Dynamic Analysis and classification of Deformation mechanism in Head Impact Injury using Image based Finite Element Method (FEM)

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MASTER THESIS WORK

We hereby recommend that the dissertation prepared under our supervision by **Samra Zahoor (00000204828)** Titled: **Dynamic Analysis and classification of Deformation mechanism in Head Impact Injury using Image based Finite Element Method (FEM)** be accepted in partial fulfillment of the requirements for the award of

MS Biomedical Sciences degree. Grade (_____)

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Date: ______________________

Declaration

I certify that this research work titled ***"Dynamic Analysis and classification of Deformation mechanism in Head Impact Injury using Image based Finite Element Method (FEM)"*** is my own work. The work has not been presented elsewhere for assessment. The material that has been used from other sources it has been properly acknowledged / referred.

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Abstract

Brain injury is the leading cause of morbidity and mortality in various scenarios and brings a lot of social and economic problems. Due to the large amount of traffic injuries (specially) with head trauma, it is crucial to investigate damage mechanisms for better treatment. Throughout the decades, finite element head models (FEHMs) have been used to assess the biomechanics of head injury mechanism. Given the fact that some of the internal biomechanical responses of the brain can neither be measured easily nor in-vivo by experimental techniques, FEHM offers a cost-effective alternative to experimental method in estimating the internal biomechanical responses of human head. By performing dynamic analysis, the impact of transient loads or to design potential noise and vibration problems, can be evaluated.

In this study, we perform computational modeling of a human head model using time variant impact analysis. The major spark of this work is based on the identification of deformation mechanisms. Due to the low cost and high accuracy, numerical simulations have been widely accepted as the best way and partial alternative to the physical tests. We ran a mechanically elastic model using static analysis (initially) on a patient specific data. Our results (2.0 e-04GPa) are quite in agreement with the results fetched from literature (1.1 e-04 GPa). Deformation mechanisms such as notching, crack initiation, crack propagation and bending were identified when an equal amount of pressure on frontal, occipital and temporal regions is applied.

Keywords: Head Impact; Static Analysis; dynamic analysis; Finite Element Analysis;

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CHAPTER 1: INTRODUCTION

Brain injury is the leading cause of morbidity and mortality in road accidents and brings a lot of social and economic problems. Due to the large amount of traffic injuries with head trauma, it is crucial to investigate damage mechanisms for better treatment. Generally, there are three approaches for injury studies, physical tests, analytical modeling, and numerical simulations. Due to the low cost and high accuracy, numerical simulations have been widely accepted as the best way and partial alternative to the physical tests. With the help of numerical models, typically finite element (FE) model, biomechanical responses, such as intracranial pressure, stress, and strain of brain tissues, can be calculated, and the mechanism of the head traumatic brain injury can be further studied. Throughout the decades, finite element head models (FEHMs) have been used to assess the biomechanics of head injury mechanism. Given the fact that some of the internal biomechanical responses of the brain can neither be measured easily nor in-vivo by experimental techniques, FEHM offers a cost-effective alternative to experimental method in estimating the internal biomechanical responses of human head. By performing Dynamic analysis, this will enable author to evaluate the impact of transient loads or to design out potential noise and vibration problems.

1.1 Problem statement

Head injuries are one of the nation's major health-care problems affecting many inhabitants. It is the main source of disability and mortality in the population. The treatment to such injuries is very expensive. To gain better understanding of such incidents, it is possible to develop computer models that can be used as a prediction tool to find out the extent of damage inside the brain.

Computer aided Finite Element method can be very advantageous to address the same compared to the other traditional approaches. This is due to its robustness, reliability and efficiency.

Therefore, computational modeling can serve as a gismo to study and investigate underlying effects of impact injury in the deep down structures of head. The aim of this study therefore is to investigate dynamics of head impact injury using finite elements and image based modeling. Moreover, the study also looks into the quasi-static analysis of deformation mechanisms in head and identify the major classification of deformation mechanisms as well.

1.2 Research question

Does the stress progression and depth of head injury/deformation increases with time?

1.3 Significance of Study

Finite element modeling has the potential to overcome drawbacks of physical experimentation for its ability to deal with very complex problems. Due to the low cost and high accuracy, numerical simulations have been widely accepted as the best way and partial alternative to the physical tests. The stress and displacement profiles are studied to determine damage progression in brain during head impact injury.

1.4 Objectives of study

a) Geometrical reconstruction (3D) and study of human head model for head impact injury using Finite Element Method (FEM).
b) Identification and Classification of the Deformation mechanisms in head impact injury using Finite Element Method.
c) To perform dynamic analysis.

1.5 Thesis layout

This dissertation has five chapters. Chapter 1 presents the research topic and discusses the problem statement, significance and objectives of the research. Chapter 2 gives an extensive literature review about anatomy and physiology of human head and brain, head impact injury, FE modeling of human head models, use of computational modeling, previous studies and their limitations. Chapter 3 discusses the adopted methodology to implement this research. The chapter sequentially elaborates the steps taken to develop this study. It covers the entire methodology starting from construction of Simple and complex model, meshing, material assignment, boundary conditions and doing finite element analysis of the developed model. The time taken for creating the realistic human head model, execution of simulation in terms of computational cost has also been elicited. Chapter 4 shows the results of the performed study and discusses the observations of the analysis. The brain injury was predicted by comparing the observed values with the literature. Chapter 5 concludes the study and provides improvement recommendations for the developed study. It also discusses the suggestion for future work.

CHAPTER 2: LITERATURE REVIEW

Head Injuries are quite common in today's times. The most common causes for these injuries are accidents, falls, physical assault, or traffic accidents. Adults undergo head injuries more often because of automobile crashes, falls, being struck or impacting by an assault or object than other age groups. Principles of mechanics have a vital role in the investigation of head injuries and we cannot fully understand the mechanism without the help of these principles. Extensive research has been carried out since the early 20th century. Most of these researches only revolved around the brain tissues and not the complete head layers. The other aspect is that the in-vivo and in-vitro characteristics of the brain tissues are quite different, and are still not quite accurately known till today. The experimental study is very critical to the analysis but it can be quite expensive and sluggish. Secondly, it is nearly impossible to measure some of the quantities directly therefore computational modeling which is an excellent approach to deal with all these problems on hand. In this approach the FE Models are widely used in the researches. 2D models were used in the past as computational powers of the computer were quite limited, but with the strides in computational power of the computers and advanced GPUs today we can use 3D models to study the brain injuries. The accuracy of these models is quite impressive and we are able to get much more realistic and definite results using these advanced models.

2.1 Human head anatomy

The human head has a very complicated geometry. To understand the biomechanics of head injury it is essential to know fundamentals of anatomy and physiology of human head. The head is a multilayered structure which majorly includes scalp, skull (compact bone), sandwiched layer spongiosa (spongy bone), cerebro-spinal fluid (CSF) and brain. The most complex organ in the head is brain, which is protected inside the bony skull. The brain has a network of interconnected neurons which controls all the major functions of the body including coordination, memory, intelligence, emotions, creativity and decision making. Every part of the brain performs the specific function, to perform more complex functions these regions are interconnected with each other. A significant disruption in the function of brain is observed in response to minor or mild injury. These injuries can bring drastic changes in the brain function and affect its performance.

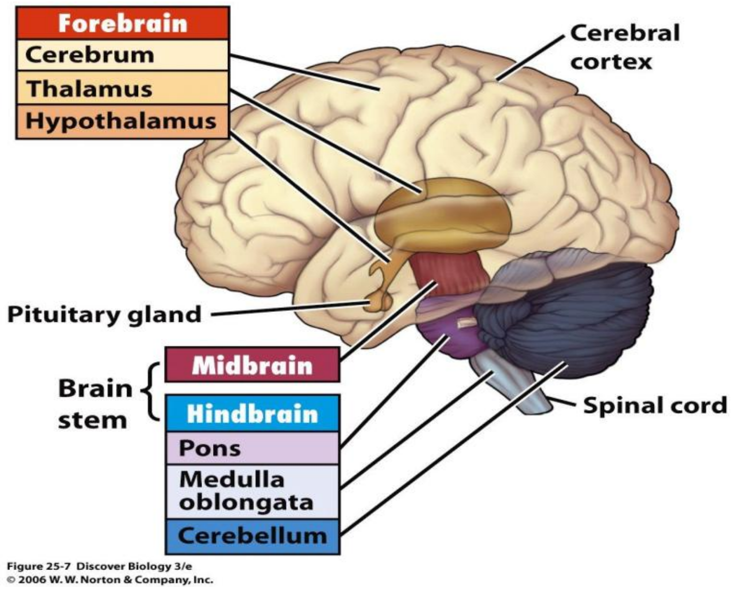


Figure 2.1: Human Brain and its important parts (Source: Discoverer Biology 3/e @2006 W.W.Norton & Company. Inc.)

2.1.1 Brain Anatomy and physiology

Physiologically, the brain is classified as left and right hemisphere. It has cerebrum, cerebellum and brain stem. The brain is divided into functional sections mainly as cerebellum, brain stem, temporal lobe, occipital lobe, frontal lobe and parietal lobe.Table 2-1 provides the location and functions of these parts.

Table 2-1: Locations and functions of the different regions of brain.

Brain Lobe	**Location**	**Function**
Frontal	right under the forehead (Anterior side)	Attention, Self-monitoring, speaking (language expression), Personality, Awareness of abilities and limitations, Emotions, Mental flexibility, Problem solving, Motor planning & initiation, Judgment, Organization, Planning and anticipation, Inhibition of behavior, concentration.
Parietal	Located near the back and top of the head	Sense of touch, Spatial & Visual perception (i.e. identification and differentiation of shapes, size, and colors).
Temporal	Above ears, on the left and right sides of the head.	Organization, Hearing, Understanding language (receptive language), Sequencing, Memory
Occipital	Located at the back of the head (Posterior)	Vision.
Cerebellum	Situated beneath the cerebrum	Skilled motor activity, Balance, Coordination, Visual perception.
Brain stem (Includes the medulla, Pons & midbrain).	Anterior to the cerebellum. Located at the juncture of the spinal column & the cerebrum.	Attention and concentration , Arousal Breathing and consciousness, Heart rate, Sleep and wake cycles

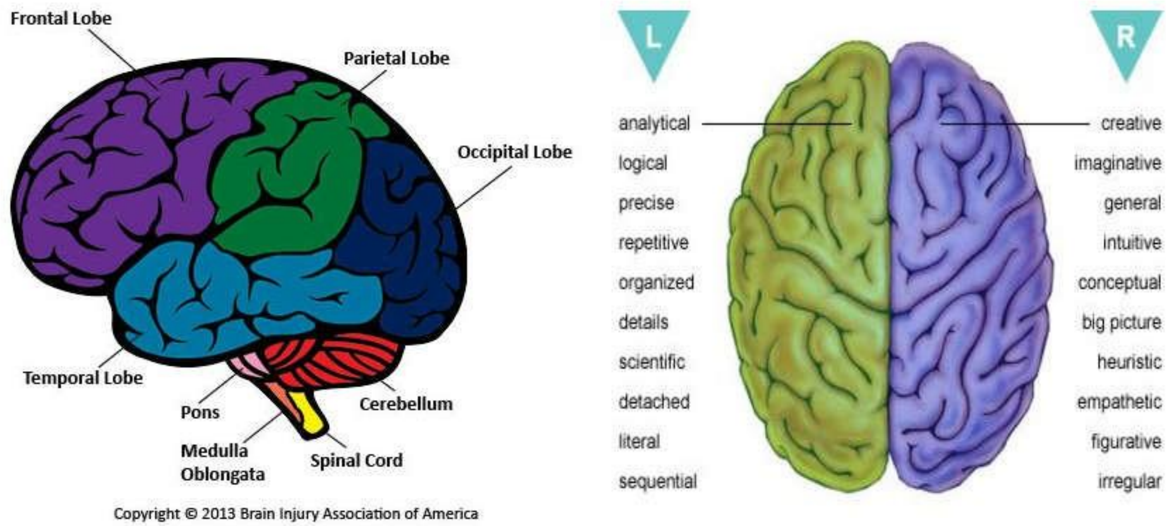


Figure 2.2: Brain regions, lobes and left and right hemispheres (L= left & R= right). (Source: http://www.biausa.org/living-with-brain-injury.htm.)

2.1.2 Head and Brain injury

In medical science, brain injury and head injury are interchangeably used [1-3]. According to literature head injury is a generic term which includes injuries to skull and brain [3, 4]. In a report [5], head injury is defined as "evidence of presumed brain involvement, i.e. concussion with loss of consciousness, post traumatic amnesia, neurologic signs of binary injury or even skull fracture." The clinical findings and Goldsmith [6] confirmed that brain damage can occur with or without skull fracture and vice versa. Also brain injury is defined as "physical damage to, or functional impairment of cranial contents from acute mechanical exchange, excluding birth trauma" [7].

During impact, four major lobes (frontal, temporal, parietal, occipital) transmit forces to the brain which cause mild traumatic brain injuries (MTBI). In investigating literature, it was found that of all injuries, MTBIs are most common and widespread. The reason of its prevalence is that stresses and strains are generated when the changes in intracranial pressure (ICPs) are happened [8, 9].

Table 2-2: Effects of brain injury on brain function.

Sr. No	Injury at	Causes
1	The left side of the brain	Sequencing difficulties, Impaired logic, Decreased control over right-sided body movements. Anxiety, depression, Difficulties in speaking, Verbal memory deficits, Difficulties in understanding language.
2	The right side of the brain	Visual memory deficits, awareness of deficits decreased, Visual-spatial impairment, and control over left-sided body movements decreased, Altered creativity and music perception.
3	Diffuse Brain Injury (scattered injuries occurred throughout both sides of the brain)	Fatigue, Confusion, Reduced concentration and attention, in all areas impaired cognitive (thinking) skills, Reduced thinking speed.

2.2 Finite Element (FE) Modeling

A FE method is the technique in which an object from the real world is breakdown into many discrete finite elements. It is an efficient method that can handle irregular nonlinear geometries, nonlinearities& multiple compositions of material and complex boundary and loading conditions of the structures. Then mathematical tools are used to predict the response and behavior of these elements. Finally, the computer computes and adds all the individual responses of these elements to give the response of the real object. Finite Element Analysis (FEA) is quite a handy tool when it comes to the understanding of complex trauma mechanisms resulting from head impacts. Enhanced FE head models present the viewpoint of delivering precise, reconstruct-able experimental analysis of every types of head injury.

The effectiveness of such models depends upon the accuracy of the geometry of the structures present inside the model. Most of the computational CAD based models are usually designed manually, but when it comes to the head and its complex internal parts, this approach tends to become error prone and can be subjected to human error. Thus in case of complex models it can provide a lot of challenges. A more appropriate approach that can minimize the inaccuracies related with modeling of extremely complex structure is well-known as 'image- based meshing'. It is an approach in which a volume scan data is converted from CT scan or MRI scan into a FE mesh directly by semi and completely automated processes through least possible user input [10]. Such approach is effective because it helps to achieve many distinguishable anatomical parts of complex structure with much needed accuracy.

2.2.1 Human head FE model

Since 1940s, many analytical solutions were provided for human head. Because of impediments and scientific challenges, these analytical and mathematical models elucidated by regular and simple geometries, homogeneous and isotropic material properties and simple boundary conditions. FE modeling is a versatile digital computational technique which has ability to handle the objects with non-uniform shapes and inhomogeneous materials. It can provide solution by use of approximations to the analytical formulation for human head model efficiently.

Hardy et.al [11] were the first to design and model the performance of human head response by using FE modeling technique. They constructed a simple 2D FE head model which had the layer of skull only. This model was augmented afterwards by another researcher Shugar et al. [12]. In his model he came up with a fluid-filled, elastic layer of brain attached to the skull. Due to the lack of available image processing and computational resources in the 60s and 70s yet these 2D strain models were the only way to simulate deformations of the head in case of impact. The results of this model were quite impractical and improbable for large deformation simulation. 3D FE head models were represented using regular geometry. For example, Chan et al. [13] developed the human head model as an ellipsoid and spherical shell while Khalil et al. [14] employed an in viscid fluid core as the intracranial content and an ellipsoidal shell for skull. These models dealt with material features of only one of either skull or the brain. In early1980s, Hosey et al. [15] presented the first 3Dhomomorphic model with the basic anatomy of both brain and skull. This model also incorporated the inertial effects and material properties of the neck and head. It was considered the most comprehensive FE head and neck model in the 80s. At that time the potential of these earlier FE head models was not realized due to lack of computing power, but later on this model proved to be the basis of analysis of head injury biomechanics. Computing capability in 90s made it possible to develop more sophisticated and realistic 3D human FE head models based on real geometry of the human head. From the Wayne State University, Ruan et al. [16] modeled a detailed and well known FE human head model, simulating the detailed and defined anatomy of the brain and skull.

In early 2000, Kleiven et al. [17] came up with KungligaTekniskaHögskolan (KTH) FE human head model. This model was unique in the sense that it was quite comprehensive and parameterized FE human head model of an adult. It included the scalp, brain, meninges, skull, cerebrospinal Fluid (CSF), simplified neck and eleven pairs of parasagittal bridging veins. It was modeled by using isotropic, homogeneous, nonlinear and viscoelastic material properties that were derived from previous work. The study revealed that in case of an impact, pressure response of the brain relied more on the interface type of skull-brain instead of constitutive parameters of the brain tissue. Upon consideration of effect of different interface conditions study also revealed that the tied interface provided the best correlation with existing literature of Nahum et al. [18]'s, Hardy et al. [19]', King et al. [20]'s experiments. Later on many researchers like Zhang et al. [21], Belingardi et al. [22], Lashkari et al. [23], Tse et.al [24], Yang et al. [25], Jin et al [26], Song et al. [27] Cotton et.al [10] have developed their 2D & 3D models with different layers, material properties, boundary conditions and different impacts. These models were tested and validated against literature available experimental results [18, 28]. Table 2-3 provides a brief summary of recent development of 3D human head model including description and validation of each reported model.

Both static and dynamic studies were done in the past having benefits and limitations as well. Jacob et al. [36] focused on helmet protection under impact of head to ground, and impact of an object to head. That study showed the effect of the helmet is based on different boundary conditions such as object height for the hard hat, and the rider speed for the bicycle and motorcycle helmets. In 2017, A. Eslaminejad [37] presented a paper in which he focused on implementation of three brain tissue constitutive relations to measure and compare the dynamic behavior of the brain under identical blast loads. This study provided a proper insight to the dynamic studies. Another study [39] shows that Finite element models (FEMs) can be used as prediction tools for human head injuries caused by falls. The purpose of this study was to demonstrate the relevance of using human head FEM to assess the possible mechanism for the origin of head injuries.

The FEM of the human head used in this study was developed in the late 1990s at the University Louis Pasteur of Strasbourg (ULP) and has been validated for human head impacts for simulating human head injuries caused by car accidents. Its use in legal medicine appears to be very useful for comparing different injury mechanisms. Figure 2.3 provide a brief background of my study giving a comparative study of dynamic versus static one. Table 2-4 gives the summary of a few works done in the past with their benefits and limitations.

Static analysis differs from dynamic analysis in two basic aspects. First, dynamic loads are applied as a function of frequency or time. The application of this load variation induces variation in response of frequency or time or frequency. Such response ultimately affects forces, accelerations, stresses, velocities and displacements. These characteristics of variation in frequency or time make major differences in dynamic analysis in comparison to static one. One of them is dynamic analysis in more realistic and more complicated than static analysis. Free vibrations and forced vibrations are two basic classes of dynamic analysis. The input of transient loads can be evaluated using dynamic analysis. It can also be used to design out potential noise and vibration problems. A simulation is called dynamic when some of parameters are variably in line with time alteration or can be said time based simulation. These methods are useful to see behavior of our model when works in over load condition such as collision analysis, crack propagation and etc.

Table 2-3: Summary of few developed 3D human head model.

Author	Year	Description	Validation
Cotton et al.[10]	2015	3D model developed from MRI data, in Simpleware and Abaqus are used softwares, tetrahedral mesh elements are used, total 3.72 Million volumetric elements of 33 layers are generated. This research developed a realistic model of complete neck and human head, used in TBI related study.	Nahum et al.[18],
Jin et al.[26]	2015	3D model, constructed from CT scan of an individual, 74,636 brick 24,391 shell elements were used. Scalp, facial bone, cerebrum, brainstem, cerebellum, two layered skulls, CSF, falx, pia and dura matter. The major finding of the study was found that for anticipating the brain response and detailed analysis of injuries during impact to the human head, CSF with high bulk modulus was more befitting and suitable.	Nahum et al. [18] for translational impact, Hardy et al. [19] for skull/brain motion in rotational impact. Trosseille et al.[28], For Rotational impact.
Yang et.al[25]	2014	3D model, 1,173,039 tetrahedral elements white and gray matters, cerebellum, CSF the entire ventricular system of the brain, midbrain, and brainstem. the maximum Von Mises stress in the brain and the maximum principal stress in the skull were discussed through this model.	-
Tse et al.[24]	2014	Mimic & hyper mesh software is used. Model constructed by using CT scans Linear hex and 03,176, linear	For localized brain motion Hardy et al.[19],

		tetra1,337,903 mesh are used. Skull bone, brainstem , CSF, cerebral peduncle, cerebellum, ventricles, cerebrum, white and gray matter, tooth, cartilages, soft tissues were modeled. The study revealed that simulated results were remarkably in accordance with experimental measured relative displacements and ICP. The Soft tissue modeled aided in damping out the oscillations of the models response.	For intracranial pressure for long duration impulse Trosseille et al. [28]. Pressure data, force, and intracranial acceleration from Nahum et al.[18] for impact for short duration impulse.
Kleiven et al.[17]	2002	Developed the Kungliga Tekniska Högskolan FE Head Model. This model has scalp, skull, meninges, brain,CSF, 11 pairs of veins and a simplified neck. It also included sliding condition between brain and skull. Different parametric researches on various skull-brain interface conditions revealed that the human head is responsive to the modeling of such interface condition during impact. The study also revealed that brain's pressure response in an impact relied more on the interface type of skull-brain instead of constitutive parameters of the brain tissue.	Nahum et al. [18], Hardy et al. [19] and King et al. [20] experiments.

Table 2-4

	Source	Limitations	Results/conclusions
1	Hamel A, Llari M, Piercecchi-Marti MD, Adalian P, Leonetti G, Thollon L. Effects of fall conditions and biological variability on the mechanism of skull fractures caused by falls. International journal of legal medicine. 2013 Jan 1;127(1):111-8.	Time lapse Limited forensic investigations.	The mechanism of skull fracture in a case of a backward fall from standing height is influenced by a combination of fall parameters and biological parameters. Head injuries caused by a fall and those caused by a blow can be distinguished by this method.
2	Viano DC, Casson IR, Pellman EJ, Zhang L, King AI, Yang KH. Concussion in professional football: brain responses by finite element analysis: part 9. Neurosurgery. 2005 Nov 1;57(5):891-916.	There are limited models of FEMs which can be used in forensic study.	Strain concentration "hot spots" migrate through the brain with time from temporal lobe to far temporal lobe. Dizziness correlated with early strain in the orbital-frontal cortex and temporal lobe. The strain migration helps explain coup-countercoup injuries.
3	Roth S, Raul JS, Ludes B, Willinger R. Finite element analysis of impact and shaking inflicted to a child. International journal of legal medicine. 2007 May 1;121(3):223-8.	Child abuse cases have increased tremendously. But these sort of issues are suppressed before they come into highlights.	Based on a detailed finite element model of the 6-month-old child head, it has been demonstrated that vigorous shaking can have the same consequence as an impact in terms of subdural bleeding. Finite element methods can be used as a complementary tool in understanding and analyzing cases of child abuse.

4	Raul JS, Deck C, Willinger R, Ludes B. Finite-element models of the human head and their applications in forensic practice. International journal of legal medicine. 2008 Sep 1;122(5):359-66.	There are limited models of FEMs which can be used in forensic study.	Finite-element methods appear to be a promising tool for assessing the consequence of a given head impact scenario and for future ballistic studies
5	Kleiven S. *Finite element modeling of the human head*(Doctoral dissertation, KTH).2000	The size dependence of the intracranial stresses associated with injury is not predicted by the HIC. Improvement in injury prediction is needed.	Intracranial stresses increase with an increase in head size i.e. From 3.6 kPa for the smallest head size to 16.3 kPa for the largest head size. Larger relative motion between the skull and the brain is more apparent for an occipital impact than for a frontal one

2.3 Deformation Mechanisms

Any changes in the shape or size of an object due to an applied external force are called deformation. These changes can be elastic, brittle or may be a fracture. Factors that influence the deformation are temperature, confining pressure, rate of deformation, composition of material etc. The various processes occurring at micro-scale that are responsible for changes in a material's internal structure, shape and volume are included in these mechanisms. Elastic deformation is a change in shape of material at low stress that is recoverable after the stress is removed. The type of deformation involves stretching of bonds, but the atoms do not slip past each other. When the stress is sufficient to permanently deform the material it is called plastic deformation. It involves the breaking of a limited number of atomic bonds by the movement of dislocations. In engineering mechanics, bending characterizes the behavior of a slender structural element subjected to an external load applied perpendicularly to a longitudinal axis of the element. Any physical object as in my study brain under some applied external force undergoes the process of bending. A break or split in material without a complete separation of parts. Generally, the term is used to describe breaks in solid material such as metals, stone, ceramics etc. There are four steps in crack; plastic deformation, crack initiation, crack propagation and eventually a fracture. Crack initiation is a process that forms cracks on the surface of a material. Physically, cracks initiate from; an imperfection, an already existing crack or due to a damaged(weekend) area. The primary reason for the formation of cracks on any surface is fatigue. Fatigue leads to progressive and localized structural damage when any material experiences cyclic loading. Fracture mechanics is the field of mechanics concerned with the study of the propagation of cracks in materials. Cracks are classified on the basis of nature, width and shape. On the base of nature, cracks are structural and non-structural. Width wise, cracks are future classified into thin crack (less than 1mm in width), medium crack (1-2mm in width), wide crack (more than 2mm in width), and crazing (occurrence of closely spaced fine cracks at the surface of a material is called crazing). On the basis of shape, cracks are sub-classified into five; straight, toothed, stepped, map pattern or of random type, vertical/ horizontal or diagonal.

Solid materials that can undergo substantial plastic deformation prior to fracture are called ductile materials. Ductile materials are materials that can be plastically twisted with no crack. A material is brittle if when subjected to stress, it breaks without significant plastic deformation.

Fatigue cracking is one of the primary damage mechanisms of structural components. It results from cyclic stresses that are below the ultimate tensile stress or even the yield stress of the material. The name fatigue is based on the concept that a material becomes 'tired' and fails at a stress level below the nominal strength of the material. Necking is a local deformation of a component. Necking begins at the tensile point, or ultimate stress point. The neck is the portion of the specimen where necking occurs. Notching is an indentation or incision on an edge or surface. It is a process that involves the cutting of various types of metal stock at an angle. Notching's are done to create a vertical cut in a tube or sheet stock. Notching is used in many different metal applications. A notch is a cut inward; from the edge of the material, and is always cut at a measured angle that is calculated in accordance with the application that requires the notching. Viscoelastic solids have molecules in which the load-deformation relationship is time-dependent. If a load is suddenly applied to such a material and then kept constant, the resulting deformation is not achieved immediately. Rather, the solid gradually deforms and attains its steady-state deformation only after a significant period of time. This behavior is called creep. Viscoelastic solids have molecules in which the load-deformation relationship is time-dependent. If a load is suddenly applied to such a material and then kept constant, the resulting deformation is not achieved immediately. Rather, the solid gradually deforms and attains its steady-state deformation only after a significant period of time. This behavior is called creep. In dynamic analysis, creep is commonly observed. It is a time-dependent deformation under a certain applied load. It generally occurs at high temperature (thermal creep), but can also occur at room temperature in certain materials. As a result, the material undergoes a time-dependent increase in length. The rate of deformation is called the 'creep rate'. The stages of creep include primary, secondary and tertiary creep. Primary creep starts at a rapid rate and slows with time. Secondary creep has a relatively uniform rate. Tertiary creep has an accelerated creep rate and terminates when the material breaks or ruptures. It is associated with both necking and formation of grain boundary voids. A force acting in a direction parallel to a surface or to a planar cross section of a body, as for example the pressure of air along the front of an airplane wing is called shear force. Shear forces often result in shear strain. Resistance to such forces in a fluid is linked to its viscosity. Also called shearing force. In mechanics, compression is the application of balanced inward forces to different points on a material or structure, that is, forces with no net sum or torque directed so as to reduce its size in one or more directions.

Compression is decrease in volume of any object or substance resulting from applied stress. Compression may be undergone by solids, liquids, and gases and by living systems. a strain produced by pressure in the structure of a substance, when its layers are laterally shifted in relation to each other is called shear. Shearing forces cause shearing deformation. An element subject to shear does not change in length but undergoes a change in shape. The change in angle at the corner of an original rectangular element is called the shear strain. Grain-boundary is the interface between two grains, or crystallites. Grain boundaries are 2D defects in the crystal structure and tend to decrease the electrical and thermal conductivity of a material. The size of grain also has an effect on the strength of the material. The boundary between grains acts as a barrier to dislocation movement and the resulting slip because adjacent grains have different orientations. Decreasing grain size decreases the amount of possible pile up at the boundary, increasing the amount of applied stress necessary to move a dislocation across a grain boundary. The higher the applied stress needed to move the dislocation, the higher the yield strength. Grain boundary strengthening is a method of strengthening materials by changing their average crystalline size or hall-patch strengthening. Strut is a rod or bar forming part of a framework and designed to resist compression.

2.4 Chapter Summary

In this chapter, an in-depth review of literature has been presented. The anatomy and physiology of human head and brain, head impact injury and the role of computational modeling have been elaborated. The chapter also discusses some deformation mechanisms.

CHAPTER 3: METHODOLOGY

The aim and first step of this research is to develop location based three dimensional FE human head models of different parts of brain. After which, the research seeks to study of damage progression in head impact injury. The total workflow was divided in three stages; Preprocessing, Analysis and Post-processing which are discussed in the later sections.

A. Preprocessing

The first step of finite element analysis (FEA) is the geometry construction of the structure which is to be analyzed. After geometry construction, model needs to be meshed. Meshing is a method to discretize and divide the model into small elements. When the FE model is made, by applying appropriate interactions and constraints the material properties are assigned to each part. In the end, loads and boundary conditions are assigned.

B. Analysis

Subsequently, with in the predefined constraints, loads and boundary condition convergence of the model is checked by using numerical solver. In order to test physical conditions efficiently, different analysis for example time based analysis (static/quasi- static/dynamics) can be used. In static, input and output parameters are time independent; hence balancing of the load and boundary conditions for the system is solved. Quasi-static means that we may assume the static condition over given instant of time and with negligible inertial effects. In this way we can simplify the nonlinear system of equations to a linear system at small increment. In dynamic, input and output are time dependent; therefore, the model shows variable behavior over the period of time. Example of dynamic case is impact loading in which mechanical response varies with the rate of loading. In this research we have assumed static as well as dynamic conditions for all the analysis.

C. Post-processing:

Last step is the post-processing, in which visualization of the results is performed. The outputs of the study give corresponding values for each node and element of different parameters for example displacements, stresses and strains etc.

The steps are summarized and are shown in Figure 3.1.

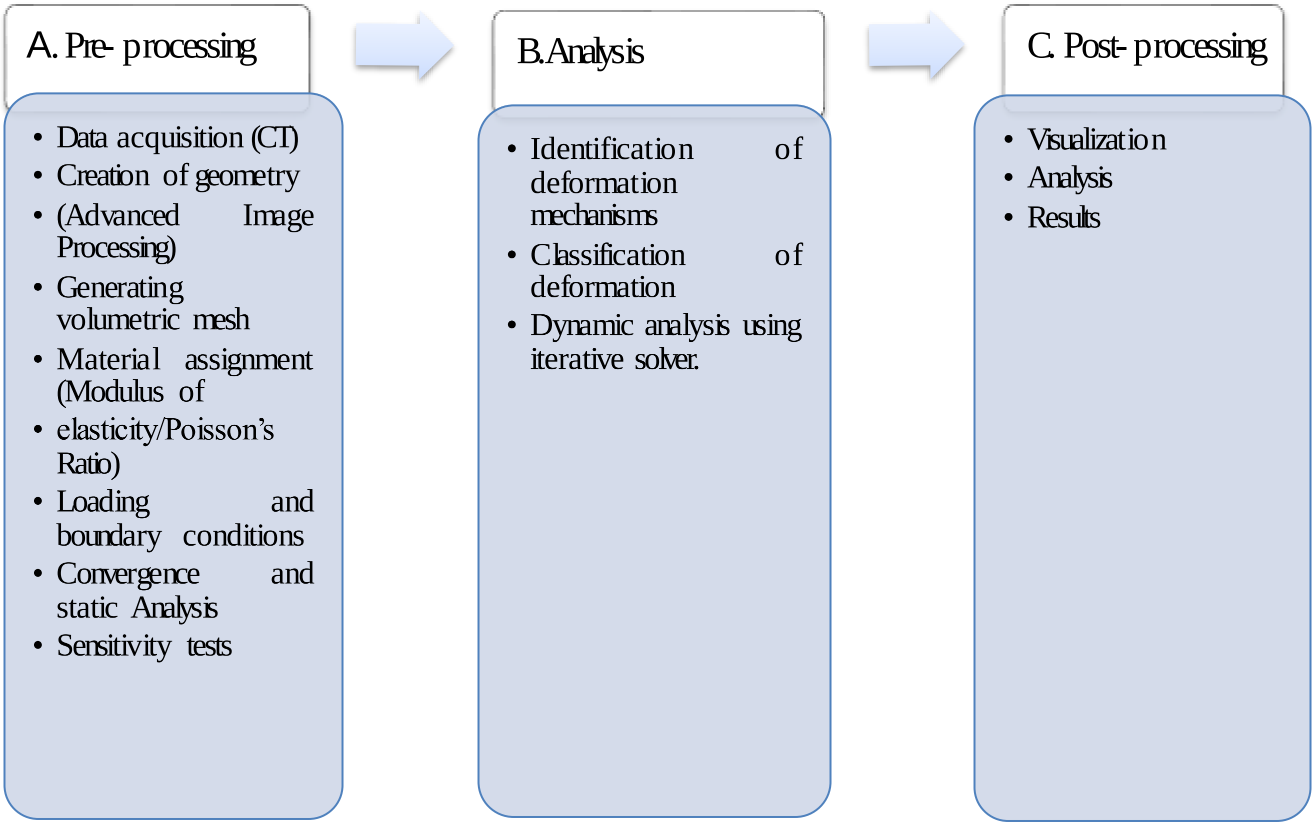


Figure 3.1: Steps of development of 3D human head FE model for the study of analysis (static and dynamic) and deformation mechanisms.

3.1 Model Description

3.1.1 Acquisition of Data

In this study, head CT scan images of a healthy male was obtained from Radiology department of Pakistan Institute of Medical Sciences (PIMS), Islamabad. Image Specifications/ Study information is as follows (table 3-1).

Table 3-1: Image Specifications.

Serial number	Specifications	Values
1	Number of slices	176
2	Slice thickness	1 mm
3	Gantry/detector tilt	0 degree
4	Field of view (FOV)	228.35 mm
5	Voltage (KVp)	120 KV
6	X-ray tube current	300 Milliamps
7	Number of bits	16
8	Pixel size	0.446 mm
9	Focal spot	0.9/0.8
10	Table height	+61
11	Samples per pixel	1
12	Beam type	Fan beam
13	Resolution	512 X 512

3.1.2 Segmentation

These raw data were imported into an advanced image processing suite, for creating 3D layers in brain. In total six layers were segmented. Scalp is the outermost layer of human head. The scalp is the anatomical area bordered by the human face at the front, and by the neck at the sides and back. Skull and skull compacta are inner bony parts. Brain interior is the inner soft tissue mass. Midbrain, also called mesencephalon, region of the developing vertebrate brain that is composed of the tectum and tegmentum. The midbrain serves important functions in motor movement, particularly movements of the eye, and in auditory and visual processing. The cerebellum (Latin for "little brain") is a major feature of the hindbrain of all vertebrates. In humans, the cerebellum plays an important role in motor control. 3D Parts of the segmented layers are shown in Figure 3.2.

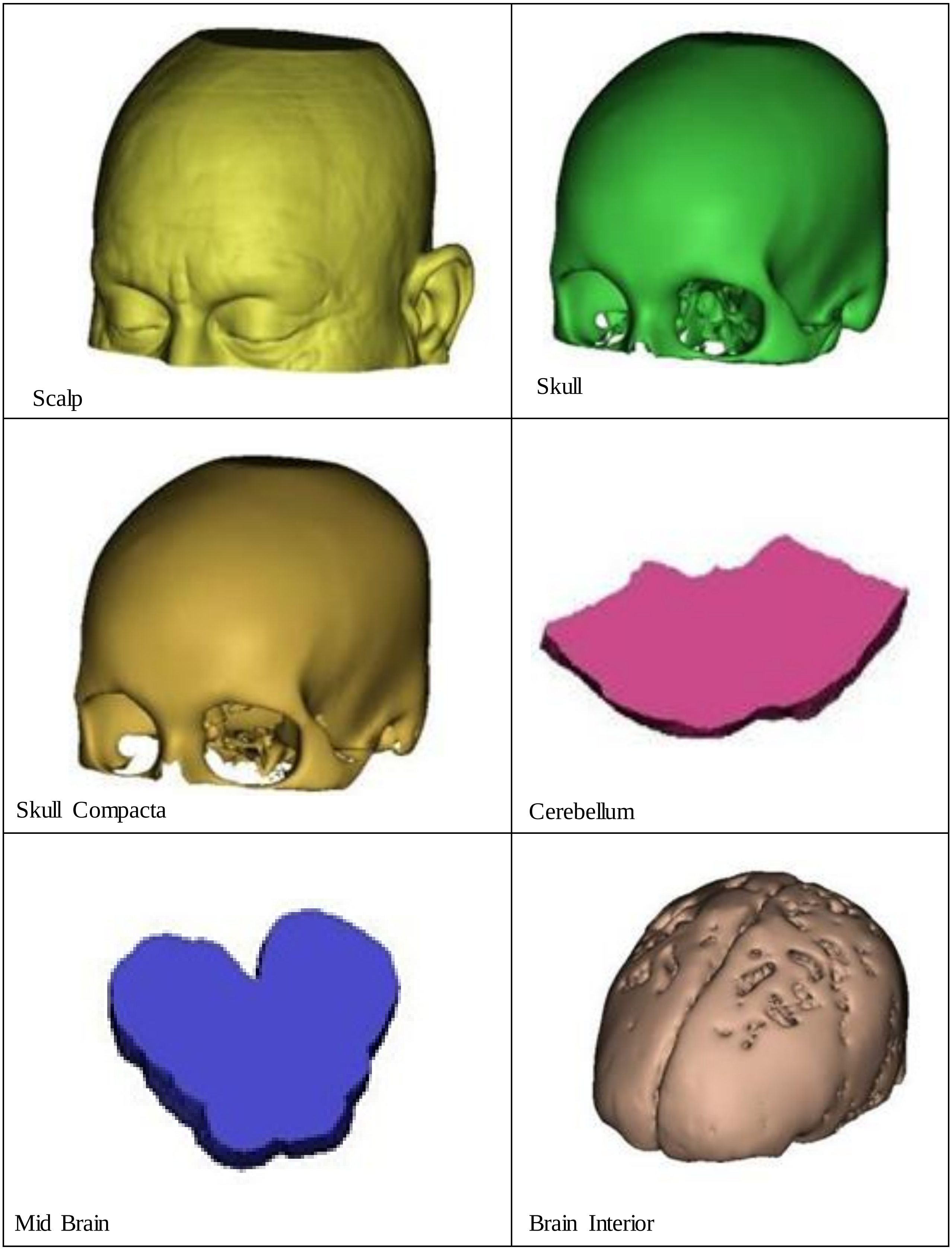


Figure 3.2: 3D Parts of the segmented layers.

3.2 Meshing Procedure

Meshing is an integral part of the computer-aided engineering simulation process. The mesh influences the accuracy, convergence and speed of the solution. Furthermore, the time it takes to create and mesh a model is often a significant portion of the time it takes to get results from a CAE solution. All 3D parts were exported (in the form of assembly) from mimics to 3-matic for further processing of images. Tetrahedral meshes were made in 3-matic Research (Materialise, Leuven, Belgium) as shown in Figure 3.3. Meshing was done in 6 models having different edge lengths for the purpose of convergence in further steps. Then volume mesh of every part was created separately in each model by adjusting edge lengths as mentioned above. This is summarized in Table 3-2. Tetrahedral elements were more preferred due to their addictiveness to highly curved complicated structures. Meshing is the most important part in any of the computer simulations, because it can show drastic changes in results obtained. We use finite element method to perform static analysis.

Table 3-2

Model	**Edge length**	**No. of volume elements**
1	9	21591
2	8	28677
3	5	105139
4	4	322487
5	3	413570
6	2.5	510483

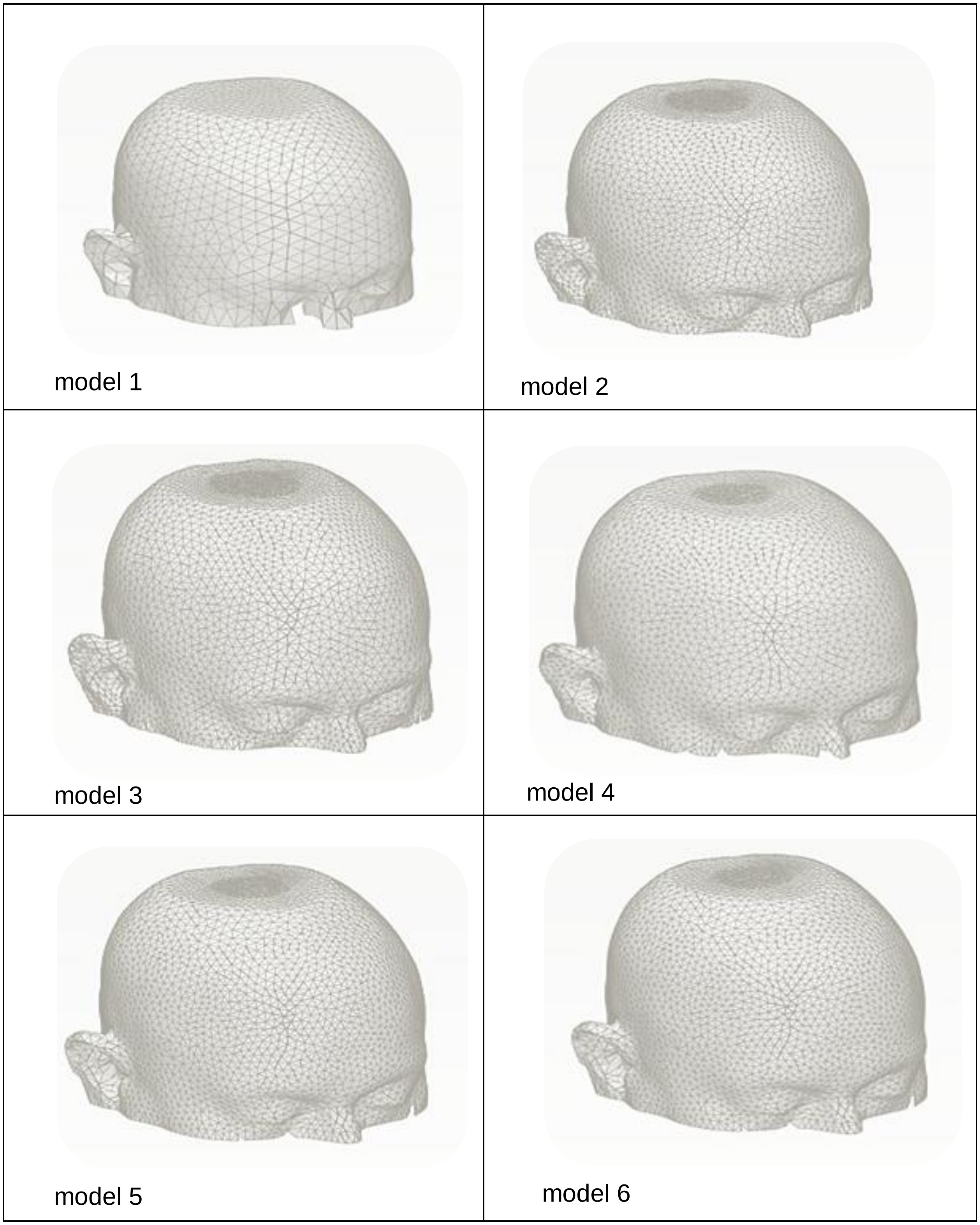
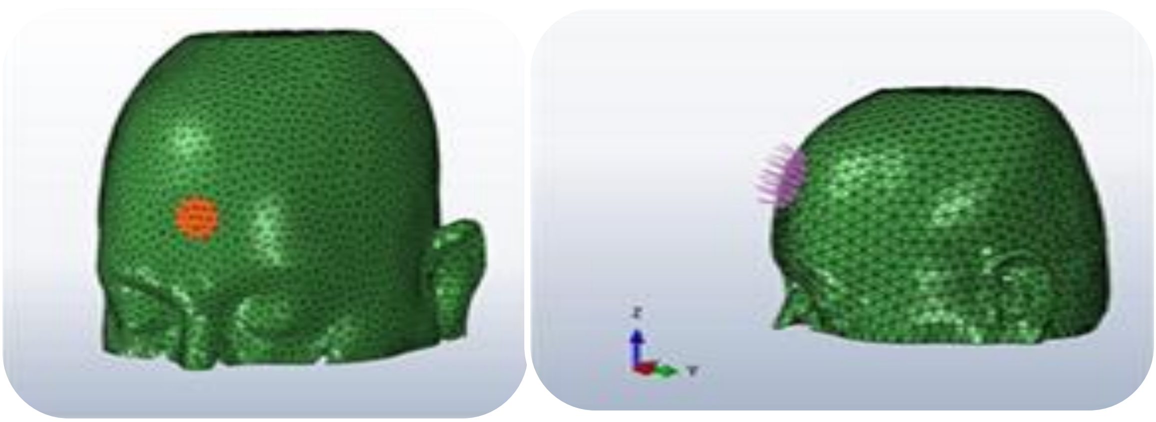


Figure 3.3: Tetrahedral Meshes of six models.

3.3 Loads and Boundary Conditions

In this step, loads and boundary conditions were applied. Head injury is the major cause of morbidity and mortality in developing countries. Majority of head impact tests has been focused on frontal position which is the best position as real car accidents impacted on head [29]. Frontal patch was created on the scalp which is the outermost layer. Load was applied on this frontal patch. The direction of load was inward in y-direction as shown in figure 3.4 This was done for all the six models. During experimental set-up conducted by Delye et.al, the skull was fixed at foramen magnum. This region was decided to represent the actual human life which is at that point was fixed the neck of human. Hence the whole assembly was constrained at this point.



The frontal patch

Load applied at frontal patch in y direction

Figure 3.4: The load applied on frontal patch.

3.4 Material Properties

Material properties assignment is the most important aspect of FE procedure as they determine the material behavior at the end when subjected to external loading. Many FE models considered different layers of head as isotropic, homogeneous, and linear/viscoelastic. The complex structures for example human skull, prior head models accepted the skull bone as a homogeneous and isotropic material. In few studies it can be seen that skull bone was treated as heterogeneous, indicated by layers and porosity (Cortical bone with 5-10% porosity, cancellous bone with 50-95% porosity) [12-14, 30]. Many researchers put their efforts to determine the constitutive properties of the human brain material. To study such properties, experimental testing on animal and cadaver brain was performed. In few earlier FE models, the brain was modeled as linear elastic material [15, 18, 31, 32] while some had considered the brain as viscoelastic [13, 14, 30]. Even though the significance of both of the material models with respect to brain tissue response was controversial [33] but it's worth mentioning that the difference of responses between viscoelastic and linear model increased with the loading time [34]. In 2007, Gao et al. [35], used inhomogeneous brain model, as mainly consists of three types of tissues, white matter gray matter and CSF.

As the human head is complex in nature hence it is difficult to estimate material properties of human's head and brain. In this research, properties of the material were consulted and selected from different literature. The material properties of different layers of the head are selected as isotropic, homogenous and elastic. The model has total six layers, namely scalp, skull, compacta, mid brain, cerebellum and brain interior. The values of elastic modulus, Poisson ratio and density used in this model have been listed in Table 3-3.

Table 3-3: Material Properties of the model.

Brain layer	Young's modulus (MPa)	Poisson's ratio	Density (kg/m^3)	References
Skull	1.500e+04	0.21	1210	[43] [41]
Scalp	1.670e+01	0.42	1200	[42] [41]
Skull compacta	1.50e+04	0.22	1210	[43] [41]
Mid brain	0.0045	0.21	1060	[43] [41]
Cerebellum	0.0000928	0.23	1040	[42] [41]
Brain Interior	6.75e-01	0.48	1040	[42] [41]

3.5 FEM

3.5.1 Simulation Parameters

After material assignment, simulation parameters are assigned to the models in order to run simulations. A static general study was performed on the developed models. With selected amount of forces, tie constraints among the layers and fixed base, simulations were performed in ABAQUS CAE 6.12.

3.5.2 Convergence

Once the model is built, it is important to perform convergence study to create error free mesh, so that there are no problems in the final results. A refined mesh yield better result. To decide the suitable levels for this study, convergence analysis was performed. Six models were created to check if the solution is mesh independent or not. As it can be seen in figure 3.5; model 5 and 6 are converging, so model 5 (coarser one) was used for analysis considering the fact that finer model will be more expensive for computer solver. Stresses and Displacements of these models are summarized in table 3-4.

Table 3-4 Stress and Displacements results.

Model	Edge length	No. of volume Elements	U, Magnitude (mm)	U, U2 (mm)	S, misses (MPa)
1	9	21591	0.4107	0.03443	0.1106
2	8	28677	0.4233	0.1929	0.1326
3	5	105139	0.2844	0.2675	0.0058
4	4	322487	0.3688	0.3652	0.2802
5	3	413570	0.4359	0.4326	0.0086
6	2.5	510483	0.4739	0.4285	0.0097

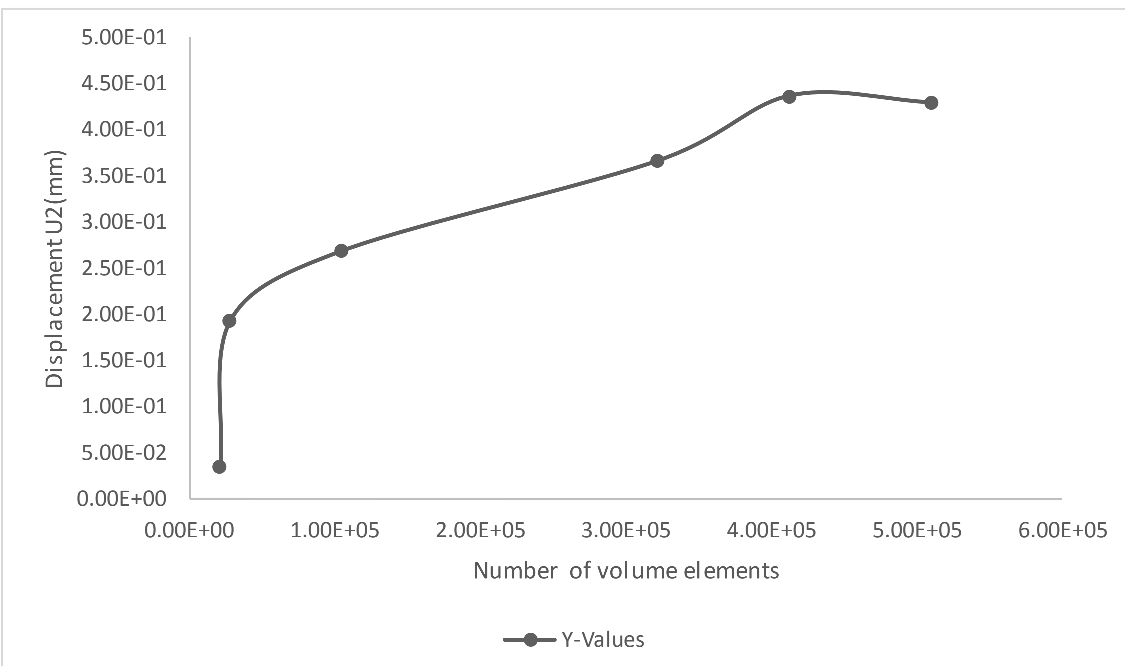


Figure 3.5 Showing Convergence of six models.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Static analysis

In this analysis we assume that all the accelerations are zero and mass can be ignored. Converged head model was used using static mechanical analysis was run. As it can be seen in figure 3.5, model 5 and 6 are converging, so model 5 was used considering the fact that finer model will be more expensive for computer solver. The analysis was run on HP Intel-core i7, 16GB RAM3.6 GHz processor at supercomputing lab RCMS. Total solution time taken by the simulations was 120 seconds. Our results show (figure 4.1) that after multiple impacts loading in axial planes on frontal region, temporal region and occipital one, larger distributions of stresses and displacements are seen on these multiple points of impact. A point of singularity was also observed, which could have direct effects on the stress plots obtained. Since the singularity may not yield a perfect stress distribution mechanism to the model hence there are more blue regions seen in the figure 4.1. The largest amount of Von Misses is reported as 1.5 Pa. Figure.4.1 shows the values of Von-Misses stresses and displacement as a result of multiple impacts loading.

In figure 4.1 (a) (b) (c) and (d) – are shown von misses stress, principle stress, deformation (magnitude) and resultant deformation respectively.

Figure 4.1 (a) shows stress mostly accumulated at one point due to singularity. This perhaps indicates there are points in the model where values tend toward an infinite value. It is usually caused by a point or line load or moment, an isolated constraint point where the reaction force acts as a point load. One of the best way to remove singularities is remeshing the finite element model. The model in this thesis can presented as an example of how singularities can cause stress failures at one specific point and raise the need of modeling with correct mesh parameters. Figure 4.1 (b) shows values of principal stress. Maximum and minimum values are shown with their directions. Arrows at different regions show how values are fluctuating in different areas of brain. Figure 4.1 (c) shows the magnitude of deformation. It shows how deformation was seen at three different areas of brain i.e.: frontal, occipital and temporal regions. And contours show how maximum values are at areas where impact loads were applied. The values of deformation at frontal, temporal and occipital regions are 3.518 mm, 3.078 mm and 2.639 mm respectively.

The maximum values of Von Misses stresses at frontal, temporal and occipital regions are 1.500 Pa, 1.375 Pa and 1.250 Pa respectively. Figure 4.1 (d) is also showing the deformation magnitudes but here it is the resultant deformation.

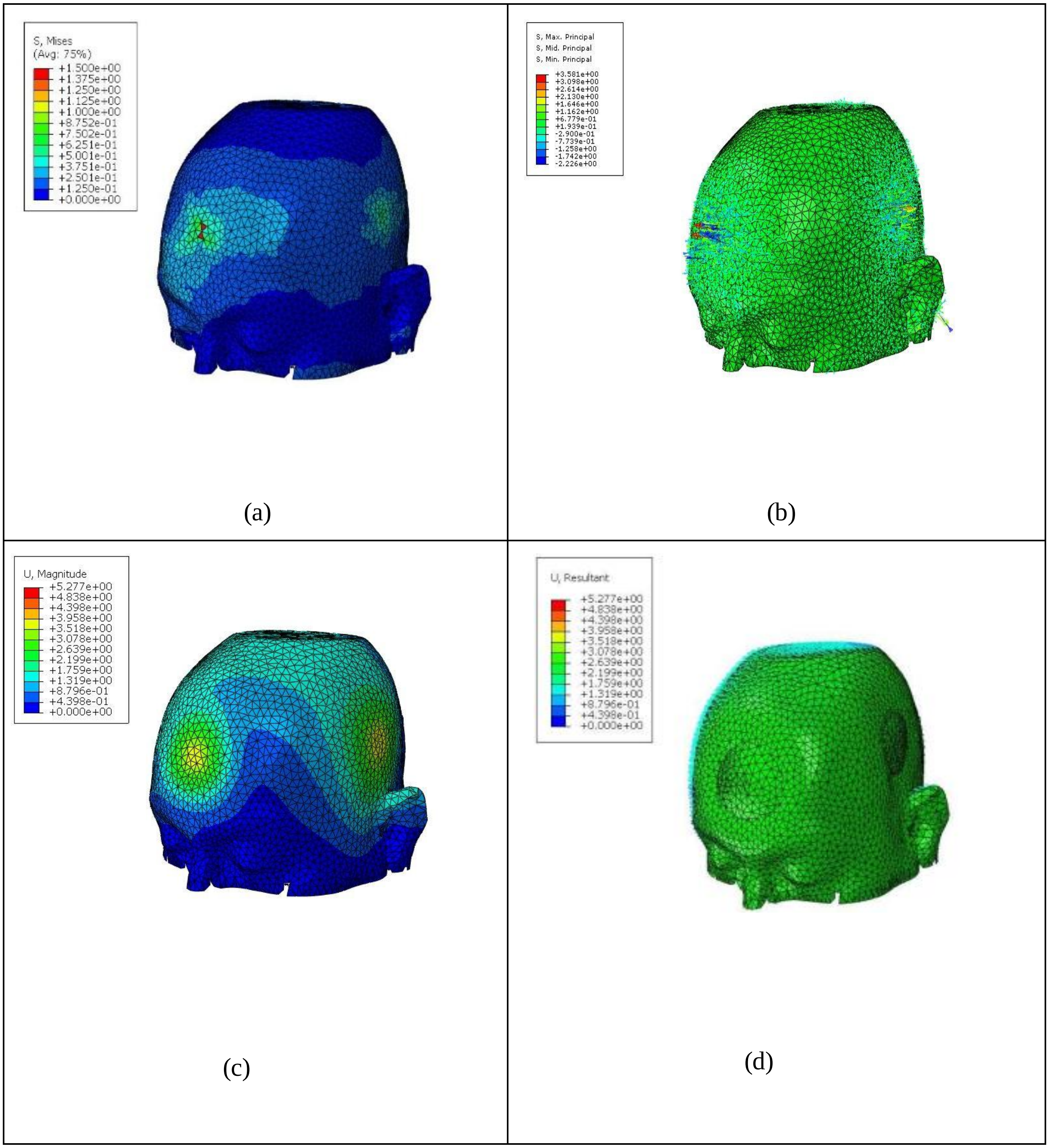


Figure 4.1: Values of stresses and displacements in static analysis.

4.2 Dynamic Analysis

Figure 4.2 shows the stress profiles on sagittal section at variable time intervals. In the frontal region, compression can be observed gradually transforming into tension in the occipital region. This is because of the forces of inertia as a result of which brain encounters coup contrecoup phenomenon against frontal and occipital regions respectively. Large stresses were observed in the connecting tissues between brain and bone at skull compacta. At about 6.3ms, the brain is at its equilibrium position. Here, equilibrium means no major stress contours were observed at that time. This is time after its first bounce and the distribution of pressure can be seen as it comes back to normal point. As the bony part of brain and soft tissues have different properties i.e. mass, density, inertia, relative velocities etc. In the soft tissues such as brain, as it has some barriers for pressure or force to reach inside it. At about 4.4ms, stresses are seen reaching till brain. (figure 4.2). Damage phenomena at variable time steps and respective regions are summarized below (table 4-1).

Table 4-1: Damage phenomena at variable time steps.

Time step (ms)	**Damage phenomena**	**Region affected**
0.4	Bending	Scalp, frontal region
1.8	Pressure	Bony part
3.0	Shear stress	Corpus callosum
4.4	Shear stress	Brain interior
5.1	Compression	Brain interior
6.3	Equilibrium state	-
7.3	Shear stress	Occipital region
9.0	Shear deformation	Brain stem

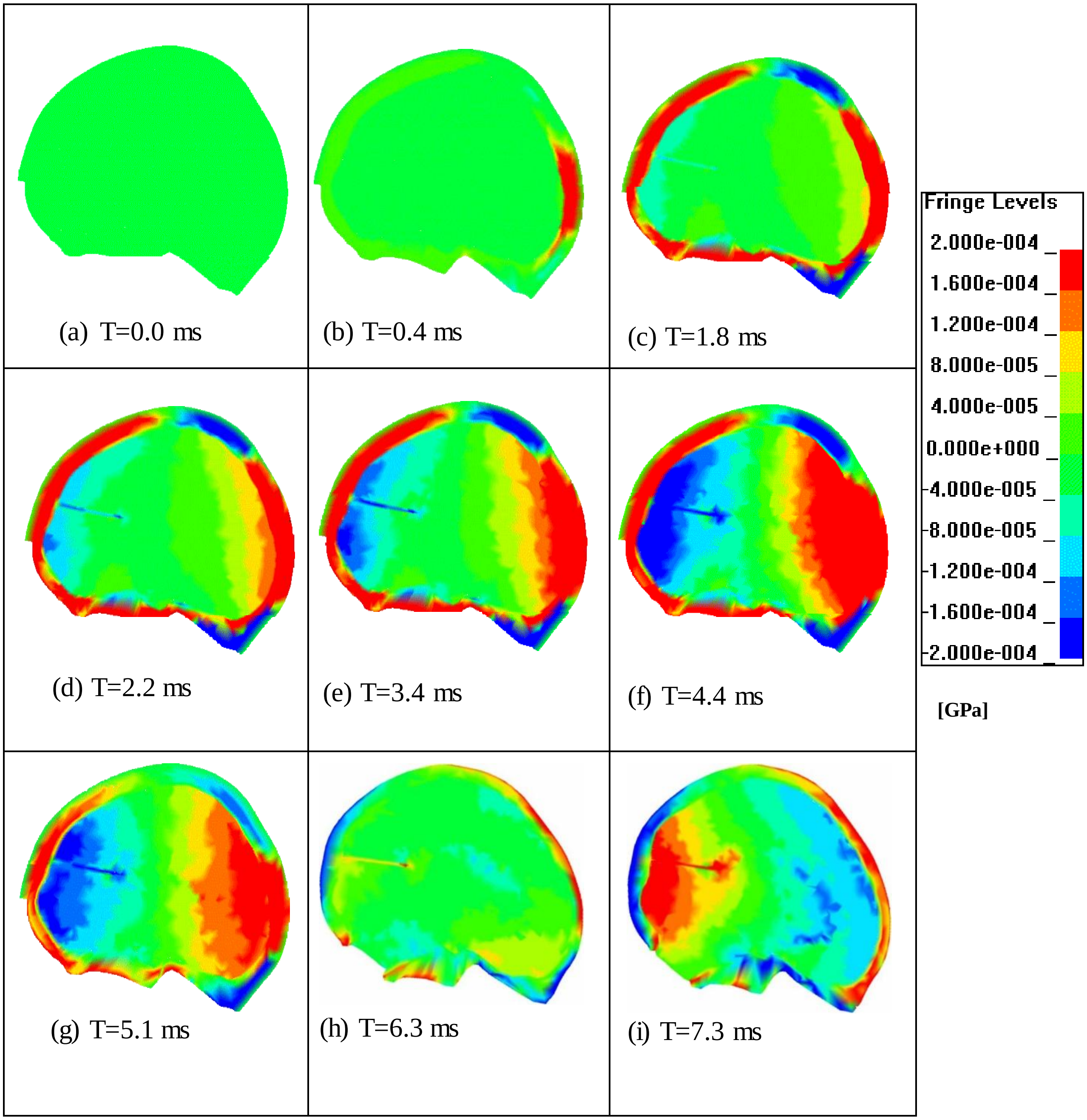


Figure 4.2: Stress profiles at variable time intervals.

Certain types of stresses like bending, compression, shear and tension were observed in the model. It can be concluded from this study, that the complexity in terms of geometry, material properties, loading and points of loading can greatly affect the overall model behavior. Injuries occurring in the brainstem and diffuse axonal injury (DAI) are usually due to the presence of large shear stresses. Critical regions include frontal region, brain interior specifically corpus callosum and brain stem as explained further. Frontal region has much importance as it is the major point of impact. Figure 4.3 shows the sagittal section and this view shows the shear stress values. Firstly, maximum values (5.00 e-05 GPa) are seen at corresponding area of corpus callosum. Later on, shear stress reaches till corresponding areas of brainstem (figure 4.3). The maximum value of shear stress at the area of brainstem is 4.500 e-05 GPa. Studies show that diffuse axonal injuries (DAI's) mostly affect these two areas of brain. Figure 4.4 shows shear stress distribution profiles on coronal section. Higher values are also seen here in corresponding area of brainstem. It can be seen on the figure that the impact keeps this area stressed on its greatest part as compared to other areas. There is a hypothesis that says that brainstem plays an important role in movements of brain and this study confirmed this phenomenon as brainstem is highly affected by stresses [44]. As the input force duration became longer, the pressure fluctuation was suppressed and the positive pressure became dominant at the impact side and the negative pressure became dominant at the opposite side, and lower frequencies became dominant.

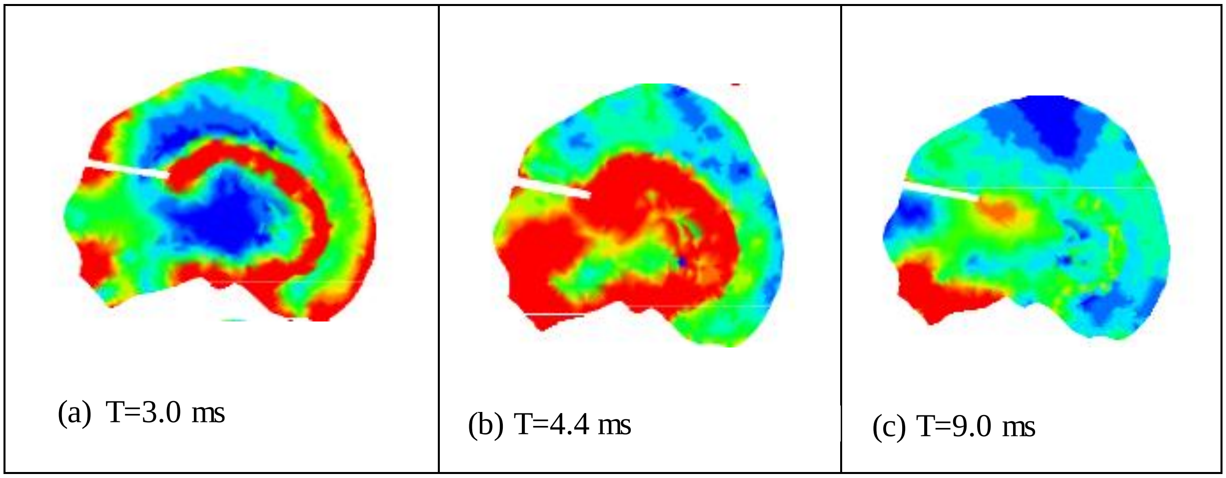


Figure 4.3: Shear stress profiles at variable time intervals.

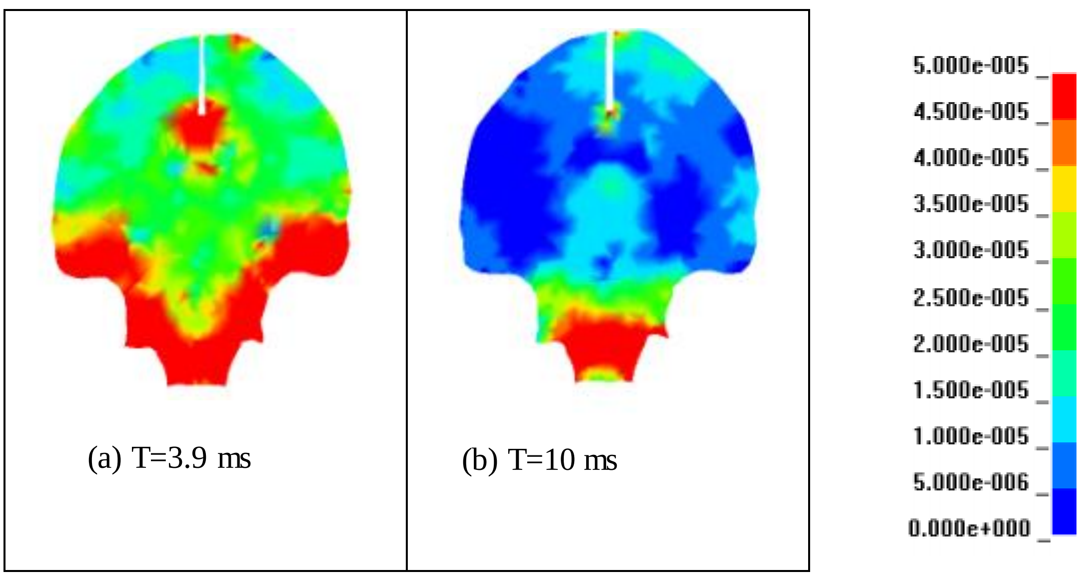


Figure 4.4: Shear stress profiles on coronal section

Maximum values of stresses were compared with literature values. Simulation result indicates the same trend of the maximum von Mises stress distribution as Marjoux et al.'s study during the period of impact, with the time at which the peak values occur. The value for von Mises stress in the brain has been used to assess the risk of brain injury used by Marjoux et al 2008 [45]. Therefore, the maximum von Mises stress in the brain during the impact simulations is shown from the FE model. As shown in figure 4.5, the graph initially shows a rising curve with increase in tine. Then after a certain time such as at 6.3 ms it follows a decreasing trend in stress values and then it rises again at 7.3 ms and 9.0 ms.

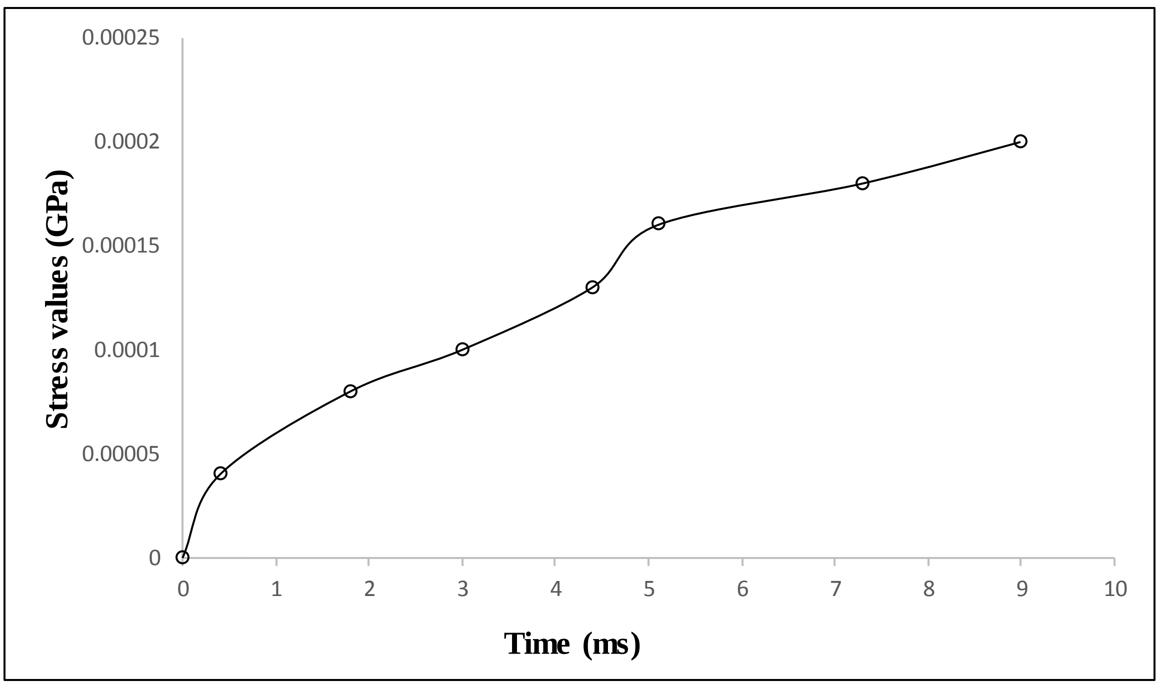


Figure 4.5: Damage progression with time.

4.3 Damage progression and its classification

Any changes in the size or shape of an object due to an applied external force is called deformation. These changes can be elastic, brittle or may be a fracture. Factors that influence the deformation are temperature, confining pressure, rate of deformation, composition of material etc. The various processes occurring at micro-scale that are responsible for changes in a material's internal structure, shape and volume are included in these mechanisms. Table 4-2 summarizes the types of deformations which were well as their appearance on respective layers.

Table 4-2: Deformation Mechanisms

Deformation mechanism	**Scalp**	**Skull**	**Skull compacta**
Bending	√	√	√
Crack initiation	√	√	-
Crack propagation	√	-	-
Notching	√	√	√
Shear deformation	√	√	√
Compression	√	-	-

4.4 Discussions

A parametric designed human head model is developed and modeled in such a way that different stimulus impact in different locations are studied and analyzed. From literature it was found that neck constraint has not contributed considerably on the results in short impacts. The model has head region only (without neck) with fixed base boundary condition, this contributes towards the reduction in performing calculations and processing time. The number of elements in meshes has been selected at certain level in order to get an efficient time computational solution. The computational model was considered to be isotropic, homogenous and linearly elastic in nature.

To address non linearity in a linear model, concept of homogenized brain model has been introduced. In this study we presented a human head model, under elastic mechanical analysis. The ultimate objective was to improve the static analysis of the previous study as conducted by Khan et al 2016. A preliminary dynamic simulation study was hence performed. It was conceived through this study, that while applying image-based modeling approach to a complex biological system like brain, model segmentation plays a crucial role for ultimate results. Moreover, for implicit dynamic analysis, the converging displacements were critical. Moreover, we simulated our models with point impacts as a first approach and we conclude that blunt and ballistic impacts are better approaches than point impacts. Simulating multiple impacts altogether also, results into problems like stress singularity. As seen in comparative study, a difference in values of stresses were observed. It is due a major reason of difference of dataset. Different mesh densities were used as compared to that used in literature [24].

We recommend two solutions of handling such problems, (i) generating meshes with reasonable aspect ratio in highly irregular geometries and (ii) using good resolution medical data. The medical data is usually obtained from CT or MRI. These images do not always give all the necessary images/slices which are required for making surfaces in numerical modeling. As the CT or MRI data is obtained keeping in view the need of specific pathology. Some anatomical parts/tissues are highlighted while others are not that much clearly visible.

The mechanical properties are defined by considering the data from literature. For performing some simulations, an average was taken by using literature values from different sources. Some values have also been modified. Some mechanical parameters have been kept constant in different simulations while others have been changed, in a significant range. By changing values, a better correlation with experimental tests can be find out. Impact force intensity obtained by Nahum [18] has been used as reference value with the numerical model. The maximum stress values obtained from this study were compared with those obtained from literature. (table 4-3).

Table 4-3: Comparative study of stresses.

Types	Obtained values (GPa)	Literature values (GPa)
Vonn-misses stress	2.0 e-04	1.1 e-04 [24]
Shear stress	5.0 e-05	3.3 e-05 [24]

CHAPTER 5: CONCLUSION AND FUTURE DIRECTIONS

Our study was focused on improving a previous research on static analysis of head impact injury (Khan et al, 2017) which was taken as the base model for this. The values obtained in the mentioned study (Khan et al, 2017) were not validated which has been improved in the current study. We have not only investigated the deformation mechanisms inside brain during injury which is one of the prominent contribution of this preliminary work but also inferred that the stresses inside the brain during head impact varies significantly in magnitude unlike the stresses obtained from static analysis of head impact modeling conducted by Khan et al 2017.

Novel classification mapping technique was used for classifying damage phenomena at different locations in head and brain. This technique was performed with time and without time. It is concluded that with the increase in time, damage was progressed to deeper layers of brain. The values of stresses also increased with an increase in time as brain has deeply encountered with impact force. As deformation is directly associated with brain functioning, so more damage was observed with increase in time and hence brain functioning was more affected at 7.3 ms and further at 9.0 ms.
Damage progression and its classification was summarized after mapping technique. It started from bending in outer layer like scalp and then ended in shear stress at occipital region.

The results were counter proved by the number of deformation mechanisms in this research. Brain injury is a very complex process and consists of four overlapping phases, which include primary injury, evolution of the primary injury, secondary or additional injury. From our results, we observe shearing and stretching of the brain tissue, which may be caused by motion of brain during the impact.

The image-based modeling seems to have a promising future and with the persistent improvement of 3D-imaging methods, in future it will allow to us to construct extremely complex models, empowered by rapid advances in computing power. In future it will enable to investigate the use of principal component analysis for the generation of a population of head models which will facilitate and encourage the analysts to learn and study the changes in anatomy across the population according to impact response. A lot of improvements can possibly be made possible in the model from an anatomical point of view. For example, by introducing more layers like bridge veins. The brain tissue differentiation between white matter, grey matter, cerebellum and brainstem behavior can also bring major improvements in the head model. Improvements could be reached by introducing more complex material models like, as an example, the real fluid behavior of the CSF or the fracture criterion for skull bones. These considerations for model improvements agree with some medical studies and more qualitative conclusions could be drawn with more experimental or clinical data. A close collaboration with doctors is considered as fundamental to obtain clinical data and information necessary to build more accurate models, to validate them and for a better comprehension of injury mechanisms. The real challenge left to deal with is the synthesis of appropriate models for soft and hard tissue structures, as the constancy of the numerically predicted responses is based on realistic material models which are quite arduous to determine experimentally for high strain and amplitudes; strain rates in biological tissues.

Image processing has seen a lot of advancement in recent times which has allowed us to develop numerically reasonable head models which are immensely flexible. This approach not only allows us to tailor the head models according to our needs for specific scenarios but also allows us to capture the miniscule details and remarkable definition of the complex head and brain geometry. We obtained Good results for the behavior of pressure distribution impact force. There have been some difficulties in simulating the behavior of pressure in posterior fossa. The same problem has been seen in the literature encountered by others authors too and is may be due to the material model adopted to simulate the CSF. In order to simulate the floating effect of brain inside cranium, an elastic material option having low stiffness value and continuous mesh can be used.

Impact modeling has vital importance in the identification of the complex mechanisms leading to cell death after brain injury. Using FEM to identify such mechanisms and classify them into different stages is quite useful. We believe FEM is the most reliable tool for injury prediction as well wherein some of the accuracy is always comprised during approximations.

CONTRIBUTIONS

Through this research, two major contributions have been made:

1. Dynamic analysis with reference to specific time intervals was performed using image processing soft wares. The results obtained by this study can be used scientifically for the assessment of damage progression as a result of head impact injury especially related to a specific time frame.
2. Damage progression and its classification using mapping technique was done.

REFERENCES

[1] J. Field, *Epidemiology of head injuries in England and Wales: with particular application to rehabilitation*: HM Stationery Office, 1976.

[2] J. F. Kraus and D. L. McArthur, "Epidemiology of brain injury," *Neurology and trauma,* vol. 2, pp. 3-18, 1996.

[3] K. M. Tse, S. P. Lim, V. B. C. Tan, and H. P. Lee, "A review of head injury and finite element head models," *Am J Eng Technol Soc,* vol. 1, pp. 28-52, 2014.

[4] B. Selecki, I. Ring, D. Simpson, G. Vanderfield, and M. Sewell, "Injuries to the Head, Spine and Peripheral Nerves: Report on a Study," *Sydney: New South Wales Government Printer,* 1981.

[5] J. F. Annegers, J. D. Grabow, L. T. Kurland, and E. R. Laws, "The incidence, causes, and secular trends of head trauma in Olmsted County, Minnesota, 1935– 1974," *Neurology,* vol. 30, pp. 912-912, 1980.

[6] W. Goldsmith, "The state of head injury biomechanics: past, present, and future: part 1," *Critical Reviews™ in Biomedical Engineering,* vol. 29, 2001.

[7] J. Jagger, J. I. Levine, J. A. Jane, and R. W. Rimel, "Epidemiologic features of head injury in a predominantly rural population," *Journal of Trauma and Acute Care Surgery,* vol. 24, pp. 40-44, 1984.

[8] S. L. Dawson, C. S. Hirsch, F. V. Lucas, and B. A. Sebek, "The contrecoup phenomenon: reappraisal of a classic problem," *Human pathology,* vol. 11, pp. 155-166, 1980.

[9] P. Dixit and G. Liu, "A Review on Recent Development of Finite Element Models for Head Injury Simulations," *Archives of Computational Methods in Engineering,* pp. 1-53, 2016.

[10] R. Cotton, C. W. Pearce, P. G. Young, N. Kota, A. Leung, A. Bagchi, *et al.*, "Development of a geometrically accurate and adaptable finite element head model for impact simulation: the Naval Research Laboratory–Simpleware Head Model," *Computer methods in biomechanics and biomedical engineering,* vol. 19, pp. 101-113, 2016.

[11] C. H. Hardy and P. V. Marcal, *Elastic analysis of a skull*: Division of Engineering, Brown University, 1971.

[12] T. Shugar, "Transient structural response of the linear skull-brain system," SAE Technical Paper 0148-7191, 1975.

[13] H. S. Chan, "Mathematical model for closed head impact," SAE Technical Paper 0148-7191, 1974.

[14] T. B. Khalil and R. P. Hubbard, "Parametric study of head response by finite element modeling," *Journal of Biomechanics,* vol. 10, pp. 119-132, 1977.

[15] R. R. Hosey and Y. K. Liu, "A homeomorphic finite element model of the human head and neck," *Finite elements in biomechanics,* pp. 379-401, 1982.

[16] J. S. Ruan, T. B. Khalil, and A. I. King, "Finite element modeling of direct head impact," SAE Technical Paper 0148-7191, 1993.

[17] S. Kleiven and W. N. Hardy, "Correlation of an FE model of the human head with local brain motion: Consequences for injury prediction," *Stapp Car Crash Journal,* vol. 46, pp. 123-144, 2002.

[18] A. M. Nahum, R. Smith, and C. C. Ward, "Intracranial pressure dynamics during head impact," SAE Technical Paper 0148-7191, 1977.

[19] W. N. Hardy, C. D. Foster, M. J. Mason, K. H. Yang, A. I. King, and S. Tashman, "Investigation of Head Injury Mechanisms Using Neutral Density Technology and High-Speed Biplanar X-ray," *Stapp car crash journal,* vol. 45, pp. 337-368, 2001.

[20] A. King, W. Hardy, M. Mason, and S. Tashman, "Comparison of relative motion between the brain and skull of the human cadaver for rotation in the coronal and sagittal planes," in *4th world congress of biomechanics*, 2002.

[21] L. Zhang, K. H. Yang, and A. I. King, "Comparison of brain responses between frontal and lateral impacts by finite element modeling," *Journal of neurotrauma,* vol. 18, pp. 21-30, 2001.

[22] G. Belingardi, G. Chiandussi, and I. Gaviglio, "Development and validation of a new finite element model of human head," in *Proc. 19th International Technical Conference of the Enhanced Safety of Vehicle (ESV), Washington, DC,* 2005.

[23] M. Lashkari, F. Frahmand, and K. Kangarlou, "Finite element modeling of the human brain under impact conditions," *Int. Res. J. Appl. Basic Sci,* vol. 6, pp. 875-881, 2013.

[24] K. M. Tse, L. B. Tan, S. J. Lee, S. P. Lim, and H. P. Lee, "Development and validation of two subject-specific finite element models of human head against three cadaveric experiments," *International journal for numerical methods in biomedical engineering,* vol. 30, pp. 397-415, 2014.

[25] B. Yang, K.-M. Tse, N. Chen, L.-B. Tan, Q.-Q. Zheng, H.-M. Yang, *et al.*, "Development of a finite element head model for the study of impact head injury," *BioMed research international,* vol. 2014, 2014.

[26] J.-X. Jin, J.-Y. Zhang, X.-W. Song, H. Hu, X.-Y. Sun, and Z.-H. Gao, "Effect of cerebrospinal fluid modeled with different material properties on a human finite element head model," *Journal of Mechanics in Medicine and Biology,* vol. 15, p. 1550027, 2015.

[27] X. Song, C. Wang, H. Hu, T. Huang, and J. Jin, "A finite element study of the dynamic response of brain based on two parasagittal slice models," *Computational and mathematical methods in medicine,* vol. 2015, 2015.

[28] X. Trosseille, C. Tarriere, F. Lavaste, F. Guillon, and A. Domont, "Development of a FEM of the human head according to a specific test protocol," SAE Technical Paper 0148-7191, 1992.

[29] Marwan SH, Abdullah AH, Mahmud J, Rashid H. Dynamic Analysis of Frontal Human Skull Using Finite Element Simulation. InAdvanced Materials Research 2013 (Vol. 647, pp. 418-423). Trans Tech Publications Ltd.

[30] V. Kenner and W. Goldsmith, "Dynamic loading of a fluid-filled spherical shell," *International Journal of Mechanical Sciences,* vol. 14, pp. 557-568, 1972.

[31] C. C. Ward and R. B. Thompson, "The development of a detailed finite element brain model," SAE Technical Paper 0148-7191, 1975.

[32] K. Ueno, J. W. Melvin, M. E. Rouhana, and J. W. Lighthall, "Two-dimensional finite element model of the cortical impact method for mechanical brain injury," *American Society of Mechanical Engineers, Applied Mechanics Division, AMD,* vol. 126, pp. 121-154, 1991.

[33] A. Kuijpers, M. Claessens, and A. Sauren, "The influence of different boundary conditions on the response of the head to impact: a two-dimensional finite element

study," *Journal of Neurotrauma*, vol. 12, pp. 715-724, 1995.

[34] S. Advani, "A constitutive relationship for large deformation finite element modeling of brain tissue," *Journal of Biomechanical Engineering*, vol. 117, p. 279, 1995.

[35] G. CHUNPING, "Finite element modeling of human brain and application in neurosurgical procedures," 2007.

[36] Jacob A, Faria C, Cardoso G, Reis K, Motta M, Meneghetti T, Cammino R, Shibli A. Evaluation of helmet protection during impact of head to ground and impact of an object to head using finite element analysis. Journal of Safety Engineering. 2016;5(1):8-16.

[37] Eslaminejad A, Sarvghad-Moghaddam H, Rezaei A, Ziejewski M, Karami G. Comparison of brain tissue material finite element models based on threshold for traumatic brain injury. InASME 2016 International Mechanical Engineering Congress and Exposition 2017 Feb 8. American Society of Mechanical Engineers Digital Collection.

[38] Marwan SH, Abdullah AH, Mahmud J, Rashid H. Dynamic Analysis of Frontal Human Skull Using Finite Element Simulation. InAdvanced Materials Research 2013 (Vol. 647, pp. 418-423). Trans Tech Publications.

[39] Raul JS, Baumgartner D, Willinger R, Ludes B. Finite element modelling of human head injuries caused by a fall. International Journal of Legal Medicine. 2006 Jul 1;120(4):212-8.

[40] Marwan SH, Abdullah AH, Mahmud J, Rashid H. Dynamic Analysis of Frontal Human Skull Using Finite Element Simulation. InAdvanced Materials Research 2013 (Vol. 647, pp. 418-423). Trans Tech Publications Ltd.

[41] Kwong, M. T et al. A review of head injury and finite element head models. American Journal of Engineering, Technology and Society 2014; 1(5): 28-52

[42] Raul JS, Baumgartner D, Willinger R, Ludes B. Finite element modelling of human head injuries caused by a fall. International Journal of Legal Medicine. 2006 Jul 1;120(4):212-8.

[43] Yang B, Tse KM, Chen N, Tan LB, Zheng QQ, Yang HM, Hu M, Pan G, Lee HP. Development of a finite element head model for the study of impact head injury. BioMed research international. 2014;2014.

[44] Sarkar S, Majumder S, Roychowdhury A. Response of human head under static & dynamic load using finite element method. Trends Biomater Artif Organs. 2004;17(2):130-4.

[45] Marjoux D, Baumgartner D, Deck C, Willinger R. Head injury prediction capability of the HIC, HIP, SIMon and ULP criteria. Accident Analysis & Prevention. 2008 May 1;40(3):1135-48.