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Thresholding Techniques for Developing Geometrically Accurate Pediatric Skull and Cervical Spine Models

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ABSTRACT

Computational finite element models of the skull and cervical spine derived from computed tomography (CT) scans are a promising tool for predicting and preventing traumatic brain injury. For pediatric heads and spines, the immaturity of the skull and spine tissue produces model geometries that are functions of the threshold used to produce them. This study seeks to provide a technique for selecting a threshold that develops a geometrically accurate representation of both the pediatric skull and cervical spine. To develop the model, two pediatric postmortem human subjects (PMHSs) were scanned at parameter settings that maximized resolutions; these parameters are not routinely used in clinical practice due to excess radiation exposure. The CT data sets were exported to Amira™ 3.0 (TGS, Inc., San Diego, CA), where 3D isosurface images could be rendered. After imaging, the mandibles of the PMHSs were dissected and detailed anatomical measurements of the jaw were acquired. Using these measurements as a theoretical standard, the errors in the anatomical measurements taken from the rendered isosurfaces were minimized to find the threshold values that produce the least error. The threshold that produced the least error was used to produce 3D models of the skull and cervical spine. The results produced a thresholding technique that produces geometrically accurate skull and cervical spine models.

INTRODUCTION

Child head and neck injury is a very costly problem, both in terms of health (morbidity and mortality) as well as healthcare dollars. Injuries account for 30% of all child deaths, which makes injuries the leading cause of death for children (Guyer and Ellers, 1990). Brain injuries due to traumatic head impact cause hospitalization or death for at least 150,000 children per year, while permanent disabilities from injuries, mostly of the head or neck, affect approximately 30,000 children per year (DIC, 1990; CDC, 1990).

The study of child head and neck injury has been hindered by a lack of available pediatric postmortem human subjects (PMHSs). As an alternative to PMHS testing, scientists turn to finite element modeling to study the mechanisms of child head and neck injury (Klinich et al., 2002). For adult models computerized tomography (CT) scans are commonly used to create geometrically accurate finite element models (FEM) of head and neck (Bandak and Eppinger, 1994). For pediatric models, previous studies have produced models by simplifying the pediatric geometry or scaling down and modifying the adult models (Klinich et al., 2002; Kumaresan et al., 2000; Margulies et al., 2000).

For adult models produced from data from CT examinations, the selection of a threshold is not a major issue because the difference in density between bone and soft tissue is large. This distinction is not as strong for pediatric specimens. The bone structure in pediatric specimens ranges from areas of dense solid bone to areas of underdeveloped bone. In the head of pediatric specimens, this underdeveloped bone appears as cartilaginous material referred to as suture or fontanelle, while in the spine the underdeveloped bone is depicted as cartilaginous synchondrotic joints (Agur and Lee, 1991). This variation in bone structure makes pediatric models especially sensitive to the threshold used to produce the model. A low threshold will make the areas of soft tissue appear as bone while a high threshold will show less bone. As a result, a range of thresholds can result in qualitatively satisfying models that can vary significantly in their size and structure.

There are a variety of threshold methods used to differentiate bone from soft tissue. Methods vary from using density thresholds and density phantoms to using algorithms that process hue value histogram data (Zoroofi et al., 2003; Won et al., 2003, Haidekker et al., 2000; Aamodt et al., 1999; Onan et al., 1998). However, none of these methods have been applied to pediatric specimens. The objective of this study is to find a thresholding technique for producing geometrically accurate cervical spine and skull pediatric models that can be validated by physical measurements. It is hypothesized that a threshold method based on quantitative comparison between CT isosurfaces of a physical model and direct measurements of the physical model will result in geometrically accurate pediatric cervical spine and skull models.

METHODS

The mandibles of two fresh-frozen unembalmed pediatric PMHSs, one full term and one premature, were used as physical models. Measurements were taken from the mandibles of pediatric PMHSs to test the hypothesis. These measurements were used to compare against measurements taken of isosurfaces from CT scans of the PMHSs.

First, the PMHSs were CT scanned using a multidetector array CT LightSpeed 16 slice scanner (GE Healthcare, Milwaukee, WI) at high-resolution parameters not typically used in clinical settings. A peak kilovoltage of 120 and a tube current of 310 milli amperes with a one second gantry rotation time were used for both PMHSs. The high resolution scanning parameters produced images with 0.43 mm/pixel resolutions and slice thickness of 0.625 mm at 0.625 mm increments. Images were imaged using a small scan field-of-view and a standard reconstruction algorithm. The CT scans were imported to Amira™ 3.0 (TGS, Inc., San Diego, CA) where the images were used to render 3D isosurfaces of the pediatric mandibles (see Figure 1). The 3D isosurfaces were highly dependent on the threshold selected to reconstruct the surface. If the threshold was too low, the 3D isosurface began to show soft tissue and if the threshold was too high, the 3D isosurface did not show all of the bone structure. To select a threshold, physical anatomical measurements of the PMHSs' mandibles were taken to compare to the same anatomical measurements taken from isosurfaces at varying thresholds.

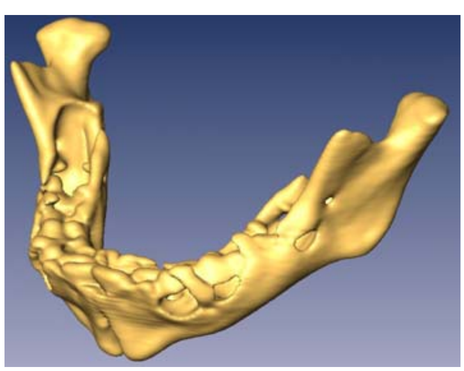

Figure 1: Example isosurface of a pediatric mandible.

The mandibles were used because they were a relatively large structure that could be measured with small error. They were dissected from the cadaver and all of the soft tissue was removed from the mandible bone. Then a series of anatomical measurements were taken of the mandible using calipers (see Table 1 and Figure 2). The physical measurements were taken at positions that had clearly identifiable landmarks. The same measurements were taken on each of the isosurfaces in Amira™ 3.0. Using the manual measurements as a theoretical standard, the errors in the measurements taken from isosurfaces were minimized to find the threshold value that produced the smallest absolute average errors. The results were plotted and a second-degree polynomial was fitted to the data using Microsoft Excel (Microsoft Corp, Seattle, WA). The minimum of the trend lines was used to select the thresholds that were used to produce the isosurfaces of the pediatric cervical spine and head.

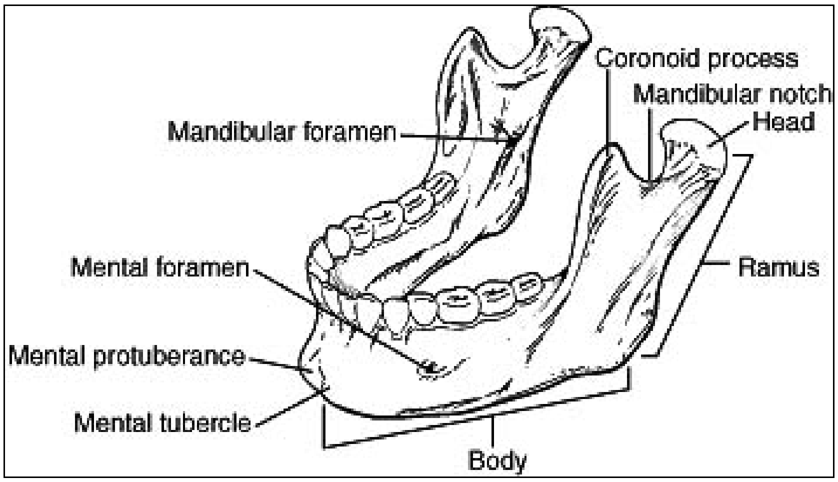

Figure 2: Anatomy of the adult mandible [www.emedicine.com].

Table 1. Anatomical measurements of the mandible taken manually using calipers and taken from rendered isosurfaces in Amira™ 3.0. Note that the measurements were different between the two specimens due to differences in identifiable landmarks.

Full Term	Premature
Mental tubercle to the back of the head (right side)	Mental tubercle to the back of the head (left side)
Mental tubercle to the back of the head (left side)	Mental tubercle to mandibular notch (right side)
Mental tubercle to the mandibular notch (left side)	Mental tubercle to mandibular notch (left side)
Long dimension head thickness (left side)	Long dimension head thickness (left side)
Long dimension head thickness (right side)	Long dimension head thickness (right side)

RESULTS

For the full term PMHS, a threshold of 52.2% of the dynamic range produced an isosurface that had the smallest average absolute error of 1.6%. Additionally, the range of thresholds that yielded an error of 2% or less was 51.52% to 52.75% of the dynamic range (see Figure 3). For the premature PMHS, the smallest error was founded to be 1.6% at a threshold of 68.2% of the dynamic range. The thresholds that yielded an average error of 2% or less were found to be 67.6% to 69.1% of the dynamic range (see Figure 4).

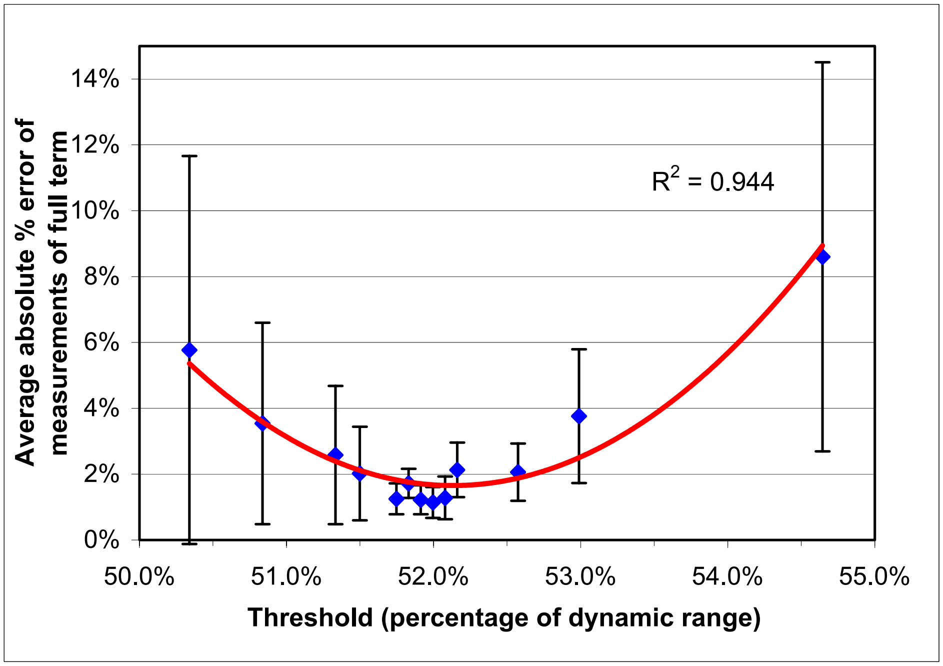

Figure 3: A graph depicting how the average absolute percent error of the anatomical measurements of the isosurfaces changed with threshold for the full term specimen.

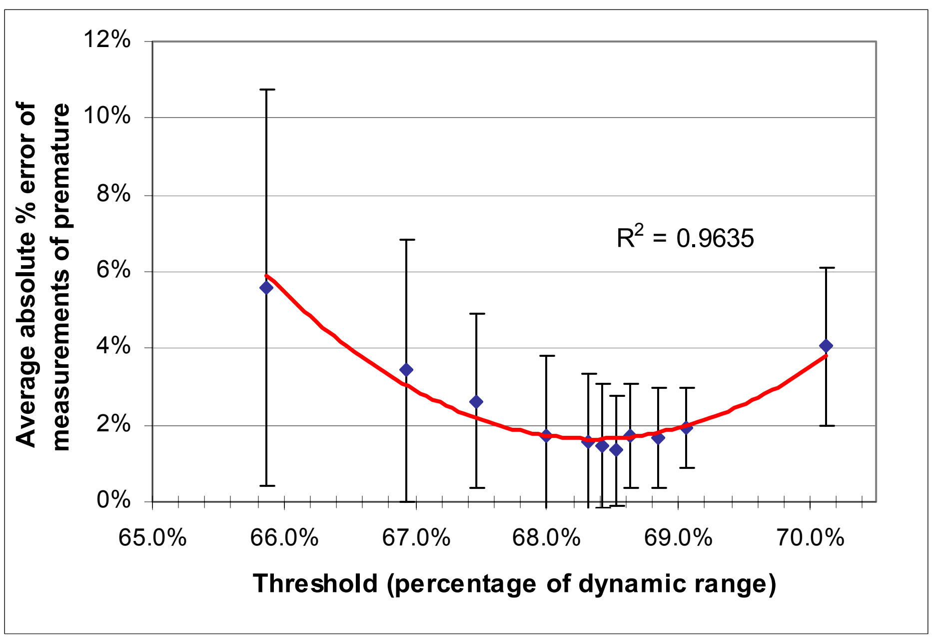

Figure 4: A graph depicting how the average absolute percent error of the anatomical measurements of the isosurfaces changed with threshold for the premature specimen.

Thresholds of 52.2% and 68.2% of the total dynamic ranges were used to produce skull and cervical spine models of full term and premature specimens, respectively. For both specimens, the selected thresholds produced head models that accurately defined the coronal, squamosal, sagittal and metopic sutures as well as the anterior, posterior, anterolateral and posterolateral fontanelles (see Figure 5 and Figure 6). There is a definitive difference in the sutures and fontanelles size between the full term and premature specimen.

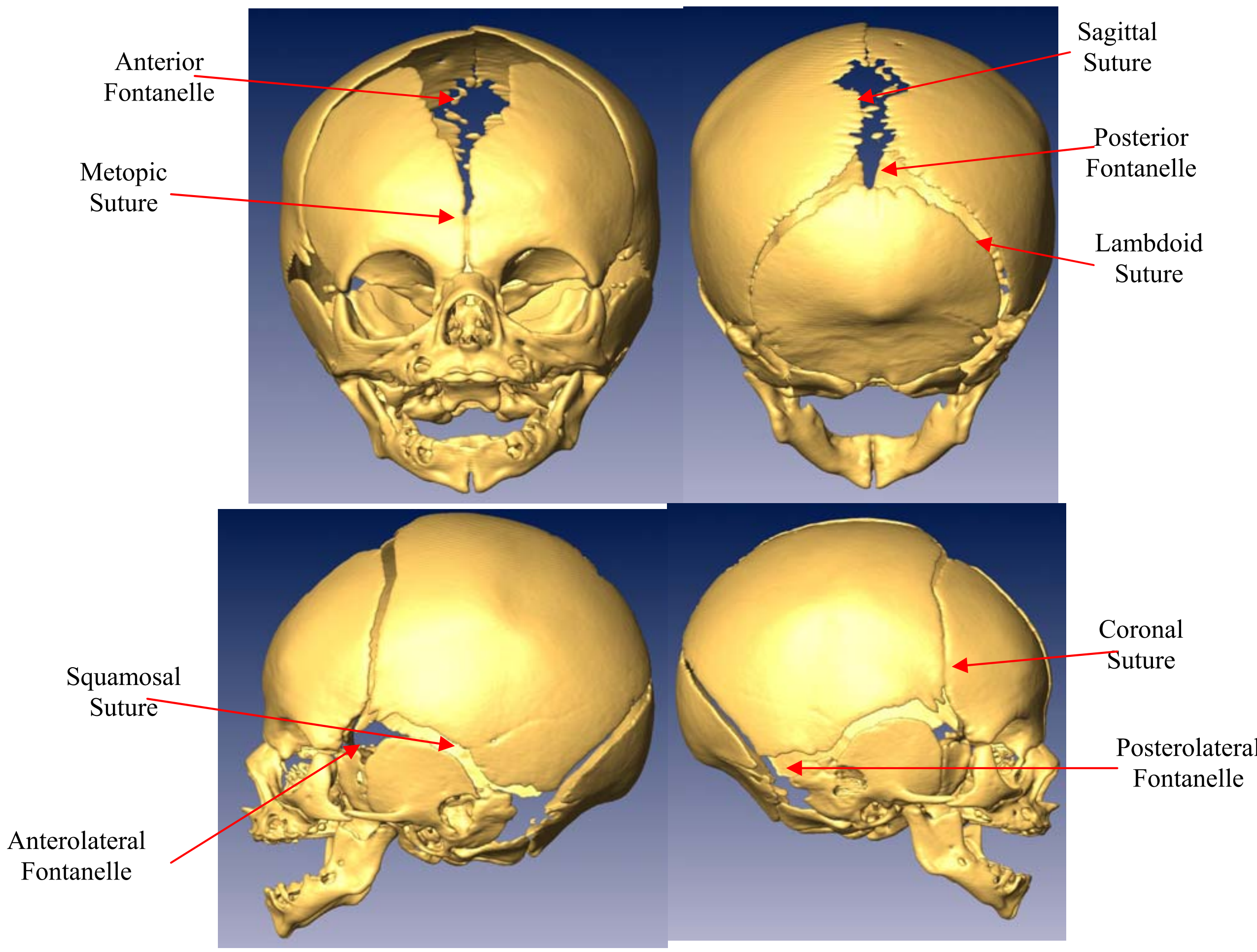

Figure 5: Views of the skull model for the full term specimen developed using a threshold of 52.2% of the dynamic range.

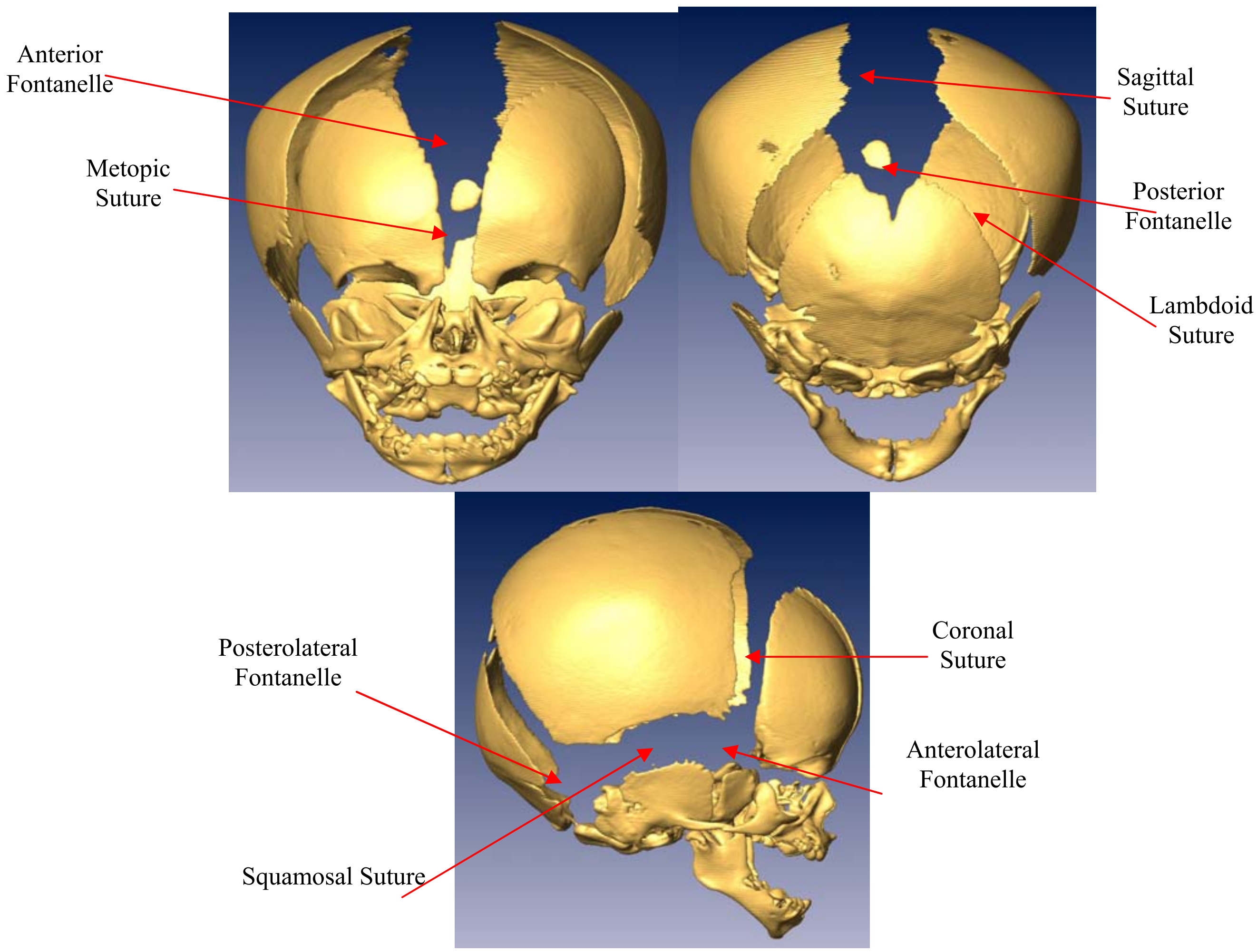

Figure 6: Views of the skull model for the premature specimen developed using a threshold of 67.6% of the dynamic range.

The cervical spine model for the full term specimen showed the presence of a posterior synchondrotic joint and no presence of neurocentral synchondrotic joints. The model also shows a curved cervical spine. This is due to the neck position when the full term PMHS was CT scanned (see Figure 7). The cervical spine model for the premature specimen showed the presence of both neurocentral and posterior synchondrotic joints (see Figure 8).

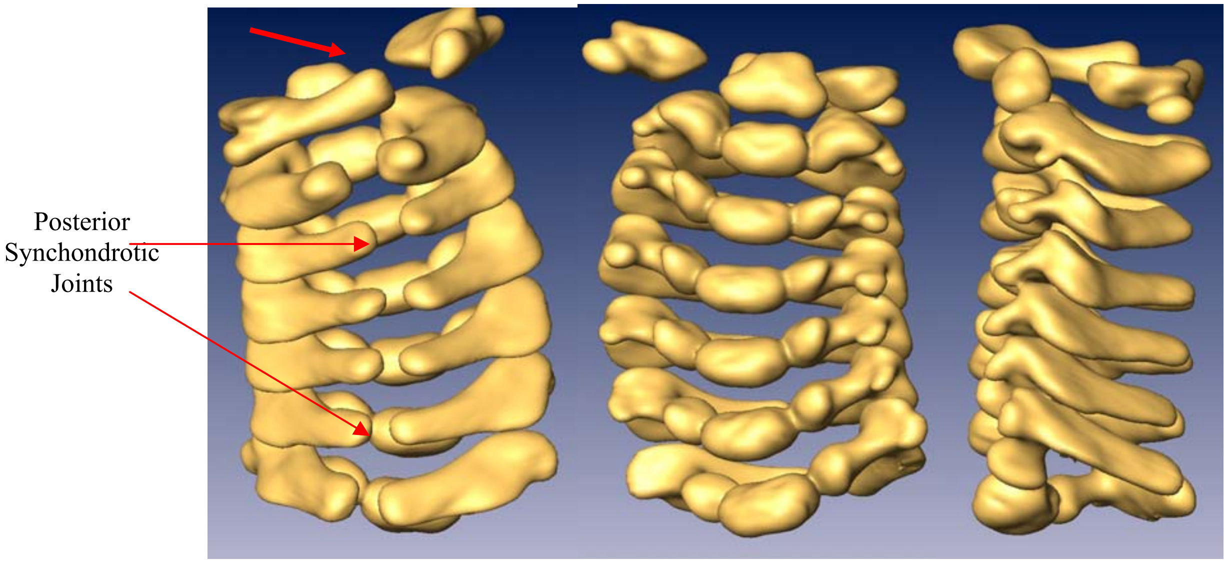

Figure 7: Posterior (left), anterior (center) and lateral (right) views of the cervical spine model of the full term specimen. Note the rotation of C1 on C2 (short arrow).

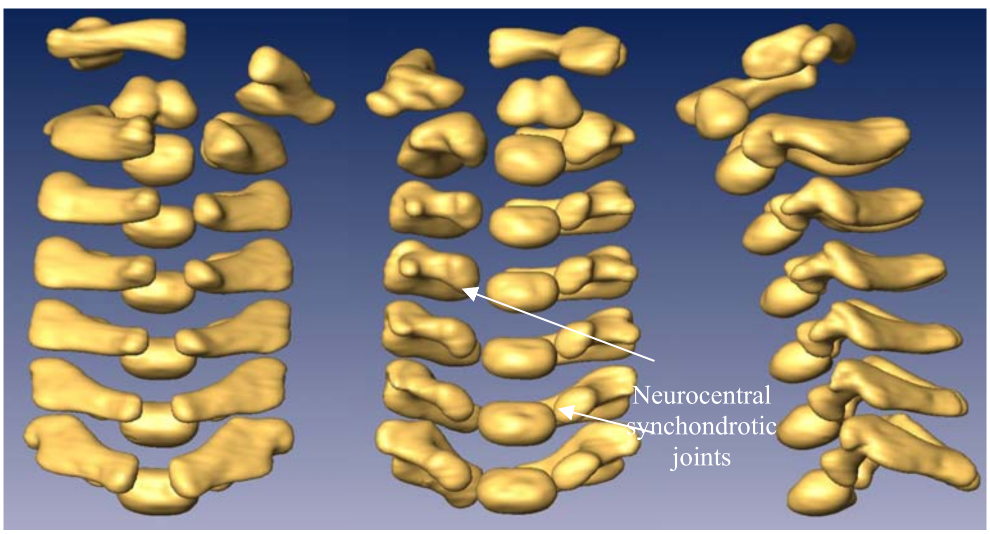

Figure 8: Posterior (left), anterior (center) and lateral (right) views of the cervical spine model of the premature specimen.

The sensitivity of the isosurfaces to small changes in the threshold was tested by using a threshold value that produced a 5% absolute error. A second set of cervical spine and head models of the full term were produced at a threshold of 50.5% of the dynamic range. For the skull model, this small change in threshold closed portions of the coronal, lambdoid and sagittal sutures and the posterolateral fontanelle (see Figure 9). For the C4 vertebral body, the threshold change removed the presence of a posterior synchondrotic joint and caused the vertebral ring to close. Additionally, the threshold change increased the thickness of the vertebral bone structure (see Figure 10).

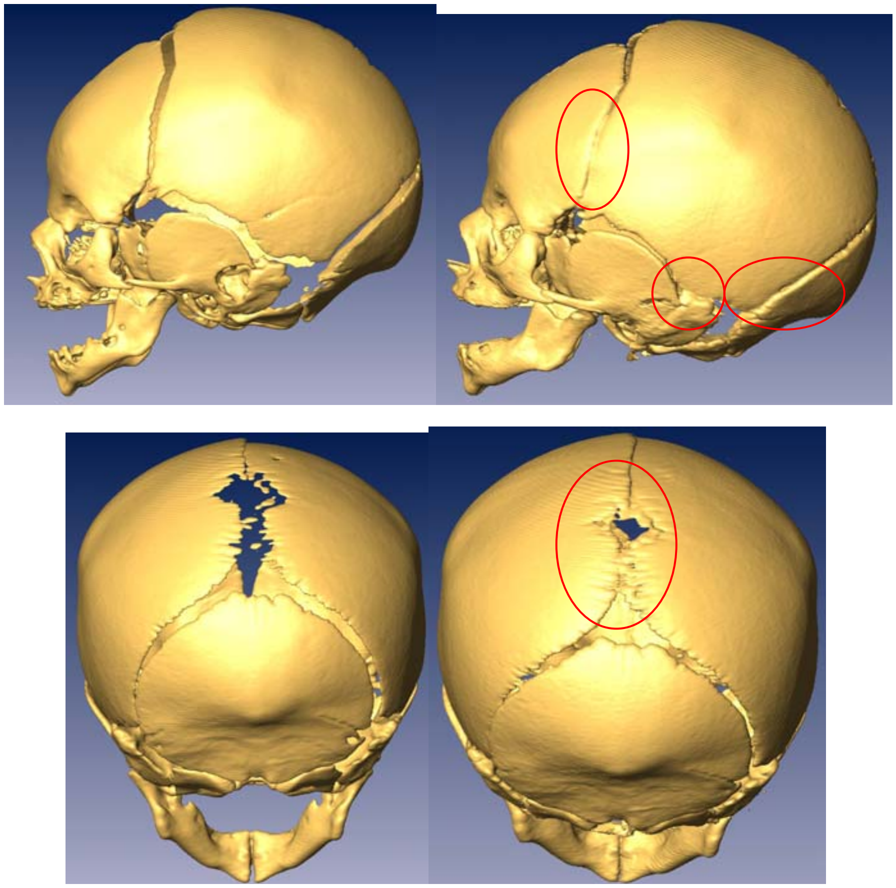

Figure 9: A comparison between two skulls of the full term specimen created at the 1.6% measurement error threshold (top and bottom left) and a 5% measurement error threshold (top and bottom right).

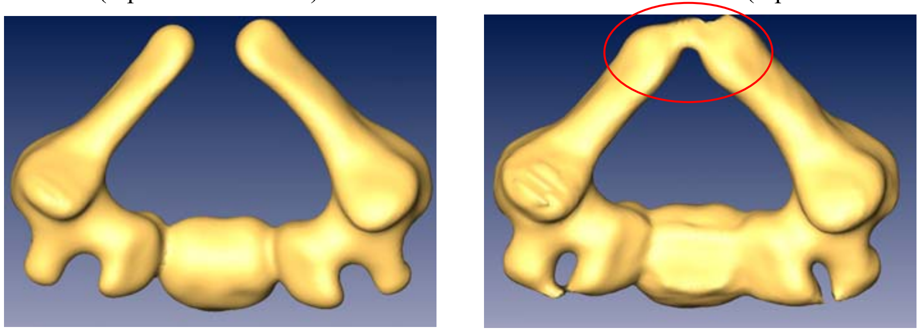

Figure 10: A comparison between two C4 vertebrae of the full term specimen created at the 1.6% measurement error threshold (left) and a 5% measurement error threshold (right).

DISCUSSION

Computational FEM derived from CT scans are valuable tools used to study traumatic head and neck injury. With a geometrically accurate FEM of the pediatric skull and neck, a better understanding of what occurs during head and neck injury of children can be gained. This study tries to provide a method for making geometrically accurate models of the pediatric skull and neck based on CT data.

One limitation to this study is the small number of samples used (n=2). This is due to the difficulty in obtaining pediatric specimens, which prevented any statistical conclusions. A second limitation is the mandible was the only physical model used in this method. The resulting cervical spine and head models presented may not be the same if a different physical model was used. Additionally, this method was only used to develop models of the pediatric cervical spine and skull. It is uncertain whether this method can produce models of other anatomical structures.

Both specimens produced very different thresholds, which supports the case that there is no one threshold for all pediatric specimen. This is expected since CT images are produced using a variety of different protocols. However, this variability does underscore the difficulties associated with choosing a threshold for bone.

This thresholding technique described in this study provides a method that is based on quantitative analysis and is validated against physical measurements. It also provides a rational and consistent methodology for differentiating the tissues in CT images. The method produced models that were qualitatively satisfying; they accurately displayed the sutures and fontanelles and posterior synchondrotic joints. For pediatric models, this method is more consistent and reliable than other techniques because a quantitative relationship between the bone structure and the threshold is established.

The results show that relatively small differences in the threshold can lead to important changes in both the pediatric cervical spine and head models. As shown in the results, a change in threshold from 52.2% to 50.5% of the dynamic range for the full term specimen closed portions of the coronal and sagittal sutures (see Figure 9). These changes will directly affect the dynamic response of the model. The same conclusion can be drawn with the cervical spine because the change in threshold removed the presence of a posterior synchondrotic joint, which would also lead to a different dynamic response (see Figure 10). This shows the importance and difficulty of selecting a threshold that produces an adequate representation of the pediatric PMHS.

Further work is needed to define a thresholding method where the specimen will not need to be dissected for validation. A noninvasive thresholding method would allow clinical scans to be used to produce FEM models of children. Additionally, this method will need to be tested at producing other models before it can be expanded beyond producing head and cervical spine models.

CONCLUSION

This study shows that by optimizing the threshold against a known and readily measurable anatomic structure, in this case the mandible, a geometrically accurate model can be produced of the pediatric head and neck.

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DISCUSSION

PAPER: **Thresholding Techniques for Developing Geometrically Accurate Pediatric Skull and Cervical Spine Models**

PRESENTER: ***Andre Loyd, Department of Biomedical Engineering and Division of Orthopedic Surgery, Duke University***

QUESTION: *Guy Nusholtz, DaimlerChrysler*

It looks like the conclusion from what you presented seems to be the greater the fidelity in the model, the greater the resolution or as you're calling it, threshold, the more accurate the model will be. That's pretty much known outside of numerical problems when you make models that are too complicated and you propagate numerical errors. Are you proposing that this method can somehow be used to define, say, for finite element models the level of resolution you will need to be fidelic?

ANSWER: No.

Q: No. Then, …what type of models are you trying to achieve?

A: Can you restate the question?

Q: Okay. … As I conclude what you're saying: If you don't have adequate resolution, you allow your error terms to be too large, then the model does not represent what is actually there. Now if I want to physically understand the mechanics behind an anatomical structure, this would tell me the limit of resolution I would need in order to build an appropriate model.

A: Ah. I see what you're saying. You're right. In terms of the resolution, the CT scan resolution: It will affect the geometrical representation. And so, it would help to have very fine CT resolution to create your model. However, I can't say anything beyond that because we haven't … tried this method on any CT scans at a lower resolution.

Q: But, you could actually find the optimal point, which means this is the minimal resolution. This is the minimum resolution that you need. If you go any further, you won't get any better.

A: Yeah.

Q: Okay. So that would be one possible usage for this technique. Okay. Thank you.

QUESTION: *Eric Meyer, Michigan State*

If you're using a certain threshold error, you showed that you got two different shapes and it seemed like there was a significant difference between two errors that you used. My question is: If you use— You have, you know, have values for gray scale and if you apply the actual material properties based on that gray scale, so you use a range of material properties depending on the gray scale values, can you eliminate some of that error in the thresholding by doing that?

ANSWER: So, you're saying apply the model. You're saying apply the—

Q: So, develop a calibration between the gray scale and the material properties.

A: Okay.

Q: And then, that might eliminate some of your error from thresholding.

A: That's a great idea, however it'd be. It's just very difficult to get that data.

Q: Well, I mean: There are software packages that will include that, as far as I know.

A: But you would have to have. You have to get that data from actual specimens.

Q: Yeah. You would have to develop the calibration scheme.

A: Okay.

Q: I'm just wondering if you think that would be applicable to maybe reducing the thresholding problem. Or, picking that one point.

A: I could see it could if you have the, if you have the information available to do that.

Q: Okay. Thank you.

COMMENT: *Barry Myers, Duke University*
Let me help out a bit. Continuous modeling of bone is something that is readily do able. You can assign bone density values, vary them. We did that in the skull with Tamacho & Hopper. The problem we have here is you're actually transitioning from a material you're calling bone to material you're calling something else and it'll have a dramatically different material model. So, it gets a lot harder to do and how you would then move from one to the other is problematic.

QUESTION: *Erik Takhounts, NHTSA*
Barry basically answered my question, but I think what are you trying to do. You tell me whether it's right or not is to develop a recommendation for those who try to model pediatric heads, where to separate the bone from soft tissue, probably something like that. Is that what you're trying to do?

ANSWER: Yes. What we're trying to do is to build a model that accurately represents the pediatric specimen.

Q: Yeah. Barry just said it's impossible so, but I think what you're trying to do is that you're trying to provide advice for those who try to model that, which way to go the best.

A: Oh, for a person.

Q: Yes. Okay. Thank you.