MADYMO simulation (top) to the physical sled test of a Hybrid III 5th percentile female dummy.

Table 3.
List and description of variables included in the MADYMO Hybrid III 5th percentile female parameter sensitivity study.

Category	Description	Component	Minimum Value	Maximum Value
Neck	Longitudinal Shear	FX	0.01	1.5
	Lateral Shear	FY	0.01	1.5
	Tension/Compression	FZ	0.01	1.5
	Lateral Bending	MX	0.01	1.5
	Flexion/Extension	MY	0.01	1.5
	Torsion	MZ	0.01	1.5
Thoracic Spine	Longitudinal Shear	FX	0.01	1.5
	Lateral Shear	FY	0.01	1.5
	Tension/Compression	FZ	0.01	1.5
	Lateral Bending	MX	0.01	1.5
	Flexion/Extension	MY	0.01	1.5
	Torsion	MZ	0.01	1.5
Lumbar Spine	Longitudinal Shear	FX	0.01	1.5
	Lateral Shear	FY	0.01	1.5
	Tension/Compression	FZ	0.01	1.5
	Lateral Bending	MX	0.01	1.5
	Flexion/Extension	MY	0.01	1.5
	Torsion	MZ	0.01	1.5
Orientation	Lateral Leaning	RX	0.0 radians	0.25 radians

Using these nineteen parameters, 5,000 designs were constructed using a randomizing algorithm that results in a uniform distribution of each variable between its minimum and maximum values. If computational errors occurred during simulation of any of the designs, the design was removed from this initial population. Such errors occurred when the chosen parameters resulted in model instability, which can occur when low restraint forces allow unrealistically high relative velocities between rigid bodies.

The output from each design was the forward head excursion, measured as the difference between the initial position of the center of gravity (CG) of the head and the forward-most position of the head CG at any point in the simulation.

This calculation assumed that the distance between the CG and the anterior portion of the head was similar to the distance between the CG and the superior portion of the head, either of which could impact the instrument panel of a vehicle in a frontal collision.

RESULTS

Video analysis

The trajectories of the head CG, shoulder, and knee joints were measured. Based on pre-test measurements, the location of the H-Point was determined based on a distal thigh marker location and the angle of the femur, which was recorded during ATD placement. Thus, the data presented are those of the actual H-Point location, except for tests involving "Lean" and "Lean-Rotate" when the out of plane positioning of the dummy eliminated the use of this procedure. In these tests, the approximate position of the H-Point was estimated during the video analysis digitization process. Figures presented are from tests where the ATD was translated forward in the seat or leaning forward (Figure 12 - Figure 18) where out of plane motion is not substantially present.

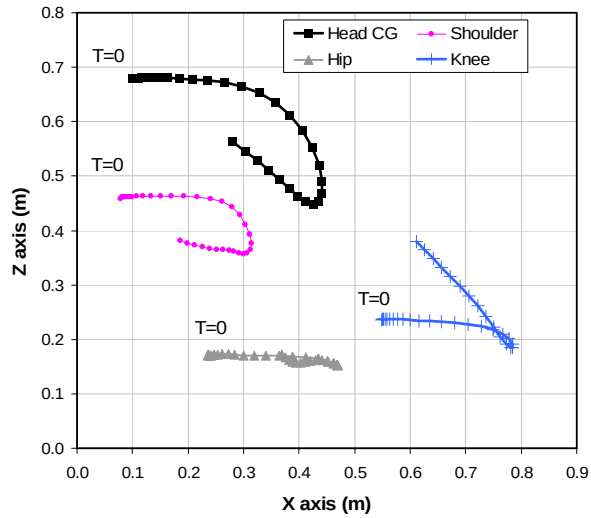

Figure 12: Kinematic trajectory for a low speed baseline test involving the Hybrid III-10 year old (Test #1267).

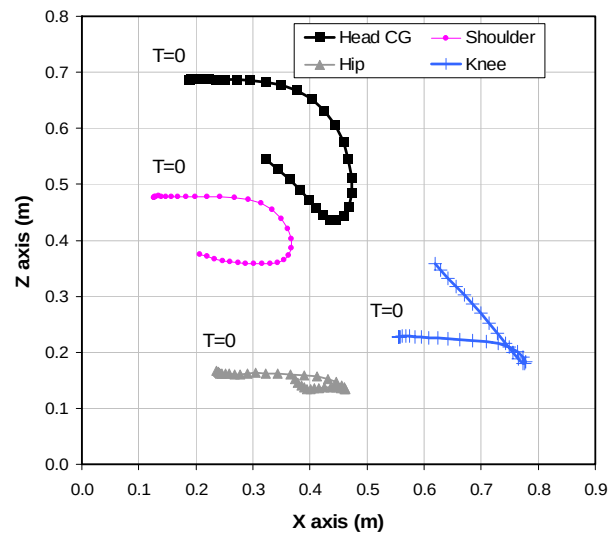

Figure 13: Kinematic trajectory for a low speed "Torso" positioned test involving the Hybrid III-10 year old (Test #1269).

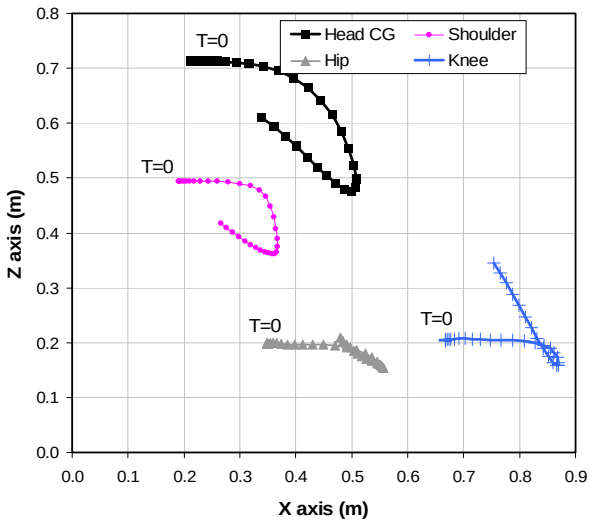

Figure 14. Kinematic trajectory for a low speed "Body" positioned test involving the Hybrid III-10 year old (Test #1270).

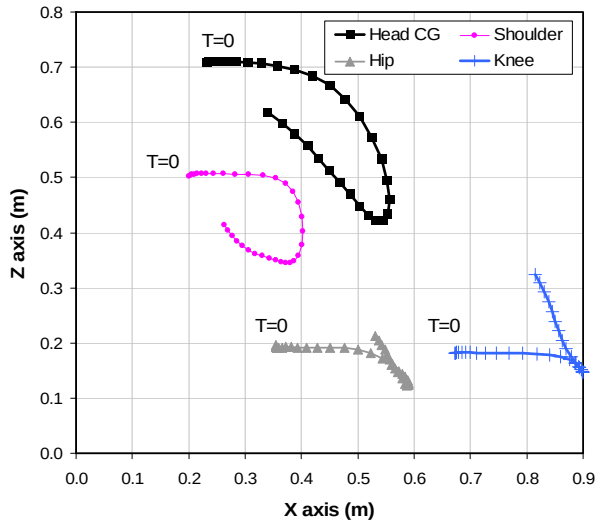

Figure 16. Kinematic trajectory for a high speed "Body" positioned test involving the Hybrid III-10 year old (Test #1274).

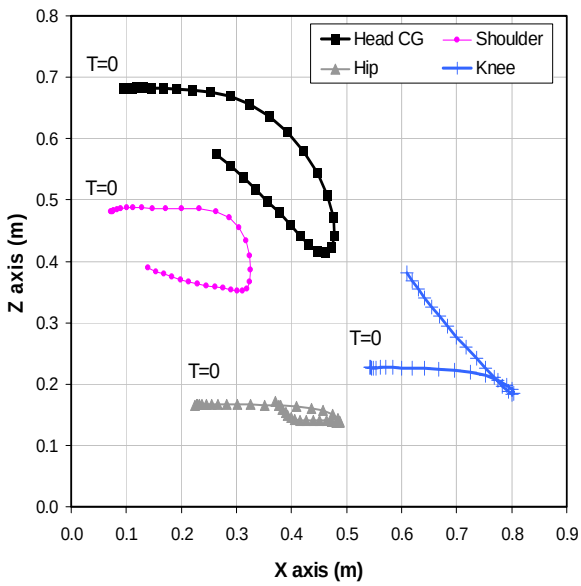

Figure 15. Kinematic trajectory for a high speed baseline test involving the Hybrid III-10 year old (Test #1273).

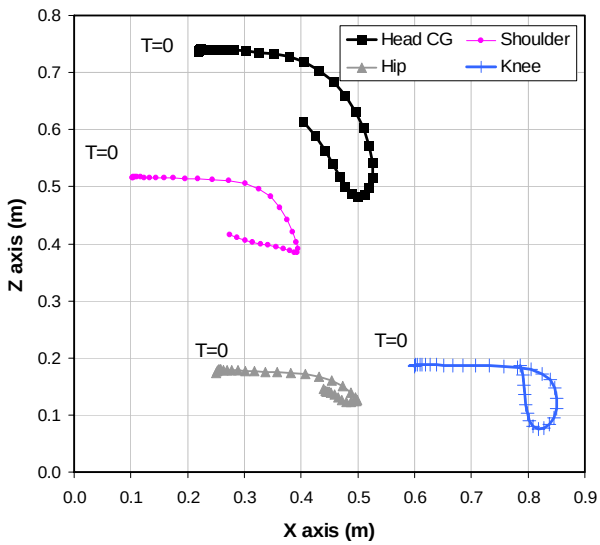

Figure 17. Kinematic trajectory for a low speed baseline test involving the 5th percentile female ATD (Test #1278).

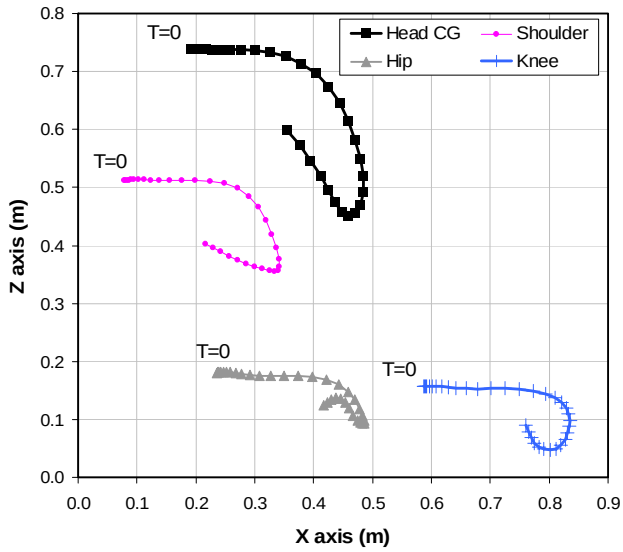

Figure 18. Kinematic trajectory for a low speed baseline test involving the 5th percentile female ATD with original (non-rigid) seat support (Test #1282).

The low speed and high speed tests under the same positioning conditions produce similar kinematic trajectories with a slightly larger head excursion value (Figure 12 vs Figure 15 and Figure 14 vs Figure 16). The effect of making the seat base rigid may cause the dummy excursion values to be overestimated. When the seat base was allowed to deform during the test, the head excursion value was reduced by 3.5 cm (Figure 18 compared to Figure 17).

In order for the ATDs to achieve a head excursion value that would cause contact with the vent on the vehicle's dashboard, the front of head excursion would need to exceed 71.3 cm in the kinematic trajectory reference frame (Figure 10). The front of head excursion value was digitized during video analysis in order to determine the forward-most point on the ATD's head (Figure 19). No excursions reached the 71.3 threshold.

Figure 19. Front of head excursion point and head CG point found during video analysis.

Table 4.
Peak Front of Head excursion data (data in cm)

	Low Speed		High Speed
	HIII 10yo	AF5	HIII 10yo
Baseline	55.4	61.0	59.1
Baseline non-rigid		57.5	
Torso	58.3		
Body	62.1	69.4	66.5
Lean	62.4	67.6	
Lean-Rotate	62.4	69.1	64.9
Truck head contact point	**71.3**	**71.3**	**71.3**

Sensitivity Study

Head excursions ranged from 24.4 to 59.6 centimeters (parameters that result in each of these conditions are listed in Table 5).

Table 5.
Parameter values that result in the lowest and highest head excursions.

Category	Component	Min. Head Excursion	Max. Head Excursion
Neck	FX	0.0116	0.9924
	FY	1.3663	0.5468
	FZ	0.1090	1.0072
	MX	1.2378	1.1990
	MY	0.9023	1.1581
	MZ	0.2820	0.8485
Thoracic Spine	FX	0.4934	0.2083
	FY	0.9801	0.1921
	FZ	0.5836	0.3922
	MX	0.9444	1.3581
	MY	0.7079	1.4102
	MZ	0.8138	0.9837
Lumbar Spine	FX	0.9353	0.8258
	FY	1.0499	0.4395
	FZ	1.2172	0.8479
	MX	0.5496	1.4118
	MY	0.7383	0.1920
	MZ	0.6336	0.9876
Orientation	RX	0.0034 rad	0.2175 rad

Table 6.
Results of an ANOVA comparing the means of head excursion between groups of values for each variable.

Category	**Component**	**F-statistic**	**P-value**
Neck	FX	19.56	<0.000001
	FY	9.48	<0.000001
	FZ	21.92	<0.000001
	MX	5.36	2.68E-04
	MY	7.36	6.71E-06
	MZ	5.76	1.29E-04
Thoracic Spine	FX	1.01	4.00E-01
	FY	6.52	3.18E-05
	FZ	3.51	7.25E-03
	MX	12.09	<0.000001
	MY	2.45	4.44E-02
	MZ	4.54	1.18E-03
Lumbar Spine	FX	8.69	<0.000001
	FY	2.16	7.08E-02
	FZ	7.21	8.93E-06
	MX	8.31	1.15E-06
	MY	3.08	1.52E-02
	MZ	6.74	2.14E-05
Orientation	RX	445.82	<0.000001

For each of the nineteen variables, an analysis of variance (ANOVA) was carried out to determine whether changes in that variable resulted in changes in head excursion. To begin this process, the head excursion values for the design population were divided into five bins based on the value of the respective variable. The ANOVA was conducted to determine whether the differences in the means of the five bins were statistically significant ($p<0.05$), which indicates that the model prediction of head excursion was sensitive to changes in the respective variable.

All but two of the nineteen parameters had a significant effect on the head excursion. The two parameters which do not affect head excursion were thoracic spine longitudinal shear (FX) stiffness and lumbar spine lateral shear (FY) stiffness. For the remaining parameters, the variance between the bins was much larger than the variance within each bin, indicating that the head excursion changed with changes in the parameter values (Table 6). The strongest trend occurred with changes the orientation of the subject in the seat, which showed an increasing trend (Figure 20). There was also a strong influence of the model prediction of head excursion with changes in longitudinal shear stiffness and tension/compression stiffness of the neck, as well as lateral rotation stiffness of the thoracic spine.

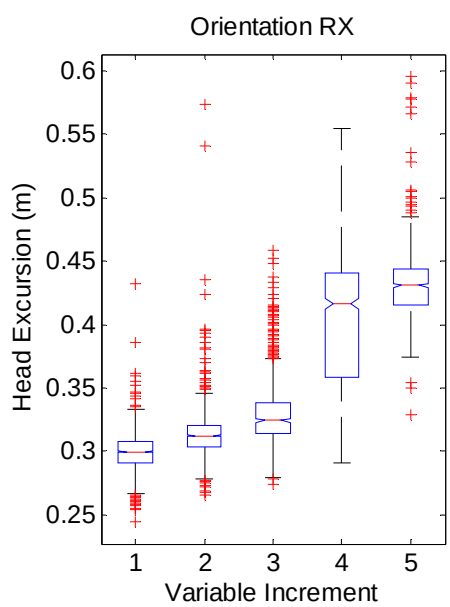

Figure 20. Median (red), 5% range (notch), and inter-quartile range (blue box) of head excursion for five increments of initial longitudinal orientation of the subject on the seat.

The sensitivity study determined an absolute difference in the head excursion between the beginning of the test and the point of maximum excursion. This excursion values can be compared to the excursion values from the ATD tests by using the initial offset in the baseline 5th percentile female test (Figure 17). This initial offset can be used because the positioning used in the MADYMO simulations before any lateral adjustments matched this test. Once the lateral adjustments were incorporated the initial X value of the head CG would still match the baseline position value since only lateral movement was included. The initial offset in the X direction of the baseline 5th percentile female was 21.8 centimeters. This offset then caused the simulation maximum excursion values to range from 56.2 to 81.4 centimeters in the kinematic trajectory coordinate system. The maximum value of the simulation maximum excursion value exceeded the truck head contact point value, indicating that the adjusted 5th percentile female from the simulations would be capable of striking the vent of the vehicle's dashboard.

DISCUSSION

The results suggest that the child dummies likely underestimate the excursion amounts experienced by the child involved in the actual crash. There were many complex factors involved in the analysis of this data, and the results do not lend themselves to definitive conclusions. There were some results, however, which are promising, and this data should be considered to be a single component of a large study of the response of pediatric ATDs.

The overall kinematic motions of the dummy were consistent and similar among all tests. Even when rotated or leaning to the left, the shoulder belt maintained its position on the chest, which is likely occurred in the actual crash as evidenced by the clavicle fracture. Despite very different initial positions, the measured forward head excursion values fell in a very narrow range. This might suggest that given any reasonable seating position, the total excursion value is relatively consistent when measured with the dummy.

This parameter sensitivity study suggested that even with spinal stiffness changes to the existing Hybrid III 5th percentile female test dummy, the head excursion necessary for a subject of similar size to impact the instrument panel was not possible without changes to the initial position of the subject from the standard seating position. However, head excursion did increase with the addition of a joint in thoracic spine of the dummy model, though the main influence of thoracic spine stiffness on head excursion occurred with changes to its lateral bending stiffness. This suggests that the dummy is more sensitive to the load path of the shoulder belt when additional degrees of freedom are introduced in the spine, as increased head excursion occurs as the dummy rotates around the axis of the shoulder belt. Adjustments to rigid spine of 5th percentile adult female yielding larger excursion values also agrees with other studies that have examined the role of the rigid spine in ATD kinematics (Sherwood, 2003 and Ash, 2009)

LIMITATIONS

A limitation of this study was the limited number of tests conducted at each position of the dummy. Additionally, though several positions were tested in an attempt to account for the unknown position of the child before the crash, the various positions were not a comprehensive examination of all possible positions. Though it would have been impractical to have each test performed on a standard, non-rigid seat, the introduction of the rigidized seat likely affected the response of the ATDs. There are also errors inherently introduced during the video analysis.

CONCLUSIONS

This study found that under the reconstructed conditions of the crash using ATDs of similar size compared with the child involved in the crash, the maximum head excursion needed to have head strike on the dash was not achievable with the current dummies. It was found that if adjustments were made to the neck, thoracic spine and lumbar spine of the 5th percentile female ATD model in MADYMO simulations, the excursion value needed for head strike was achievable.

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