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Research Paper

The validation and application of a finite element human head model for frontal skull fracture analysis

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ARTICLE INFO

Article history:
Received 31 May 2012
Received in revised form
13 February 2013
Accepted 18 February 2013
Available online 13 March 2013

Keywords:
Skull fracture
Finite element method
Head injury
Forensic science

ABSTRACT

Traumatic head injuries can result from vehicular accidents, sports, falls or assaults. The current advances in computational methods and the detailed finite element models of the human head provide a significant opportunity for biomechanical study of human head injuries. The biomechanical characteristics of the human head through head impact scenarios can be studied in detail by using the finite element models. Skull fracture is one of the most frequent occurring types of head injuries. The purpose of this study is to analyse the experimental head impacts on cadavers by means of the Strasbourg University Finite Element Head Model (SUFEHM). The results of the numerical model and experimental data are compared for validation purpose. The finite element model has also been applied to predict the skull bone fracture in frontal impacts. The head model includes the scalp, the facial bone, the skull, the cerebral spinal fluid, the meninges, the cerebrum and the cerebellum. The model is used to simulate the experimental frontal head impact tests using a cylindrical padded impactor. Results of the computational simulation shows that the model correlated well with a number of experimental data and a global fracture pattern has been predicted well by the model. Therefore the presented numerical model could be used for reconstruction of head impacts in different impact conditions also the forensic application of the head model would provide a tool for investigation of the causes and mechanism of head injuries.

1. Introduction

A head injury is any trauma that leads to the injury of the scalp, skull, or brain. Head injury is classified as open (penetrating) or closed. An open head injury occurs when an object such as a bullet, backed by strong force, fractures the skull and damages brain tissue or the surrounding membranes. A closed head injury is any injury to the head that does not penetrate the skull and is usually caused by blows to the head. Evaluation of accidents statistics shows that more than 30% of all vehicular traumas are related to head injuries (Allsop and Kennett, 2002; Kramer, 1998). In western countries road accidents are the cause of up to 60% of head injuries followed by falls, assaults and sport injuries (Jannett, 1996; Kraus et al., 1996). In the United States, motor vehicle crashes are the number one cause of fatal injuries for people aged up to 34 (CDC, 2003). According to National Head Injury Foundation the major causes of head injuries are road traffic accidents, domestic accidents, sport injuries, assault, warfare and civil violence, recreational and industrial accidents. Over the years, various methods have been employed to understand the head injuries and underlying injury

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1751-6161/$ - see front matter
http://dx.doi.org/10.1016/j.jmbbm.2013.02.010

mechanisms. Furthermore, biomechanical response of the head has been experimentally investigated (Hodgson et al., 1970; Yoganandan et al., 1995). In recent years, computational models of the head have been further developed and finite element analysis of head injury have been advanced by further development of more biofidelic finite element head models (Ruan and Prasad, 1998). A validated FE model is able to simulate the dynamic load response realistically and can provide valuable information for prediction of head injuries.

In this study, the main objective is to show the ability of a FE model in predicting human head trauma and specifically the occurrence of skull fractures. Verschueren et al., 2007 proposed a new experimental setup for cadaveric frontal head impact tests. Frontal human cadaver tests for injury assessment is earlier reported by McElhaney et al. (1976), Sances and Yoganandan (1986) Sances et al. (1981) Yoganandan et al. (1998). Several head impact test set-ups have been proposed for investigating skull fracture. In the 1940s, Gurdjian and Webster (1958), Gurdjian et al. (1949) conducted impact tests to investigate the mechanics of head injury. They used a free-fall method on embalmed intact human head cadavers and biomechanical data of input external energy were reported (Gurdjian et al., 1949). In studies of Gurdjian it was shown that linear fractures occurred secondary to tensile stresses caused by local skull bending due to impact.

In the 1960s and 1970s, Hodgson and co-workers performed two impacting methods (a pivoting table for a free fall of human head and a guided drop tower). Frontal, occipital and facial regions were considered (Hodgson, 1967; Hodgson and Thomas, 1971). Nahum et al. (1968) performed impact tests on unembalmed and embalmed human heads and skulls. They studied the effect of impact location on skull bone fracture tolerance (Nahum et al., 1968). Yoganandan et al. (1995) conducted static and dynamic impact tests on intact human heads. In their experiment, the head was fixed on a rigid platform. An electro-hydraulic piston was used as an impactor. Local deformations of the skull were measured and recorded. Yoganandan et al. (1995) proposed that the energy to failure was a possible tolerance criterion.

Later Yoganandan and Pintar (2004) performed free fall impact tests on unembalmed post-mortem human subjects to provide force and acceleration corridors at different range of velocities. The main focus of these studies has been derivation of the head injury mechanisms and the measurement of mechanical parameters responsible for the skull fracture.

Recently, Verschueren et al. (2007) proposed a new type of set-up for cadaver impact test which combines the strengths of the most frequently used techniques. The set-up consists of two pendulums, with one degree of freedom of rotational motion. Local skull deformation and impact force are measured and energy-to-failure of intact unembalmed human heads in frontal impacts under dynamic loading is investigated. The experimental data suggest an energy failure level of 22–24 J for dynamic frontal loading of an intact unembalmed head. Peak force and energy variables have been used for describing the biomechanics of the impact.

The FE model that is used in the present study is the one that has been developed at the University of Strasbourg (Willinger et al., 1999). It is commonly called the Strasbourg University Finite Element Head Model (SUFEHM). This model is used to numerically simulate the experimental cadaver head impact tests. The cases stem from the experiment performed by Verschueren et al. (2007) at University of Leuven. Frontal impact tests were conducted on specimens from 18 unembalmed post-mortem human subjects as detailed in Delye et al. (2007). Each experimental case has been numerically reconstructed in terms of mechanical parameters such as bone density and thickness at impact site, impactor weight and velocity and head weight. The parameters of finite element model are adapted to the corresponding values of experimental case. Head impact tests were conducted for low, medium and high-velocity range. Peak force for the experiment and numerical simulation are compared. Skull fractures were observed in each case and reconstructed numerically by the FE model of human head.

2. Materials and methods

2.1. *Human head FE model*

The (SUFEHM) includes the main anatomical features of the human head: face, scalp, skull, falx of the brain, tentorium of the cerebellum, brain/skull interface, brain, cerebellum, brain stem, as illustrated in Fig. 1. The falx of the brain and the tentorium of the cerebellum are meshed in shell elements. The skull is meshed by three layered composite shell elements and the other features are represented by brick elements. The FE mesh is continuous and represents an average adult human head. The brain/skull interface was modelled to represent every anatomical component that is included in that space: membranes (dura, arachnoid and pia), cerebral spinal fluid and vessels. This space is meshed in one layer of brick elements and surrounds entirely the brain, the cerebellum and the brain stem. The tentorium of the cerebellum separates the brain and cerebellum and the falx of the brain divides both hemispheres. One layer of brick element simulating the cerebral spinal fluid surrounds theses membranes. The skin was modelled by one layer of brick elements and surrounds the skull and the facial bone. Globally, the SUFEHM consists of 13,208 elements. Its total mass is 4.5 kg. Material properties assigned to the different parts are all isotropic, homogenous and elastic. They stem from generally accepted literature. In particular, the skull was modelled by three layered composite shell elements representing the cortical inner table, the diplöe and the cortical external table of the human cranial bone. In order to

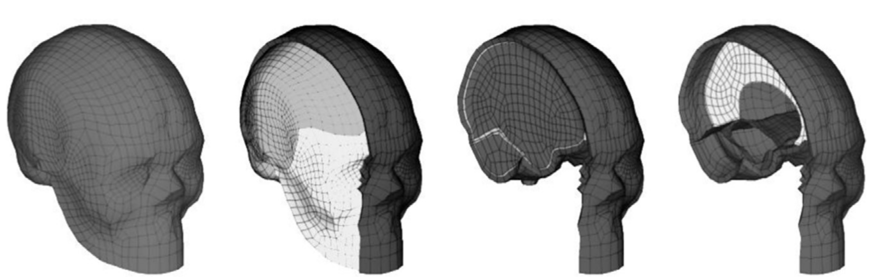

Fig. 1 – Mesh of the SUFEHM.