Finding Cadaveric Human Head Masses and Center of Gravity: A Comparison of Direct Measurement to 3D ing

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FINDING CADAVERIC HUMAN HEAD MASSES AND CENTER OF GRAVITY: A
COMPARISON OF DIRECT MEASUREMENT TO 3D MODELING

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science

By

GRANT CORWIN ROUSH
B.S., Wright State University, 2005

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December 19, 2009

I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION
BY Grant Corwin Roush ENTITLED Finding Cadaveric Human Head Masses and Center of
Gravity: A Comparison of Direct Measurement to 3D Modeling BE ACCEPTED IN PARTIAL
FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF Master of Science in
Engineering

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ABSTRACT


Mass properties of the human head are critical elements in developing neck injury threshold criteria in acceleration and impact environments. In order to accurately simulate the dynamics of the head in impact and acceleration environments, valid mass properties data for the human head must exist.

The purpose of this study was two-fold: First, to directly measure and generate a useful data set of human head mass properties and anthropometry, and second, compare the results from the direct measurement to measurements obtained using computed tomographic (CT) analyses of the human head. Four cadaveric human heads, all male, were measured.

For the direct measurement procedure, each frozen specimen was secured in a lightweight-aluminum box. The mass, center of gravity (CG) and principal moments of inertia (MOI) were then measured. These same properties of the box alone were subtracted from the measured quantities to determine each specimen’s mass properties. For the CT analysis, the identical specimen preparation was imaged with CT. With both slice collimation and table feed set at 1 mm, the CT image resolution was 0.284 mm³/voxel. Segmentation of tissue types based on density thresholds was used to divide the volumetric data into brain matter, bone, and fat/skin. Surfaces from these groups were extracted to create volumes representing these structures. Assigning mass densities to the segmented volumes, the mass properties of the head were calculated using MIMICS, a 3D modeling program and results were compared.
The final results showed the method to be accurate. The average weight for the directly measured heads was 8.96 lb compared to 8.99 lb for the calculated. The average shift in the z-axis ($CG_z$) for the directly measured heads was 0.91 in above the Frankfort origin while the measured shift was 1.00 in on average. Overall, there was no significant difference seen among any of the parameters at $\alpha = 0.05$. 
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INTRODUCTION

The human body’s response to excessive accelerations and impact is largely dependent on the body’s inertial properties and any encumbering equipment. Without doubt, the head and neck are among the most exposed elements of the body in these harsh dynamic environments. This issue has been recognized by the government and within the medical and commercial communities for several decades. A great deal of research has been performed on characterizing the inertial properties of the heads and necks of cadavers and living humans (Harless, 1860; Clauser, McConville, Young, 1969; Becker 1972; Walker, Harris, Pontius, 1973; Chandler, Clauser, McConville, Reynolds, Young, 1974; Beier, Schuller, Schuck, Ewing, Becker, Thomas, 1980; McConville, Churchill, Kaleps, Clauser, Cuzzi, 1980; Kaleps, Clauser, Young, Zehner, McConville, 1984).

Within the United States Air Force, devices that encumber the head and neck often include helmets, oxygen masks, and helmet-mounted optics, especially for an aircrew member. The mass properties and the mass distribution of these devices relative to the head are critical design parameters for helmets and head-supported equipment. These parameters could affect the comfort, fit, performance and crash or ejection safety of head-mounted equipment. The distribution of head-supported mass could also affect the fatigue experienced by aircrew members. The mass properties parameters which have been identified as most important when designing helmet systems are total head-supported mass, moments of inertia (MOI), and the center of gravity (CG) location of the head-supported equipment (Knox, Buhrman, Perry, 1992; Self, Spittle, Kaleps, Albery, 1992; Whitestone, Albery, 1996). Likewise, for advanced computations and accurate dynamic modeling, it is essential to have a prior knowledge of the mass properties of these equipment simulated in the model (Schultz, Obergefell, Rizer, Albery, Anderson, 1997; Beier et al., 1980; Clauser, Thomas, Sances, Larson, 1983).
BACKGROUND

One of the missions of 711 HPW/RHPA is to conduct experimental research to define the human response to transient biodynamic stresses such as impact acceleration and aerodynamic forces. With the goal of developing aeromedical injury tolerance criteria, it is essential to understand the envelope of dynamic stresses within which the human body can operate without injury. Towards establishing these criteria, the experimental research often includes the exposures of human volunteers to a defined range of acceleration pulses. In order to accurately develop these criteria and successfully model the head and neck reaction to these pulses, it is important to have accurate mass properties of volunteer-subjects’ heads. Exhaustive work has been done by researchers to continue to improve fidelity to current regression models (Clauser, Thomas, 1972), but data is based upon a certain population, and often conflicting. Since it is impossible to directly measure the subjects’ head mass properties accurately without segmentation, it would be very helpful to develop a method for computing the head mass properties of the living human to improve in vivo simulation models. Hence, the current studies were conducted to investigate the potential for using computed tomography (CT) analysis to accurately calculate the inertial properties of the living human head. Another application of this methodology is custom-fit and ballasted helmets to lessen the risk of increased bending and rotational moments due to an offset of the current head CG.

Due to recent advancements in medical imaging, we can now provide three-dimensional representations of CT data. Live human heads can now be volume rendered. Segmentation of tissue types including brain matter, fat, bone, and skin will allow for a morphological map of the head to which mass densities can be assigned. Assuming that a relationship exists between Hounsfield Units (a normalized index of x-ray attenuation used in CT imaging based on a scale of -1000 (air) to +1000 (bone), with water being 0) and physical density, each voxel (a contraction for volume element that is the base unit for CT reconstruction; represented as a pixel in the display of the CT image) representing the object can be
assigned a physical density. These segmented volumes can then be used to determine mass properties of the whole head.

To determine the reliability of using electronic imaging to determine mass properties, a commercial mass properties measurement system with known accuracy (Self et al., 1992) can be used to directly measure and validate the imaging results. Our immediate objective was to develop the methodology for calculating the inertial properties of these specimens using CT analyses, and compare these calculated mass properties to those of the directly measured mass properties. Once these methodologies are proven accurate and reliable, the ultimate goal of verifying the efficacy for using CT analysis to accurately calculate the inertial properties of the living human head will be completed. This will lead to the development of a useful database of human head mass properties and anthropometry. The results of these two procedures will provide human head mass properties data, both measured and calculated, with respect to a head anatomical coordinate system. This common coordinate system allows for comparison of the two methods of data collection.
METHODS

Specimens

In all, four male cadaver specimens were measured. The male specimens ranged in age from 76-83 years at time of death, with a mean age of 79.5 ± 4.04 years.

The adult human cadaver specimens were obtained from the OSU anatomical gift program. Before delivery, all specimens were scanned for blood-borne pathogens, such as hepatitis and HIV. The specimens were complete human bodies, and the head was segmented using a previous methodology (Walker, Harris, Pontius, 1973; Beier, Schuller, Schuck, Ewing, Becker, Thomas, 1980; Albery, Whitestone, 2003). The rest of the body parts were used in another concurrent study. In order for the specimens to be considered, they had to have no history of head or neck trauma. The head specimens were scanned for gross degenerative changes or abnormalities and visually inspected for confounding pathologies. Any specimens not meeting our requirements were rejected. All specimens were handled according to Center for Disease Control (CDC) guidelines upon delivery. All specimens remained frozen (-20°C) until they were used in the study, at which time they were thawed according to the requirements for that particular part of the study. In addition, none of the specimens were flushed or embalmed.

Mass Properties: Direct Measurement

Procedural overview: The procedure consists of measuring the combined mass, CG, and principal MOI of a specimen secured within a support box, and then measuring the properties of the support box by itself. The contribution from the support box is then subtracted from the combination, resulting in the mass, CG, and MOI of the specimen alone. All predetermined landmarks on the head were then digitized in order to generate a head anatomical coordinate system and to acquire the data necessary to calculate various anthropometry. The CG location of each specimen was calculated with respect to a head
anatomical axis system. The head anatomical axis system was used to locate the position of the CG with respect to the head and was defined by anatomical landmarks on the surface of the head and face. The principal MOI were defined at the CG location.

**Equipment:** The direct measurement procedure included a three-sided orthogonal support box to secure the specimen during testing; a digital balance and moment table to determine the weight and CG; an MOI instrument to record each specimen’s principal MOI; and a three-dimensional digitizer to determine the anatomical coordinate system and location of the predetermined anatomical landmarks.

**The head anatomical coordinate system:** This system is based on the Frankfort plane of the head. The Y axis of the head anatomical coordinate system (positive to the left) is generated by digitizing the left and right tragions, located at the notch just above the tragus of the left and right ear. A vector from the right infraorbitale normal to the Y axis establishes the X axis of the head anatomical coordinate system (positive toward the front). The infraorbitale is located at the lowest point on the inferior margin of the orbit of the right eyesocket. The origin of the head anatomical coordinate system is at the intersection of these axes with the Z axis positive upward. The coordinate system is finally translated to the mid-sagittal plane of the head by digitizing the sellion, located at the greatest indentation of the nasal root depression (Figure 1).
Figure 1. Head anatomical coordinate system

**Dissection of the neck from the head:** The head was dissected from neck at the head/neck joint as shown in Figure 2 by the red dotted line.

Figure 2. Method of segmentation of the head from the neck

The head was segmented using a previous methodology for determining inertial properties of human head specimens (Walker, Harris, Pontius, 1973; Beier, Schuller, Schuck, Ewing, Becker, Thomas, 1980; Albery, Whitestone, 2003).

**Securing the head within the support box:** In order to directly measure the mass properties, the specimen was first mounted in a lightweight orthogonal support box. The three sides of the support box form mutually perpendicular planes that form the X, Y and Z axes, with the corner designated as the origin. Hook-and-loop straps or strips of tape were used to hold the specimen
tightly within the box. The box properties are predetermined and later subtracted, leaving just the specimen properties. The box not only serves as a means for fixing the specimen during testing, it also serves as a source from which all the data are initially referenced.

Figure 3. Manikin head within the support box being measured for CGX

**Mass and CG determination:** The mass of the specimen was determined by placing the specimen and support box on an electronic balance and recording the weight (Figure 3).

The CG location was determined with the use of the balance and a moment table assembly. The moment table is an aluminum plate supported by two steel knife-edge blades with their edges parallel to each other and separated by a known distance. An aluminum chock is secured to the top of the plate directly above one of the steel blades. During testing, the chock side of the table is placed on an adjustable stand and the other side is placed on the electronic balance. The stand is adjusted until the table is level, and then the balance is zeroed. The force of the first moment of the specimen within the box along each axis is determined directly from the balance reading. With the mass of the specimen within the box as well as the blade-to-blade horizontal separation
distance, the position of the composite center of mass is calculated using summation of moments about the chock edge and results in:

\[ X_{CG} = \frac{F_S R_S}{F_{CG}} \]  

(1)

Where:

- \( F_S \) = Balance reading of specimen within the support box on moment table (converted to weight)
- \( F_{CG} \) = Weight of the specimen within the support box
- \( R_S \) = Known moment arm blade separation distance
- \( X_{CG} \) = CG coordinate of specimen within the support box with respect to the support box in contact with the chock.

To determine the CG of the specimen alone, the entire procedure was repeated for the empty support box. The empty support box CG was then subtracted from the combined specimen and box data, resulting in the CG of the specimen. Since first moments are additive, the center of mass of the specimen with respect to the support box axis system is determined by subtracting the support box contribution:

\[ X_T = \frac{F_{CG} X_{CG} - F_B X_B}{F_T} \]  

(2)

Where:

- \( F_T \) = Weight of the specimen
- \( F_{CG} \) = Weight of the specimen within the support box
- \( F_B \) = Weight of the support box
- \( X_T \) = X axis CG location of the specimen
- \( X_{CG} \) = X axis CG location of the specimen within the support box
- \( X_B \) = X axis CG location of the support box.

This procedure is repeated for the Y and Z axis CG locations.

Once the CG is calculated, the moments about the combined CG of the specimen and box can be
measured.

**MOI determination:** Specimen MOI were measured with the specimen secured in the support box and placed on an XR-50 Space Electronics Mass Properties Instrument. The instrument measures the MOI about a torsional pendulum axis. The moment measured was that of the pendulum itself, plus the pendulum platform, and the specimen within the box upon the pendulum platform. The pendulum platform consisted of a 1’ x 1’ x 0.25” honeycomb gridded platter. This platter is marked in 0.1 in. increments to ensure accurate placement of the specimen within the box.

This instrument functions most accurately when the CG position of the object being tested is initially aligned with the fixed pendulum axis. Therefore, the standard procedure was to mount the specimen within the box on the gridded test platter with the horizontal CG position of the composite within +/- 0.1 in. of the pendulum’s vertical axis. Once the specimen within the box was in place, the MOI measurement was recorded. This process was repeated for all six MOI, with the specimen within the box being reoriented between each measurement.

When the platter, given an angular displacement $\theta$, from its equilibrium position, is triggered, it oscillates due to the restoring torque, $T$, exerted by the instrument’s shaft. The magnitude of $T$ is given by:

$$T = \frac{GJ}{L} \theta = K_r \theta \quad (3)$$

where $K_r$ is the torsional spring constant of the shaft and is a function of the shear modulus, $G$. 
the length of the shaft, \( L \), and the polar moment of inertia, \( J \), of the cross section of the shaft.

If the torsional moment of inertia of the platter is \( I \) and the torsional force acts to bring the system back to equilibrium, then we can write:

\[
-K_t \theta = I \frac{d^2 \theta}{dt^2}
\]

This equation can also be written as:

\[
\frac{d^2 \theta}{dt^2} + \frac{K_t}{I} \theta = 0
\]

Which is a homogenous differential equation for which the solution is:

\[
\theta = C_1 \cos \sqrt{\frac{K_t}{I}} t + C_2 \sin \sqrt{\frac{K_t}{I}} t
\]

where \( C_1 \) and \( C_2 \) are constants which can be determined from the initial conditions. If the initial conditions are:

\[
\theta = 0 \text{ at } t = 0
\]

\[
\theta = A \text{ at } t = \frac{\pi}{2} \sqrt{\frac{I}{K_t}}
\]

then \( C_1 = 0 \), and \( C_2 = A \), and the previous equation becomes

\[
\theta = A \sin \sqrt{\frac{K_t}{I}} t
\]

This is the equation for simple harmonic motion where \( \sqrt{\frac{K_t}{I}} \) is the angular frequency, \( \omega_n \), at which the platter and shaft oscillate in radians per second. The period of oscillation, \( \tau_n \), is given
Solving this equation for the moment of inertia gives:

\[ I = K_i \tau_n^2 \]  \hspace{1cm} (10)

The rotational inertial properties of the specimen within the box can be expressed by an inertia tensor. The tensor values depend on the coordinate system origin and orientation with respect to the tensor being calculated. Moment of inertia measurements were taken about six different axes to generate an inertia tensor from which the orientation of the principal axes and the magnitudes of the principal MOI were determined. For simplicity, three of the axes chosen (X, Y, Z) were about the cardinal axes (box edges) of the support box. Figure 4 shows a manikin head being measured about one of the cardinal axes. The remaining three axes (XY, YZ, XZ) were axes in the planes of the three walls of the support box at 45-degree angles to the cardinal axes. These 45-degree measurements were taken using a custom-made lightweight jig, as shown in Figure 5. All six axes intersect at the origin of the box’s coordinate system.

Figure 4. Manikin head within the support box being measured for MOI about a cardinal axis
From the six moment measurements, the products of inertia or diagonal elements of the inertia tensor can be determined from the equation:

\[ P_{ab} = \frac{I_a + I_b \tan^2 \theta - (1 + \tan^2 \theta)I_{ab}}{2 \tan \theta} \]  \hspace{1cm} (11)

Where:
- \( P_{ab} \) = the product of inertia in the ab plane
- \( I_a \) = the moment of inertia about the cardinal axis a
- \( I_b \) = the moment of inertia about the cardinal axis b
- \( I_{ab} \) = the moment of inertia about the noncardinal axis in the ab plane
- \( \theta \) = the angle between axis a and axis b.

Because the angle between axes is 45 degrees, the equation simplifies to:

\[ P_{ab} = \frac{I_a + I_b - 2I_{ab}}{2} \]  \hspace{1cm} (12)

Upon completion of the six moment measurements with the specimen within the box, the entire procedure was repeated with the empty box. The box plus jig inertial properties were subtracted from the measured composite properties using the parallel axis theorem.
The resulting inertia tensor, which was with respect to the center of mass of the test object, can be written as:

\[
\mathbf{T} = \begin{bmatrix}
I_x & -P_{xy} & -P_{xz} \\
-P_{yx} & I_y & -P_{yz} \\
-P_{zx} & -P_{zy} & I_z
\end{bmatrix}
\]

This inertia tensor is symmetric and can be reduced to diagonal form in which the products equal zero and the diagonal elements are the principal moments. This is accomplished by determining the values of \( \lambda \) which satisfy the equation:

\[
(T - \lambda I)\omega = 0
\]

where \( I \) are the principal moments of inertia. The vectors associated with these values are the directions of the principal axes associated with the principal moments of inertia. These vectors, expressed as a matrix of cosines, define the directions of the principal axes with respect to the axis parallel to the box axis system, but are centered at the specimen CG.

**Coordinate system transformation:** To this point, all measurements were located with respect to the box coordinate axes. To reference the properties of the specimen to a head anatomical coordinate system, the specimen landmarks were digitized with respect to the box coordinate system (box edges) using the electronic position coordinate digitizer. The box origin, located at the rear and right-hand corner of the outer box, and points representing the X, Y, and Z axes of the box (box edges) were digitized along with all the pre-marked head and face landmarks (Figure 6). Those points not accessible due to the frame of the box were digitized upon removal of the box along with at least three points from the previous set, thus allowing for inclusion in
the final data set.

**Mass Properties: Computed Tomography (CT) Protocol**

**Overview:** Four unembalmed cadaver heads were used for estimating mass properties. The spiral CT data were collected by the Ohio State University’s Injury Biomechanics Lab, located at the OSU Medical Center, Columbus, OH.

Figure 6. Manikin head and helmet within support box being digitized

**CT imaging:** The CT imager used was the GE High Speed Advantage System. This system has an X-ray strength of 120kV at 80mA. With both slice collimation (thickness) and table feed set at 1 mm, the following are the resultant dimensional resolutions:

- 1-D resolution = 273 mm circle at 512 pixels = 0.5332 mm/pixel
- 2-D resolution = 273 mm x 273 mm at 512 pixels x 512 pixels = 0.2843 mm²/pixel²
- 3-D resolution = 273 mm x 273 mm x 1 mm at 512 pixels x 512 pixels x 1 pixel = 0.2843 mm³/pixel³ = 0.2843 mm³/voxel

Figure 7 shows an example slice of spiral CT data. The image is represented as a gray scale
image and shows the 2-D view of the head.

Figure 7. CT Slice from M1

3D Modeling and calculation of mass properties:

Determining the Frankfort coordinate system: For 3D modeling of the head, the software program MIMICS (Materialise; Leuven, Belgium) was used. MIMICS software allows for transformation of 2D image data, such as CT or MRI, to 3D.

The first step needed to determine the inertial properties of the head is finding the origin of the Frankfort Plane. The Frankfort plane (also called the Auriculo-Orbital plane) was established at the World Congress on Anthropology in Frankfurt, Germany in 1884, and decreed as the anatomical position of the human skull. It was decided that a plane passing through the inferior margin of the left orbit (the point called the left Orbitale) and the upper margin of each ear canal (the point called the Porion) was most nearly parallel to the surface of the earth, and also close to the position the head is normally carried in the living subject.
However, MIMICS does not utilize the Frankfort Plane as its coordinate system. Therefore, the coordinates of the Frankfort plane must first be found in order to draw comparison. To do this, the MedCAD package for MIMICS was utilized to indicate important features, and planes were established in the X, Y, and Z axes.

To do this, planes must be established in the axial, sagittal, and coronal orientations in MIMICS. The following is a step by step method of determining planes using the software:

1.) Place points on the left and right porions and the left and right orbitales (4 total).
2.) Connect the right and left porions with a line.
3.) Connect the right and left orbitales with a line.
4.) Place a point directly on the line connecting the right and left orbitales directly on the vomer (near the midpoint of the two orbitale point markers).
5.) Place a point directly on the line connecting the right and left porion, make sure the point lies directly behind the vomer point that was established in step four (very near the midpoint between the two porion point markers). This point will become the origin of our coordinate system, so determine the X, Y, and Z coordinates by utilizing the “Properties” tab in MIMICS.
6.) Place a point at the top of the head in line with the origin point established in step 5.
7.) Connect the right and left porion points and the vomer point to establish the axial plane (Figure 8)
8.) Connect the origin point to the vomer point to the top of the head point to establish the sagittal plane (Figure 9).
9.) Connect the right and left porion points to the top of the head point to establish the coronal
After doing the above analyses, the Frankfort planes have been established, and the origin defined. Figures 8-10 show each of the axes of the Frankfort plane, and Figure 11 shows the plane in its entirety:

Figure 8. The axial plane of the Frankfort coordinate system
Figure 9. The sagittal plane of the Frankfort coordinate system

Figure 10. The coronal plane of the Frankfort coordinate system
With this information, the point where these three planes intersect will become the origin (Figure 12):
Table 1. MIMICS coordinates of origin

<table>
<thead>
<tr>
<th>Origin</th>
<th>mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>227.3736</td>
</tr>
<tr>
<td>Y</td>
<td>210.0879</td>
</tr>
<tr>
<td>Z</td>
<td>-220.0000</td>
</tr>
</tbody>
</table>

**Determining Center of Mass (COM):** The MIMICS Software is able to find the Center of Gravity (CG) of an object of constant density. However, MIMICS is not able to find a CG of a composite material, such as the human head. Therefore, thresholding of the 3 tissue types (brain, bone, and soft tissue) must be performed and the CG of each of these materials must be determined. To do this the “Rotate” application in the software must be run along the inertial axis with the pivot point being the mass center. From the analysis the coordinates in each of the 3 planes (axial, coronal, and sagittal) can be determined (Figures 13-15).

Figure 13. COM Coordinates in the axial plane
Figure 14. COM coordinates in the coronal plane

Figure 15. COM Coordinates in the sagittal plane
From the data, the COM can be determined (Table 2), and can be transferred to the Frankfort plane by simply subtracting by the origin (Table 3). For data consistent with the actual measurements, the data will then be converted to inches (Table 4):

**Table 2. Coordinates for the skull COM from MIMICS**

<table>
<thead>
<tr>
<th>COM</th>
<th>Skull, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>224.2</td>
</tr>
<tr>
<td>Y</td>
<td>208.7</td>
</tr>
<tr>
<td>Z</td>
<td>-190.27</td>
</tr>
</tbody>
</table>

**Table 3. Coordinates after subtracting by the origin (Frankfort Plane)**

<table>
<thead>
<tr>
<th>Corrected COM</th>
<th>Skull, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>-3.1736</td>
</tr>
<tr>
<td>Y</td>
<td>-1.3879</td>
</tr>
<tr>
<td>Z</td>
<td>29.7300</td>
</tr>
</tbody>
</table>

**Table 4. Final coordinates in the Frankfort Plane (in inches)**

<table>
<thead>
<tr>
<th>Final COM</th>
<th>Skull, in</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>-0.12</td>
</tr>
<tr>
<td>Y</td>
<td>-0.05</td>
</tr>
<tr>
<td>Z</td>
<td>1.17</td>
</tr>
</tbody>
</table>

Doing the same analysis for both the brain and the skull we can get our coordinates for each segment’s COM (Table 5):

**Table 5. Coordinates for each of the 3 tissue types in the Frankfort plane**

<table>
<thead>
<tr>
<th>Final COM</th>
<th>Skull, in</th>
<th>Brain, in</th>
<th>Soft Tissue, in</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>-0.12</td>
<td>-0.16</td>
<td>-0.10</td>
</tr>
<tr>
<td>Y</td>
<td>-0.05</td>
<td>0.75</td>
<td>-0.50</td>
</tr>
<tr>
<td>Z</td>
<td>1.17</td>
<td>1.72</td>
<td>0.90</td>
</tr>
</tbody>
</table>

Figures 16-17 show both a frontal and side view of each of the tissue types location with respect to the origin.
Figure 16. Frontal view of COM shown for each of the 3 masks (Brain, Bone, and Soft Tissue)

Figure 17. Side view of COM shown for each of the 3 masks
Determining the inertial axis: In order to calculate a composite center of mass, additional inertial properties must be known about each material. In this case, MIMICS will calculate the inertial axes, complete with the unit vector showing direction, as well as the magnitude of each vector (in the X, Y, and Z direction for each point). Figure 18 shows the inertial axes for the skull (measurements for the X-vector shown in upper left-hand hand corner). In this case, the directional vector (unit vector) for the x-axis is $u = 0.9937i + 0.0423j +0.1035k$, and the magnitude is 161.2277mm. The data for each of the three segments is listed in Tables 6-8, with the L being listen in inches for consistency with the measured data.

Figure 18. The inertial axis about the CG of the skull (with x-direction measurements shown)
Table 6. The cosines and magnitude of the inertial axis of the skull

<table>
<thead>
<tr>
<th>MOI</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>L, in</th>
</tr>
</thead>
<tbody>
<tr>
<td>X (red)</td>
<td>0.9937</td>
<td>0.0423</td>
<td>0.1035</td>
<td>6.3475394</td>
</tr>
<tr>
<td>Y (green)</td>
<td>-0.0856</td>
<td>0.8833</td>
<td>0.4609</td>
<td>9.654937</td>
</tr>
<tr>
<td>Z (blue)</td>
<td>0.0719</td>
<td>0.4669</td>
<td>-0.8814</td>
<td>7.3339528</td>
</tr>
</tbody>
</table>

Table 7. The cosines and magnitude of the inertial axis of the brain

<table>
<thead>
<tr>
<th>MOI</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>L, in</th>
</tr>
</thead>
<tbody>
<tr>
<td>X (red)</td>
<td>0.0745</td>
<td>0.7638</td>
<td>0.6411</td>
<td>7.2111102</td>
</tr>
<tr>
<td>Y (green)</td>
<td>-0.1448</td>
<td>-0.6278</td>
<td>0.7648</td>
<td>6.8117323</td>
</tr>
<tr>
<td>Z (blue)</td>
<td>-0.9866</td>
<td>0.1498</td>
<td>-0.0638</td>
<td>5.9891378</td>
</tr>
</tbody>
</table>

Table 8. The cosines and magnitude of the inertial axis of the soft tissue

<table>
<thead>
<tr>
<th>MOI</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>L, in</th>
</tr>
</thead>
<tbody>
<tr>
<td>X (red)</td>
<td>-0.5242</td>
<td>-0.4527</td>
<td>0.7214</td>
<td>8.01938189</td>
</tr>
<tr>
<td>Y (green)</td>
<td>-0.0724</td>
<td>0.8677</td>
<td>0.4918</td>
<td>10.15462205</td>
</tr>
<tr>
<td>Z (blue)</td>
<td>-0.8485</td>
<td>0.2056</td>
<td>-0.4876</td>
<td>7.939767717</td>
</tr>
</tbody>
</table>

Finding the mass: The last piece of information needed to determine the composite center of mass is the mass of each of the three tissue types. Unfortunately, the MIMICS software is not able to output a mass of a segment. However, MIMICS does output a volume for each of the three tissue types (Figure 19 shows for soft tissue). Therefore, densities for each of the tissue types must be determined. For bone, the average density is assumed to be ~1800 kg/m$^3$, while the brain and soft tissue both have a density of ~1040 kg/m$^3$ (Park, Lakes, 1992). By multiplying the volume by the density, the overall mass of each of the segments can be determined (Table 9).
Table 9. The weights of each of the three tissue types

<table>
<thead>
<tr>
<th>Segment weights</th>
<th>Density, kg/m^3</th>
<th>Volume, m^3</th>
<th>Weight, kg</th>
<th>Weight, lb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bone</td>
<td>1800</td>
<td>0.000651014</td>
<td>1.1718256</td>
<td>2.583434</td>
</tr>
<tr>
<td>Brain</td>
<td>1040</td>
<td>0.001577989</td>
<td>1.6411086</td>
<td>3.618026</td>
</tr>
<tr>
<td>Soft Tissue</td>
<td>1040</td>
<td>0.001270715</td>
<td>1.3215439</td>
<td>2.913506</td>
</tr>
<tr>
<td>total</td>
<td></td>
<td></td>
<td>9.114965</td>
<td></td>
</tr>
</tbody>
</table>

**Finding the composite CG:** Now that the inertial properties of the 3 separate parts are known, the parallel axis theorem can be used to determine the overall CG of the head.

Parallel Axis Theorem: \( I = I_{CM} + md^2 \)

To accomplish this, an in-house program called “combine” (attained from Wright-Patterson AFB), can be used to find the coordinates for the CG. The program was designed to combine two points, so the program must be run twice in order to satisfy three different tissue types. Table 10 shows the final coordinates determined by the program.
Table 10. The coordinates for the overall COM

<table>
<thead>
<tr>
<th>Final COM</th>
<th>in</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>-0.1316</td>
</tr>
<tr>
<td>Y</td>
<td>-0.1212</td>
</tr>
<tr>
<td>Z</td>
<td>1.301</td>
</tr>
</tbody>
</table>

Figures 20-21 show a front and side view of the determined CG on the 3D model of the head.

The rest of the cadaver heads will be analyzed using the exact same methodology.
Figure 20. Side view of the established COM

Figure 21. Front view of the established COM
RESULTS

For the study, four male cadavers were studied. Table 11 shows the age, height, and weight for each of the four specimens.

Table 11. Age, height, and weight for each of the specimens

<table>
<thead>
<tr>
<th>Cadaver</th>
<th>Age (yr)</th>
<th>Height (in)</th>
<th>Weight (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>83</td>
<td>68.11</td>
<td>143.30</td>
</tr>
<tr>
<td>M2</td>
<td>83</td>
<td>71.26</td>
<td>180.34</td>
</tr>
<tr>
<td>M3</td>
<td>76</td>
<td>69.02</td>
<td>154.98</td>
</tr>
<tr>
<td>M4</td>
<td>76</td>
<td>70.98</td>
<td>199.96</td>
</tr>
<tr>
<td>Ave.</td>
<td></td>
<td>79.5</td>
<td>69.84</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td></td>
<td>4.04</td>
<td>1.53</td>
</tr>
</tbody>
</table>

After the heads were directly measured, the data was compiled into a table (Table 12) and averages were found. The average measured head weight was 8.96 lbs with a standard deviation of ±0.17 lbs. The range of the head weights was 8.75 lbs to 9.15 lbs (or 0.4 lb difference). The average coordinates for the CG of the head were -0.12in (±0.09in) in the x-axis, 0.01in (±0.18in) in the y-axis, and 0.91in (±0.23in) in the z-axis. In the case of the y-axis, two of the specimens had a CG, reading exactly on the axis (y = 0in), and in the x-axis, the highest reading was -0.24in in the –x direction with an average of 0.12in (±0.09in) in the –x direction. Therefore, the z-axis is the most significant when analyzing CG in the Frankfort plane.

Table 12. Data from the direct measurement method

<table>
<thead>
<tr>
<th>Subject</th>
<th>Wt, lbs</th>
<th>CGx, in</th>
<th>CGy, in</th>
<th>CGz, in</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>9.15</td>
<td>-0.09</td>
<td>-0.20</td>
<td>1.21</td>
</tr>
<tr>
<td>M2</td>
<td>8.75</td>
<td>-0.11</td>
<td>0.00</td>
<td>0.91</td>
</tr>
<tr>
<td>M3</td>
<td>8.91</td>
<td>-0.24</td>
<td>0.00</td>
<td>0.66</td>
</tr>
<tr>
<td>M4</td>
<td>9.02</td>
<td>-0.03</td>
<td>0.24</td>
<td>0.84</td>
</tr>
<tr>
<td>Average</td>
<td>8.96</td>
<td>-0.12</td>
<td>0.01</td>
<td>0.91</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>0.17</td>
<td>0.09</td>
<td>0.18</td>
<td>0.23</td>
</tr>
</tbody>
</table>
Once all of the modeling was completed, a similar table was completed (Table 13). The average determined weight of the specimens was 8.99 lbs with a standard deviation of ±0.18 lbs. The range of determined head weights was 8.73 lbs to 9.11 lbs (or a 0.38 lb difference). The average coordinates for the CG of the head were -0.15in (±0.09in) in the x-axis, 0.03in (±0.12in) in the y-axis, and 1.00 (±0.32in) in the z-axis.

Table 13. Data from the 3D modeling method

<table>
<thead>
<tr>
<th>Subject</th>
<th>Wt, lbs</th>
<th>CGx, in</th>
<th>CGy, in</th>
<th>CGz, in</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>9.11</td>
<td>-0.13</td>
<td>-0.12</td>
<td>1.30</td>
</tr>
<tr>
<td>M2</td>
<td>8.73</td>
<td>-0.04</td>
<td>0.00</td>
<td>1.24</td>
</tr>
<tr>
<td>M3</td>
<td>9.10</td>
<td>-0.27</td>
<td>0.09</td>
<td>0.66</td>
</tr>
<tr>
<td>M4</td>
<td>9.03</td>
<td>-0.16</td>
<td>0.15</td>
<td>0.79</td>
</tr>
<tr>
<td>Average</td>
<td>8.99</td>
<td>-0.15</td>
<td>0.03</td>
<td>1.00</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>0.18</td>
<td>0.09</td>
<td>0.12</td>
<td>0.32</td>
</tr>
</tbody>
</table>

Now that the data is known for both methods, a student (paired) t-test can be used to see if there is any significance between the two methods. For the analysis, the Statistica 9 software package was used. An \(\alpha\)-value of 0.05 was used.

Table 14. Statistical evaluation between the two methods

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean, Actual</th>
<th>Std.Dev., Actual</th>
<th>Mean, MIMICS</th>
<th>Std.Dev., MIMICS</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>8.96</td>
<td>0.17</td>
<td>8.99</td>
<td>0.18</td>
<td>0.79</td>
</tr>
<tr>
<td>CGx, (in)</td>
<td>-0.12</td>
<td>0.09</td>
<td>-0.15</td>
<td>0.09</td>
<td>0.63</td>
</tr>
<tr>
<td>CGy, (in)</td>
<td>0.01</td>
<td>0.18</td>
<td>0.03</td>
<td>0.12</td>
<td>0.86</td>
</tr>
<tr>
<td>CGz, (in)</td>
<td>0.91</td>
<td>0.23</td>
<td>1.00</td>
<td>0.32</td>
<td>0.65</td>
</tr>
</tbody>
</table>

Table 14 shows that the data does not prove to be significant in any of the cases. The lowest \(p\)-value (\(p = 0.63\)) attained from the analysis was for the \(CG_x\) variable.

Graphical comparisons of actual versus measured head weight and \(CG_x\) are shown in Figures 22-
Figure 22. Comparing the measured head weights to those found using MIMICS

Figure 23. Comparing the measured CG\textsubscript{z} values to those found using MIMICS

Viewing the actual CG point compared to the calculated CG point on the 3D model for M1 (Figure 24-25), the accuracy of the method can be clearly seen as the points nearly overlap.
Figure 24. Side view of the actual CG and the calculated CG for M1

Figure 25. Frontal view of the actual CG and the calculated CG for M1
DISCUSSION

Based upon the data, using 3D modeling appears to be an accurate as a means to find the weight and center of gravity of the human head. The largest discrepancy in weight was only 0.19 lb, and the largest discrepancy in \( CG_z \) was seen to be 0.33in. Based upon results of the t-test, in no case was the difference significant \( (\alpha = 0.05) \).

In all cases, the CG for the three tissue types was consistent in location. The CG of the soft tissue was always above the origin and always anterior and below the CG of the bone and brain. The CG for the bone (skull) was always near to the origin in the x and y direction and shifted up from the origin in the z direction. The CG for the brain was always the most posterior and up; shifted back from the origin (-x) and up (+z) and near to the midpoint of the head (y~0). In all cases, the three tissue types had a near linear relationship. In every case the CG of the skull was nearest to both the actual and measured CG of the composite head, and would be the best point to estimate from if only one tissue type is to be analyzed.

With respect to the Frankfort plane, the y and x coordinates tend to be ~0, as the CG of the head lies close to the midpoint of the body (else our heads would naturally want to rotate). The z-coordinate often lays ~1in above the origin in the Frankfort plane. Any significant difference using this coordinate system would lead to large statistical differences. However, if using a different coordinate system (like the right posterior portion of a CT scan for example) it is important to know that all 3 coordinate points provide a good representation of the overall CG of the head. Based upon the accuracy of the data based upon the Frankfort plane, it would be safe to conclude that using 3D modeling is an accurate way to find inertial properties of the head.
using any coordinate system.

Throughout the study, the cadavers remained frozen (until thawed for measurement), and in good condition. The soft tissues and the bone remained perfectly intact. However, the brain of cadaver specimens begins to deteriorate quite quickly post-mortem. For all four specimens, gaps were seen in the anterior portion of the brain from the CT (due to the fact they were laid on their back). This fact should not affect the data, as oftentimes the head was scanned within a few hours of testing. In addition, once frozen, the brain will keep the shape in which it was frozen.

To further investigate the accuracy of the findings, previous studies were analyzed. Table 13 shows the weight, $CG_x$, and $CG_z$ values reported from 3 separate studies. In all cases, the data was found using the direct measurement method.

<table>
<thead>
<tr>
<th>Study</th>
<th>Weight, lbs</th>
<th>$CG_x$, in</th>
<th>$CG_z$, in</th>
</tr>
</thead>
<tbody>
<tr>
<td>Albery</td>
<td>7.1</td>
<td>0.03</td>
<td>1.09</td>
</tr>
<tr>
<td>Beier</td>
<td>9.49</td>
<td>0.33</td>
<td>1.23</td>
</tr>
<tr>
<td>Walker</td>
<td>9.65</td>
<td>0.56</td>
<td>0.95</td>
</tr>
</tbody>
</table>

Albery (2002). n = 15 (8 male) – heads drained
Beier (1980). n = 21 (19 male)
Walker (1973). n = 20 male (20 male)

The results from 3D analysis compared to the previous studies again shows that our data is accurate. The lower weight from the Albery study has to do with the fact that the heads were drained prior to analysis, and 7 of his specimens were females (smaller heads), thereby leading to lower head weights. The studies by Beier and Walker showed to have a higher average body weight of specimens, therefore the heads tended to have a slightly higher weight.
The drawback of CT scanning live individuals is the amount of radiation to which the individual is exposed. Currently, CT scans can only be done on persons who have medical reason. However, the potential is there to utilize medical images given that the proper privacy rights are not interfered upon (and with Internal Review Board approval). With the CT images available, and an accurate method of determining inertial properties using the scans, a large database of living human inertial properties could be compiled. Also, exploration of safer methods of scanning should continue. Lower radiation alternatives such as Duel Energy X-ray Absorption (DEXA) provide a means of imaging internal structures with a lower exposure to radiation. Magnetic Resonance Imaging scans would allow for the imaging of internal structures with no radiation involved. Laser scanning of the skin surface would also allow for exploration of correlation between CG and center of volume with no radiation involved. Therefore, continued exploration is necessary to further advance the knowledge of human biomechanical response.
CONCLUSION
From the analysis of the both the segmentation data and the calculated data, it appears that both provide a means to accurately determine the weight and CG of the human head, and likely the moments of inertia. When comparing the two methods with one another, no significance can be found in either the weight of the head or any of the coordinate axes. Comparing the data to outside studies reaffirms our conclusions, as the average of the data falls well within the limits of previous analysis. This method can provide for a more cost effective means of determining human inertial properties, as well as allow researchers the ability to determine these properties using live human subjects. In essence, the use of 3D modeling would allow for more optimal helmet design (or even custom helmet design), more accurate computer simulation models, and better designed anthropomorphic testing manikins.
REFERENCES


