Mechanical Properties of Brain-Skull Interface in Compression

Sudip Agrawal[1], Adam Wittek[1], Grand Joldes[1], Stuart Bunt[2] and Karol Miller[1]

[1] Intelligent System for Medicine Laboratory (ISML), School of Mechanical Engineering, The university of Western Australia, Crawley-Perth 6009, WA, Australia.

[2] School of Anatomy, Physiology and Human Biology, The University of Western Australia, Crawley-Perth 6009, WA, Australia.

Abstract. This study investigated mechanical properties of brain-skull interface, important for surgery simulation and injury biomechanics. Direct examination of brain-skull interface is difficult due to its delicate nature and complex geometry that follows the skull and brain surface. Hence, we conducted uniaxial compression tests on samples containing skull, meninges and brain. We combined sophisticated measurement data with non-linear finite element analysis to obtain properties brain-skull interface. Skull was considered a rigid object as forces obtained were very small to induce any measurable deformation on it. Surface contact model between brain and skull was used to simulate the brain-skull interface. Good correlation between sample deformation in experiment and simulation was used to confirm the brain skull interface property.

Keyword Brain-Skull interface, Meninges, Mechanical properties, Biomechanics

1 Introduction

Advancement in computing technology has accelerated interest in numerical modelling of brain for application in various fields like surgery simulation, computer aided and image guided surgery [1]. A typical example of modelling and simulation of brain is to compute craniotomy induced brain shift that results in movement of tumor and healthy brain tissue. Such application involving deformation requires material properties of various tissues and components inside cranium, and loading and boundary condition for accurate results. In brain modelling, the mechanical properties of brain-skull interface determine the boundary condition. However, the existing quantitative data regarding the mechanical properties of the brain–skull interface, the complex comprising the meninges, skull and fluid filled spaces in-between them, are very limited.

A number of studies have been conducted to determine the mechanical properties of brain tissue. Those studies have established that brain tissue is a very soft, non-linearly viscoelastic solid material, with very low linear viscoelastic strain limit (of the order of 0.1-0.3%) [1]. However, there is no consensus regarding material properties of the brain skull interface. Different research groups have implemented different ideas to address the issue in their model. Some assume the brain to be fixed to the surface of the skull [2, 3], while some use a gap between the brain and skull allowing motion of brain within the cranial cavity [4-9] and others use a frictionless sliding contact model [10, 11].

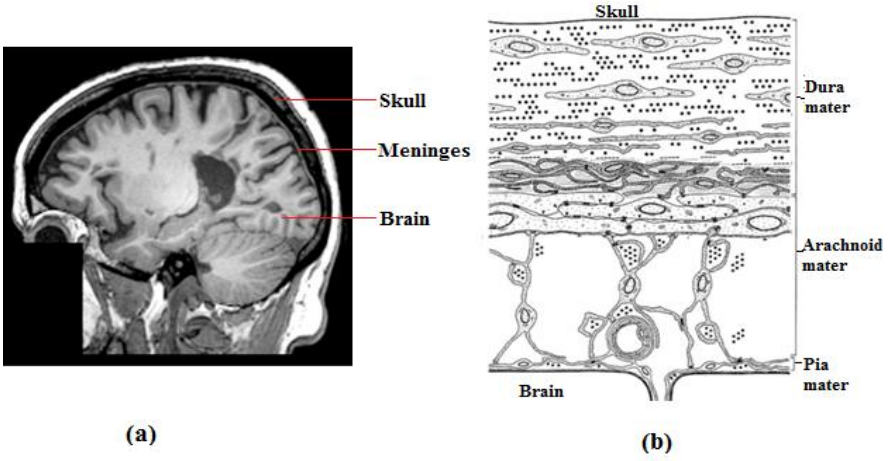


Figure 1 Brain skull interface (a) lateral section through human head showing the brain and surrounding tissue(taken from NAMIC registration case inventory brain) (b) detailed representation of the Meninges (modified from Haines et al. [2])

Anatomically the brain skull interface is comprised of rigid cranial inner surface (also referred to as inner table), the meninges and the outer brain surface. The meninges are comprised of dura mater, arachnoid mater and pia mater [12]. The dura mater is attached to the skull. It consists of periosteal dura, meningeal dura and dural border. The connection between arachnoid and meningeal dura is established through the dural border and arachnoid border cells. From arachnoid mater's inner surface its fibres (arachnoid trabeculae) extend to the Subarachnoid space (SAS) and becomes continuous with the pia mater. The pia mater is a thin delicate membrane which is attached to the brain outer surface. There is a fluid filled space between the dural surface of arachnoid matter and the pia mater because arachnoid mater doesn't follow the contours of the brain like the pia mater.

However the exact anatomical structure of this interface is still hotly debated [12]. A detailed representation of the brain-skull interface is shown in Figure 1.

In this study we have conduct ex vivo uniaxial compression tests on a sample containing skull, meninges and brain and the simulations of the experiment to establish mechanical behaviour and properties of brain-skull interface. All the necessary ethical approvals were obtained prior to the experiment from Animal Ethics committee, University of Western Australia (UWA). The approach ensured we could examine brain skull interface in its closest natural state in a controlled study.

2 Materials and methods

2.1 Sample preparation

Sheep heads were collected from Royal Perth Hospital (RPH), Perth. The specimens were taken as by product of anaesthesia training programme. They were sacrificed using high dose of triple drip (a combination of xylazine, ketamine and guaifenesin, all anaesthetics compound). They were transported to the testing facility in a sealed container and stored at 4° C before further processing and testing. Samples were tested within 24 h from time of death to reduce variability due to post-mortem changes[13]. The specimens were not frozen at any time.

The heads were skinned and a rectangular cut of ~30X30 mm was made on the skull on top of the cranium (above cerebrum) using vibrating saw. Adjoining cut of ~30X10mm was also made. Using a microtome blade (Feather s35) the underlying brain was cut vertically in sagittal and coronal plane through the opening in skull. The smaller of the skull was removed along with the underlying brain tissue using forceps and scalpel to create an opening into cranium and the sample. From the opening, a horizontal cut (in transverse plane) was made in the brain leaving approximately 12 mm of tissue attached to skull using a bent razor blade. The free specimen was lifted out from the skull with the blade to ensure minimal damage to the meninges. The skull was set on epoxy putty (Selleys Knead It Multipurpose) base to roughly level the four corner of skull. The putty set in 10 minutes. The top surface of the brain was carefully levelled using microtome blade. ~5 mm of brain tissue from all edges were removed using microtome blade and scalpel to ensure we discarded damaged meninges and tissues in the edges that may have been caused by the vibrating saw. This formed our test sample (with brain-skull interface). The process can be seen in Figure 2(a-g).

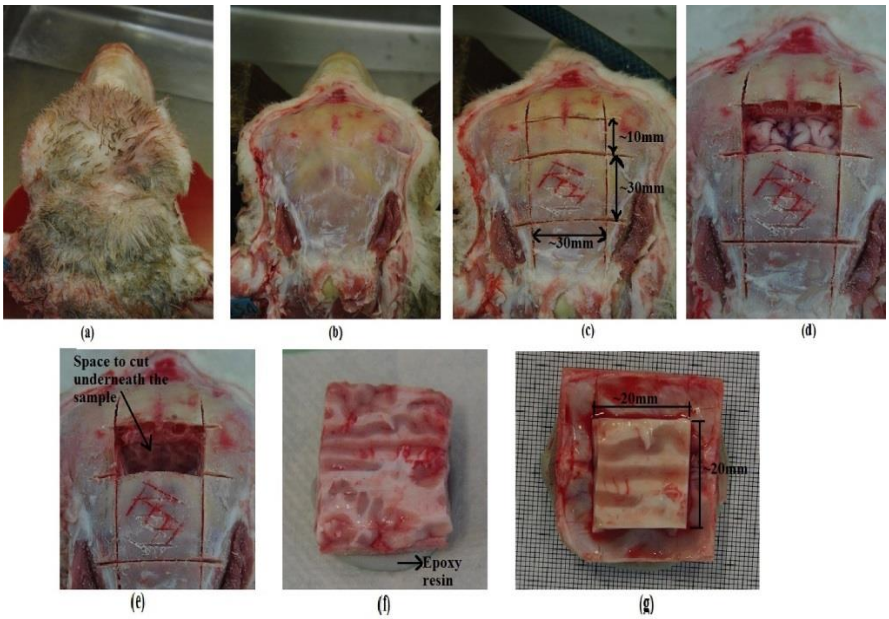


Figure 2 Sample preparation (a) head (b) skinned for extraction (c) skull cut using vibrating saw, lower ~30x30 mm and upper `10x30 (d-e) smaller free skull and brain removed (f) sample extracted and mounted in epoxy resin (g) Complete sample A

The resulting sample had brain tissue resting on skull with brain-skull interface intact. Width of the faces of brain tissue, position of four corners in contact with the skull and height at the corner of sample were measured. The widths of the faces of the samples were taken midway between the base and the top surface of brain tissue.

2.2 Experimental Setup

Uniaxial compressions of the samples were performed in setup shown in Figure 3. The experiment was done in a testing device developed in-house[14]. The displacement of impermeable loading plate was done by Haydon Kerk Linear actuator 43F4A-3.22-099, a stepper motor screw drive actuator. It has a displacement control of 7.9 micron per step and allowed loading velocities of 0.001 to 5 mm/s. The displacement was measured by MTS CS core sensor with analog output. The forces were measured by Burster 8523-20 0-20N loadcell with linear output in the required range of 1N with error less than 0.15% [14]. The experiment was documented using Pentax K5 camera with FA 50mm f1:1.4 lens. The images were used to study deformation of samples after the experiment.

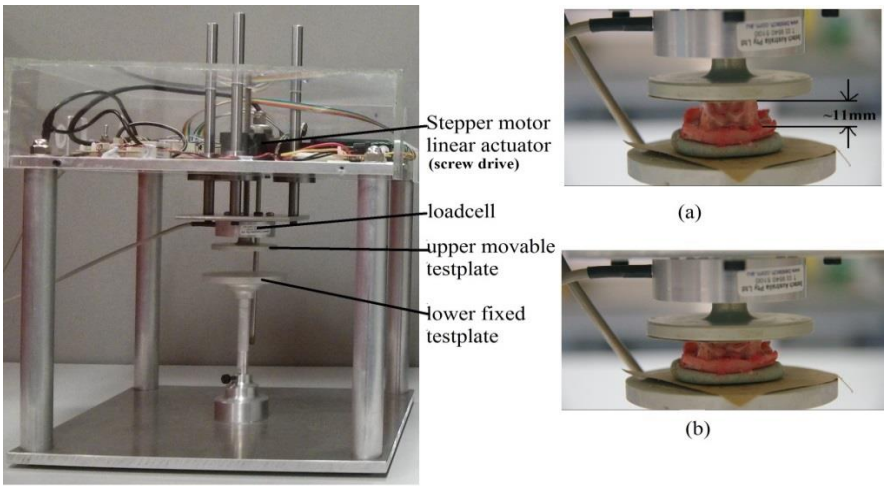


Figure 3 Experimental setup (a) sample before compression (b) sample after compression

2.3 Experimental Protocol

The experimental protocol follows Miller and Chenzei [15]. The samples were compressed between two impermeable platens in a semi-confined uniaxial setup. No preconditioning was done to samples done to the samples.

Tests were done at two different loading speeds 1 and 0.01 mm/s. The tests were performed at room temperature as suggested by literature [13, 15, 16]. The movement of the platen began about .5 mm above the sample and care was taken the sample didn't touch the loading platen before compression started. The samples were compressed about 3 mm corresponding to approximate strain of 0.3. 120 grid sand papers were glued to both the platens to ensure no relative movement occurs between sample and loading plates so no slip boundary condition could be used in the analysis.

The linear stepper motor screw drive actuator had very high acceleration and hence the loading velocity was assumed to be achieved instantaneously.

2.4 Analysis

Dimensions of brain tissue in both the samples were measured. Geometry of internal surface of skull was required to create a model for both samples. After the experiment, the brain tissue and meninges were scraped from the skull and the internal surface of the skull was scanned using MODELA MDX-20 Scanner. The scanned surface of skull and the initial dimensions of the brain tissue were used to create models of the samples. Side walls of brain were assumed to be orthogonal

and the top surface was assumed to be parallel to sample resting plane. Skull was assumed to be rigid body as it was orders of magnitude stiffer than brain tissue. Computational grid was created on the geometry. All the pre-processing of the model including mesh generation was done using Altair HyperMesh. The brain tissue was modelled using the Ogden-type [17] Hyperelastic model as proposed by Miller and Chenzei [16].

$$W = \frac{2\mu}{\alpha^2}(\lambda_1^\alpha + \lambda_2^\alpha + \lambda_3^\alpha - 3) \quad (1)$$

Where W is strain energy potential, λ_i principal stretches, μ relaxed shear modulus and α material coefficient. The experiment was simulated by applying fixed boundary condition at the skull and prescribed displacement at top surface of brain as shown in Figure 4. The interface was simulated as friction less sliding contact. Loading surface reaction force-time relation was obtained from simulation using ABAQUS™ was matched close to data measured by the experiment to determine coefficients μ and α following Morris et al [18]. This formed subject specific material property of brain tissue for the sheep from which the sample was taken.

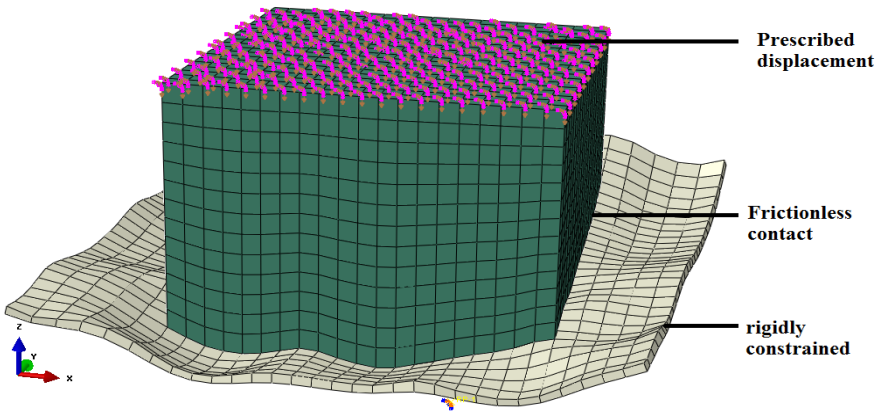
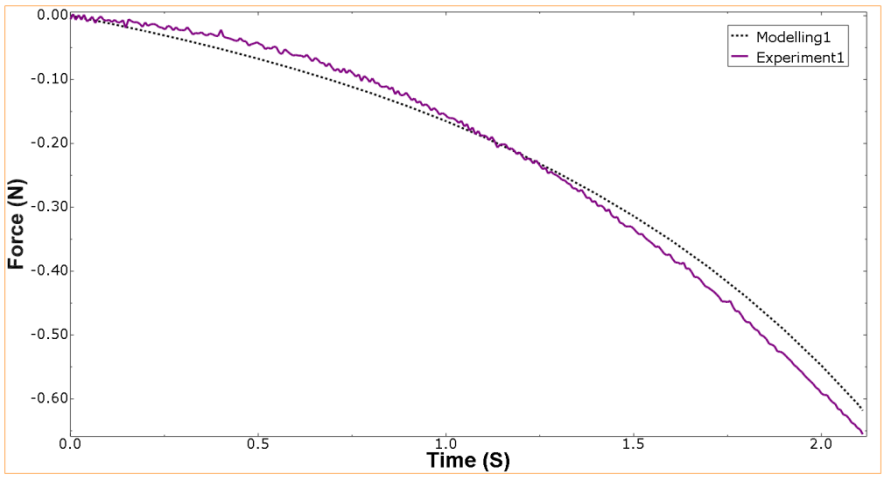


Figure 4 Rigid Skull (white) constrained in all direction at reference point and brain tissue (tissue) loading by displacement of nodes in z direction and constrained in x and y axis.

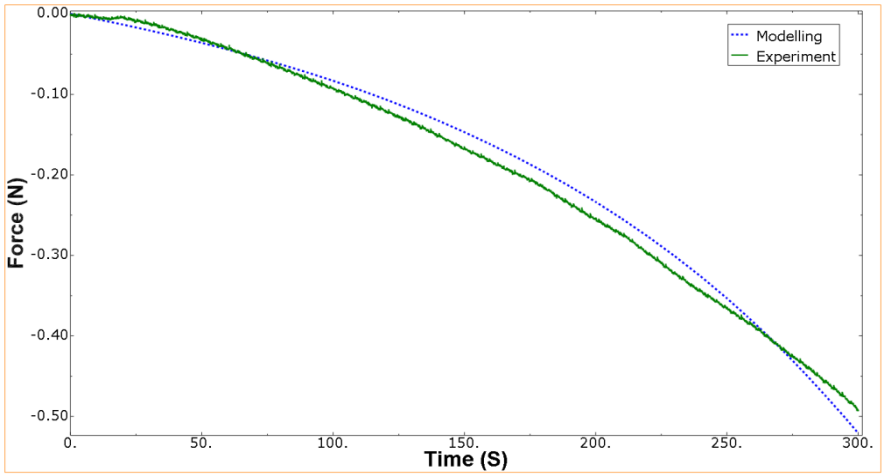
Width of sample after the test was obtained from images of the experiment. Any lens distortion was corrected using camera software (Camera's Jpeg engine) distributed by manufacturer (Ricoh, Japan). The width of each pixel was estimated using initial width measured and image before loading. It was compared with the results from simulation.

3 Results

Comparison of force vs time relation from the experiments and modelling are presented in Figure 5 for both the samples. Corresponding material parameters and loading speed for the samples are listed in Table 1.



(a)



(b)

Figure 5 Uniaxial compression of samples: comparison of modelling and experimental results (a) loading speed 1mm/s (b) loading speed 0.01mm/s

Table 1 Odgen type hyper elastic material constants for tissue samples by calibrating the model using ABAQUS finite element solver

Sample	Loading speed(mm/s)	μ(Pa)	α
a	1	790	-6.3
b	0.01	600	-6.3

For compression of up to 3mm (~0.3 strain) the model can predict force magnitude with error less than 5%. Comparison of width of side monitored by video with the modelling result along with initial width is presented in Table 2. The interface was represented by friction less sliding contact. The data showed there is good correlation between measured and predicted width for the two test samples.

Table 2 Comparison of width of monitored side of brain tissue

Loading speed mm/s	Initial width	Final width(mm)		Difference(mm)
		Experiment	Simulation	
1	18.99	20.65	20.85	0.20
0.01	20.47	21.93	21.90	0.03

4 Discussion

In this study, we presented results of compression experiment on samples containing sheep's skull, meninges and brain and evaluated behaviour of brain-skull interface through use of non-linear finite element modelling. To obtain the properties and behaviour of interface we performed uniaxial compression experiment on the tissue sample under controlled condition. Base of skull and top of brain were fixed to impermeable testing platens to implement non-slip boundary condition during analysis. We measured initial width of faces brain tissue of sample and utilized video and image of the experiment to obtain width of a face after the compression. A model of sample was created where the skull, treated as rigid object, was fixed on a reference point and the compression of sample was achieved by nodal dis-

placement of nodes on upper surface of brain. The brain-skull interface was modelled as friction less contact interaction between brain and skull. The finite element model accurately predicted the compressive forces (Fig 5) and changes in width of the face of sample (Table 2).

We hypothesize that the minor discrepancies between the modelling and experimental result could be attributed to minor inaccuracies in determining the geometry of brain and skull surface. The sample was manually prepared using by hand using tools like scalpel blade and razor blade and contained unevenness reducing the geometric and measured dimension accuracy to about 1mm. This also affected image processing to obtain final width of the face.

A limitation of our study is the number of experiment conducted. The preparations of samples were very challenging and delicate process and it resulted in a lot of damaged samples during the testing. Another limitation is as the experiment is ex-vivo, we assume some of cerebrospinal fluid (CSF) leaks from the meninges. Hence this approach may not be sufficient to represent brain-skull interface during very high speed impacts where fluids may have greater relevance. We observed that deformation shape of sample was mainly dictated by the geometry of skull. Depending on slope of skull surface in contact with brain, the deformation tends to be more toward the inclination of the surface. For further validation and improvement of the model more experiment needs to be conducted and feature or deformation has to be tracked and compared in 3D to have better correlation with simulation on a number of samples.

The study presents experimental results with quantitative assessment of brain-skull interface compression to determine its properties. The result suggests that frictionless contact can replicate brain-skull interaction of the samples in compression, when brain presses against the skull, at low loading speeds.

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