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Variation of bone layer thicknesses and trabecular volume fraction in the adult male human calvarium

Sourabh Boruah [a], Glenn R. Paskoff [b], Barry S. Shender [b], Damien L. Subit [a], Robert S. Salzar [a], Jeff R. Crandall [a]

[a] Center for Applied Biomechanics, University of Virginia, Charlottesville, VA, USA

[b] Human Systems Department, Naval Air Warfare Center Aircraft Division, Patuxent River, MD, USA

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A B S T R A C T

The human calvarium is a sandwich structure with two dense layers of cortical bone separated by porous cancellous bone. The variation of the three dimensional geometry, including the layer thicknesses and the volume fraction of the cancellous layer across the population, is unavailable in the current literature. This information is of particular importance to mathematical models of the human head used to simulate mechanical response. Although the target geometry for these models is the median geometry of the population, the best attempt so far has been the scaling of a unique geometry based on a few median anthropometric measurements of the head. However, this method does not represent the median geometry.

This paper reports the average three dimensional geometry of the calvarium from X-ray computed tomography (CT) imaging and layer thickness and trabecular volume fraction from micro CT (μCT) imaging of ten adult male post-mortem human surrogates (PMHS). Skull bone samples have been obtained and μCT imaging was done at a resolution of 30 μm. Monte Carlo simulation was done to estimate the variance in these measurements due to the uncertainty in image segmentation. The layer thickness data has been averaged over areas of 5 mm^2. The outer cortical layer was found to be significantly ($p < 0.01$; Student's t test) thicker than the inner layer (median of thickness ratio 1.68). Although there was significant location to location difference in all the layer thicknesses and volume fraction measurements, there was no trend. Average distribution and the variance of these metrics on the calvarium have been shown. The findings have been reported as colormaps on a 2D projection of the cranial vault.

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Introduction

Geometry of the human cranial vault

The human skull has been studied and measured since the beginning of the nineteenth century. Historically, these studies have been motivated by anthropological questions, such as correlation of measurements with growth, race, and evolution, or medical questions, such as correlation with pathological conditions [1–8]. Special devices were built in the 1910s to aid location of landmarks both inside and outside the anthropoid skull [9]. The most comprehensive study of the variation of cranial morphology in humans was done by Howells [10]. More than 1000 skulls were studied with almost a hundred measurements for each. The early studies have always used two dimensional (2D) measurements and have focused on distances and angles between landmarks. A device to capture the 3D shape of the cranium was developed by Oyen and Walker [11] and christened the “stereoplotting craniostat.” They also introduced the idea of representing cranial measurements on a 2D figure. With the advent of computed tomography (CT), studying the 3D shape of the skull was simplified. Mathematical models of the head in injury studies have utilized CT for their 3D geometrical definition, but they have always been based on the skull of a unique individual [12,13]. Current literature addressing the three dimensional shape of the human cranium and its variation in the population is extremely limited.

Three dimensional imaging

The geometry of the human head can be derived from imaging using multiple modalities such as X-ray computed tomography (CT), magnetic resonance imaging (MRI) and microtomy. A multi-modality approach allows discerning of the various components of the head which is not entirely possible using a single modality. The Visible Human Project has been used by many researchers as the source for 3D morphological data of the human body [14,15]. Because of the time consuming nature of such imaging studies, they are often augmented by anthropometric studies [16] which can provide a statistical distribution of geometrical parameters in the population. A more recent study [13] uses an individual more closely resembling the 50th percentile male. In human safety research, the importance of the three dimensional shape of the cranium has only recently been acknowledged [17].

E-mail address: sourabhboruah@gmail.com (S. Boruah).

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Structure of the cranial vault

Apart from the maxillofacial region and the foramen magnum (red box in Fig. 1), the cranial vault is composed of three layers. Two dense layers of cortical bone on the inner and outer surface of the cranial vault, called the cortical tables, are separated by a porous layer of cancellous bone called the diploe. The thickness of these layers determines the rigidity of the cranial vault and is particularly important for accurate mathematical modeling of the head. Several studies have looked at the variation of total thickness, but the number of studies regarding the thicknesses of the individual layers is very limited.

Todd [19] observed the cranial thickness at four cranial landmarks and their relationship with age. It was observed that cranial thickness increases with age until around 60 years of age. Todd also notes the remarkable variability in thickness. McElhaney et al. [20] determined layer thicknesses from 180 specimens harvested from 14 donors. They noted that the diploe layer was thicker away from the sutures. However, the regional variation of this thickness and the strategy of measurement were not discussed. Ross et al. [21] found that skulls of women were significantly thicker than those of men. All of these measurements have been made at the plane of dissection using calipers, with or without photography and averaging. Similar visual techniques are still in use [22–31]. In addition to the limited number of points on the skull where thickness has been measured, in the studies where skull layer thicknesses have been measured, there is no clear and precise methodology for distinguishing the different layers beyond visual inspection. Due to this, the measurements for the different layers may be very subjective. Thickness measurement of the skull has also been done using X-ray and magnetic resonance imaging [32–40]. Lynnerup et al. [34] found that diploe layer thickness in the frontal bone is significantly greater in males than in females. Ultrasound methods have also been used for thickness measurement [41–43]. The objective of these studies was to find any correlation between thickness and age, sex, race, or general body build in order to exploit this relationship usually in forensic or anthropological studies, or to explore the cranium to find suitable donor sites for harvesting bone grafts. The mechanical response of the cranium may be highly sensitive to the presence of pores in the material. Therefore development of a mathematical model of the head that describes its mechanical response requires a more detailed and objective study of the thicknesses of the different layers of the skull. No systematic and objective study of cranial vault thickness across the calvarium exists in the literature. The advent of micro CT has offered much greater resolution, allowing detection of much smaller pores and discerning of individual bone trabeculae in porous bone. Lillie et al. [40] have used micro CT imaging to validate a new approach to determine cortical layer thickness from clinical CT.

The cancellous diploe layer is inhomogeneous and therefore, apart from its thickness, the histology of this layer may be of interest, especially for predicting its mechanical response. It is known that mechanical properties of cancellous bone depend on the volume fraction of bone [44,45]. Surgeons have studied the remodeling of parietal bone using light microscopy on microtome sections [46–48]. However the relationship of volume fraction of trabecular bone in the cranium with mechanical properties has not been studied.

Mathematical models and scope in traumatic brain injury research

Traumatic brain injury (TBI) is an important public health problem in the United States [49] and across the world. It was estimated in 1996 that at least 10 million TBIs occur annually that were serious enough to lead to death or hospitalization [50]. TBI related outcomes from road traffic accidents may involve between 700,000 and 5.6 million people annually ranging from severe and long term to mild TBI respectively [51].

Due to the unrepeatable, expensive, and time-consuming nature of post-mortem human surrogate (PMHS) studies, mathematical models Q5 of the human body have been used as a tool for safety assessment in the automotive and military industry. They also find use in the medical industry for design and simulation of medical procedures like surgery and devices like prosthetics.

All of the contemporary mathematical models of the head for simulation of mechanical response [52–64] have skull geometry identical to one individual, whose head geometry may not match the median head geometry in the population. The geometry data is usually derived from studies like the Visible Human Project [12]. None of these models assess the effects of variation in geometry and layer thicknesses. Additionally, information about the histology of the diploe layer of the human

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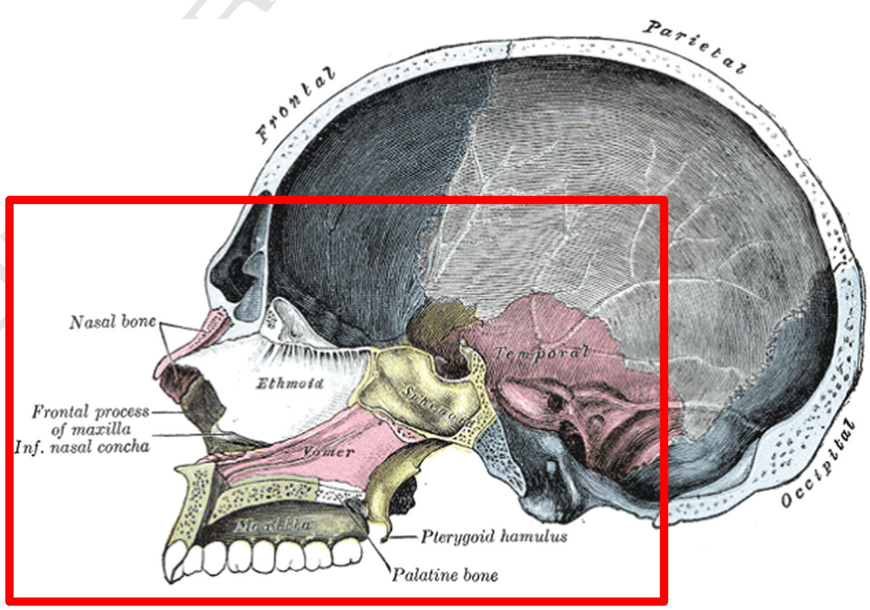

Fig. 1. The human cranial vault; mid-sagittal section [18]; red box shows region of the cranial vault which does not have the sandwich structure. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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