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Statistical analysis of biomechanical properties of the adult sagittal suture using a bending method in a Japanese forensic sample

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ABSTRACT

This study examined the mechanical properties of the adult sagittal suture compared with surrounding parietal bones using bending tests and investigated the association between the mechanical properties of the suture and age. We used the heads of 116 Japanese cadavers (76 male cadavers and 40 female cadavers) of known age and sex. A total of 1160 cranial samples, 10 from each skull, were collected. The samples were imaged using multidetector computed tomography, and the sample thickness at the center of each sample (ST) was measured. The failure stress of each sample (FS) was measured by a bending test, and the ratio of failure stress to the square of sample thickness (FS/ST^2) was calculated. Statistical analyses revealed that the FS and FS/ST^2 values were significantly lower at all suture sites than at all bone sites regardless of sex. There were not significant but slight positive correlations between age and FS and FS/ST^2 values at any suture site in male samples. In female samples, age had significant positive correlations with FS and FS/ST^2 values at the middle suture sites, whereas there were not significant but slight positive correlations between age and FS and FS/ST^2 values at the edges of the suture. Statistical analyses also demonstrated that FS and FS/ST^2 values were significantly greater in male samples than in female samples at the middle suture sites. These findings suggest that the bending strength of the adult sagittal suture is significantly lower than that of surrounding parietal bones. Therefore, avoiding direct impact on cranial sutures may be important for preventing skull fractures and severe complications that can cause death. The results of this study also revealed that the bending strength of the middle sagittal suture significantly increases with age in only female samples, whereas the bending strength is significantly higher in male samples than in female samples at the middle suture sites, indicating the possibility of sex difference in the bony interdigitation of the sutures during childhood.

1. Introduction

The head is one of the body's most frequently injured structures, and worldwide studies have proven that a traumatic head injury often causes death [1]. For this reason, close examination of head wounds is crucial for forensic analysis [2]. Skull fracture is a particularly important finding because it carries an independent risk factor for life-threatening intracranial complications such as epidural hematoma, subdural hematoma, and cerebral hemorrhagic contusion [3]. In addition, skull fracture may be helpful in estimating the direction and severity of external force. It is therefore vital to have a sound understanding of the biomechanical properties of the skull to provide accurate estimates of these aspects of force. In previous studies, the mechanical properties of human cranial bones have been tested using a variety of methods, such as compression, tension, and bending tests [4–13]. However, few published reports have investigated the mechanical properties of cranial sutures [14–20].

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Cranial sutures are deformable joints made up of collagenous fibers bridging two adjacent bone surfaces of the skull [14]. Previous researchers have reported that sutures are more energy-absorbent materials than cranial bones [15]. Therefore, sutures can experience and transmit mechanical stresses that are generated exogenously during trauma and by therapeutic mechanical devices [21]. This effect is probably because of the lower Young's modulus and elastic modulus in the sutures than in the bones, which allow the sutures to act as a cushion within the skull [14,22–24]. Sutures also have a growth function; they allow rapid brain growth and expansion and permit critical cranial kinesis during birth through the inferior pelvic aperture, which is of great importance in the evolution of *Homo sapiens* [25].

The best-studied aspect of the mechanical properties of infant cranial suture is their change with age. Force-bearing sutural ligaments that unite the bones are poorly developed in fetal and early postnatal skulls [26], and bony interdigitation is a late-developing feature [27]. Several studies suggest that infant sutures should be less stiff and less capable of energy absorption than older sutures [28–30]. However, little has been reported on the mechanical properties of human adult cranial sutures [19]. The purpose of this study was to examine the mechanical properties of the adult sagittal suture compared with surrounding parietal bones using bending tests and to investigate the association between the mechanical properties of the suture and age.

2. Materials and methods

This study protocol was approved by the ethics committee of our university, and the requirement for approval from subjects' relatives was waived.

2.1. Subjects

The skulls used in this study were obtained from 116 Japanese cadavers of known age and sex that were autopsied at the department of legal medicine at our university between June 2013 and January 2014. Subjects included 76 male cadavers (23–95 years; mean age, 61.8 $\pm$ 19.8 years) and 40 female cadavers (24–89 years; mean age, 61.9 $\pm$ 19.8 years). Subjects were excluded if the history highlighted conditions or events that could have affected the skull; for example, fracture, burning, obvious head injuries, and acquired or congenital abnormalities were excluded from this research.

2.2. Samples

During autopsy, bone and suture samples were taken from 10 cranial sites from each cadaver skull. Fig. 1 depicts the orientations of samples extracted from each cadaveric skull. The length of each sample was fixed at 50 mm, and the width was fixed at 10 mm. The left and right anterior samples of parietal bones (L1 and R1) were tangent to the bregma and the sagittal suture. The left and right posterior samples of parietal bones (L3 and R3) were tangent to the lambda and the sagittal suture. The left and right median samples of the parietal bone (L2 and R2) were located at the midpoint between L1 and L3, and R1 and R3, respectively. The anterior sample crossing the sagittal suture (S1) was tangent to L1 and R1. The posterior sample crossing the sagittal suture (S4) was tangent to L3 and R3. The samples tangent to the anterior and posterior sides of L2 and R2 crossing the sagittal suture were defined as S2 and S3, respectively. Samples were obtained using an oscillating saw and washed with saline. A total of 1160 samples were collected.

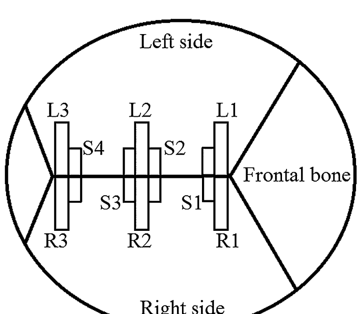

Fig. 1. Orientations of samples exrtracted from the cadaveric skulls.

2.3. Imaging protocol and measurement

The cranial samples obtained were imaged using a 16-row detector computed tomography (CT) system (Eclos; Hitachi Medical Corporation, Tokyo, Japan). The scanning protocol was as follows: collimation of 0.63 mm, reconstruction interval of 0.63 mm, tube voltage of 120 kV, tube current of 200 mA, and rotation time of 1 r/s. A hard filter was used. Image data were processed on a workstation (Synapse Vincent; Fujifilm Medical, Tokyo, Japan) to obtain orthogonal multiplanar reconstruction images and volume-rendering technique images. The sample thickness at the center of each sample (ST, mm) was measured using a reconstructed cross-sectional image viewed with a window width and level of 2000 and 500 HU, respectively. Measurements were taken to the nearest 0.1 mm. The ST of 20 randomly selected subjects was remeasured by both the original researcher and a second researcher to evaluate intraobserver and interobserver error.

2.4. Bending tests

Bending tests, which have been performed to determine the mechanical properties of various beam samples taken from layered structures including that of the human skull in previous studies [7,13,19,31–33], were used with a three-point-bending apparatus (JSV-H1000, JISC, Nara, Japan) as depicted in Fig. 2. Two lower supports of the apparatus were set 40 mm apart, and each cranial sample was placed on the two supports. Above this setup was a 1000-N load cell that applied stress at the center of the sample from the outer surface at a constant speed of 100 μm/s until the sample fractured. The applied load was monitored using a Handy force gauge (HF-100, JISC) attached to the apparatus, and the device recorded the failure stress (FS, N) that produced failure of the sample to the nearest 0.1 N.

2.5. Statistical analysis

The ratio of failure stress to the square of sample thickness (FS/ST^2), in Newtons per square of millimeter, was determined by dividing the failure stress by the square of sample thickness. All statistical analyses were performed on a personal computer using Statistical Package for the Social Sciences (SPSS) version 21.0 (IBM Corp., Armonk, NY, USA). The Mann–Whitney *U*-test was used to compare FS, ST, and FS/ST^2 values between male and female samples by site. The Mann–Whitney *U*-test was also used to compare FS and FS/ST^2 values between all suture sites (S1, S2, S3, and S4) and all bone sites (L1, R1, L2, R2, L3, and R3) by sex. In addition, the Mann–Whitney *U*-test was used to compare FS and FS/ST^2 values between suture sites by sex. The Wilcoxon test was used to estimate the amount of intraobserver and interobserver error. To investigate the degree of correlation between age and FS and FS/ST^2 values, the Pearson product-moment correlation coefficient (r) was calculated. A p value $<$0.05 was considered statistically significant.