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3-D Average Skull Contour Data for 3-year-olds and 5-year-olds: A Pilot Study

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ABSTRACT

Child head injury is one of the least characterized problems in automotive biomechanics. The cost within the United States exceeds $10 billion per year and it is responsible for 30% of all childhood injury deaths (James, 1999; Kraus et al., 1990; Ommaya et al., 2002). The common tool for studying this problem is child anthropomorphic test devices (ATDs). However, current child head ATDs are standardized around length, width and height measurements with little attention given to the contour of the skull (Irwin and Mertz, 1997; Mertz et al., 1989; Weber et al., 1985). The goals of this study were to produce pediatric skull contour data that can be used for the design of child ATDs and finite element models (FEMs) and to investigate methods of providing average skull contours. We obtained CT scans with patient information removed according to HIPAA standards (OCR, 2003) and we developed an orthographic viewer using MATLAB 7.0 (The Mathworks, Inc.) to collect individual skull contours from 3-years-olds and 5-years-olds. The contours were then averaged together using five different averaging techniques. The results showed that the average skull contour data is insensitive to the averaging technique used and that average three-dimensional (3-D) contour data could be produced for child skull ATD design and FEMs. No meaningful statistical differences were found between male and female 3-year-old skull contours, while differences were found at the occiput and in the frontal bone of the contours for the male and female 5-year-olds. The skull contours will be available from the Duke University Injury and Orthopaedics Biomechanics website: http://biomechanics.bme.duke.edu

INTRODUCTION

Child head injury is a very costly problem, both in terms of health (morbidity and mortality) as well as healthcare dollars. Child head injury is the top cause of death and disability for children under age 18-years-old (CDC, 1990). Child head injury causes 500,000 trips to the hospital each year with 95,000 of these injuries requiring admission. For children between the ages of newborn and 14 years old, traumatic brain injury results in 435,000 emergency room visits and 37,000 hospitalizations, and 2685 deaths (Langlosis et al., 2004). Permanent disabilities from injuries, mostly of the head or neck, affect approximately 30,000 children per year. In fact, 30% of childhood injury deaths are caused by head injury (James, 1999; Kraus et al., 1990). Financially, the cost of child head injury has been reported to exceed $10 billion annually (Ommaya et al., 2002).

Currently research in child head injury is conducted using child anthropomorphic test devices (ATDs) (Irwin and Mertz, 1997). Child ATDs are used to predict the impact response and produce injury criteria for the pediatric head (Mertz et al., 1989; Mertz, 1985). With the lack of availability of child post mortem human subjects (PMHS), the advancement of child head injury research is currently dependent upon the accuracy of child ATDs. However, the current child ATDs are based on adult PMHS data that has been scaled to produce child data using scaling rules (Mertz et al., 1989; Prange et al., 2004). Additionally, the current biofidelic geometry standard for the child head is based only on average head length, width, and height measurements with no reference to head three-dimensional (3-D) contour (Hubbard and McLead, 1973; Hubbard and McLeod, 1973; Irwin and Mertz, 1997).

Studies have noted the difficulty in producing average accurate contour data from image data (Cohen et al., 2003; Fripp et al., 2006). Contour data is easily gathered from imaged data; however, difficulty arises when averaging the data together to produce representative contours smoothes out some of the fine anatomical details. Researchers have addressed this problem by incorporating some form of scaling to the contour before any averaging is done (Cohen et al., 2003), however, these techniques have never been applied to the child skull.

Accordingly, the purpose of this study is to produce representative skull contours for 3-year-olds and 5-year-olds and to test averaging techniques for producing average skull contour data that preserve all anatomical detail.

METHODS

This pilot study was conducted on two age groups, 3-year-olds and 5-year-olds. Head computerized tomography (CT) scans of 3-year-olds and 5-year-olds were analyzed using a ray analysis technique to obtain average skull contours and to investigate six different averaging techniques.

First an orthographic viewer was developed using MATLAB 7.0 (The Mathworks, Inc.) in a joint effort between Duke University's Interdisciplinary Craniofacial Research Laboratory and the Injury and Orthopaedic Biomechanics Laboratory (Figure 1). The orthographic viewer was designed to do five things: 1) to allow three-dimensional (3-D) visualization of the head with a 3-D isosurface and three orthogonal two-dimensional (2-D) views; 2) to allow the user to define a coordinate system within the head; 3) to allow the user to select a threshold; 4) to automatically take radial measurements from a select origin within the head to the outer table of the skull at specified angle increments (this technique is called ray analysis); and 5) to export the data as a point cloud dataset.

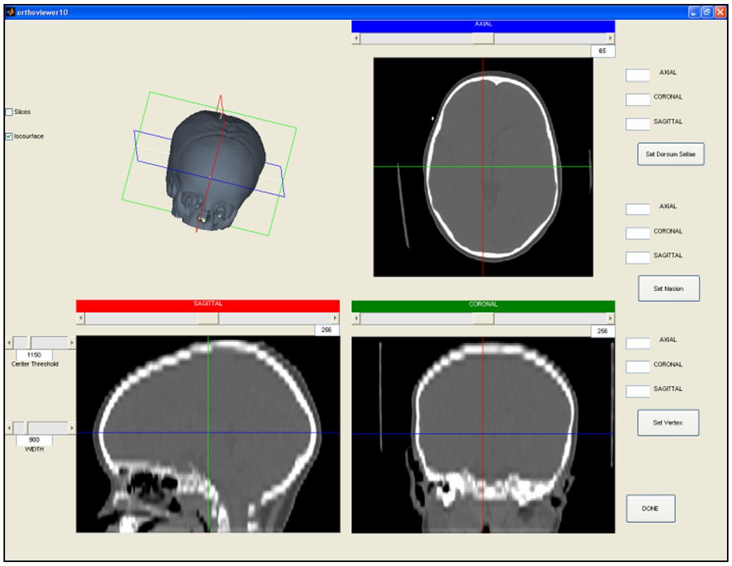

Figure 1: Orthographic viewer that was developed by Duke University's Radiology department and the Injury and Orthopaedic Biomechanics Laboratory.

After the orthographic viewer was developed, clinical CT scans were gathered from the Duke University archives and stripped of all patient identification information according to Health Insurance Portability and Accountability Act of 1996 (HIPAA) standards (OCR, 2003). Next, DICOM datasets of the CT scans were imported into the orthographic viewer and a threshold was selected so that there were no voids or soft tissue showing in the skull. Next, the coordinate system was defined with the dorsum sellae set as the origin. The vector from the dorsum sellae to the nasion was defined as the positive y-axis and the vertex was used to define the vertical direction. The x-axis was defined as being positive from right to left. The z-axis was orthogonal to the other two axes and its positive direction was superior.

Once the coordinate system was established, a ray analysis was performed in which radial vector measurements were taken from the dorsum sellae to the outer table at different angle increments. The vector measurements were made in 1° increments about the x-axis from 0° to 180° and the y-axis from 0° to 210°, which totaled more than 37,000 data points. When the points were plotted in 3-D, a point cloud of the skull contour was produced that helped visualize the skull contour (Figure 2 and Figure 3).

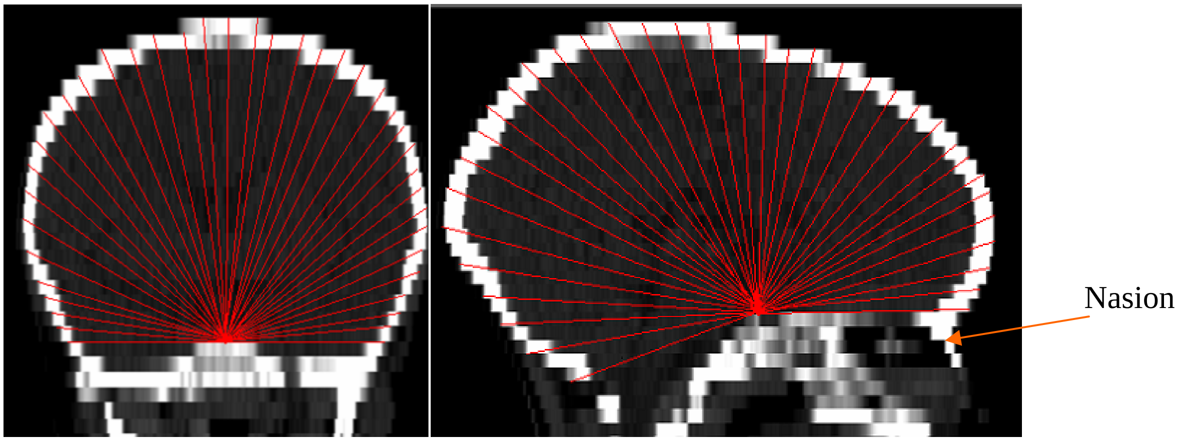

Figure 2: Illustration of radial measurements from the dorsum sellae about the x-axis (left) and the y-axis (right). The origin was at the dorsum sellae and the x-axis was positive from the dorsum sellae to the nasion.

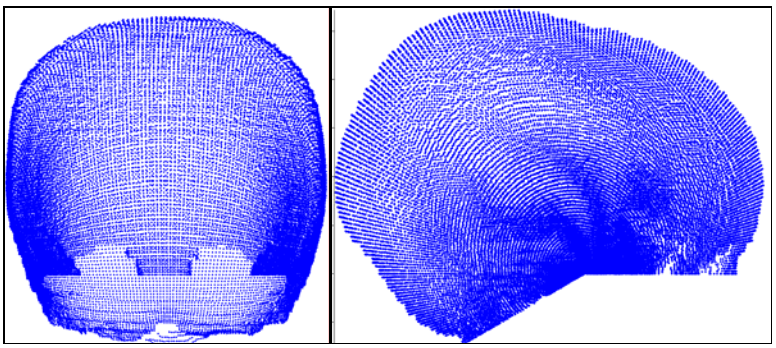

Figure 3: Example of skull contour point cloud that was produce using the orthographic viewer and ray analysis.

The point cloud of each specimen was used to determine the maximum width, maximum length, and maximum height of each specimen. The maximum height is defined from the dorsum sellae vertically to the outer table. The maximum width was taken from the two most lateral points and the maximum length was taken from the most posterior and anterior points. The average maximum length, maximum width, and maximum height were found for both male and female 3-year-olds and 5-year-olds.

Five different averaging techniques were applied to produce average skull contours. For the first technique, the radial vectors of each specimen's point cloud were scaled based on the average maximum length. The scaling factor that was employed on each specimen was calculated by dividing the average maximum length across all specimens in a group by the specimen's maximum length (Equation 1). This scaling factor was then multiplied by each of the radial vectors of the specimen's point cloud. Once all specimens were scaled, the contours were averaged together at each radial vector to produce an average skull contour. For the second and third techniques, the maximum width and maximum height were used to scale the radial vectors. The contours were scaled and averaged in the same manner as the first technique.

$$ScalingFactor = \frac{AverageMaxDimension}{SpecimenMaxDimension} \tag{1}$$

For the fourth technique, the x, y, and z components were all scaled. The x component was scaled based on the maximum width and Equation 1. Likewise, the y and z components were scaled based on the maximum length and maximum height and Equation 1. Once the x, y, and z components of the radial vectors were scaled for all specimens, the radial vectors were averaged together to produce an average skull contour. Lastly, for the fifth technique, no scaling was done and the radial vectors were averaged together. A summary of the averaging techniques is shown (Table 1).

Table 1. Averaging Techniques and Dimension That Was Scaled.

	Averaging Technique	**Dimension Scaled**
1	Average max length	radii
2	Average max width	radii
3	Average max height	radii
4	Average max width, length and height	x, y, z
5	No scaling	none

Once the average datasets were established for each averaging technique, the average RMS error was calculated by comparing the average radial vectors to the radial vectors of the individual skull contours (Equation 2). Next an analysis of variance (ANOVA) was done with the RMS error from the averaging techniques to look for significant difference ($p<0.05$) between the techniques. To check for significant differences between male and female, t-tests were done on all the radial vectors at each angle increment.

$$RMS \quad Error = \sqrt{\frac{1}{n}\sum_{j=1}^{n}(r_{avg} - r_{real})^2} \qquad (2)$$

RESULTS

The average age for both the male and female 3-years-olds groups was 2.9 years. The average ages for the female and male 5-years-olds were 5.0 years and 4.9 years, respectively (Table 2). Sagittal and coronal views of various 5-year-old skull contours illustrate variation in the skull shape with specimen (Figure 4). The results of the averaging techniques for the 3-year-old males are shown (Figure 5). The graph shows all six averaging techniques plotted together and demonstrates that there is visually no difference between any of the techniques. Quantifying this observation, each of the averaging techniques produced an RMS value of 3.6 mm for the male 3-year-olds and ANOVA between the techniques produced p-values greater than 0.95 indicating no difference between techniques. This comparison between results was consistent across both sexes for both age groups and no statistical or visual difference was observed between averaging techniques (Appendix). Hence, the average skull contour results were insensitive to the average technique.

Table 2. Specimen Age Statistics.

age group	**sex**	**N**	**average age (years)**	**age standard deviation (years)**
3-year-olds	male	5	2.9	0.3
	female	3	2.9	0.4
5-year-olds	male	6	4.9	0.3
	female	4	5	0.3

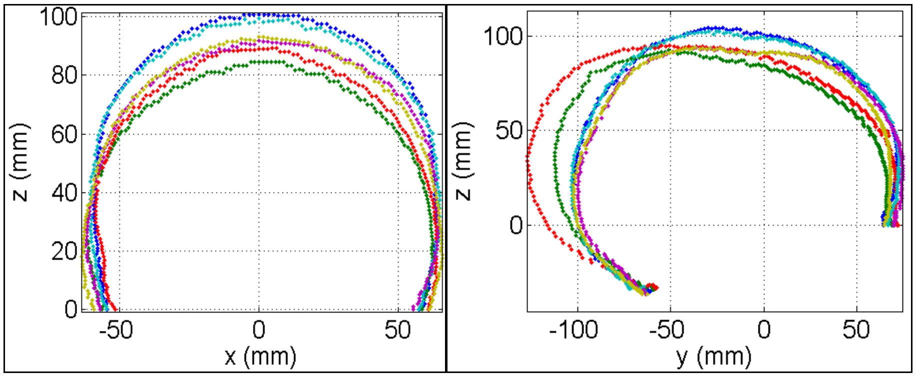

Figure 4: Sagittal (right) and coronal (left) contours for 5-year-old males.

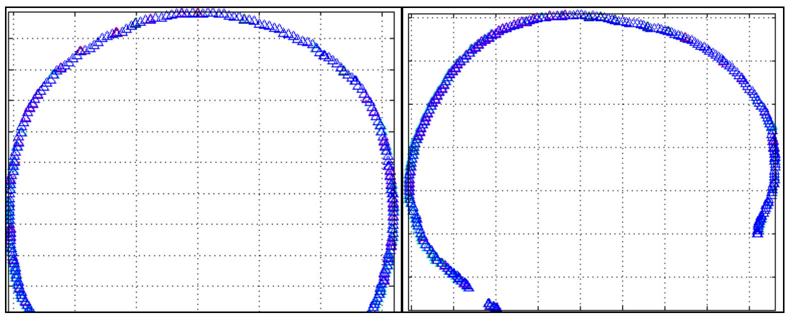

Figure 5: The averaging results for all five of the averaging techniques. This figure shows that there is visually no difference between any of the averaging techniques. Statistically there was no difference between any of the techniques with all p-values>0.95.

The point-by-point student t-test showed that there was only a statistical difference between 2 of the 37000 points (0.01%) between male and female 3-year-olds ($p<0.05$) (Figure 6). The location of the two significantly different points were located in the right frontal bone. The average absolute difference between the points of the male and female 3-year-olds was 3.3mm. For the 5-year-olds 18% of the points were statistically different between male and female ($p<0.05$). The regions of significant difference are located at the occiput and the frontal bones of the skull (Figure 8). The average absolute difference between the male and female 5-year-old skull contours was 4.6 mm. Since less then 0.01% of the points were statistically different between male and female 3-year-olds, the skull contours were averaged together to produce one representative average while the male and female 5-year-old skull contours were not averaged (Figure 7and 8).

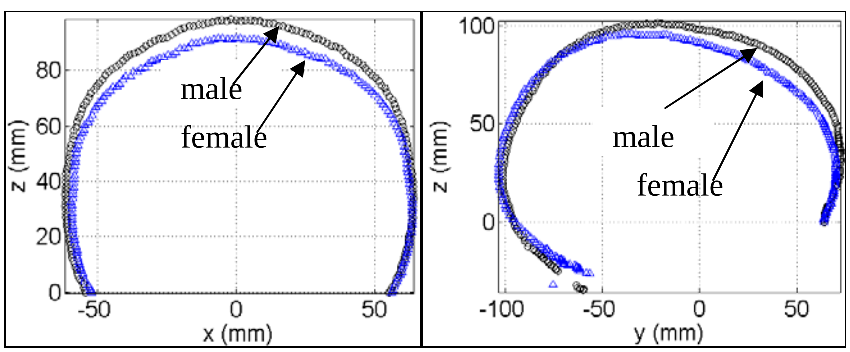

Figure 6: Average 3-year-old male and female skull contour. The average absolute difference between the male and female was 3.3 mm.

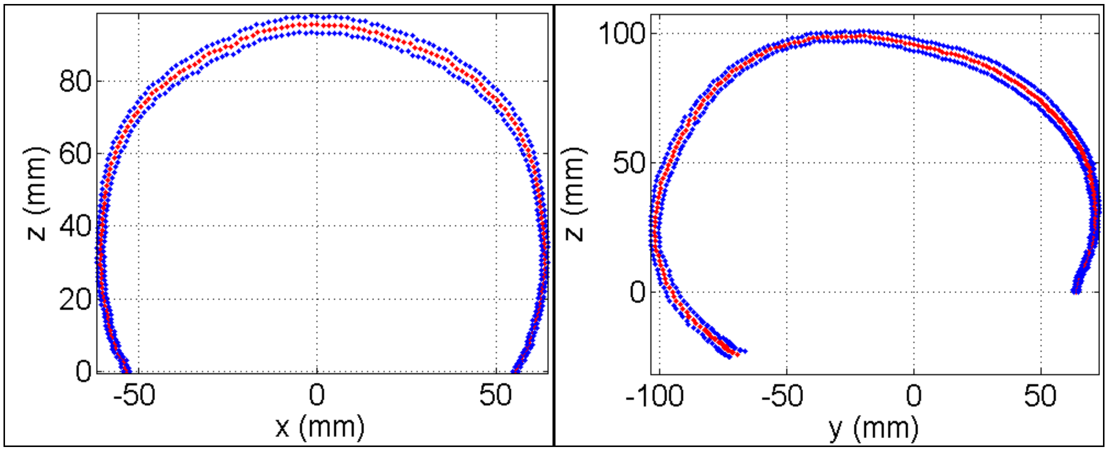

Figure 7: Average 3-year-old skull contour with male and female skull contours averaged together. The average contour is the centerline and the contours of plus and minus one standard deviation are outer and inner lines.

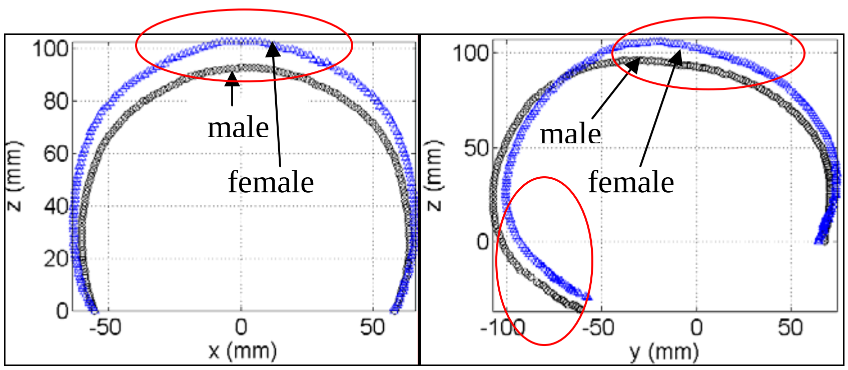

Figure 8: Average 5-year-old male and female skull contours. The regions of significant differences are circled. The average absolute difference between the male and female skull contour was 4.6 mm.

DISCUSSION

Child crash test dummies are very important for the study of child head injury (CDC, 1990). In spite of their importance, current crash test dummy heads are not based on detailed 3-D anthropometry owing to a lack of data (Irwin and Mertz, 1997; Mertz et al., 1989; Weber et al., 1985). Accordingly, the goals of this study were to produce average skull contours for 3-year-olds and 5-year-olds and to investigate the methods used for producing the average skull contours.

One of the limitations of this study is that clinical CT scans are limited to 2.5 mm – 5 mm slice increments. This limited the accuracy of the skull contour in the slicing direction which was in the superior-inferior direction. The second limitation was that the threshold that was used was selected by the user by inspection and hence is subject to user dependency (Zoroofi et al., 2003).

The current ray analysis technique differs from other techniques in two ways. The current technique relates the contour to an anatomical landmark as opposed to an outside landmark (Ateshian, 1993). This allows for an easier implementation into the FEMs. The other way this technique differs is its use of point clouds to represent the contours instead of surface grids, B-spines, or mathematical formulas (Ateshian, 1993; Ateshian et al., 1992; Ateshian et al., 1991). This difference allowed the averaging and comparing of the contours to be done on a point-by-point basis without any interpolations or mathematical manipulations.

The length and width dimensions in this study closely agreed with the average head dimensions published by Weber and the University of Michigan Transportation Research Institute (UMTRI) and showed that the contours are good representations of a larger sample of the population (Weber et al., 1985) (Table 3). Since the five averaging techniques tested showed no difference (visually or statistically), we recommended that for all contour data that is represented by angle and radii measurements, any of the techniques tested in this paper can be used to produce average skull contour data. However, our preference is for the averaging with no scaling due to its simplicity. Because ray analysis provides a consistent coordinate system and contours that can be easily averaged together, it is also recommended that this methodology be used for creating average skull contours.

Table 3. Comparison Between Average Skull Contour Data and UMTRI Data.

		Average max width		Average max length	
Age	**Sex**	**Skull Contour (mm)**	**UMTRI (mm)**	**Skull Contour (mm)**	**UMTRI (mm)**
3 year	Both	133	134	174	175
5 year	Male	134	137	178	177
5 year	Female	136	135	175	183

Lastly, the results for the male and female 5-year-olds showed that the contours were significantly different. However, this difference is small and does not appear to be biomechanically meaningful. Additionally, these results may change with an increase in sample size and larger sample sizes of skull contours will be used to decide whether or not the differences reported here are meaningful.

CONCLUSION

The study shows that the average skull contours are insensitive to the averaging technique and that simply averaging skull contours together produces adequate results. Second, the study shows that CT scans and ray analysis can produce biofidelic 3-D geometries of the pediatric skull that can be applied to ATD design and finite element modeling. All of the skull contour datasets will be available at Duke University's Injury and Orthopaedic Biomechanics Laboratory website: *http://biomechanics.bme.duke.edu*

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APPENDIX

Table A1: Average RMS Error For Each Averaging Technique For The 3-Year-Old Male.

Averaging Technique	Mean RMS Error (mm)	Standard Dev. (mm)
No scaling	3.6	0.9
Average max width and length	3.6	0.9
Average max width	3.6	0.9
Average max length	3.6	0.9
Average max height	3.6	1.0
Average max width, length and height	3.6	0.9

Table A2: Average RMS Error For Each Averaging Technique For The 3-Year-Old Female.

Averaging Technique	Mean RMS Error (mm)	Standard Dev. (mm)
No scaling	3.5	0.6
Average max width and length	3.5	0.6
Average max width	3.5	0.6
Average max length	3.5	0.6
Average max height	3.5	0.6
Average max width, length and height	3.5	0.6

Table A3: Average RMS Error For Each Averaging Technique For 5-Year-Old Male

Averaging Technique	Mean RMS Error (mm)	Standard Dev. (mm)
No scaling	3.6	1.0
Average max width and length	3.6	1.0
Average max width	3.6	1.1
Average max length	3.6	1.3
Average max height	3.6	0.9
Average max width, length and height	3.6	1.0

Table A4: Average RMS Error For Each Averaging Technique For The 5-Year-Old Female

Averaging Technique	Mean RMS Error (mm)	Standard Dev. (mm)
No scaling	3.4	0.6
Average max width and length	3.4	0.6
Average max width	3.4	0.6
Average max length	3.4	0.6
Average max height	3.4	0.7
Average max width, length and height	3.4	0.6

DISCUSSION

PAPER: **3-D Average Skull Contour Data for 3-year-olds and 5-year-olds: A Pilot Study**

PRESENTER: ***André Loyd, Department of Biomedical Engineering Duke University***

QUESTION: *Stephan Duma, Virginia Tech*
Nice talk, André. I was wondering if you have an idea of the timeframe of these scans. Are they recent? Five years old? Ten years old?

ANSWER: Like, when the day—?

Q: When that person--

A: Day the person was scanned?

Q: Right.

A: We do have that information. We're able to get that information, but I don't have it with me currently.

Q: Just a comment: I think what you're doing is really neat. We're working with a group at Wake Forest and what they're seeing is in the past five or seven years, there's been a big focus on putting your infant's back to the bed and parents are not rotating them. They're seeing a shift in, basically, flatter child backs of their heads. And, it's been neat to kind of look at, if you have some recent data and you can get 15 year-old data, kind of to see if there is a shift because they're seeing more problems because of that. It's just a comment, but I think it's a real nice study.

A: That is interesting.

Q: *Guy Nusholtz, Daimler Chrysler*
Have you looked into whether the averaging head form that you have is different where the current heads are or the shapes of the heads that are just done from general scaling? Say, from the dummies?

A: From the dummies?

Q: Yeah.

A: We haven't yet.

Q: Just another question: You've done five different averaging techniques and that, hopefully, would resolve the issue that you would have because the shapes of the skulls will be somewhat different. And when you average them, you can actually distort the shapes through that process. And so, your average may not represent a good estimate of what the shape would be. How do you know that the different averaging techniques you're using span the necessary space of uncertainty to cover that particular problem?

A: [pause]

Q: Okay. We'll talk about it outside of this. Thank you.

Q: *Hans Delye, Catholic University of Leuven, Belgium*
Actually, our center is more or less doing something similar. We're interested in protecting children's head by bicycle helmets and for that, we were looking and searching for a dominant model of children's head. And then, you come upon the problem of the scaling and that child's head is not an adult head just made smaller. So one of the things we're going to do is to do a CT study as well, to see how the shape of the skull changes in age. And, one of the particular problems there is the fontanel. And I was just wondering: One of your three points to get your orthogonal system right is

the vertex point, but that can be very different in small children in fontanels and things like that. So, I wondered how—What would you consider to be the vertex? I mean, it's kind of an area. So, what point would you take? Would that be like just above the foramen magnum or something like that?

A: That's an interesting question. I don't have an answer for you at this second.

Q: Okay. We'll talk later.