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The results of compression forces applied to the isolated human calvaria

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Data for the force necessary to fracture the isolated calvaria (skull cap) are not available in the extant literature. Twenty dry adult calvaria were tested to failure quasistatically at the vertex using a 15-kN load cell. The forces necessary to fracture or cause diastasis of calvarial sutures were then documented and gross examination of the specimens made. Failure forces had a mean measurement of 2772 N. Initial fractures did not cross suture lines. Prior to complete destruction of the calvaria there were 7 specimens in which all sutures of the calvaria became diastatic, 6 specimens in which the calvaria became diastatic along only the coronal sutures, 2 specimens in which the calvaria became diastatic along only the sagittal suture and 5 specimens in which there were diagonal linear parietal bone fractures. Our hopes are that these data may contribute to the structural design of more safer protective devices for use in our society, assist in predicting injury and aid in the construction of treatment paradigms.

Key words: skull, fracture, quantitation, trauma

INTRODUCTION

Head injuries have a significant impact on our society. Research efforts to determine the biomechanics of the skull and its individual bones are, therefore, of critical importance. Fractures of the skull occur when the dynamic input exceeds the tolerance of the skull [10]. A variety of biomechanical impact protocols can be noted in the existing literature for the study of cadaveric skulls [6, 10]. However, we were unable to find studies that measured the compression forces (static loading that occurs when forces are applied slowly to the head) necessary to fracture the isolated calvaria. Therefore, our methods represent a novel approach to the analysis of calvaria fracture. A blunt impact to the calvaria may result in a remote linear fracture in the skull base. This is thought to be a consequence of the skull cap being strong enough to withstand the force of the impact, which is therefore transmitted to the much thinner bone found in parts of the skull base. However, data for compression forces to the isolated calvaria are not available in the extant literature. Our current study analyses the compression forces necessary to fracture the isolated adult human calvaria.

MATERIAL AND METHODS

Twenty adult dry calvaria were placed vertex up in a hydraulic press (MTS 858 Mini Bionix, Eden Prarie, Minnesota, USA) (Figs. 1, 2). The calvaria was defined as the cranium superior to a horizontal line through the glabella and parallel to the Frankfurt plane [13]. Specimens were tested to failure quasistatically at the vertex. A 15-kN load cell was incorporated to deliver force slowly at a load rate of 2.5 mm/s. All the calva-

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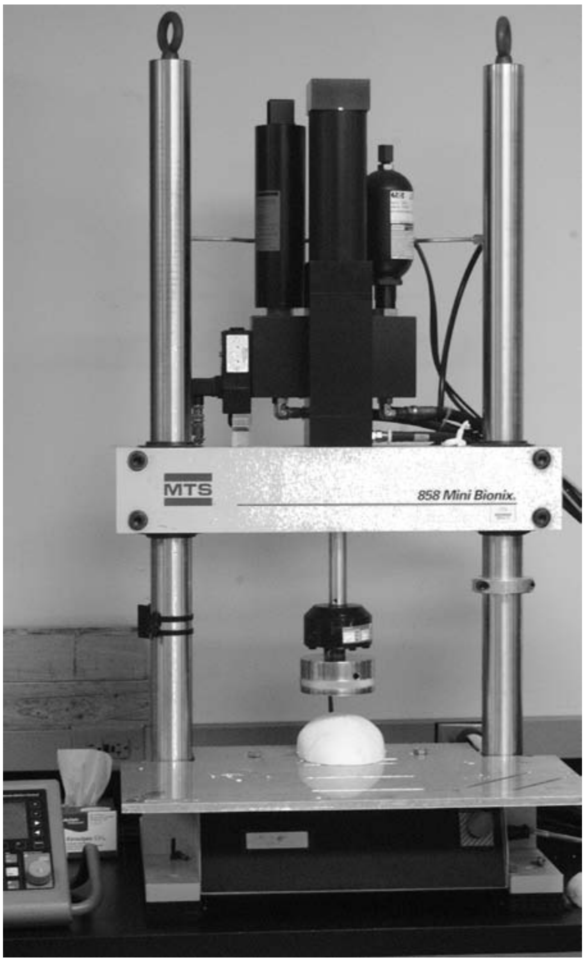

Figure 1. Hydraulic press set up as used in our study.

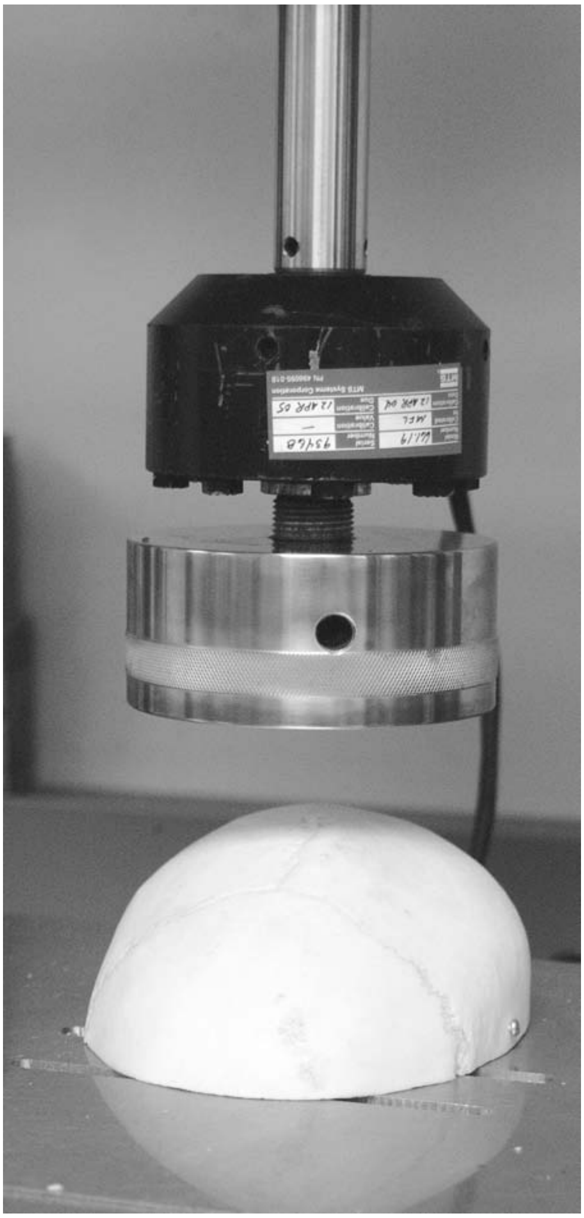

Figure 2. Close up of the above figure illustrating the positioning of the specimen on the apparatus.

ria had an evenly cut inferior surface. Fracture location was closely observed at the onset and crushing was halted after substantial deformation of the calvaria (when the calvaria was annihilated into small unrecognisable fragments and bone dust). Data were collected using RTS software at a sampling rate of 100/s. Macroscopic evaluation was made of all specimens following the initial fracture. No pathology or anomaly was noted in any specimen such as prior fracture sites, prior surgery, hyperostosis *frontalis interna*, or craniosynostosis. Statistical analysis was performed using Student's t-tests.

RESULTS

The maximal depth of the calvaria used for this study ranged from 3.3 to 5.3 cm (mean 4.6 cm). The mean thickness of the midline frontal and occipital bones was 6 mm and 7 mm respectively. The mean thickness of the left temporal bone was 4.3 mm and the mean thickness of the right temporal bone was 4.2 mm. Compression forces to the vertex of the isolated human calvaria resulted in initial diastasis of all calvarial sutures in 7 specimens, diastasis of the coronal suture in 6 specimens, diastasis of the sagittal suture in 2 specimens, and fracture of the parietal bone in 5 specimens. Failure forces ranged from 1615 N to 9885 N (mean 2772 N) (Figs. 3, 4). Initial fractures did not cross suture lines (Fig. 5, 6). Occasionally, additional fracture sites would occur before the specimen lost its structural integrity (Fig. 7). Prior to complete destruction of the calvaria there were 7 specimens in which all sutures of the calvaria became diastatic, 6 specimens in which the calvaria became diastatic along only the coronal sutures,

Figure 3. Example of fractures created following compression forces applied to the vertex of the isolated calvaria. The first fracture was the parietal bone fracture. Diastases of the sagittal and lambdoid sutures occurred next, followed by fracture of the frontal bone.

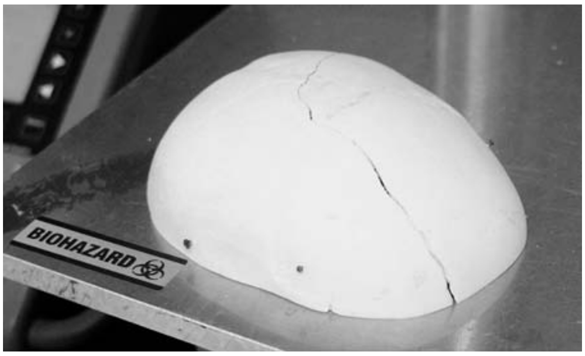

Figure 4. An additional example of skull fractures seen in our study. The first fracture to occur was the parietal bone fracture followed by the frontal bone fracture.

Figure 5. Posterior view of a calvaria. Note the posterior fracture of the right parietal bone, which occurred first and extended to but not beyond the sagittal suture. Also seen is a later fracture that occurred in the left anterior parietal bone.

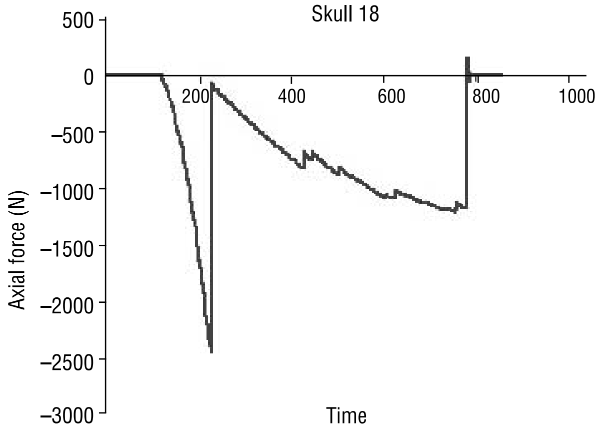

Figure 6. Graphical example of specimen 18 (Fig. 5) illustrating the 2500 N of force needed to cause this initial fracture.

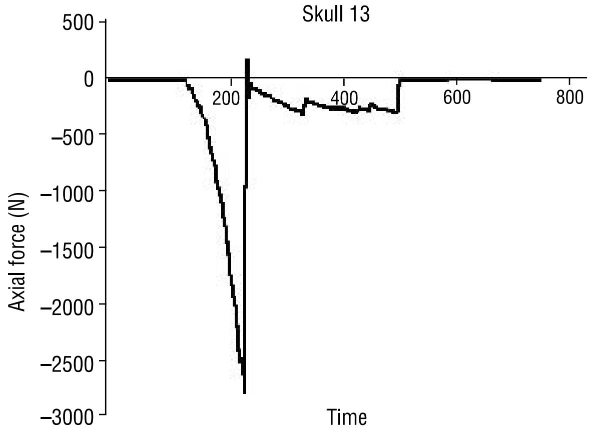

Figure 7. Graphical examples of an isolated calvaria (specimen 13, Fig. 4) following the application of compressive forces to the vertex. The initial fracture occurred at 2700 N.

2 specimens in which the calvaria became diastatic along only the sagittal suture, and 5 specimens in which there were diagonal linear parietal bone fractures (two left and three right). No isolated pterional diastases were noted. Table 1 lists the above-described measurements for each specimen. Statistically, there was no significant difference between the thicknesses of the various bones or between the left and right temporal bones ($p > 0.05$, Student's t-tests). The coronal suture was the most likely to become diastatic in isolation. The parietal bones were the only bones to fracture initially. Neither the thickness of individual bones nor calvarial depth correlated either with which bone would fracture or with which suture would disarticulate itself.

Table 1. Measurements. Observations for calvarial specimens 1–20

Vault depth [cm]	Frontal [mm]	Occipital [mm]	Left temporal [mm]	Right temporal [mm]	Initial fracture/ /diastasis
5	6	10	5	6	Coronal suture
4.6	4	5	3	2	All sutures
4.7	9	9	5	5	Parietal
4.5	8	5	4	4	Coronal suture
4.4	7	8	4	5	All sutures
4.8	5	7	3	4	Sagittal suture
3.8	7	7	6	5	Coronal suture
4.6	9	6	5	5	All sutures
4.9	5	6	4	5	Posterior parietal
4.4	7	7	4	4	Anterior parietal
3.3	6	8	4	5	Left coronal suture
4.5	4	7	3	4	All sutures
3.6	4	7	4	2	Right posterior parietal
4.9	7	6	6	4	All sutures
5.2	7	6	4	4	All sutures
4.9	4	9	4	3	Left coronal
4.7	6	7	4	4	All sutures
5.3	4	7	3	3	Left posterior parietal
5	4	6	4	4	Sagittal suture
4.4	8	8	7	5	Coronal suture

DISCUSSION

Although bones (the hip joint and lumbar spine, for instance) are known to lose strength with advancing age, this tendency is not particularly evident with skull bones, so that these data from the adult skulls used in our study may be extrapolated to the living adult [12]. There are regional variations, for example in the bone thickness of the skull; the temporal region is thinner compared to the parietal, occipital, and frontal areas [12]. Multiple variations such as shape, blood vessel erosion, foramina, and table geometry can also alter skull thickness.

Gurdjian et al. [6] found that the energy requirements for the production of single fractures with blows to the midfrontal, anterior interparietal, midoccipital, and posterior parietal regions ranged from 400 to 900 inch pounds. The mean energy required to fracture the midfrontal region was 571 inch pounds. Gurdjian et al. [6] have concluded, following blows to intact human cadaver heads, that a reduction in fatalities can be achieved by keeping accidental input energy to the skull below 400 inch pounds. In their study the average energy necessary to produce a single linear fracture with blows in the frontal midline region was 571 inch pounds; in the back midline region, 517 inch pounds; in the top midline region, 710 inch pounds and in the region superior to the ear on either side, 615 inch pounds. These authors state that the average energies for complete destruction of the cranium were very close to those required to produce single linear fractures. Our data revealed that this was quite variable, with initial fracture force and complete destruction forces varying from 200 N to 2200 N (mean 1160 N). Poisson's effect was proved for our calvarial fractures; compressive loading in one direction resulted in tensile deformations in the perpendicular direction (when material is compressed in one direction it undergoes expansion in the plane perpendicular to the direction of compression) [7, 12]. This is uniaxial compression with uniaxial stress, as the material undergoes stress only in the direction of compression.

Yoganandan et al. [11] found that impact loading resulted in fracture widths that were consistently greater at sites remote from the loading region. This was found to be true in our study using compressive force. These same authors also performed one crush injury to a human cadaveric head at a loading rate of 0.002 mm/s and at 4464 N of force observed a linear parietotemporal skull fracture [11]. Our study found that compression forces to the vertex of the isolated human calvaria resulted in initial diastasis of all calvarial sutures in 35% of specimens, diastasis of the coronal suture in 30% of specimens, diastasis of the sagittal suture in 10% of specimens, and fracture of the parietal bone in 25%. On the basis of these data and with the calvaria in isolation and under compression forces applied to the vertex, it appears that sutures such as the lambdoid and temporal sutures are stronger (no diastases in our study) than the coronal and sagittal sutures (6 and 2 diastases in our study respectively). However, 35% of our specimens had diastasis of all calvarial sutures with maximal axial forces. Hence, one must not consider the human calvaria as a simple bony hemisphere but rather an outer containment composed of several bony pieces. This arrangement effectively aids in allowing the newborn to pass through the birth canal but weakens the overall construct of the skull cap [8]. Congruently, and also based on these data, the parietal bone seems to be the least able to sustain compression forces applied to the vertex, with all initial fractures occurring in this bone. This does not support the findings of Yoganandan and Pintar [12], who note that the human parietal bone is stronger than the frontal bone under impact loading. In an image-based computational study of skull fracture, Bandak et al. [2] found that the highest value of the maximum principle strain occurred at a point on the inner table of the skull just anterior to the crown. Murray [8] has stated that the skull vault absorbs tension in both meridional and latitudinal directions with the meridional support being stronger.

Crushing head injuries (quasistatic loading), although not seen as often as impact (dynamic acceleration/deceleration injuries) injuries, are defined as forces applied to the skull over longer periods of time (> 200 ms) [10]. Sawauchi et al. [10] have reported industrial accidents of this nature. Crush injuries have also been noted in natural disasters (such as earthquakes) and with heads that are run over by motor vehicles, such as those of children run over by vehicles reversing in driveways or parking lots [4]. Duhaime et al. [4] have also reported this type of injury in children on whom heavy objects such as stone fireplaces (180 kg), large clocks (45 kg) or televisions have fallen. Blair et al. [3] have also reported garage door injuries of this nature in children.

On the basis of our study it should be possible to predict the position of an initial fracture or suture diastasis if compression forces are applied to the vertex of the calvaria. However, one must also consider the energy-absorbing capacity of the scalp and its protective function *in vivo* or in experimentation utilising intact cadaveric heads [5]. Furthermore, the mechanically relevant material make-up of the brain is multiphasic, consisting of solid and fluid materials [1]. Thus our data must be considered in the context of the living cranium with both external and internal soft tissues intact. One must also consider the possible buttressing effect of the skull base and mandible. Parenthetically, impacts to a stationary specimen may produce results different from a test in which a moving specimen strikes a hard object [9].

Our hopes are that these data may contribute to the structural design of safer protective devices (such as helmets and motor vehicle safety features) for use in our society, assist in predicting injury, and aid in the construction of treatment paradigms.

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