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ABSTRACT

Advanced airbag systems use information from a variety of sensors to tune the airbag performance for crash severity and occupant characteristics. A new family of Occupant Classification ATDs (OCATD) have been developed for use in the design and testing of advanced airbag systems. This paper describes the development of anthropometric standards for an OCATD that represents a typical six-year-old child. Detailed analyses of existing child anthropometry databases were conducted to develop reference dimensions. A child who closely matched the reference dimensions was measured in a variety of conditions. A custom molded measurement seat was constructed using foam-in-place seating material. The surface of the child's body was scanned as he sat in the custom seat, and the three-dimensional locations of body landmarks defining the skeleton position were recorded. These data were used to create a three-dimensional CAD surface representation of the six-year-old child, along with the internal location of the skeleton. Minimal scaling was required to adjust the resulting model to match the reference dimensions developed from the large-scale anthropometric database. The resulting OCATD dimensions accurately represent both the body segment dimensions and the exterior surface shape of a typical six-year-old child.

INTRODUCTION

Recent changes in Federal Motor Vehicle Safety Standards have led to the rapid introduction of occupant sensing and characterization systems intended, in part, to suppress airbag deployment when the corresponding seating position is not occupied by a normally positioned adult. One obstacle to the development and implementation of these systems is the lack of appropriate human surrogates for use in testing and validation. For example, some of the currently available occupant classification systems use seat surface pressure distribution as one input to the classification algorithm. However, previous investigations at UMTRI have shown that existing human surrogates, such as the Hybrid-III and THOR crash dummies, do not produce realistic seat surface pressure distributions (1[*]). Development and testing of occupant classification systems also requires testing surrogates in a wide range of postures, but many postures that are possible for humans cannot be attained with crash dummies.

In response to these needs, First Technology Safety Systems (FTSS) has lead an effort to develop two surrogates for occupant characterization applications, representing a small adult woman and a typical six-year-old child. These Occupant Classification Anthropomorphic Test Devices (OCATD — pronounced "oh-cat") are designed to be quantitatively representative of humans in the corresponding anthropometric categories with respect to external anthropometry, skeletal linkage, body mass, and segment mass distribution. Most importantly, these devices are designed to produce seat surface pressure distributions that are quantitatively representative of human vehicle occupants.

This paper describes research conducted at UMTRI as part of the OCATD development program. A detailed study of the body dimensions and surface contours of the typical six-year-old child was conducted to determine the anthropometric specifications for the six-year-old OCATD (OCATD6). Several existing anthropometric databases were analyzed to determine overall body dimensions. Detailed measurements of a representative child were used to obtain an external surface model and skeletal linkage.

[*] Numbers in parentheses denote references.

METHODS

TARGET ANTHROPOMETRY DEFINITION – The newly revised FMVSS 208 specifies stature and weight categories for small women and children who may be used to test airbag suppression systems. Table 1 lists the FMVSS specifications. The target values for the OCATD6 were defined at the middle of the stature and weight ranges specified in FMVSS for six-year-old children.

Table 1
FMVSS Anthropometric Categories and OCATD6 Targets

Dimension	FMVSS Range	OCATD6 Target
Stature: mm (in.)	1140-1245 (45-49)	1193 (47.0)
Weight: kg (lb)	21-25.6 (46.5-56.5)	23.4 (51.5)

Although target values for two dimensions could be defined from the FMVSS categories, much more information was needed to define the OCATD6 anthropometry. A review of the literature identified several sources of potentially useful information. The most complete anthropometric information for children in the U.S. is available from a study conducted by UMTRI (formerly HSRI) for the Consumer Product Safety Commission (CPSC) in the late 1970s (2). More recent data are available for a few dimensions (among them stature and weight) from the third National Health Examination and Nutrition Survey (NHANES III), conducted from 1988 to 1994 (3). The NHANES data were used to determine if the FMVSS-derived targets were in fact representative of U.S. six-year-olds. The CPSC data were used to determine the target values for a range of anthropometric dimensions from the target stature and weight.

Table 2 demonstrates that the OCATD6 targets derived from FMVSS 208 are reasonable values for both the stature and weight of six-year-old children in the U.S. The OCATD6 targets are very close to the mean values for children who are 78 months old in the NHANES data. Of course, the purposes of using a child category in restraint system testing are served regardless of whether the target anthropometry is exactly that of a typical U.S. six-year-old, but the correspondence helps to justify referring to the OCATD6 as representative of U.S. six-year-olds.

Linear regression analyses of the data from the CPSC study were used to determine the relationships among anthropometric dimensions and to establish target values. Values of interesting dimensions, such as erect sitting height and hip breadth, were calculated as a function of the OCATD6 stature and weight specifications. Because stature and weight are well correlated (r = 0.85 in the CPSC data for children 48 to 96 months old), a measure of weight-for-stature was used in place of weight. Body Mass Index (BMI) is calculated as the weight in kilograms divided by the stature in meters squared. BMI is less correlated with weight (r = 0.25 for CPSC children 48 to 96 months old) and has a distribution that more closely approximates the normal. Linear regressions were conducted using CPSC data from children 48 to 96 months old (N=966), considering both stature and BMI as potential predictors. A predictor was included in the regression model if the p-value for the term was less than 0.05. Table 3 shows the regression results, including the R^2 value and residual variance (root mean square error). The OCATD6 target stature and weight were then used with the linear regression fit to estimate the appropriate dimensions for the OCATD6.

SURFACE CONTOUR MEASURMENT– Analyses of existing anthropometric databases provided target values for typical anthropometric dimensions, but detailed external contour data were not available from any source. In the 1970s, Reynolds et al. (4) created a full-size, three-dimensional clay model of a six-year-old to use for crash dummy development. However, no data from this model are currently available, except the published linear dimensions.

In the absence of publicly available data, a three-dimensional surface contour model for the OCATD6 was created by scanning the body contours of a six-year-old child who closely matched the target anthropometric specifications. Table 4 compares selected body dimensions for the reference subject to the OCATD specifications. The discrepancies are usefully evaluated after dividing by the root mean square error from the regression analyses presented in Table 3. The RMSE can be interpreted as the standard deviation of the body dimension for children who match the target stature and BMI. For approximately 95 percent of such children, the scaled difference will lie in the range from –2 to +2. Consequently, scaled differences in this range indicate that the subject is representative of the target category. For most of the dimensions of interest, both the actual and scaled differences between the targets and the reference subject's dimensions are small.

Table 2
Means and Medians of Stature and Weight for Six-Year-Old Children
(medians in parentheses)

	CPSC (2)		NHANES III (3)	
Age	Stature (mm)	Weight (kg)	Stature (mm)	Weight (kg)
72 months old*	1148.8 (1149.1)	21.0 (20.7)	1161.4 (1157.9)	22.4 (21.3)
72 to 83 months old†	1179.2 (1179.0)	22.0 (21.3)	1189.8 (1186.0)	23.1 (21.5)
78 months old*	1180.7 (1180.7)	22.3 (21.9)	1194.1 (1190.4)	23.8 (22.7)

* Means obtained by linear regressions vs. age in months for children ages 48 to 96 months. Medians obtained by linear regression on median weight in month cohorts.
† Mean (median) for children in the specified age range

Table 3
Regression Analyses with CPSC Data to Obtain OCATD6 Anthropometry Targets

Variable*	Intercept	Stature (mm)	BMI (kg/m^2)	N**	R^2	RMSE	OCATD6 Target (mm)
9. Erect Sitting Height	115.9	0.4222	2.027	955	0.86	15.2	653
11. Seated Hip Breadth	-40.2	0.1295	6.884	910	0.79	9.2	227
14. Buttock-Knee Length	-99.4	0.3579	3.362	955	0.89	11.5	383
15. Knee Height	-80.6	0.3637	0.739	876	0.90	10.7	365
34. Clavicle-Acromion Length	-2.8	0.0904	1.544	294	0.57	7.3	130
35. Shoulder Breadth	-20.5	0.1716	6.674	920	0.80	10.7	294
36. Biacromial Breadth	-4.7	0.1901	2.755	296	0.80	8.9	267
37. Shoulder-Elbow Length	-13.3	0.2145	0	923	0.84	8.2	243
38. Acromion-Radiale Length	-16.6	0.1942	0	296	0.75	9.7	215
39. Upper Arm Circumference	-41.7	0.0761	8.106	921	0.81	7.8	182
41. Elbow-Hand Length	-11.4	0.2566	1.207	922	0.87	9.1	315
42. Radiale-Styloid Length	-6.4	0.1506	0	297	0.61	10.3	173
43. Forearm Circumference	-2.7	0.0783	5.337	922	0.79	6.3	178
44. Forearm Breadth	-9.7	0.036	1.307	338	0.53	4.0	55
63. Chest Circumference	-29.0	0.3227	14.803	921	0.84	18.2	599
64. Chest Breadth	6.6	0.0989	3.844	341	0.59	9.9	188
66. Waist Circumference	-52.1	0.2322	19.825	919	0.78	22.5	551
67. Waist Breadth	-32.4	0.1079	5.911	340	0.68	10.3	194
72. Hip Breadth Standing	-15.3	0.1231	4.955	295	0.83	6.1	213
74. Bispinous Breadth	8.7	0.0971	2.748	296	0.44	11.1	170
86. Foot Length	-6.6	0.1477	1.079	924	0.84	6.0	187
87. Foot Breadth	2.3	0.0456	1.053	925	0.64	3.5	74

* Variable numbers from Snyder et al. (2).
** Number of data points used in analysis.

Table 4
Comparison of Anthropometric Dimensions of the Reference Child to the OCATD6 Targets (mm)

Variable	RMSE*	OCATD6 Target (mm)	Reference Child	Difference	Scaled Difference
Weight (lb)	--	51.5	52.8	1.3	--
Stature	--	1193	1183	-10	--
Erect Sitting Height	15.2	653	645	-8	-0.53
Seated Hip Breadth	9.2	227	240	13	1.41
Buttock-Knee Length	11.5	383	378	-5	-0.43
Knee Height	10.7	365	366	1	0.09
Shoulder Breadth	10.7	294	306	12	1.12
Biacromial Breadth	8.9	267	260	-7	-0.79
Shoulder-Elbow Length	8.2	243	254	11	1.34
Elbow-Hand Length	9.1	315	330	15	1.65
Chest Breadth	9.9	188	193	5	0.51
Waist Circumference	22.5	551	549	-2	-0.09
Bispinous Breadth	11.1	170	159	-11	-0.99
Foot Length	6	187	189	2	0.33

* Root mean squared error from regression analysis in Table 3
** Measurement for reference child minus target divided by RMSE

Because the interaction between the seat and the OCATD is of great interest, it was necessary to determine the contour of the subject's back, buttocks, and thighs while under loading typical of a sitting situation. After considering several alternatives, a foam-in-place seating material used to create customized wheelchair cushions (Dynamic Systems Foam-In-Place Sun Foam) was used. The liquid material was poured into a plastic bag placed on a specially constructed chair, as shown in Figure 1. The subject then sat in the chair as the foam grew around him and solidified, a process that took about five minutes. The result, shown in Figure 2, was a rigid foam seat with the contours of the sitter's back, buttocks, and thighs. After the seat was trimmed for better access, a FARO arm was used to record the surface contours of the reference subject, as shown in Figure 3. The FARO arm is a portable three-dimensional coordinate measurement machine used routinely at UMTRI for human posture and contour data collection. Several thousand data points were gathered defining the shape of the right side of the subject's body, including the torso, right arm, right thigh, and right leg. The locations of 26 body landmarks were recorded. These body landmark locations were used to estimate the locations and orientations of the major bones of the skeleton. The contact surfaces on the foam seat were also digitized.

Figure 1. Creating the custom foam seat.

Figure 2. The trimmed foam seat. The slit in the back allows access to the sitter's spinous process landmarks. Black lines indicate the edges of the sitter contact area.

Figure 3. Digitizing the contours and body landmark locations of the reference subject in the foam seat.

Table 5
Body Landmarks Recorded Using FARO Arm

Glabella	Posterior Superior Iliac Spine (R&L)
Infraorbitale	Anterior Superior Iliac Spine (R&L)
Vertex	Pubic Symphysis
Tragion	Iliocristale
Back of Head	Lateral Femoral Condyle
C7*	Medial Femoral Condyle
T1	Lateral Malleolus
T4	Medial Malleolus
T8	Acromion
T10	Suprasternale
T12	Substernale
L3	Lateral Humeral Epicondyle
L5	Ulnar Styloid

* Vertebral landmarks refer to the surface spinous process landmarks

SURFACE MODEL DEFINITION – The scanned surface data were viewed and edited in a computer environment. The scans from individual body areas were aligned using reference skeletal landmarks recorded with each scan. The scans from the seat contact areas were aligned with the subject's body scan data using reference points on the seat. The Wrap and Shape programs from Geomagic, Inc. were used to create and edit a polygon-mesh model. Surface anomalies due to the manual digitizing process were removed and irregular areas between scan patches were smoothed. The polygon mesh from the right side of the body was reflected to the left to obtain a complete body description. Body width data obtained using both the FARO arm and manual methods were used to ensure that the whole-body model was the appropriate width. Minor scaling was performed to adjust the external dimensions to the target values. A NURBS surface model was then constructed over the polygon model. Figure 5 shows the completed model, which was submitted to FTSS to use in developing the OCATD6 external contour.

SKELETAL LINKAGE DEFINITION – The surface landmark locations were used to estimate internal joint locations using methods developed at UMTRI for the ASPECT program (5). The source data on which these methods are based were obtained from radiographic and cadaveric studies of adult men, since no child-derived data are available. Surface landmark locations and preliminary joint locations were used to scale a model of a midsize adult male skeleton to fit the OCATD6 linkage (a CAD model of a child skeleton was not available). UMTRI researchers worked with the engineers at FTSS to scale and position the skeleton within the surface model in a manner consistent with the measured external body landmark locations. Figure 6 shows the skeleton fit to the external surface model. Table 6 lists the joint locations with respect to the midpoint between the hip joints.

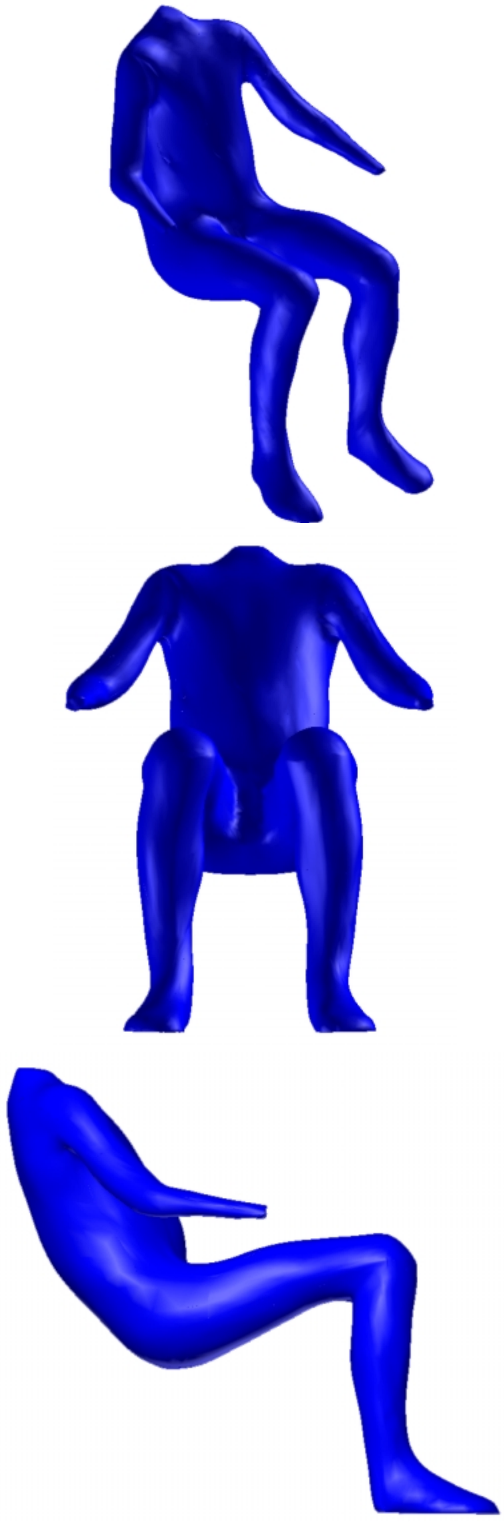

Figure 4. Surface model of six-year-old created at UMTRI.

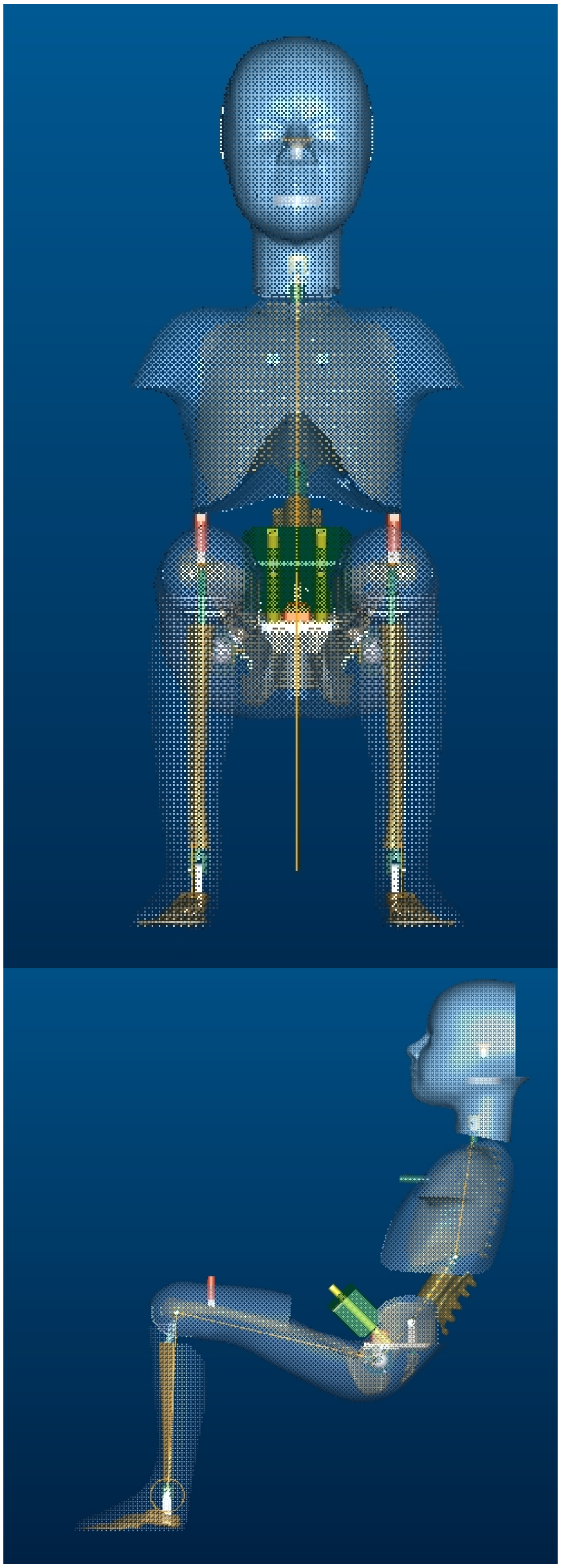

Figure 5. CAD model of OCATD from FTSS, showing external surface contours generated from UMTRI model. Head is based on Hybrid-II ATD.

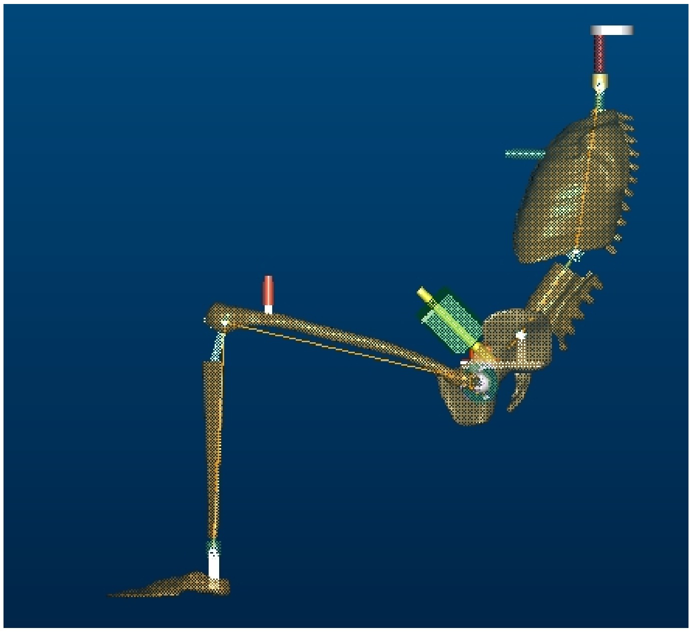

Figure 6. Internal skeleton of OCATD developed at FTSS using joint location and surface landmark data from UMTRI. Thorax and lumbar spine are rigid sections. Additional hardware attached to skeleton is shown.

Table 6
OCATD6 Skeletal Joint Locations in Design Position*

Joint	X	Y	Z
C7/T1 (lower neck joint)	138.4	0	344.2
T12/L1 (upper lumbar joint)	110.5	0	151.4
L5/S1 (lower lumbar joint)	46.5	0	55.5
Hip (right and left)	0	±68.3	0
Knee (right and left)	-298.2	±87.4	69.6
Ankle (right and left)	-311.4	±89.7	-200.1

* Joint locations in mm with respect to the midpoint between the hip joints. X is positive rearward, Y is positive to the left and Z is positive upward.

Table 7 compares some external dimensions of the final OCATD prototype to the targets established in Table 3. Body weight is not compared because ballast weights can be added to the OCATD6 to match any weight near the target. The difference between the measured dimensions of the OCATD6 and the targets can be evaluated with reference to the standard deviation of the residual variance from the regression analyses used to determine the targets. For example, Table 3 indicates that, for children who have stature and body weight matching the OCATD6 targets, erect sitting height is normally distributed with a mean of 653 mm (the target) and a standard deviation (RMSE) of 15.2 mm. The completed OCATD6 has an erect sitting height differing by only a millimeter from the target (0.07 standard deviations). The pelvis breadth, chest breadth, and lower-extremity dimensions are also very close to the targets. Shoulder breadth is not a well-defined dimension on the OCATD6, because the shoulders are not fully formed (see Figure 5). However, the good agreement on the chest-breadth dimension suggests that the torso is the appropriate width.

DISCUSSION

The anthropometric specifications for OCATD6 were developed using analyses of existing databases and detailed measurements on one representative subject. Because extensive standard anthropometry of children has been conducted in other studies, target values for the primary external dimensions, such as sitting height, hip breadth, and leg lengths, could readily be determined. However, no data on external contour, necessary for a constructing a three-dimensional surrogate, were available. Fortuitously, a child who closely matched the target dimensions agreed to be measured.

The surface scanning was done using a FARO arm, which had both advantages and disadvantages. The FARO arm was used with a probe that requires contact with the surface to be measured. This facilitated accurate measurement of body landmark locations, such as bony prominences that must be located by palpation. However, contact scanning is difficult on irregularly curved, soft surfaces such as the human body. As a result, a fair amount of data cleaning was required to produce a smooth contour. With minor scaling, the resulting surface model closely matched the targets for overall anthropometry.

The computer model could have been further adjusted to match all of the potential target values exactly, but the additional work was not warranted for two reasons. First and foremost, the purposes of the OCATD6 would not be better served by making the device incrementally more representative of the target population. Just as a small female Hybrid-III ATD is equally useful regardless of whether its weight is actually 5th-percentile for women in the target population, the OCATD6 can be effective for the development and testing of restraint systems without all of its measurable dimensions being exactly the median values for children matching its target stature and weight. Second, there is a practical limitation on accuracy imposed by the changeable nature of the target population and its dimensions. For example, thigh circumference, breadth, and depth are dependent on posture and the degree of tissue compression. The OCATD6 represents a reasonable but essentially fixed approximation of these changeable dimensions.

Table 7
Comparison of Final OCATD6 Dimensions to Targets (mm)

Dimension	Target (mm)	Target S.D.*	OCATD6	OCATD6 Minus Target	Scaled Difference**
Erect Sitting Height	653	15.2	654	1	0.07
Sitting Buttock-Knee Length	383	11.5	391	8	0.70
Knee Height	365	10.7	357	-8	-0.75
Shoulder Breadth	294	10.7	275	-19	-1.78
Hip Breadth (sitting)	227	9.2	230	3	0.33
Bispinous (Bi-ASIS) Breadth	170	11.1	173	3	0.27
Chest Breadth	188	9.9	191	3	0.30

* Residual standard deviation (RMSE) from Table 3
** OCATD6 value minus target value divided by target standard deviation.

The internal skeleton geometry of the OCATD6, including its link lengths and joint locations, was developed using reasonable estimates based on very sparse background information. No models of a six-year-old child skeleton are available, for example, and generating one from original bone measurements would be large undertaking. Further, no published relationships between external body landmarks and internal joints are available for children. The only published data were obtained using male volunteers (x-ray studies) and cadavers (dissection studies). While application of these data produces reasonable estimates of bone dimensions and joint locations, the OCATD6 linkage geometry should not be construed as a necessarily accurate representation of a typical six-year-old child's skeleton. Nonetheless, it is adequate for its intended application.

CONCLUSIONS

Anthropometric standards for a new surrogate representing a six-year-old vehicle occupant were developed. Analyses of existing data were supplemented with detailed measurements of a representative child. The result is an accurate description of the external surface and internal skeletal geometry of a child using methods not previously applied to the development of surrogates for automotive safety applications.

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