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A CT Method for Finding the Pediatric Head Center of Gravity and Inertial Properties

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This paper has not been screened for accuracy nor refereed by any body of scientific peers and should not be referenced in the open literature.

ABSTRACT

The development of child crash test dummies has been slowed by the lack of available child cadavers to validate the dummies against. Information such as the head mass, head center of gravity (CG) locations and head inertial properties for children ranging in age from infant to 18-years old have not been obtained. This study examined two methods for finding the CG and inertia properties of the pediatric head and compared the two methods against each other to see if they produced the same results. One method was a mechanical method where the pediatric head was hung and swung to find the properties and the other was a CT method where a computer model was developed from CT scans and used to obtain the properties. Two pediatric post mortem human subjects (PMHSs) were imaged using CT and were dissected. The two methods were applied to each of them. The results showed that the two methods give different values for the moment of inertia (MOI), CG location and mass for both heads of pediatric PMHSs. A review of the mechanical method revealed that the pediatric sutures allowed for potentially large errors in the CG location and MOI measurements. The sutures allowed the pediatric head to change shape during the mechanical method, which adversely affected the quality of the results. However, the CT method provided a reference geometry for the CG and inertial properties and was less sensitive to error. The CT method is recommended for finding the CG and moment of inertia of the pediatric head.

INTRODUCTION

Child head and neck injury is a very costly problem, both in terms of health (morbidity and mortality) as well as healthcare dollars. Head injuries account for 30% of all child deaths, which makes injuries the leading cause of death for children (Guyer and Ellers, 1990; Kraus et al., 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).

Child crash test dummies have been developed as a tool for studying methods of preventing child head and neck injury (Mertz et al., 1982; Wolanin et al., 1982). These child crash test dummies were designed based extensively on anthropomorphic data taken from pediatric volunteers (Reynolds et al., 1976;

Weber et al., 1985). However, data for the pediatric head center of gravity (CG) location and moment of inertia (MOI) cannot be obtained from volunteer studies. This data is typically derived from postmortem human subjects (PMHSs), but pediatric PMHSs are very uncommon. So as a substitute for cadaver data, scaling rules and porcine data have been used to define the moment of inertia and center of gravity location for child crash test dummies (Irwin and Mertz, 1997; Mertz et al., 1982).

Two methods are commonly used to find the moment of inertia and center of gravity properties of biological tissues: a mechanical method and a computerized tomography (CT) method. The mechanical method requires the biological tissue to be hung from two points to get the CG location and requires the biological tissue to be swung to get the MOI. This method has been the method of choice for finding adult head CG and MOI properties (Walker et al., 1973). The CT method uses CT scans to create three-dimensional solid models of the biological tissues and uses density estimates to get the values for the CG location and MOI (Wei and Jensen, 1990; Zhang et al., 2002). The CT method is commonly used for complex objects, however, it has not been validated for the human head.

This paper will examine both the mechanical method and the CT method for finding CG location and MOI of pediatric heads. It is hypothesized that both methods will produce the same moment of inertia, mass and center of gravity location values.

METHODS

Two fresh-frozen unembalmed PMHSs, a one-day-old and an eleven-day-old, were examined to find the mass, center of gravity and inertial properties of the pediatric heads. These properties were found using two methods, a mechanical method and a CT method, and the results were compared against each other.

CT Method

The PMHSs were imaged using a 16-slice multidetector array CT scanner (LightSpeed 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 (310 mAs) were used for both PMHSs and along with a configuration of 16 x 0.625 and a slice thickness of 0.625 mm. The examination was performed using a small scan field-of-view, a 512 x 512 display matrix and a standard reconstruction algorithm using a 0.1 mm reconstruction interval. The high resolution scanning parameters produced images with 0.43 mm/pixel resolution.

The CT scans were imported to Amira™ 3.0 (TGS, Inc., San Diego CA) and each image was segmented into three parts; brain, bone and extracranial soft tissue. To segment the bone, a thresholding technique was used where measurements of the mandible were compared to measurements of rendered isosurfaces of the mandible. The threshold that produced the least error in the measurements was used for the bone. Then the material that was inside and outside of the cranium was segmented as the brain and extracranial soft tissue, respectively (Figure 1).

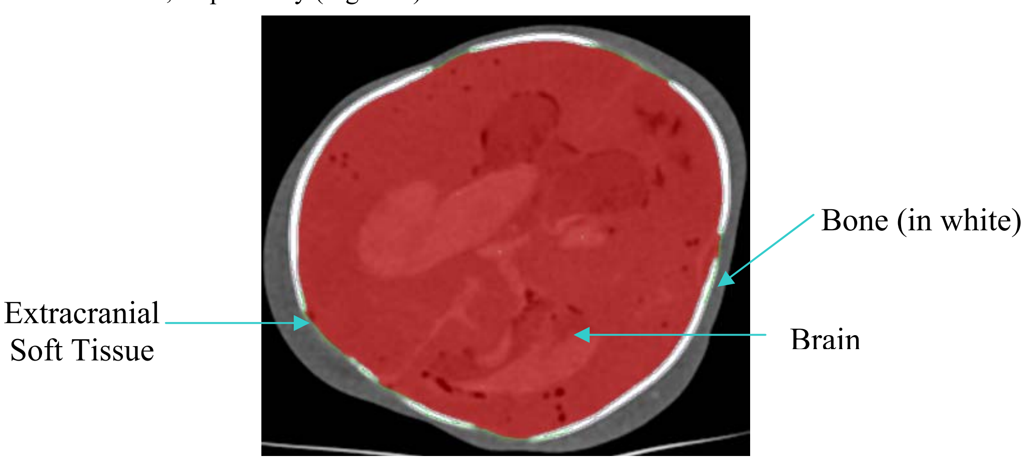
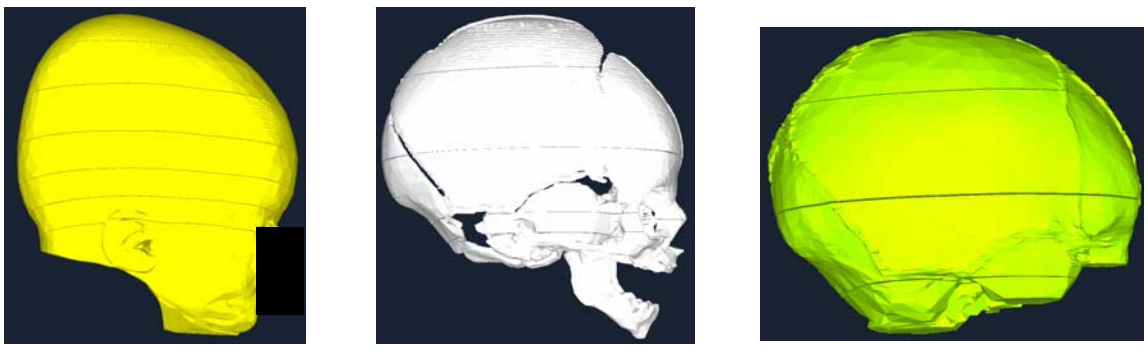


Figure 1: Example of a CT Scan segmented into the parts of brain, bone and soft tissue.

Once the scans were segmented, the CT slices were "stacked" to produce three-dimensional isosurfaces of each part. The head was separated from the neck at the occipital condyles. Therefore, the bone and extracranial soft tissue isosurfaces were cut at the plane of the occipital condyles (Figure 2). Using Amira™ 3.0, the isosurfaces were converted into tetrahedral meshes and exported into HyperMesh™ 7.0 (Altair Engineering, Troy MI). In HyperMesh™ 7.0, densities were assigned to each mesh and the three meshes were combined into one model. Density values of 2100 kg/m^3, 1200 kg/m^3 and 1040 kg/m^3 were taken from the literature and used for the bone, extracranial soft tissue and brain, respectively (Zhang et al., 2001; Ruan et al., 1991). Next, the model was aligned in the anatomical directions. The x-axis was defined along the Frankfort plane. The y-axis was from the left acoustic meatus to the right acoustic meatus and the z-axis was vertically perpendicular to the Frankfort plane with inferior being positive (Walker et al., 1973). For alignment, the right and left apexes of the acoustic meatuses were aligned within 1 mm in both the x- and z-directions. The right apex of the acoustic meatus and the right infraorbital foramen was aligned within 1 mm in the z-direction. Lastly, the model was exported into LS-Dyna (LSTC, Troy MI) to compute the moment of inertia, center of gravity location and mass values.



Soft Tissue Bone Brain

Figure 2: Hexahedral meshes of the extracranial soft tissue, bone and brain.

Mechanical Method

The same two PMHSs that were used for the CT method were used for the mechanical method. The mechanical method was performed after the PMHSs were thawed and put through a battery of quasi-static neck tension and head compression tests that were unrelated to this study. After the quasi-static testing, the heads were filled with saline and sealed at the occipital condyles with polymethylmethacrylate (PMMA). Pins were placed at the right acoustic meatus and the right infraorbital foramen to denote the Frankfort plane. The heads were weighed and the center of gravity of the head was found using a method explained by Walker et al. (1973). Two small screw hooks were inserted into regions of bone along the sagittal plane of the heads. Ideally, the two screw hooks would be placed approximately 90° apart. However, the pediatric sutures in the head prevented this and screw hooks were hung at angles of 17° and 45° apart from each other for the one-day-old and eleven-day-old, respectively. Then the head was hung from each hook inside a frame. Within the frame there was a plumbline and a scale. The plumbline was used as a reference for the vertical direction (Figure 3). Two static pictures were taken of the right side of the pediatric heads using a high-speed digital imaging system at a resolution of 512 x 512 pixels while the head was hanging from each hang point. These pictures were used to locate the CG position. Then the head was swung at small amplitudes (<5°) and recorded at 50 frames per second. This video was used to find the MOI (Prange et al., 2004).

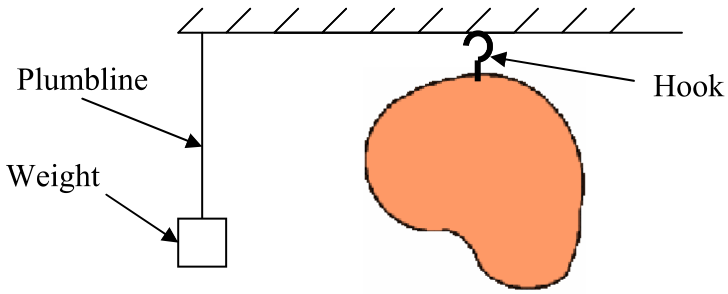


Figure 3: Setup for the mechanical method.

The CG for each head was found mathematically by drawing a vertical line from the hang point in the two pictures and using the intersection of the two lines as the center of gravity. The digital imaging data was used to get the period of the oscillation (T) and the distance from the pivot point to the center of gravity (d). This information and the parallel axis theorem were used to find the moment of inertia in the y-direction (Equation 1). In equation 1, I_{yy} is the inertia value, m is the mass and g is gravitational acceleration (Prange et al., 2004).

$$I_{yy} = mgd * \frac{T^2}{4\pi} - md^2 \tag{1}$$

RESULTS

The mechanical method produced moment of inertia values (I_{yy}) of 5172 gm*cm^2 and 4850 gm*cm^2 and mass values of 0.70 kg and 0.68 kg for the eleven-day-old and one-day-old, respectively (Table 1). The center of gravity from the mechanical method was found to be 31 mm from the right apex of the acoustic meatus for the eleven-day-old and 29 mm from the apex of the right acoustic meatus for the one-day-old (Table 2).

The CT method produced moment of inertia values of 14600 gm*cm^2 and 14400 gm*cm^2 and mass values of 0.93 kg and 0.89 kg for the eleven-day-old and one-day-old, respectively (Table 1). Using the CT method, the center of gravity positions were found to be 32.2 mm and 25.5 mm from the apex of the right acoustic meatus for the eleven-day-old and one-day-old, respectively (Table 2). Direct comparisons between the two methods are seen in the table below (Table 3).

Table 1. Mass and MOI values for the two PMHSs found using the CT method and mechanical method.

	Mass (kg)		I_{yy} (gm*cm^2)	
	Mechanical	**CT**	**Mechanical**	**CT**
one-day-old	0.68	0.89	4850	14400
eleven-day-old	0.70	0.93	5172	14600

Table 2. Distance from the apex of the right acoustic meatus to CG. Positive z-direction is inferior.

	CT		**Mechanical**	
	x (mm)	z (mm)	x (mm)	z (mm)
one-day-old	1	-26	4	-29
eleven-day-old	4	-32	10	-29

Table 3. Direct comparison between the CT and mechanical methods using the CT method as the standard.

	Mass	**MOI**	**Differences in CG Position**
one-day-old	-23.6%	-66.3%	3mm
eleven-day-old	-24.7%	-64.6%	1mm

ANALYSIS

Mechanical Method

Review of the mechanical method found three potential sources of error. First, the mechanical method was done after a series of neck and head quasi-static tests, which took place over a period of four days. This allowed ample time for the pediatric heads to lose cranial fluid content and blood. The loss of blood and fluid lowered the mass of the pediatric heads by the time they were weighed. Additionally, the dissection process in which the neck is removed from the head could not be matched with the removal of the neck in the computational model. Together, these two observations lead to the mass measurement differences between the two methods.

The third source of error was caused by the presence of pediatric sutures in the heads. Sutures in between the bone plates allowed the shape of the pediatric head to change and made the assumption that the head is a rigid body invalid (Figure 4). During the CG and MOI testing, it was observed that the pediatric heads changed shape when the heads were hung from the two hang points. This deformation was quantified for both specimens (Table 4). The static pictures indicate that there are significant changes in shape during the mechanical testing method, which makes both the CG and MOI values questionable.

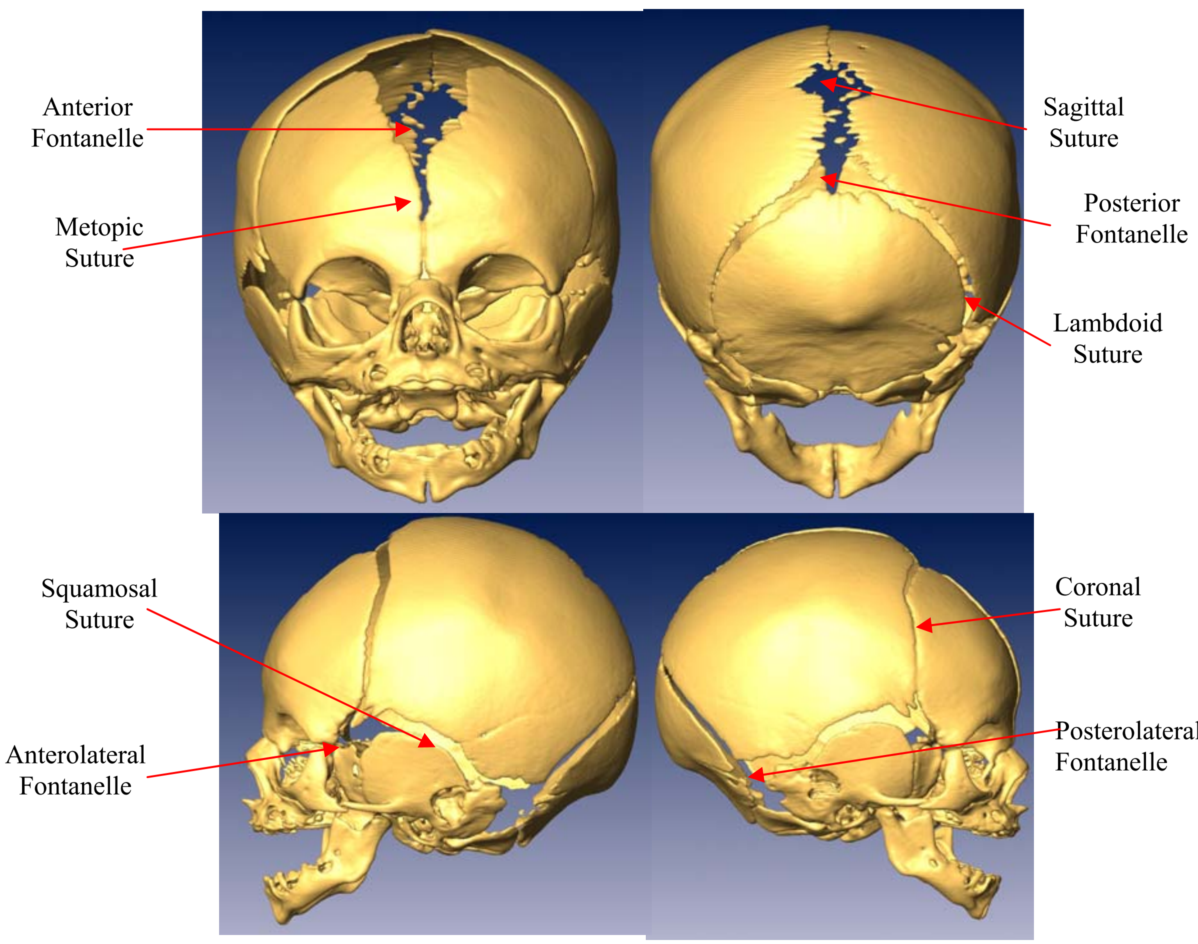


Figure 4: Illustrates the presence of sutures and fontanelle throughout the pediatric head (top row - anteroposterior and posteroanterior projections; bottom row - left and right lateral projections).

Table 4. The percentage dimensional changes of the pediatric heads between the two hang points. The x-direction is along the Frankfort plane and the z-direction is perpendicular to the Frankfort plane. These values were obtained by comparing the shape of the head while hanging at the two hang points.

	X	Z
One-day-old	14.0%	-11.4%
Eleven-day-old	-5.3%	12.0%

Moreover, the sutures limited the locations in which the screw hooks could be placed within the pediatric head. Ideally, the sutures would be in positions that would be 90° apart, however, limited regions of bone caused the hang points to be at an angle that was considered small for one of the specimen (<30°). Small errors in this angle will lead to a CG position error and large moment of inertia error. An example of this accumulation of errors was quantified for the one-day-old in Table 5.

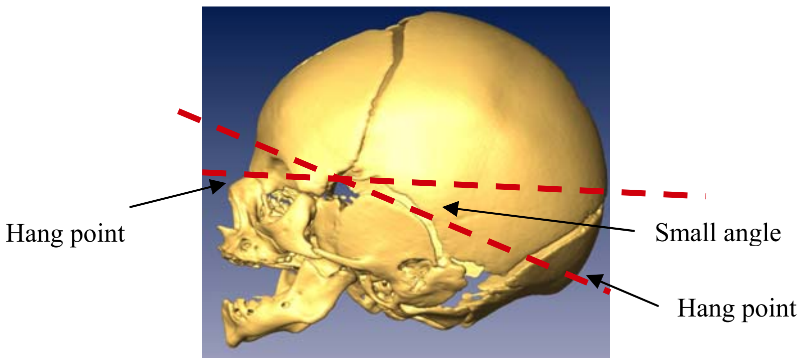


Figure 5: The hang point locations and small angle between the two hang points. The lines depict the vertical direction when the head is hung from that hang point. The angle here is approximately 17°.

Table 5. Angle error between the hang points and its effect on the measurement of CG position and MOI calculations. This example data is for the one-day-old. Angle error is the difference from the real angle of 17° and the mechanical method's original results were used as the standard.

Angle Error	CG Error	MOI Error
-5°	-4.4 mm	-51%
-1°	-1 mm	-12%
1°	1.1 mm	12%
5°	6.9 mm	78%

CT Method

The potential sources of error in the CT method were the densities and formation of the three meshes (brain, bone and extracranial soft tissue) of the model. The "extracranial soft tissue" included the skin, fat and muscular structure of the face. The "brain" included both the brain and intracranial fluid. The bone was selected by thresholding out the bone. Lumping material together made selecting density for the extracranial soft tissue and brain difficult. In addition, the presence of the trabecular bone in the pediatric skull was negligible. This fact made the selection of a bone density complicated because the only available data was based on adult bone measurements that included large presences of trabecular bone. A sensitivity study was done to quantify the effect that varying the densities would have on the MOI, mass and CG position data.

Each mesh density for the one-day-old model was varied by 25% and its effect on the MOI, CG position and mass values were recorded (Table 6). The data showed that the errors in the densities of 25% produced errors in the MOI that ranged from 5% to 8% and errors in the mass values ranged from 4% to

13%. Additionally, the center of gravity location moved a maximum of 1.4 mm. Overall, the CT method produced small errors when there were relatively large errors in the densities of the parts.

Table 6. Density error and its effect on mass, MOI, and CG position. All comparisons are using the original CT method results as the standard.

Part	Density Error	Mass Error	MOI Error	CG Position Change
Bone	25%	4.3%	4.6%	0.0 mm
Brain	25%	10.1%	7.1%	1.4 mm
Soft Tissue	25%	12.6%	7.9%	-1.4 mm

One advantage to the CT method was that it provides a reference geometry for the shape of the pediatric head. This is important because, as it was noted earlier, the pediatric heads deform under their own weight. Since the pediatric head is a deforming mass, a reference geometry is needed to provide the MOI, mass and CG values.

DISCUSSION

The mass, moment of inertia and center of gravity properties of the pediatric head are very important parameters in the development of child crash test dummies. However, due to limited pediatric cadaveric data, current child crash test properties are based on porcine data or scaling rules (Irwin and Mertz, 1997; Mertz et al., 1982). This study looked at two methods of finding the MOI, mass and center of gravity for the pediatric head. Then, the methods were compared against each other to see if they produced the same results.

One major limitation to this study was the small number of specimens that were tested (n=2). This prevented any statistical analysis from being done. The second limitation to this study is that the pediatric specimens were also being tested for neck tensile and head compression properties. This testing was done prior to the application of the mechanical method.

The advantage of the mechanical method is that it has precedence in the literature and it is standard protocol for finding the inertial properties of the adult heads (Walker et al., 1973; Prange et al., 2004). However, there are major drawbacks with applying the mechanical method to pediatric heads. Unlike the adult head, the pediatric head has sutures that limit the insertion locations for screw hooks and allows the pediatric head to deform. In the adult, screw hooks would be placed at points that were close to 90° apart. This reduces the errors associated with the intersection of acute line segments.

Also the sutures allowed the pediatric head to deform under its own weight, which negated the assumption that the pediatric head is a rigid body. Since the shape of the pediatric head is changing, it can be inferred that the MOI and CG position is changing as the shape changes. This fact makes the data produced by the mechanical method very unreliable because the method allows the MOI and CG position to change during the measurement.

The mechanical method did give a much smaller value for the masses then the CT method. This discrepancy was due primarily to the loss of blood and fluid during the quasi-static neck tension testing. Dissecting and weighing the head from the neck before any mechanical testing was done could have prevented this problem. Although it was not practical for this experiment, it is recommended for future head mass measurements.

One great advantage of the CT is that it provides a reference geometry of the pediatric head for the MOI and CG position. This is important due to the fact that the pediatric head is not rigid. Additionally, the CT method was less sensitive to errors in the input values. Compared to the mechanical method, the CT method produces consistent values even with large errors in the input values. Additionally, the CT method provides more information than the mechanical method. Using the CT method, the full inertia tensor and anatomical landmarks can be identified for the pediatric head (Appendices A and B). Lastly, another great advantage of the CT method is that clinical CT scans can be used to find the MOI and CG of the pediatric head. Clinical CT scans will provide a large database of pediatric heads that can be used to find the MOI and CG position while eliminating the need for pediatric cadavers to find those properties. The problems with the CT method are that the geometry of the pediatric head is simplified and that the method is density dependent. Lumping all of the soft tissue into one part may not be the most accurate method because there may be significant variations in density. The same can be said for the brain.

Overall, the results of this study disprove the hypothesis that the mechanical method and the CT method would produce identical values for the center of gravity, MOI and mass of the pediatric head. It is proposed that the CT method be used for finding the MOI and CG properties of the pediatric head until the sutures and fontanelles are fused closed.

Further research is needed to validate the CT method. This experiment needs to be repeated on adult heads to see if the CT method produced results that match the mechanical method since it is known that the mechanical method is accurate for the adult head (Walker et al. 1973). Additionally, it is theorized that the problems associated with using the mechanical method on the pediatric head will diminish as the sutures close.

CONCLUSION

This study shows that a computational model of the pediatric head produced from CT scans can be used to produce adequate values for the center of gravity, MOI and mass while providing a reference geometry for those values. It also shows that the mechanical method, which is commonly used on adult heads, does not produce reliable data for the CG position, MOI and mass values for pediatric heads.

ACKNOWLEDGEMENTS

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APPENDIX A: Moment of Inertia Matrixes From CT Method.

<u>One-day-old</u>

$$\begin{bmatrix} I_{xx} & -I_{xy} & -I_{xz} \\ -I_{yx} & I_{yy} & -I_{yz} \\ -I_{zx} & -I_{zy} & I_{zz} \end{bmatrix} = \begin{bmatrix} 11600 & 100 & 1900 \\ 100 & 14400 & -200 \\ 1900 & -200 & 11800 \end{bmatrix} gm * cm^2$$

<u>Eleven-day-old</u>

$$\begin{bmatrix} I_{xx} & -I_{xy} & -I_{xz} \\ -I_{yx} & I_{yy} & -I_{yz} \\ -I_{zx} & -I_{zy} & I_{zz} \end{bmatrix} = \begin{bmatrix} 12600 & -700 & 1600 \\ -700 & 14600 & -100 \\ 1600 & -100 & 13600 \end{bmatrix} gm * cm^2$$

APPENDIX B: Anatomical Positions.

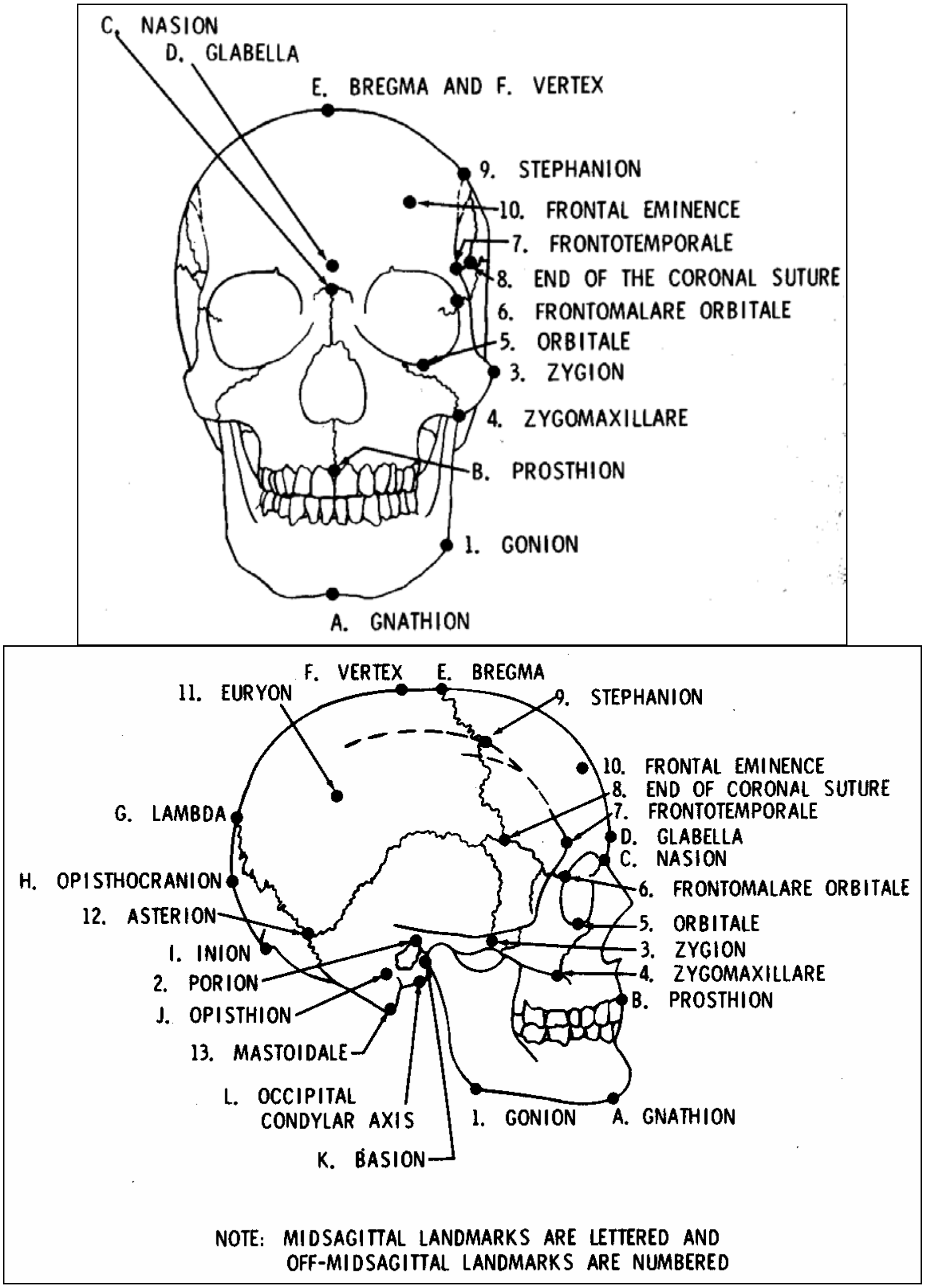

Figure B1: Anatomy of the Head (Hubbard and McLeod,1973).

Table B1. One-day-old.

	x (mm)	y (mm)	z (mm)
Apex of left acoustic meatus	0.0	0.0	0.0
Apex of right acoustic meatus	-0.5	52.9	-0.9
Left infraorbital foramen	39.5	14.6	-0.6
Right infraorbital foramen	39.5	39.7	-0.4
Left Infraorbitale	40.4	5.6	-2.2
Right Infraorbitale	39.4	47.5	-2.3
Left gonion	16.3	4.0	20.0
Right gonion	14.5	48.1	20.8
Gnathion	33.8	25.6	33.3
Left zygion	23.3	57.9	1.7
Right zygion	24.9	-4.8	1.7
Basion	-4.5	26.1	2.8
Nasion	46.7	26.4	-17.2
Opisthion	-30.6	25.9	-0.6
Center of gravity	0.4	24.9	-26.4

Table B2. Eleven-day-old.

	x (mm)	y (mm)	z (mm)
Apex of left acoustic meatus	0.0	0.0	0.0
Apex of right acoustic meatus	0.5	47.5	0.0
Left infraorbital foramen	39.3	34.6	-0.3
Right infraorbital foramen	38.8	11.3	-0.3
Left infraorbitale	38.8	8.2	-0.3
Right infraorbitale	37.8	40.0	-0.8
Left gonion	13.4	5.2	15.5
Right gonion	13.5	42.3	17.0
Gnathion	30.0	24.3	30.9
Left zygion	23.5	-7.1	2.0
Right zygion	20.1	53.3	1.7
Basion	-3.2	23.0	4.1
Nasion	47.1	22.3	-14.6
Opisthion	-22.7	23.4	-2.6
Center of gravity	4.0	22.9	-32.3

DISCUSSION

PAPER: **A CT Method for Finding Pediatric Head Center of Gravity and Inertial Properties**

PRESENTER: ***Andre' M. Loyd, Duke University***

QUESTION: *Frank Pintar. Medical College of Wisconsin*
Tough subject. Did you look at all—I assume when you did the CT that you used some thresholding technique?

ANSWER: Yes.

Q: Do you look into the error that picking the right threshold would give you?

A: No. No, we didn't.

Q: Because sometimes when we've done this, some of the gunshot wound patients that we've looked at, the thresholding actually can distort the boundary a little bit.

A: Okay.

Q: And then it will create error in your measurements. So I would like you to look at, perhaps, a chryomicrotome technique where you can actually measure skull thickness or other kind of things, or maybe you already measure skull thickness, and compare that to the thicknesses that you actually get from the CTs.

A: We have a thresholding method where we take the jawbone, take measurements of it to get the threshold for the bone so we're pretty sure where the bone location is. At least, where the bone boundary is. And then, what we did—

Q: Could you actually look at thickness, though? Skull thickness?

A: Yeah. We take physical measurements of the jawbone.

Q: Okay.

A: And use that as a threshold, to pick a threshold for the bone. And then for everything else, we take the— For the material inside of the skull, we called everything brain and for everything outside the bone, we called it soft tissue.

Q: Did you try any parametric analysis by changing the threshold and see if you actual get different values?

A: No, we hadn't.

Q: *Guy Nusholtz, Daimler Chrysler*
First a couple small things: Did you look—When you had your pediatric tissue, did you x-ray it to see whether there was any air there? If you're going to cut off the neck to measure the moments, it's easy for air to leak in there. Did you check to see whether any air had leaked in, which means that your material falls down with gravity? And so, that changes your moment of inertia as well.

A: Yeah. We didn't x-ray, but what we did was we did fill the head with saline as best we could and sealed it. That way, before we did—

Q: Okay. That would address the problem provided you could make sure you get all the air out. The other thing is pressurizing is a very messy job and you may have made the decision. You seem to get distortions in the skull when you changed positions.

A: Yes.

Q: That may be a very profound result because it implies that in a dynamic situation, you're going to get the same. You get distortions at 1 g, you're going to get more distortions at higher g's. The implication is that your moment of inertia becomes meaningless because the head is dynamically changing over time.

And so finding the moment of inertia becomes only one part, then you have to figure out how it's going to deform under loading conditions. So you got a lot more work cut out for you. So you should, need to go back to NHTSA and get more money

Q: *Joel Stitzel, Virginia Tech - Wake Forest University*
Talking to some of the pediatric surgeons at the hospital, they've—it's kind of amazed me. They said the way they do surgery on kids is they'll actually use scissors to cut the skull it's so thin. So my question related to that is: What's the resolution of your CT scanner? Do you feel like you're accurately capturing the thickness of the skull? And then, I wanted to recommend: I don't know about the average board diameter of a micro CT, but if one would fit in the micro CT, that'd be something you'd want to look at to get a much better, you know, analysis of shape and size.

A: Okay. Currently, the resolution of our, of the CT scans is .6 mm actually and .2 mm, I guess, across and 40 micro CT scans. You can't get a pediatric head in it so we—because we're at the top resolution that the CT scans, a typical CT scan can be used.

Q: *Richard Kent, University of Virginia*
Sort of building on Guy's point, if the head deforms under 1 g when it's hanging, it seems like it should deform under 1 g when it's laying on a CT scanner as well. Have you got a sense of how that deformation is also affecting the CT results if you were to have a child, say, sitting in a child's seat or something like that?

A: No. We're not sure of that. We are aware that when the pediatric cadaver is frozen in some type of deformed state and that's when the CT scan is taken and where the values are, the values are center of gravity, moment of inertia come from. That's why we noted that the CT scan has the advantage of having a reference geometry so you'll say at this geometry, your center of gravity and moment of inertia are this.