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Research paper

Computational Analysis on Skull Fractures and Brain Injury using Finite Element Analysis

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Abstract

Traumatic Brain Injury (TBI) is a complex injury with a broad spectrum of disabilities and symptoms. Basically it happen when head is impact with certain value of force and the victim has to bear with a certain mechanism of injury. This research has investigated the potential for TBI using Finite Element (FE) analysis with rear impact on the head at different velocities. A 3D human skull and brain were presented and run through simulation in explicit dynamic analysis using commercial finite element software. The risk of skull fractures and brain injury were predicted based on the resulting maximum principal stress, shear strain and total displacement. Final objective of this research is to provide a predictive tool as FE model that can aid in injury diagnosis and design protective devices to minimize the impact effects.

Keywords*: *Traumatic brain injury; finite element analysis; rear impact; human brain; skull fracture

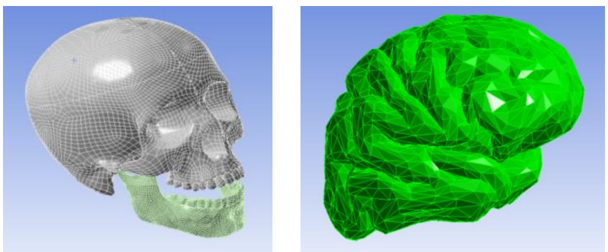
1. Introduction

Traumatic Brain Injury (TBI) is a crucial public setback that has a major influence in social and economic impact [1]. When a sudden trauma happened, it causes impairment to the brain. Frequently, it can best described as sudden and violent hits on an object, in this case human head or objects penetrates the skull and enter the brain. TBI can be categorized into three, which are mild, moderate, or severity depends on the degree of the damage to the brain. Sudden unconsciousness might be experienced by the mild kind victim either a few minutes or seconds.

Other symptoms of mild TBI include light headedness, confusion, headache, blurred vision or tired eyes, dizziness, fatigue or lethargy, ringing in the ears, bad taste in the mouth, a change in sleep patterns, concentration, attention, or thinking, behavioral or mood changes, and trouble with memory. A victim with a moderate or severe TBI may show these same symptoms, however might also get worse or does not go away, convulsions or seizures, dilation of one or both pupils of the eyes, repeated vomiting or nausea, inability to awaken from sleep, slurred speech, loss of coordination, weakness or numbness in the extremities, and increased confusion, restlessness, or agitation.

Computer models range from simple lump-mass models to detailed anatomically FE models. The Finite element method is a numerical method that can be used to solve complex problems. It was first introduced in structural mechanics, but extension used today in a very broad context. The first finite element head model was developed during the 1970s. With the advanced in computer technology, more detailed models have been developed [2].

In addition, Finite Element Model (FEM) has been used significantly in recreating accident vicinity in order to make analysis and simulation. It is known that FEM has the great ability to predict strain and stress distributions through complex media. FEM have become a huge utility approach to get the best accuracy and efficient meshing complex biological structures such as vertebrae bones and human brain modeling [3]. The technology and computational power nowadays offer an opening for biomechanical investigators to develop experimental and theoretical models of the human head [4][5][6]. In this case, the resolution of human head model depends strongly on several integral key aspects such as accuracy of the meshing which are the high number of elements and nodes, plus with model segmentation. However, an accurate segmentation of the human head model is not easy to gain and a very complex task. Figure 1 shows the sample of FEM of the human head model that been used in this report.



(a) (b)

Figure 1: FEM of a) human skull b) human brain.

Furthermore, in forensic investigation these data are important to help the officers or surgeon to solve and come out with the reason or causes of the injury. In the nip of time, they can search reasoning using these past data. Basically, forensic officers will do an investigation into how the brain is injured by conducting biomechanical analyses to determine the direction, duration, and magnitude of the forces generated during an accident. The idea quite similar to biomedical engineering, which diagnosis the case identifies the situation whether the subject is susceptible to sustain TBI and therefore can develop various protective measures or medicine.

This study is important because it highlights the current situation of the Traumatic Brain Injury that has immensely grown in most. This study proposed head impact test simulation using finite element software instead of using experimental apparatus which can cause more cost to the investigating process.

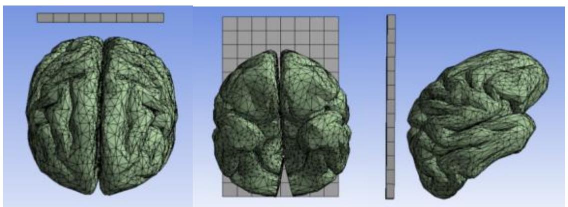
2. Methodology

The need of this research is clear and the challenging task is the development of such detail model due to complex geometry of human head's, material composition, boundary conditions as well as insufficient experimental data for model validation. However, many FE head model have been design and developed with various degrees of simplification. At present, there are more advanced FE head models suited to the development of latest technology of MRI scanning process that can scan and reconstruct the human head model with more detail and precise. In this research, only brain and human skull was taken into consideration even though other parts also involved in real like cerebrospinal fluid, ventricles, brainstem, blood vessels and others. This is due to material degradation that will limit the process [2].

There are two parts in which to develop the 3D head model. First where the model is develop using CAD programs such as Catia and Solidwork 2016. The second part is to develop the simulation in ANSYS LS-Dyna Workbench software in which to analyse the impact to the human head model, specifically on the stress distribution and total deformation.

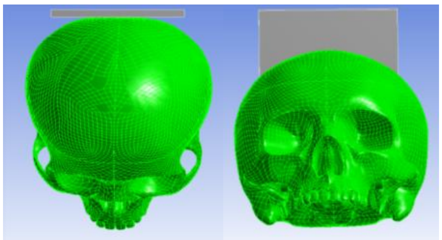
2.1 Finite Element Model

The adult human head skull is developed; the skull consists of 22 individual bones in total, 21 of which are immobile and united into a single unit. The 22nd bone is the mandible (lower jaw), which is the only moveable bone of the skull. However, the lower jaw is removed in the Design Modeler to reduce the time taken for mesh and solving output. The geometry of the FE human skull mesh is based on structural data of a healthy adult. The FE mesh consists entirely of hexahedral elements with the element size of 0.03mm. Globally, the model has a total of 106511 elements and 28386 nodes. Meanwhile the brain is design successfully with implying the unique folding structure of the cerebral cortex and not declared as smooth surface. Studies have suggested that the folding structure of the brain surface greatly influence both the distribution and the magnitude of the maximum stress and strain in the brain subjected to impact [1]. The FE mesh consists entirely of tetrahedral elements with the element size of 0.03mm and the model has a total of 29513 elements and 7296 nodes. Both are developed in rigid body behaviour and been fully meshed. A wall also was also drafted in as where the head will impact the wall. Thus making the human head model consists of a total 136128 elements and 35934 nodes. This requires more computing power and running time for solver output. Figure 2 and 3 shows the head model after being meshed.



(a) (b) (c)

Figure 2: The FE model of brain with tetrahedron element at a) top view b) front view c) side view



(a) (b)

Figure 3: The 3D model of human skull at (a) top and (b) frontal views

2.2 Mechanical Properties

Most biological tissues are known as anisotropic, nonlinear and inhomogeneous. Nevertheless, the challenging is a complete material characterization of biological tissues. All material phases in the model were assumed to be homogeneous and isotropic. Table 1 shows the mechanical properties of the human head model.

Table 1: Mechanical Properties

Components	Brain	Skull	Wall
Young's Modulus (Pa)	6.67E+04	8E+09	3E+10
Density (kg/m3)	1040	2070	2300
Bulk Modulus (Pa)	2313.3	8.9286E+08	1.562E+10
Shear Modulus (Pa)	239.31	6.1475E+08	1.2712E+10
Poisson Ratio	0.48	0.22	0.18
References	[7]	[8]	Ansys Workbench

2.3 Boundary Conditions

The skull and brain are both designed in solid form. The skull bone that consists of two main components only considered compact bones and not facial bones. The brain however is more advanced due to its unique folding structures instead of plain and smooth surface. This model has been considered as free in correspondence of the neck constraints [10]. The initial conditions of the simulations assumed the wall is at rest and the human head striking the wall at certain values which are 2 m/s, 3 m/s, 4 m/s, 5 m/s and 6 m/s. This speed range was taken into consideration because it is the optimum speed for any head accident or falling person head on the floor and still in lower speed for any accident reconstruction done by U.S Department of Transportation [9].

3. Results & Discussion

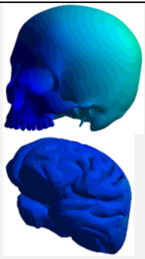
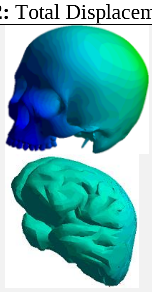
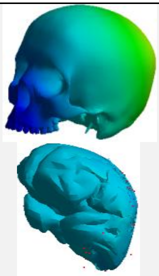
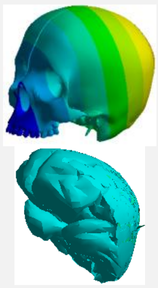
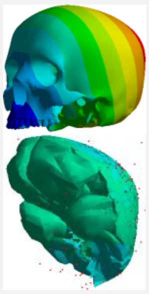
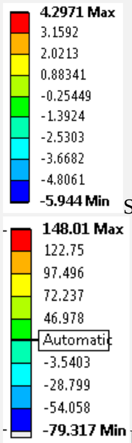
During the simulation, it became apparent that distinct cell damage mechanism can occur, depending on whether the brain is subjected to isotropic stress or shearing stress. Specifically, impact that imposes the human head tends to change the displacement like the deformation of the brain and change the internal structure. These damage mechanisms are at play in most incidents leading to TBI. As such, the result was presented using the simulation by first analysing the deformation of the model followed by the principal stress distribution and shear strain experienced in the head model. The simulation was conducted at 5 different velocities and the mechanical behaviors of the human skull and brain models after impact were investigated.

3.1 Distribution of Total Deformation

When varying the velocity of the human head hitting the wall, the deformation of the human head also was being simulated. Interestingly, it can be seen that the brain make a slightest movement as the deformation takes place inside the human skull.

Table 2 shows the findings of total deformation of the human skull and brain with the presentation of contour colour. The result shows that the deformation was high at the impacted region and the magnitude was directly increasing with the increment of the velocity. The deformation of the brain was limited as it was protected by the human skull. At 6 m/s of impact velocity, the skull was projected to deform up to 4mm which may lead to brain vibration.

Table 2: Total Displacement for Skull and Brain

		
2 m/s	3m/s	4 m/s
		 Skull (mm) Brain (mm)
5 m/s	6 m/s	

3.2 Distribution of Principal Stress

The result of maximum principal stress is important to investigate the impact of head injury. The value for maximum principal stress distribution in the human brain has been used to assess the risk of brain injury. The findings of the maximum principal stress in the brain during the rear impact are shown in Table 3. As similar to that predicted in the deformation findings, the magnitude of principal stress was also increases with the increment of the velocity. Instead of the impact region, the rear region of the skull was also observed experiencing higher stress. The higher stress magnitude at the skull may drive to the potential of bone fractures. Previous research conducted by Marwan et al. [9] indicated that higher velocity at 11 m/s may lead to multiple fractures at the skull. Aligned with this simulation, even at the speed of 6m/s the highest stress recorded 184.2 MPa has exceeded the ultimate strength of the human skull which is 79.2MPa at 11 m/s. Therefore, the skull fracture has to be occurred in this study and an internal injury of the brain. Thus, the maximum stress 0.1013 MPa occurred to brain was also believed to be exceeding the yield strength of brain.

Table 3: Maximum Principal Stress for Skull and Brain Models

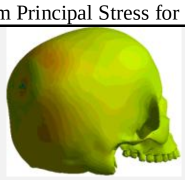
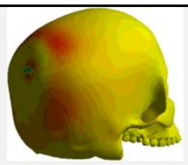
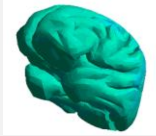
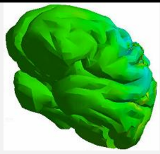
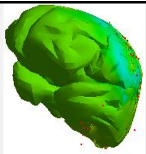
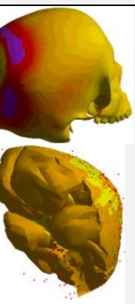
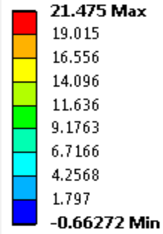
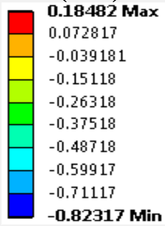
		
		
2 ms	3ms	4 ms
		 Skull (MPa)  Brain (MPa)
5 ms	6 ms	

Figure 3 shows the Von Misses Stress of the human skull and brain models at 5 different velocities. The findings in the simulation indicate that the highest stress contributes for both skull and brain are 184.02 MPa and 0.10139 MPa, respectively. This value has exceeded the yield strength and the deformation is very small. Hence, it was assumed there will some fracture to the skull that can lead to fatal. However, the brain having injury as shear strain shows the brain danced vigorously in the skull. Since the stress has exceeding the yield strength, the victim will be affected by TBI.

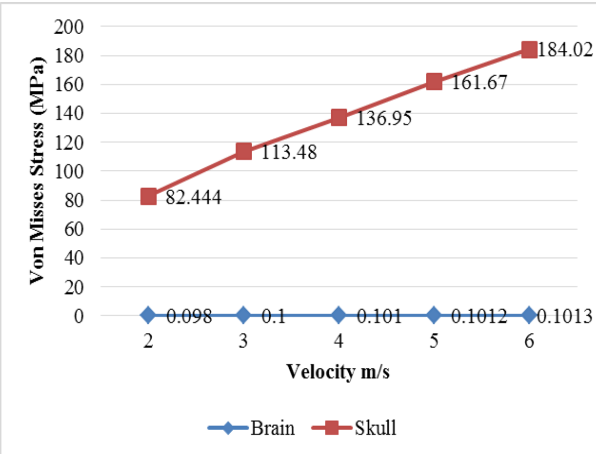


Figure 3: Stress distribution (von misses) in skull and brain at different velocity.

4. Conclusion

The findings in this study suggested that the human skull fractures and brain injury can be preliminary predicted using Finite Element Analysis. The magnitude of total deformation and maximum principal stress of human skull will increase linearly with the increment of impact velocity.

The purpose of this research is to investigate the influence of impact to the human head for better understanding in the head injury mechanism by developing a virtual condition in ANSYS Workbench 16.0. In this study an FE human head model has been presented. This model has been developed for accurate investigation of the mechanics of brain injuries under dynamic load. The current head models mainly focused on the rear part of the head. The neck vertebrae in this simulation are rather assumed as unknown. The FE head model with detailed skull and brain structures were developed. The structural and material properties were analysed based on the synthesis on the current latest thesis. Head injuries are very difficult to study experimentally due to a large number of variables involved and a large number of experiments have been done. Thus, a parametric study using a mathematical model is very helpful. In this report, the result was compared with experimental one. When comparing the contour colour on each criterion, it can be concluded that when the velocity of the human head hit the wall with initial value of 4m/s the brain hit and danced abruptly inside the skull.

4.1 Recommendation/Future Work

For a better result, the FE head model should later consider the Cerebrospinal Fluid (CSF) as fluid properties. This will cause an improvement and a change in the result of Von Misses Stress and displacement. Furthermore, the present head model can be coupled together with a human body so that the state of the art human FE model can be developed. In this case, this model can helps in better understanding the injury mechanism during vehicle collisions and develop more advanced restraint system. The meshing and validation of the FE model can be further investigated. With increasing computing power to handle a very define model thus can decrease minimum necessary processing time.

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