A Realistic Subject-Specific Finite Element Model of Human Head-Development and Experimental Validation

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Abstract— **Head injury, being one of the main causes of death or permanent disability, continues to remain as a major health problem with significant socioeconomic costs. Therefore, there is a need for biomechanical studies of head injury. To assess the biomechanics of head injury mechanism, many finite element head models (FEHMs) had been built. However, in order to reduce the computation efforts, most of these FEHMs were simplified and details of complex head anatomical features are often ignored in modeling. The main purpose of the present work is to build and validate a detailed finite element model of human head in order to better predict the mechanical responses of the human head during head injury. Geometrical information of a human head is obtained from medical images of computed tomography (CT) and magnetic resonance imaging (MRI) with the use of image-processing software, for segmentation and reconstruction of a comprehensive FEHM. The head model is then validated against both intracranial pressure (ICP) data of the two experimental cadaver tests. General shape trends, magnitudes and duration of the pressure pulses in the simulation agree well with the experimental pressure pulse. Overall, there is a good correlation between the simulations and the experiments. Once being validated, this representative FEHM can be used in the assessment of the injurious effects of different loading conditions and enable the development of enhanced head injury and protection equipments through the reconstruction of the available real-world accidents information.**

Keywords— **Finite element (FE), head injury, head model, validation**

I. INTRODUCTION

Head injury, being one of the main causes of death or permanent disability, continues to remain as a major health problem with significant socioeconomic costs. Therefore, there is a need for biomechanical studies of head injury. To assess the biomechanics of head injury mechanism, many finite element head models (FEHMs) had been built, however, some of them had not been validated. Experimental validation of a numerical model is necessary in determining the degrees to which the model accurately predicts the real-world phenomena well. Only when this is achieved, the model does represent a powerful tool with which to correlate the biomechanical parameters involved in the head injury with the clinical observations. Most of the FEHMs [1-8] had been validated against the intracranial pressure (ICP) data of Nahum et al. [9]'s cadaver experiments, with some [3-5, 10] having been validated against another ICP data of Trosseille et al. [11]'s longer duration impact. However, some of these earlier idealized FEHMs, which were developed mainly for automobile related head injuries, are generally unrealistic with simplifications in the facial details. The objective of this study is to build a detailed and realistic model of subject-specific head using computed tomography (CT) and magnetic resonance imaging (MRI), and to validate it against both ICP data of the experimental cadaver tests under different impact conditions.

II. METHODS AND MATERIALS

A. Model Description

Geometrical information of the human skull was obtained from 460 computed tomography (CT) axial images of a middle-aged male with in-plane resolution of 512 by 512 pixels with a pixel size of 0.488 mm and slice thickness of 1.0 mm. As for the intracranial contents, the magnetic resonance imaging (MRI) data of the brain, with in-plane resolution of 1659 by 962 pixels with a pixel size of 0.500 mm and slice thickness of 4.0 mm, was employed for the segmentation of the brain (Fig. 1). These medical images were imported into Mimics v13.0-v14.0 (Materialise, Leuven, Belgium) for segmentation and reconstruction of the FEHM (Fig. 1). A semi-automatic meshing technique was employed in HyperMesh v10.0 (Altair HyperWorks, Troy, MI, USA) to optimize between computational efficiency and element quality, with the average element size of 1.57 mm, as well as aspect ratio of 1.61 for the model.

The FEHM consisted of a cranial skull with detailed facial bone features, teeth, cervical vertebrae, nasal septal cartilage, nasal lateral cartilages; brain components such as cerebral white matter and gray matter, cerebellum and brainstem, the cerebral peduncle (midbrain), and the entire ventricular system, as well as the cerebrospinal fluid (CSF)

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separating the skull and the brain; lastly soft tissue overlaying the skull. The entire model is approximately 4.73 kg and consisted of 327536 nodes and 1337903 linear hexahedral elements (Fig.1).

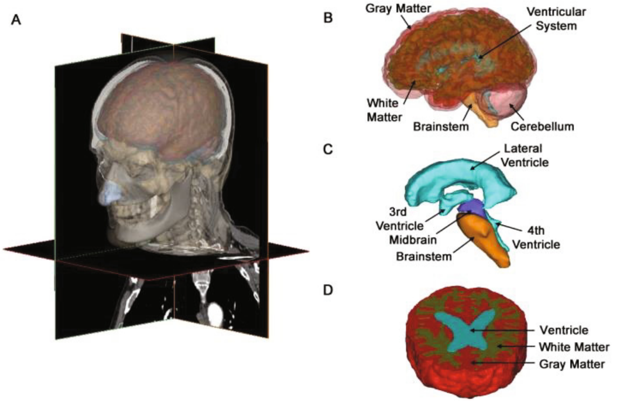


Fig. 1: The subject-specific finite element model of human head.

B. Material Properties

Like most previous FEHMs, all the skeletal tissues such as cartilages, teeth and cervical vertebrae are modeled as linear elastic, isotropic materials it has been considered to have homogeneous and isotropic behavior [12-14] (Table 1). As for the brain tissues, it has adopted a linear viscoelastic material behavior combined with the large-deformation theory [15-17] (Table 1).

Table 1: Material properties of the various parts in the head model.

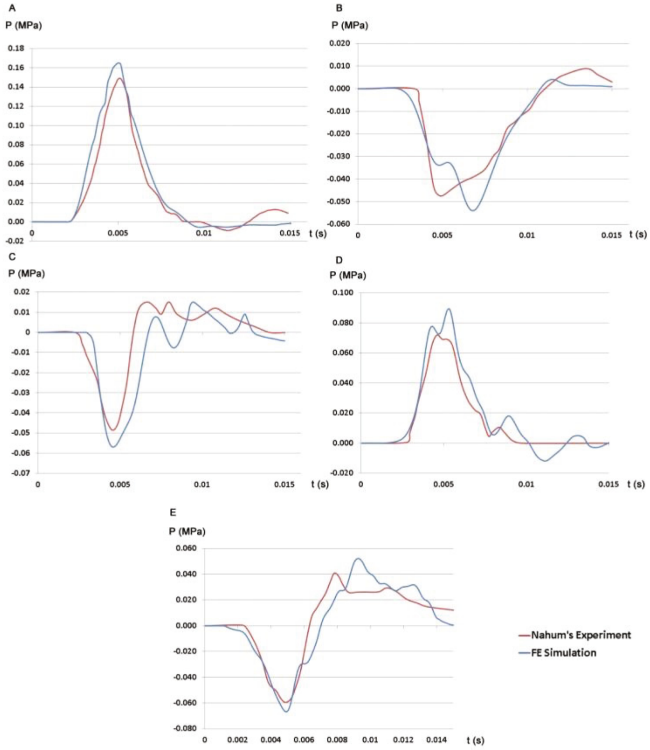
Parts	Young's Modulus, E (MPa)	Poisson's ratio, υ	Density, ρ (kg/mm^3)	Sources
Brainstem	G_0 = 0.0225 MPa, G_∞ = 0.0045 MPa, β = 80 s^{-1}	0.4996	1.06E-06	[10]
Cerebral Peduncle	G_0 = 0.0225 MPa, G_∞ = 0.0045 MPa, β = 80 s^{-1}	0.4996	1.06E-06	[10]
Cerebellum	G_0 = 0.528 MPa, G_∞ = 0.168 MPa, β = 35 s^{-1}	0.48	1.14E-06	[3, 17-20]
CSF	E = 1.314	0.4999	1.04E-06	[21, 22]
Gray Matter	G_0 = 0.034 MPa, G_∞ = 0.0064 MPa, β = 700 s^{-1}	0.4996	1.04E-06	[21, 22]
Lateral Cartilage	E = 30	0.45	1.50E-06	[23]
Septum Cartilage	E = 9	0.32	1.50E-06	[24]
Bone	E = 8000	0.22	1.21E-06	[22]
Soft Tissues	E = 16.7	0.46	1.04E-06	[22, 25]
Ventricles	G_0 = 0.101 MPa, G_∞ = 0.00101 MPa, β = 100 s^{-1}	0.49	1.08E-06	[22]
White Matter	G_0 = 0.041 MPa, G_∞ = 0.0078 MPa, β = 700 s^{1}	0.4996	1.04E-06	[21]

C. Boundary Conditions

Both the skull-CSF and brain-CSF interfaces are modeled as contact pairs with a tangential sliding boundary condition with the coefficient of friction of 0.2 [5, 25, 26] and a normal hard contact pressure-overclosure condition. All the interfaces between other intracranial contents and those between skull, cartilages and soft tissues are implemented with tie-constraints. The interaction between the head and the foreign impactor is defined by a contact algorithm, which has hard contact pressure-overclosure with default constrain enforcement method [27].

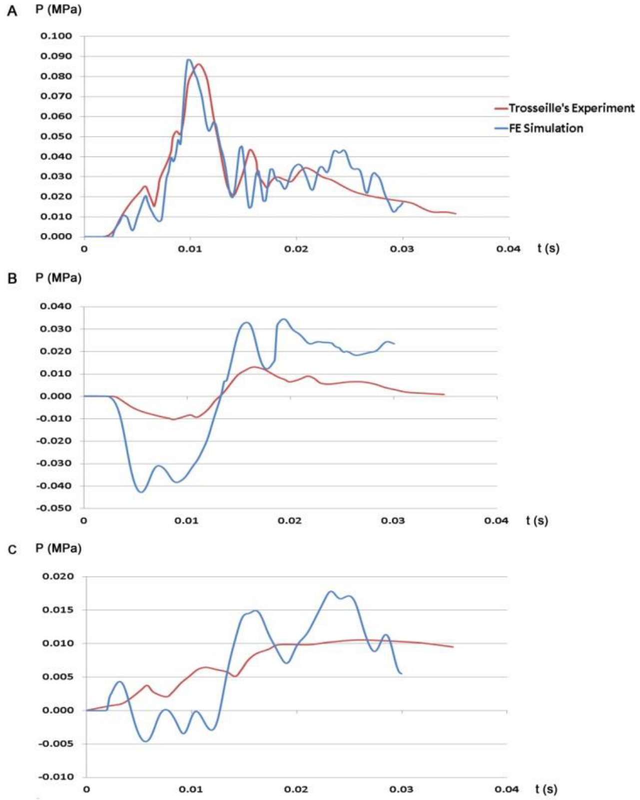
III. RESULTS AND DISCUSSIONS

The FEHM is first validated against the ICP-time histories of Nahum et al. [9]'s cadaver experiment 37, in which the FEHM is impacted by a cylindrical mass of 5.59 kg at frontal bone region and the impact velocity is 9.94 m·s^{-1}.



In comparison with Nahum et al. [9]'s experimental pressures, the simulate results have generally agree well with the experimental pressures, in terms of magnitudes and duration of the pulses, except for the great variation in bilateral occipital pressures. This could probably be due to the uneven distribution of white and gray matters in the model. Additionally, there are small oscillations in the simulated frontal and parietal pressures.

Then, the FEHM is impacted by a 23.4 kg impactor, travelling at 7 $m \cdot s^{-1}$ and hit at the nasal region, similar to the Trosseille [11]'s cadaveric experiment MS 428-2. The ICP history plots for the frontal, occipital and temporal regions, are shown in Fig. 3.



The simulated pressure at the frontal lobe agrees well with the experimental pressure. However, this is not true for the occipital pressure and temporal pressure, in particular, the occipital pressure in which its peak was overestimated by three-folds. Overall, the general trend of predicted pressure pulses matched reasonably well with the Trosseille [11]'s cadaveric experiment.

Up to date, to the authors' knowledge, there is no reported subject-specific FEHM, with such detailed features including soft tissues, being validated against these cadaveric tests. In the present study, a realistic FEHM, with detailed anatomical features, have been developed and validated against the ICP data of the two cadaver experimental tests. The comparisons of the simulated results are largely consistent and are in good agreement with the experimental measured ICP and relative displacements. Despite the fundamental differences in the numerical formulation in this FEHM as compared to others FEHMs [1-8], there exist little evident differences in the predicted ICP when comparing with the experimental ICP. This may indicate that the advancements on the details of the extracranial features and overlying soft tissue would not improve the model's predicting capabilities in brain injury as it seems that the prediction replies more on skull's mass properties and kinematics rather than its geometrical details. As a corollary, a model with the attributes of simplified extracranial features may be sufficient for modeling traumatic brain injury (TBI). Nevertheless, this newly developed FEHM, with detailed realistic anatomical features, can be used in the evaluation of either facial or brain injury.

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