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Characterization of the bending strength of craniofacial sutures

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ABSTRACT

The complex, thin and irregular bones of the human craniofacial skeleton (CFS) are connected together through bony articulations and connective tissues. These articulations are known as sutures and are commonly divided into two groups, facial and cranial sutures, based on their location in the CFS. CFS sutures can exhibit highly variable degrees of interdigitation and complexity and are believed to play a role in accommodating the mechanical demands of the skull. This study aimed to evaluate the mechanical behavior of CFS bone samples with and without sutures and to determine the effect of sutural interdigitations on mechanical strength. Sagittal, coronal, frontozygomatic and zygomatico-temporal sutures along with adjacent bone samples not containing sutures were excised from six fresh-frozen cadaveric heads. The interdigitation of the sutures was quantified through μCT based analysis. Three-point bending to failure was performed on a total of 29 samples. The bending strength of bone samples without sutures demonstrated a non-significant increase of 14% as compared to samples containing sutures ($P=0.2$). The bending strength of bones containing sutures was positively correlated to the sutural interdigitation index ($R=0.701$, $P=0.002$). The higher interdigitation indices found in human cranial vs. facial sutures may be present to resist bending loads as a functional requirement in protecting the brain.

1. Introduction

The delicate and intricate architecture of the craniofacial skeleton (CFS) makes it more susceptible to fractures than other parts of the human skeleton (Hardt and Kuttenberger, 2010). The frequency of head injuries and complications in craniomaxillofacial surgery has inspired numerous studies to characterize the biomechanical behavior of the CFS (Herring et al., 1996; Hylander and Johnson, 1997; Kasrai et al., 1999; Nagase et al., 2005; Orringer et al., 1998; Oyen and Tsay, 1991; Rudderman and Mullen, 1992; Szwedowski et al., 2010). For example, the recent work by Motherway et al. has provided important information about the correlation between cranial bone morphological parameters and their mechanical properties, demonstrating that cranial bones exhibit viscoelasticity that improves their ability to protect the internal vital soft tissue organs of the CFS. Such knowledge of the biomechanical behavior of the cranial bones can aid the design of energy absorbing head protection systems (Motherway et al., 2009). However, much of the work on understanding the biomechanical behavior of the CFS has focused on analyzing bone samples without accounting for the presence of important morphological structures, such as the sutures (Delille et al., 2007; Motherway et al., 2009).

Sutures are articulations in which the margins of adjacent bones are united by fibrous or bony tissue in the CFS. They function to hold the bones of the skull together while allowing for mechanical stress transmission and deformation (i.e. distortion during childbirth, cyclic loading from muscle activity, forces from therapeutic mechanical devices and traumatic impacts; Mao et al., 2003). Sutures play different functions during the different stages of development. In early development the sutures provide high flexibility to allow for enlargement of the head around the eyes, brain and other organs. The sutures in the CFS can be divided into two groups based on their location: cranial and facial sutures. Cranial sutures undergo most of their growth during these early stages of development, whereas facial sutures are most active during adolescence. The adult CFS is viewed as a stable and static entity with sutures primarily functioning as shock absorbers to dissipate stresses transmitted through the skull (Buckland-Wright, 1978; Byron et al., 2004; Herring and Teng, 2000; Jaslow, 1990b; Jaslow and Biewener, 1995; Pritchard et al., 1956; Rafferty et al., 2003; Rayfield, 2004, 2005).

Suture morphology changes from a simple flat joint in post-natal stages (which must stay patent to function) to a joint with

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differing degrees of interdigitation and interlocking projections in adulthood (Rice, 2008). Such changes in suture morphology in healthy adults or in craniosynostosis patients remain unclear but are thought to be related to mechanical, genetic and hormonal factors (Herring, 2008; Persson et al., 1978). Under normal conditions, sutures in the human skeleton have been reported to be fully fused by late adulthood (Rice, 2008). However, recent advances in micro-computed tomography allow for detailed investigations of the internal surfaces of the sutures and have shown that they remain partially open even beyond the seventh decade, with various degrees of connectivity across the suture gap (Maloul et al., 2010).

The relationship between the morphological aspects of the sutures and the mechanical demands based on dietary habits in animals has been investigated through various studies such as Herring et al. (1972), and Jaslow et al. (1990a, 1990b). A study by Jaslow et al. (1990a, 1990b) using bone/suture samples from goats was the first to investigate the contribution of sutural morphology in animals to the function of the CFS. They confirmed prior postulations put forward about the biomechanical behavior of the sutures which associated highly interdigitated sutures with mechanical advantage during mastication. However, to date there is no data to support that findings from studies on animal sutures are representative of the mechanical response of sutures in the human CFS. Differences in suture material properties and morphology between species may result in differences in mechanical response (Carmody et al., 2008). Yet, the majority of studies about suture biomechanics have been conducted in animals such as pigs, monkeys and goats and little work has been done on human samples. Animals have different dietary requirements and experience different loadings than those of humans (e.g. head butting in goats). As such, sutures may have evolved to serve the loading regimes specific to each species. Experimental testing of CFS sutures in human bone samples is needed to determine their biomechanical behavior and to identify species specific similarities and/or differences that may exist between human tissue and animal models. In considering external trauma due to impact forces, the bones of the CFS at and adjacent to the impact zone are subjected to high bending forces. As such, accurate evaluation of the bending strength of CFS bones with and without sutures is important in order to develop a comprehensive understanding of its mechanical response and the potential role of sutures in head protection.

The aim of this study was to determine how bending strength is impacted by sutural interdigitation and to evaluate the mechanical property of bending strength in CFS bones with and without sutures. It is hypothesized that the bending strength of sutures is elevated with increased sutural interdigitation in the human CFS.

2. Materials and methods

Six fresh frozen human cadaver heads ($F=3$, $M=3$; 81 ± 15 years old, maximum 101 years old, minimum 56 years old) were obtained through the Division of Anatomy at the University of Toronto. The study was conducted at Sunnybrook Health Sciences Center in accordance with research board ethics guidelines. The heads were used to obtain test specimens of bone and sutures. Four sutures were studied: (1) sagittal, (2) coronal, (3) frontozygomatic (FZ), and (4) zygomaticotemporal (ZT) (Fig. 1). The heads were dissected of all soft issue and stripped of the periosteum. A total of 20 sutures/bone samples and 9 bone only samples (adjacent to the sagittal suture, coronal suture, and ZT suture) were excised from the heads. Excising additional non-suture samples was limited by the complex morphology of the bone adjacent to the sutures (e.g. FZ). Samples were cut to 10 mm wide by 15–20 mm long. Specimen thickness ranged from 3 to 8 mm. Because most of the samples were irregularly shaped, each specimen was individually trimmed using an Isomet saw (IsoMet® Low Speed Saw, Buehler Canada) to produce relatively uniform samples that resembled straight beams. Four suture-bone samples were eliminated due to their high curvature from which it was not possible to produce sufficiently uniform samples.

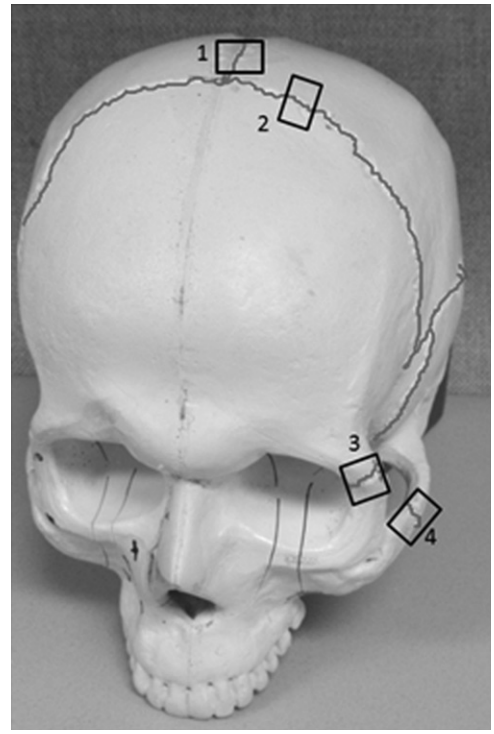

Fig. 1. Location of the four sutures excised from the CFS: (1) sagittal suture, (2) coronal suture, (3) frontozygomatic suture (FZ), and (4) zygomaticotemporal suture (ZT).

The samples were μCT scanned at an isotropic voxel size of 14 μm (GE Explore Locus, General Electric Company). Two hydroxyapatite phantoms (BMD phantom set, Skyscan Corp, San Jose, CA) were scanned with the bone samples to quantify the bone mineral density. The μCT scans were used to obtain information about the geometry and sutural morphology of the specimens. Using tools in the imaging software AmiraDev (Amira 5.2.2, Visage Imaging, San Diego, CA) the sample width (w), mean thickness (h), and bone mineral density were measured (BMD). The degree of interdigitation (Interdigitation Index I.I.) of each suture was calculated from the μCT scans by generating 3D surfaces, tracing the path of the suture external surface and dividing that length by the straight distance between the two ends of the suture (Rafferty and Herring, 1999).

A custom-made three point bending fixture was used to perform the bending test. Prior to testing, the samples were thawed to room temperature. The samples were loaded as beams in three-point bending using a Bionix 858 Material Testing Systems (MTS Systems, Eden Prairie, MN). Each sample was loaded at mid-span on the external suture surface to simulate external loading on the CFS and sutures. Bending tests of the specimens were performed at a slow displacement rate of 0.8 mm/s (Jaslow, 1990a; Fig. 2). Each sample was loaded to failure (indicated by force measurement of approximately zero). To standardize for size differences between the samples, the bending strength was calculated based on the elastic beam theory:

$$\sigma_{\max} = Mc/I$$

where $\sigma_{\max}$ is the bending strength (Pa), $M=Fd$ is the maximum bending moment (Nm), F is the peak force (N), d is the half the span length (m), c is the half of mean specimen thickness (m), $I=(wh^3)/12$ is the second moment of area (m^4), w the specimen width (m) and h is mean specimen thickness(m)

Linear regression analysis was used to determine if the interdigitation index predicts bending strength, controlling for density. A Wilcoxon rank sum test was run to assess differences in bending strength between bone samples containing sutures and bone samples without sutures. The significance level for all analyses was set as $p < 0.05$ and all statistical analyses were performed using SPSS (SPSS Comprehensive Statistical Software, Chicago, IL).

3. Results

In the specimens containing sutures, regression showed that bending strength increased significantly with increasing I.I. ($R=0.701$, $P=0.002$; Fig. 3). The highest I.I. was found in the