A New Database of Child Anthropometry and Seated Posture for Automotive Safety Applications

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ABSTRACT

This paper presents a laboratory study of body dimensions, seated posture, and seatbelt fit for children weighing from 40 to 100 lb (18 to 45 kg). Sixty-two boys and girls were measured in three vehicle seats with and without each of three belt-positioning boosters. In addition to standard anthropometric measurements, three-dimensional body landmark locations were recorded with a coordinate digitizer in sitter-selected and standardized postures. This new database quantifies the vehicle-seated postures of children and provides quantitative evidence of the effects of belt-positioning boosters on belt fit. The data will provide guidance for child restraint design, crash dummy development, and crash dummy positioning procedures.

INTRODUCTION

Occupant protection for children who have outgrown harness-based restraints has received increased regulatory and legislative attention in recent years. The U.S. National Highway Traffic Safety Administration (NHTSA) recommends that children who are ages four to eight and over 40 lb (18 kg) use belt-positioning boosters (also known as booster seats) with a three-point (lap-shoulder) vehicle belt (NHTSA 2004). A belt-positioning booster is designed to position the child and route the vehicle seatbelt such that the child is well restrained by the belt.

The recent emphasis on booster usage follows evidence from the field that children from four to eight years of age are less likely to be properly restrained than vehicle occupants in any other age group. Many children move directly from harness restraints to vehicle belts even though the children are often too small to obtain good restraint from the vehicle belts alone. The serious consequences of poor belt fit include injuries to the lumbar spine and abdomen as the lap portion of the belt slides off the pelvis and loads the abdomen during a frontal impact. This pattern of occupant motion relative to the belt is often referred to as submarining.

Belt-positioning boosters have been shown to be effective in preventing these injuries. Durbin et al. (2003) examined data from crashes involving 4243 children ranging in age from four to seven years in a large, cross-sectional study of crash-involved children. The odds of injury, after adjusting for a variety of potentially confounding factors, were 59% lower for children using belt-positioning boosters than for children using only the seat belt. No injuries to the abdomen, spine, or lower extremities were reported for children using boosters, whereas children using belts alone had injuries to all body regions.

Using data from the same ongoing study, Nance et al. (2004) examined the incidence of abdominal injury in restrained children. Optimal restraint was defined as usage of a child safety seat with harness for children four years of age or less; lap-shoulder belt with a belt positioning booster for children four to eight years of age; and lap-shoulder belt for children older than eight years. Any other restraint configuration, such as a four-year-old child in a vehicle belt alone, was considered suboptimal. An analysis of data from large-scale survey of children involved in crashes showed that abdominal injuries were three times less likely among children who were optimally restrained. The percentage of restrained, crash-involved children who sustained abdominal injury peaked in the six- to eight-year-old range within which the percentage of children who were optimally restrained (using belt-positioning boosters, under this definition) was less than ten percent.

Arbogast et al. (2004) analyzed data from the same study to show that children four to eight years old are at significantly greater risk of serious abdominal injuries than older or younger children, where serious injuries are those scored as 2 or greater on the Abbreviated Injury Scale (AIS). Among this age group, children who were restrained by a vehicle belt alone (lap or lap/shoulder) were about 34 times more likely to sustain an AIS2+ abdominal injury than those using belt-positioning boosters or harness restraints.

In the past three years, at least 22 U.S. states have passed legislation that addresses occupant protection for children over four years of age, and similar legislation has been introduced in the remaining states (SAFE KIDS, 2004). Most state child-restraint laws classify children based on age, typically requiring child restraint use up to six years of age. Most parents and caregivers rely on legislation as their guide to appropriate restraint use, so legislation is seen as a critical step for reducing injury for this population. However, because children of the same age vary widely in size, age-based regulation with too low of a cutoff age may not achieve the goal of properly matching children and restraints.

In 2002, the U.S. Congress passed legislation known as Anton's Law that directs NHTSA to take a variety of actions addressing safety for older children. Among the major provisions, NHTSA was directed to revise FMVSS 208 to require lap-shoulder belts in all rear seating positions, to incorporate in regulation a crash dummy representing a 10-year-old child, and to study the effectiveness of vehicle-integrated child restraints. In addition, NHTSA was directed to "consider whether to establish performance requirements for seat belt fit when used with booster seats and other belt guidance devices."

Few previous studies have examined belt fit for children in booster seats. Klinich et al. (1994) studied belt fit for 155 children between seven and twelve years of age in three rear vehicle seats and three belt-positioning boosters. Belt fit and posture were evaluated subjectively using multi-category scales by examining videos of the children in each of the test conditions. The boosters were found to improve belt fit significantly for most children in most of the tested combinations of booster and vehicle seat. The researchers noted that one cause of poor belt fit in the absence of a belt-positioning booster was the tendency of the children to slouch rather than to sit maximally rearward on the seat. Discomfort associated with extended knees was identified as the impetus for the slouched posture, and the boosters were shown to allow postures with greater knee flexion and less slouching. Poor belt fit resulting from slouching has been implicated in abdominal injuries (Glassman et al. 1992; Johnson et al. 1990), particularly when children are restrained by a lap belt alone.

Chamourd et al. (1996) identified significant problems with the pelvis and thigh dimensions of the 3YO, 6YO, and 10YO P3 dummies and 3YO and 6YO Hybrid-III dummies. Pelvis measurements from 54 children sitting on the ground with their backs against a wall were compared to dummy dimensions in similar postures. Radiographs of seven children in standing and seated postures were used to assess the fidelity of the crash dummy pelves. They authors concluded that the combination of unrealistic thigh flesh and pelvis dimensions made the dummies much less susceptible to submarining than children. Submarining occurs when the pelvis slides below the lap portion of the belt, allowing the belt to load directly onto the abdomen. These limitations made the dummies insensitive to differences in booster design and belt routing that would significantly affect safety for child occupants. Using a modified P3 dummy, the authors showed that good booster seat design requires lap belt guides that hold the belt flat on the upper thighs of the child, rather than targeting the anterior surface of the pelvis. The data from Chamourd et al. are limited in that the child anthropometry was measured in postures that are not representative of child postures in vehicle seats or boosters, and three-dimensional measurements of skeletal posture were not made. In particular, the seated pelvis orientation for the child volunteers and the routing of the belt relative to the skeleton were not reported.

Other data on child body dimensions have been used for child restraint design. Weber et al. (1985) extracted data from a large-scale survey of standard and functional child anthropometry (Snyder et al. 1977) to recommend dimensions for child restraints. These data are limited, however, by the differences between the vehicle-seated postures and the measurement postures, and by the lack of detailed information on the three-dimensional positions and orientations of key skeletal structures, such as the pelvis.

The current study was conducted to address some of the limitations of previous research on children in booster seats. In particular, the objectives of the current study are to:

1. develop a detailed database on vehicle-seated anthropometry, posture, and position for children and adolescents sitting in harness restraints, belt-positioning boosters, and vehicle seats with three-point belts;

2. develop a positioning procedure for six-year-old and 10-year-old crash dummies that provides representative posture and position on booster seats and vehicle seats;

3. develop a physical belt-fit assessment procedure for children from 40 to 100 lb that uses crash dummies (six-year-old and 10-year-old Hybrid III); and

4. identify differences between children and crash dummies that could adversely affect the fidelity of crash-test assessments of belt-positioning boosters.

This paper reports on the development of the child anthropometry database. Seated posture and belt fit were measured for 62 boys and girls weighing between 40 and 100 lb in a range of vehicle- and booster-seat conditions. Three-dimensional data on body landmark and seatbelt locations were obtained using a portable coordinate measurement machine. The data will be made available in a relational database to aid in the improvement of restraint systems for children.

METHODS

Reconfigurable Vehicle Mockup

Testing was conducted in an UMTRI laboratory using a reconfigurable mockup of a vehicle rear seating area shown in Figure 1. Four vehicle rear seats, shown in Figure 2, could be interchanged in the mockup. Two seats were obtained from sedans and one (seat 2) from a minivan. The seats were mounted high enough from the floor that none of the children were able to touch the floor with their feet while sitting all the way back on the seat, reproducing the typical situation for children in rear vehicle seats. Testing was conducted in the right outboard seating position on each seat, except that testing with seat D was conducted only in center seating position, which was equipped with an integrated harness restraint. The H-point location, seat back angles, and seat cushion angles were measured for each seat using the procedures in SAE J826 (SAE, 2004). All three seats were mounted so that the seat cushion angle (SAE A27) was 14.5 degrees, a typical value for vehicle seats. The seat back angle was varied across test conditions.

Figure 1. Reconfigurable vehicle rear-seat mockup in laboratory. The FARO Arm coordinate measurement device is visible at the right side of the picture.

Vehicle Belt Configurations

The vehicle mockup was equipped with a three-point belt system with a sliding latchplate and emergency locking retractor obtained from a late-model sedan. The retractor and D-ring were mounted to an adjustable fixture that provided a large range of fore-aft, vertical, and lateral adjustability. Each seat was equipped with a webbing-mounted buckle. In seat B, the location of the buckle anchorage could be varied over a wide range. The outboard anchorage was located in the same position with respect to H-point for each seat. The outboard anchorage location routed the belt near the seat bight, simulating typical rear-seat belt geometry.

Child Restraint Systems (CRS)

Figure 3 shows the four child restraints used in the study. CRS-A is a backless belt-positioning booster equipped with fixed-position belt guides. A flexible attachment provided with the restraint that is used to improve torso belt fit was not needed with the tested belt geometries and hence was not used. CRS-B is a high-back belt-positioning booster with an adjustable back angle. The back is height adjustable and is equipped with a path for the torso portion of the belt. During testing, the back height was adjusted for each participant to place the torso belt guide above the shoulders, following the manufacturer’s instructions. The lap belt guides, which are height adjustable, were tested at their lowest setting. CRS-C is a rigid-shell combination restraint that can be used with an integrated five-point harness or as a belt-positioning booster. Testing was conducted using the restraint as a belt-positioning booster with the harness removed. Open slots in the shell provide a lower belt path and a three-position clip on the upper portion of the back is provided to assist in routing the torso portion of the belt. CRS-D is a forward-facing-only restraint with a five-point harness that is rated by its manufacturer for children up to 36 kg (80 lb). CR-E is a restraint with a five-point harness that is integrated into a minivan bench seat. The vehicle owners’ manual recommends the restraint for children from 10 to 18 kg (22 to 40 lb).

Figure 2. Vehicle rear seats used in testing. From left, seats 1, 2, and 3.

A B C D E

Figure 3. Child restraints shown with 6YO and 3YO crash dummies (CRS E is integrated in vehicle seat 4).

Test Conditions

Data were gathered in the 20 test conditions listed in Table 1. The test conditions were selected to investigate particular factors that were hypothesized to affect child posture or belt fit. Most of the testing was conducted in vehicle seat 1, a low-contour seat from a popular sedan. The first twelve test conditions examined the effects of seat back angle, sitting instructions, and booster use. The first six “sitter-selected posture” trials were conducted at the start of each participant’s testing. Tests with and without the CRS were blocked, and the order of the blocks and of trials within each block were randomized. The participant was instructed to sit in the vehicle seat or child restraint and to put on the belt. The child chose his or her preferred posture and buckled the belt without coaching or further instruction. Test conditions 7-12 were conducted next, using the same blocking and randomization approach used in trials 1-6. In these trials, the participants were instructed to sit as far back as possible on the seat with the arms and legs sagittally symmetric and the hands on the thighs. This “standard” posture conditions are intended to produce less-variable postures that might be appropriate to reproduce with crash dummies. The investigator deployed and buckled the belt in the standard-posture trials.

Trials 13, 14, and 15 used child restraints B, C, and D on seat 1 with a fixed back angle of 23 degrees. In trial 16, children were tested on seat 2 without a child restraint. Trials 17-19 were conducted on seat 3 with no child restraint and with three different buckle locations to quantify the effect of seatbelt geometry on belt fit. In trial 20, children who meet the weight requirements for the integrated restraint were tested in seat 4 (restraint E). In test conditions 1-14 and 16 the buckle location was set to position measured in the vehicle from which the test seat was obtained. The D-ring position was set to location in the vehicle model from which each seat was obtained, except that the D-ring position was rotated around the H-point with seat back angle changes.

Participants and Standard Anthropometry

Sixty-two children (27 girls and 35 boys) were recruited for testing by word-of-mouth, fliers, and newspaper advertisements. Table 2 summarizes some of the participant characteristics. The goal was to recruit children who spanned the range of potential users of belt-positioning boosters with respect to stature and weight, including the range between the masses of the 6YO and 10YO Hybrid-III crash dummies (23 kg and 32 kg, respectively). Anthropometric dimensions were recorded using standard techniques (Roebuck, 1994). Figure 4 shows the measurement of knee height.

Table 1
Test Conditions

Condition	Vehicle Seat	CRS	Posture	Buckle Location	Seat Back Angle (SAE A40)
1	1	A	Sitter-Selected	Standard	19
2	1	A	Sitter-Selected	Standard	23
3	1	A	Sitter-Selected	Standard	27
4	1	None	Sitter-Selected	Standard	19
5	1	None	Sitter-Selected	Standard	23
6	1	None	Sitter-Selected	Standard	27
7	1	A	Standard	Standard	19
8	1	A	Standard	Standard	23
9	1	A	Standard	Standard	27
10	1	None	Standard	Standard	19
11	1	None	Standard	Standard	23
12	1	None	Standard	Standard	27
13	1	C	Standard	Standard	23
14	1	B	Standard	Standard	23
15	1	D	Standard	n/a	23
16	2	None	Standard	Standard	23
17	3	None	Standard	Low	23
18	3	None	Standard	Middle	23
19	3	None	Standard	High	23
20	4	E	Standard	n/a	23

Table 2
Participant Characteristics and Standard Anthropometric Measures

Measure*	Mean	S.D.	5th%ile	25th%ile	50th%ile	75th%ile	95th%ile
Age (years)	8.4	1.9	5	7	9	10	11
Stature	1334	115	1121	1245	1354	1430	1483
Stature (in)	52.5	4.5	44.1	49.0	53.3	56.3	58.4
Weight (kg)	31.8	7.8	19.4	25.1	32.1	37.3	43.8
Weight (lb)	70.1	17.3	42.7	55.3	70.8	82.3	96.5
Head Length	177	9	164	171	175	182	191
Erect Sitting Height	706	52	609	675	719	744	770
Shoulder Height	455	58	381	417	461	478	504
Acromion Height	436	42	372	401	448	469	489
Knee Height	401	41	329	375	405	435	455
Bideltoid Breadth	328	34	275	302	332	351	385
Biacromial Breadth	248	29	198	231	249	268	294
Hip Breadth	268	29	220	246	272	290	310
Shoulder-Elbow Length	286	27	242	264	291	310	322
Elbow-Fingertip Length	355	36	298	332	359	382	401
Buttock-Knee Length	457	49	377	418	470	494	519
Chest Depth†	152	17	124	140	149	168	178
Abdomen Depth†	168	25	135	152	165	182	214
Chest Width†	224	23	189	205	227	239	257
Abdomen Width†	213	26	178	192	208	234	260

* Dimensions in mm unless otherwise noted.
† Measured in hardseat in automotive posture (see text).

Figure 4. Fixtures for standard anthropometric measurements showing measurement of knee height.

Figure 5 shows the stature and weight of the participants in the context of the 1990 U.S. population based on NHANES III (see NCHS, 2004). Percentiles of weight were computed in 5-cm bins for children from 3 to 14 years old in NHANES III using the appropriate sample weights. The actual (unweighted) observations from NHANES III are shown in gray. As intended, the sample spans the reference stature and weight for both the 6YO and 10YO Hybrid-III dummies.

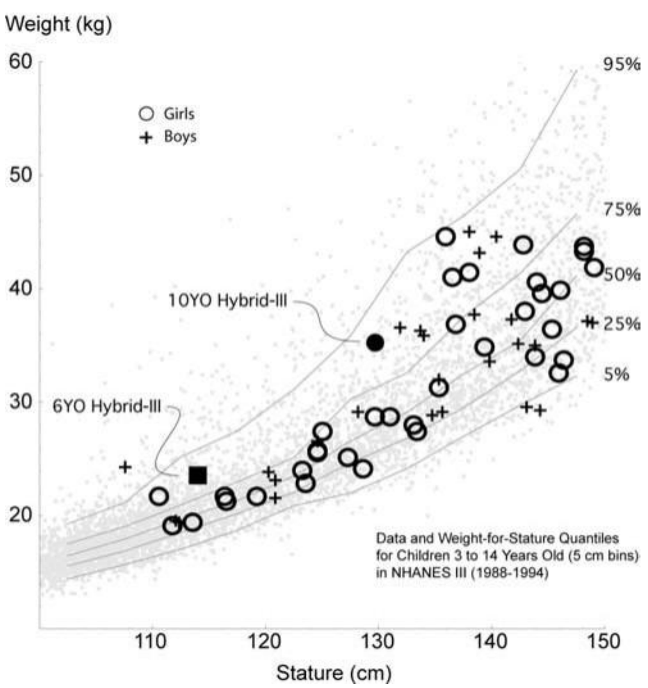

Figure 5. Stature and weight for the current sample compared with children from 3 to 14 years old in NHANES III (1990 U.S. population). Lines show quantiles in NHANES III based on 5-cm-wide bins. The reference stature and weight for the 6-year-old and 10-year-old Hybrid-III ATDs are shown.

Three-Dimensional Anthropometry

The three-dimensional location of body landmarks was measured in this study using a FARO Arm coordinate digitizer (FARO Technologies, Lake Mary, FL). The procedures were very similar to those used previously in many studies of adult occupant posture and position (Reed et al. 1999). The investigator located the desired landmark by palpation, placed the tip of the FARO Arm probe on the landmark, and pressed a button to record the location. All data were expressed in a laboratory coordinate system with the X axis positive rearward, Y-axis positive to the right, and Z-axis positive upward. Landmark data were recorded in each of the test conditions in Table 1 and while the participant sat in a specially constructed laboratory hardseat. The hardseat, shown in Figure 6, is designed to produce a posture similar to a vehicle-seated posture but to provide access to posterior landmarks on the spine and pelvis.

Table 3 lists the landmarks that were recorded during the vehicle-seat and hardseat trials. Reference points on the seat, CRS, and belt were recorded where applicable. The reference points allow the body landmark data to be referenced to a seat or CRS coordinate system. Points were digitized on the seatbelt or harness where it passed over the sternum, clavicle, and the lateral positions of the left and right anterior-superior iliac spines (ASIS). The landmark data for the participant were sufficient to define the three-dimensional locations of the major skeletal components, including the head, thorax, pelvis, clavicles, and the right humerus and femur. Figure 7 shows the landmarks schematically. In the hardseat, surface landmarks over the C7, T4, T8, T12, L3, and L5 spinous processes were recorded along with the locations of the left and right posterior-superior iliac spines (PSIS). Combined with the ASIS points, the PSIS points give the three-dimensional position and orientation of the pelvis. The spinous process landmarks were digitized twice and the pelvis landmarks four times to ensure that a consistent set of points was obtained.

Figure 6. Participant seated in a laboratory hardseat used to obtain posterior and anterior body landmarks in same posture. A slightly larger hardseat was used with the larger participants.

Table 3
Body, CRS, and Seat Landmarks Digitized During Testing

Hardware Reference Points	
Vehicle Seat Points (3*)	Torso Belt on Clavicle (2)
D-ring Location (3)	Torso Belt on Sternum (2)
Lap Belt Anchor	Lap Belt at ASIS-R (2)
Buckle Stalk (2)	Lap Belt at ASIS-L (2)
CRS Reference Points (5)	
Landmarks on Participant	
Top Head	Lat. Femoral Condyle (R)
Glabella	Suprapatella
Infraorbitale (R)	Lateral Malleolus (R)
Corner of Eye (R)	Heel of Shoe
Tragion (R)	Toe of Shoe
Acromion (R)	Shoulder Clearance Point
Acromion (L)	Hip Clearance Point
Lat. Humeral Epicondyle (R)	Elbow Clearance Point
Wrist (R)	ASIS (R)
Suprasternale	ASIS (L)
Substernale	
Participant Landmarks Recorded Only in Hardseat	
C7	PSIS (L)
T4	PSIS (L)
T8	Abd. Midsagittal Profile (7)
T12	Abd. Lateral Profile (7)
L3	
L5	

* Numbers in parentheses indicate the number of points digitized in each category. (R) and (L) indicate right and left, respectively.

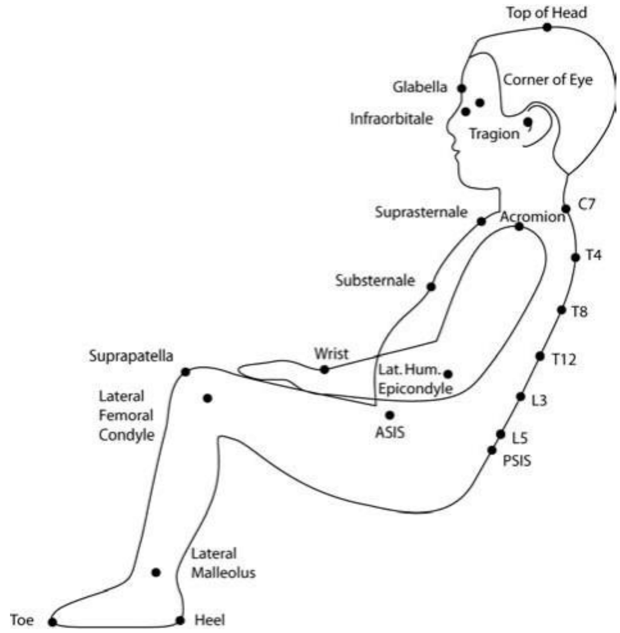

Figure 7. Schematic illustration of body landmarks digitized during testing. Posterior spine landmarks and PSIS were recorded only in the hardseat.

Pelvis Angle Measurement

A new method was applied to quantify pelvis orientation in the vehicle-seated conditions. A low-profile inclinometer capable of measuring orientation with respect to gravity on two axes was taped to the skin over the sacrum. Thin-film pressure transducers under the inclinometer plate provide compensation for changes in orientation due to deformation of soft tissue under the inclinometer. During the hardseat landmark measurements, the inclinometer pressure compensation was calibrated by pressing on the inclinometer with a range of pressure levels and gradients. Figure 8 shows the inclinometer on a participant's sacrum. The data from the ASIS and PSIS locations measured in the hardseat were used to convert the inclinometer-measured angles to a three-dimensional representation of the orientation of the bony pelvis.

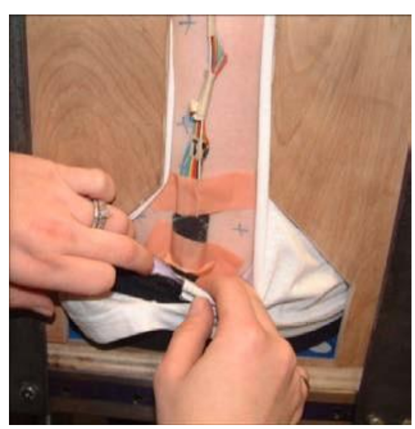

Figure 8. Pelvis inclinometer on participant's sacrum. Some tape has been removed to provide a better view of the sensor.

Protocol

The protocol for human subject testing was approved by an institutional review board at the University of Michigan. Written informed consent was obtained from the parent or guardian of each participant and each child assented orally. The parent or guardian was present during testing and was paid $24 for participating. The child changed into loose-fitting test garments (a T-shirt and sweat pants) that allowed easy access to posterior body landmarks (see Figure 8). The investigator recorded standard anthropometric dimensions. The child sat in the hardseat (Figure 6) and the investigator applied the pelvis inclinometer to the skin over the child's sacrum with medical tape. The FARO Arm was then used to digitize the landmarks listed in Table 3 while the child held a relaxed, sagittally symmetric posture. The landmarks were digitized in several overlapping sets. If the child moved appreciably during a set, the set was repeated. The data from each set were aligned to the first set using repeated points on the pelvis and thorax.

A pelvis coordinate system was defined using the anterior-superior and posterior-superior iliac spine landmarks following the methods in Reed et al. (1999). The angular offset between the measurements obtained from the pelvis inclinometer and the pelvis coordinate system was used to calculate the pelvis orientation from the inclinometer data in subsequent test conditions.

Following the hardseat measurements, the participant was tested in each of vehicle-seat test conditions, most of which included a CRS (see Table 1). The investigator recorded the locations of the landmarks listed in Table 3 using the FARO Arm while the participant sat approximately motionless. The children were usually able to hold the posture during measurement as well as adult participants have in similar studies. However, if the child moved substantially, the landmark measurements were repeated. A digital photograph was taken of the participant in every test trial. Testing required approximately two hours for each participant.

Detailed Measurements

Twelve participants (six boys and six girls) who were close to the reference stature and weight of the 6YO and 10YO Hybrid-III ATDs returned to the laboratory on another day for more detailed contour measurements. Data were collected with the participant seated in the hardseat and in test conditions 2 and 8. In addition to the landmarks listed in Table 3, the FARO Arm was used to record point streams describing contours on the participants' bodies in areas of interest for restraint system design. In particular, contours were gathered on the neck, shoulders, chest, abdomen, pelvis, and thighs. Figure 9 shows a typical set of data.

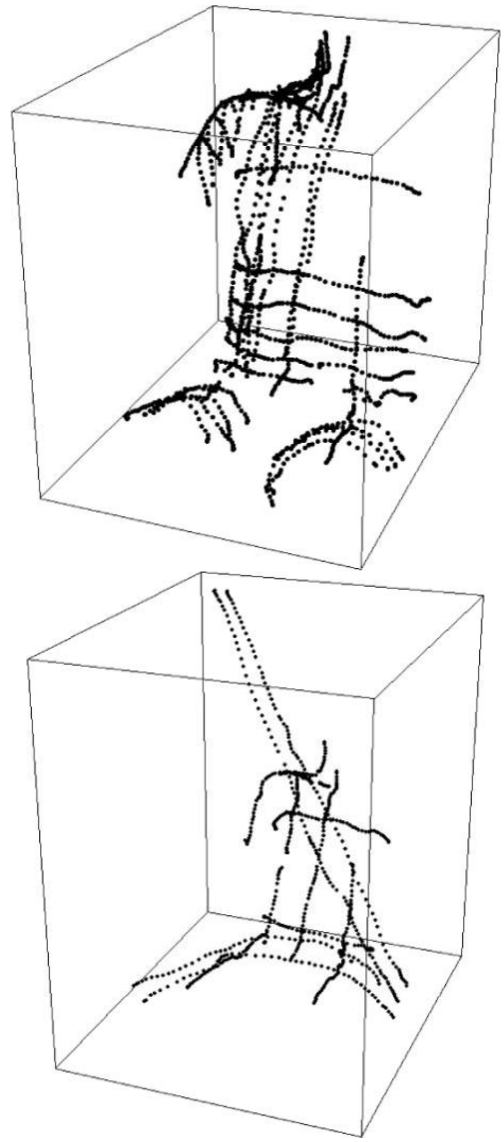

Figure 9. Point streams on surface contours for one participant who was similar in size to the 10YO Hybrid-III ATD in the hardseat (left) and vehicle seat (right).

Skeletal Linkage and Posture Variables

To facilitate the analysis, a kinematic linkage representing primary skeletal mobility was calculated using the data from each trial. Figure 10 shows the linkage system with the joints and body segments labeled. Figure 11 shows some of the posture variables that can be calculated using the linkage system. The methods for estimating joint locations are described in Reed et al. (1999). These methods were developed using data from adult studies, but no similar data on internal joint locations with respect to external landmarks are available for children. Hence, the joint locations and resulting body segment angles should be interpreted with caution. The body segment orientations are most useful for comparisons across test conditions.

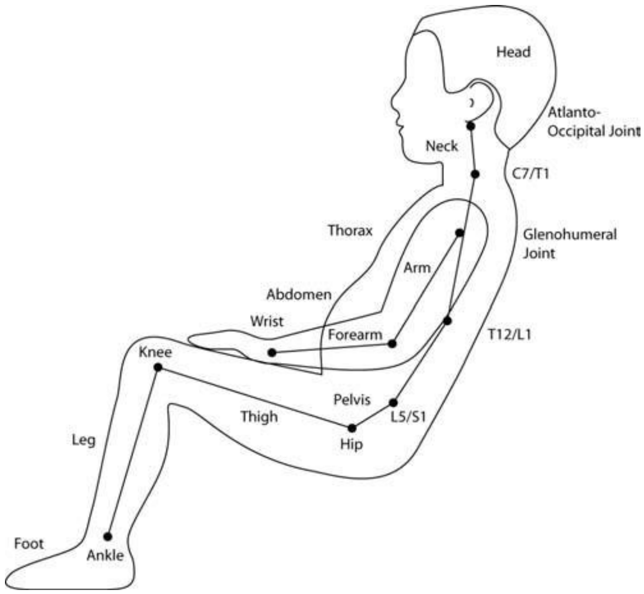

Figure 10. Kinematic linkage used to represent posture.

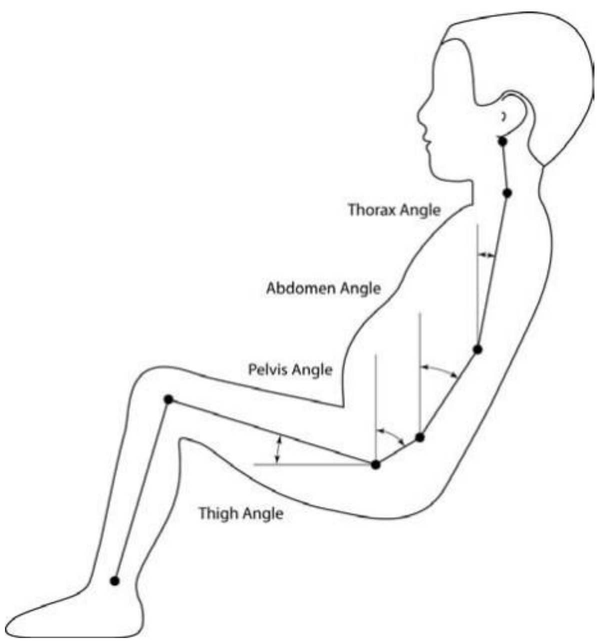

Figure 11. A subset of posture variables derive from the skeletal linkage in Figure 10.

PRELIMINARY RESULTS

Qualitative Observations

Figure 12 shows some of the more extreme postures observed during the sitter-selected-posture trials, in which the children were free to choose their own sitting posture and donned the belt themselves. Qualitative observations suggested that children sat more slumped and with looser belt fit in these trials than in the subsequent standard posture trials. Asymmetric leg postures, slack in the lap portion of the belt, and belt routing over the abdomen were common. Slumping could be observed most clearly by noting the height of the participant's heads relative to the seat. Figure 13 shows an example of a sitter-selected and standard posture trials in which the difference in the height of the child's head with respect to the seat back is visible.

Quantitative Observations

Figure 14 shows the top-of-head (vertex) height above H-point in conditions 2, 5, 8, and 11 for all participants as a function of stature. These data were obtained in vehicle seat 1 with and without CRS A in the sitter-selected and standard postures. As expected, the booster increases top-of-head height, and the effect is independent of stature. Top-of-head height is significantly greater in the standard posture than in the sitter-selected posture ($p<0.01$) and the effect is larger without the CRS, averaging 14 mm on the vehicle seat and 7 mm on CRS A.

Figure 12. Photographs of sitter-selected-posture trials showing poor lap belt fit.

Sitter-Selected Standard Sitter-Selected, CRS A

Figure 13. Comparison of a sitter-selected-posture trial with a standard-posture trial and a trial with CRS A (condition 8) showing difference in seated height and lap belt fit.

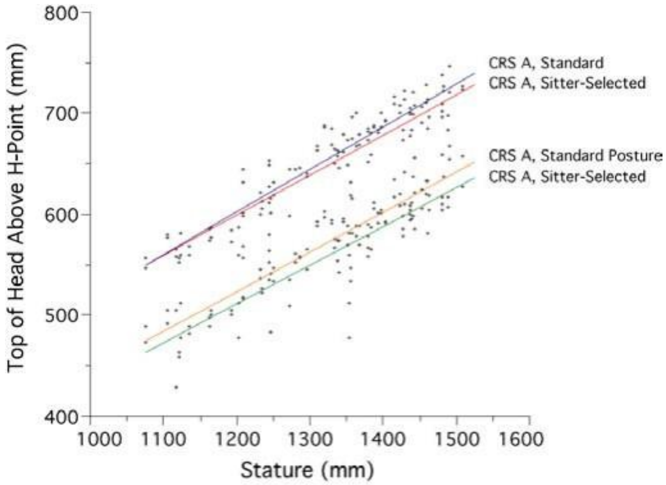

Figure 14. Top-of-head (vertex) height for all participants above H-point in vehicle seat 1 with and without CRS A in the sitter-selected and standard postures. Lines are linear fits to the data in each CRS/Posture category.

Table 4 lists the means and standard deviations of several body segment angles for these four test conditions. The abdomen and pelvis segments were significantly more reclined (larger angles with respect to vertical) in the sitter-selected posture than in the standard posture (p<0.001), consistent with greater slumping (lumbar spine flexion) in the sitter-selected posture. Thorax orientation was significantly greater when participants sat with no CRS than with CRS A (p<0.001), and thigh angle with respect to horizontal was greater with no CRS than with CRS A (p<0.001).

Database Development

The data gathered in this study will be tabulated in a relational database and made publicly available. The database interface will allow selection of specific cases or calculation of summary statistics across conditions of interest. The interface provides for graphical review of data, which can subsequently be exported for more detailed analysis.

Table 4
Means and Standard Deviations of Posture Variables in Conditions 2, 5, 8, and 11

Posture Variable* (degrees)	CRS A		No CRS	
	Sitter-Selected	Standard	Sitter-Selected	Standard
Neck Angle	2.0 (11.1)	3.2 (10.8)	3.5 (11.4)	3.3 (12.5)
Thorax Angle†	5.6 (6.9)	5.8 (6.6)	10.0 (6.8)	9.8 (7.8)
Abdomen Angle††	43.8 (13.4)	39.9 (12.2)	45.0 (12.0)	34.7 (18.2)
Pelvis Angle††	47.2 (13.0)	39.2 (12.4)	47.6 (12.8)	43.5 (11.2)
Thigh Angle†	10.4 (6.0)	11.5 (4.0)	15.8 (6.9)	14.9 (5.8)

* See Figure 11 for variable definitions.
† Values are significantly different across CRS condition (p<0.001)
†† Values are significantly different across posture conditions (p<0.001)

DISCUSSION

Applications

This study provides a new database of anthropometry and posture for children for children in rear vehicle seats. The data illustrate the effects of sitting instruction on child posture and quantify the effects of three types of booster seat on both posture and belt fit. This study is the first to gather three-dimensional coordinate data for important skeletal landmarks in this population and to measure child pelvis posture in vehicle seating conditions.

The data on child body dimensions, seated posture, and belt fit gathered in this study are applicable to a wide range of issues in child passenger safety, including:

- the quantification of the belt-fit advantages of boosters;
- the design of anthropomorphic test devices (crash dummies), particularly for quantifying external contours relative to skeletal landmarks in the critical shoulder and pelvic areas;
- the development of ATD positioning procedures that produce more representative postures and belt fit; and
- child restraint design.

For most of these applications, a statistical analysis of the data is required to weight the results to be applicable to the target population. For example, the data can be analyzed to predict child head location relative to H-point as a function of child stature. Predicting the distribution of child occupant head locations in normal seated positions would then require convolving the relationship observed in this study with the expected distribution of occupant stature. These statistical procedures have been developed previously for application to adult occupant protection (Manary et al. 1998, Reed et al. 2001).

Study Limitations

The current study is limited primarily by the range of test conditions that it was feasible to present within the attention span of the participants. The test conditions were selected to focus on quantification of seated posture for children on vehicle seats and with representative belt-positioning boosters. The study did not examine the effects of vehicle seat cushion angle or length and did not manipulate D-ring position to represent a wide range of different belt geometries. Only five CRS were used (three boosters), which represents a small fraction of the CRS market. Nonetheless, the three boosters used in the study include the primary features of most of the booster models currently sold in the U.S. The effects of interactions between the booster and vehicle seat designs on child posture were not examined, although they are believed to be minimal in most cases.

The vehicle seats were mounted so that none of the children could touch the floor with their feet during testing. In some production vehicles, the larger participants would have been able to touch the floor, and this may have altered their postures. In particular, the children may have been inclined to slouch more so that their feet would be supported.

A larger sample of children would always be desirable, but the current sample provides a good description of typical child postures and belt fit for the studied conditions. The analysis approach does not assume that the sample is representative of any particular group of children, but rather examines the relationships between outcome measures (e.g., in-vehicle seated height) and child descriptors (erect seated height). These relationships allow for predictions of the distributions of outcome measures for populations of children described by age or body dimensions.

Recent data from the National Center for Health Statistics (NCHS) indicate that the upper percentiles of weight-for-stature, as measured by body mass index, are increasing for U.S. children (as they are for adults). The current sample includes a wide distribution of weight-for-stature only in the upper stature ranges (above 130 cm — see Figure 5). An analysis of trends in this group should show the potential impact of shifts in average body mass index on belt fit for most children. Morbidly obese children were not included in this sample and additional data collection would be needed to quantify the effects of child obesity on posture and belt fit.

Because the study was conducted in the laboratory with short-duration sitting sessions, the observed postural variability, both within- and between-subjects, is likely to be less than would be observed in vehicles driven on-road. However, there is no reason to believe that the mean postures would differ substantially from those measured in the sitter-selected-posture trials in this study.

Future Work

Beyond the applications of the data gathered in the current study, the highest priority for future research in this area should be quantifying the effects of vehicle belt geometry on belt fit for children on vehicle seats (i.e., without boosters). Current best-practice guidelines recommend that children use boosters until they are nine years old or 57 inches (145 cm) tall (NHTSA 2004). However, preliminary analyses of the data from the current study suggest that children taller than the current criterion may experience improved belt fit when using a booster. Seatbelt buckle, outboard lower anchor, and D-ring locations vary widely across vehicles. Buckles and outboard lower anchors are often located in the seat bight, which may produce poorer belt fit for children sitting without a booster than do anchor locations that are further forward. Ironically, more-rearward anchor locations often improve the installation of child-restraints that are secured with the vehicle belts, so there may be tradeoffs in child passenger safety associated with anchorage locations. As NHTSA moves toward mandating three-point belts in all seating positions and introducing a 10-year-old dummy to regulation, a validated procedure for assessing belt fit for children in rear seating positions is needed.

Additionally, dynamic testing is needed to assess the safety implications of the range of belt fit observed in this study. Field data suggest that children using vehicle belts without boosters are more likely to sustain abdominal injuries suggestive of belt loading (Durbin et al. 2003). However, current ATDs may not be sufficiently biofidelic to show decreased performance, particularly submarining, using realistic starting belt positions. As the use of belt-positioning boosters increases, test procedures that can differentiate among booster designs on performance measures that are relevant to child occupant protection are needed.

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