Accident Analysis and Prevention 79 (2015) 13–32

Contents lists available at ScienceDirect

Accident Analysis and Prevention

journal homepage: www.elsevier.com/locate/aap

Investigation of the relationship between facial injuries and traumatic brain injuries using a realistic subject-specific finite element head model

Kwong Ming Tse [a,*], Long Bin Tan [a], Shu Jin Lee [b], Siak Piang Lim [a], Heow Pueh Lee [a,c,*]

[a] Department of Mechanical Engineering, National University of Singapore, 9 Engineering Drive 1, Singapore 117576
[b] Division of Plastic, Reconstructive and Aesthetic Surgery, National University Health System, 5 Lower Kent Ridge Road, Singapore 119074
[c] National University of Singapore (Suzhou) Research Institute, 377 Lin Quan Street, Suzhou Industrial Park, Jiangsu 215123, People's Republic of China

ARTICLE INFO

Article history:
Received 20 May 2014
Received in revised form 2 February 2015
Accepted 10 March 2015
Available online 17 March 2015

Keywords:
Finite element
Concomitant injury
Facial trauma
Traumatic brain injury (TBI)
Blunt impacts

ABSTRACT

In spite of anatomic proximity of the facial skeleton and cranium, there is lack of information in the literature regarding the relationship between facial and brain injuries. This study aims to correlate brain injuries with facial injuries using finite element method (FEM). Nine common impact scenarios of facial injuries are simulated with their individual stress wave propagation paths in the facial skeleton and the intracranial brain. Fractures of cranio-facial bones and intracranial injuries are evaluated based on the tolerance limits of the biomechanical parameters. General trend of maximum intracranial biomechanical parameters found in nasal bone and zygomaticomaxillary impacts indicates that severity of brain injury is highly associated with the proximity of location of impact to the brain. It is hypothesized that the midface is capable of absorbing considerable energy and protecting the brain from impact. The nasal cartilages dissipate the impact energy in the form of large scale deformation and fracture, with the vomer–ethmoid diverging stress to the "crumpling zone" of air-filled sphenoid and ethmoidal sinuses; in its most natural manner, the face protects the brain. This numerical study hopes to provide surgeons some insight in what possible brain injuries to be expected in various scenarios of facial trauma and to help in better diagnosis of unsuspected brain injury, thereby resulting in decreasing the morbidity and mortality associated with facial trauma.

1. Introduction

Facial injury and concomitant traumatic brain injury (TBI) have been the focus of numerous investigations over the past few decades. On account of the close anatomical proximity of the facial skeleton and cranium, it is not surprising that patients with facial trauma are at higher risk for suffering brain injuries. Early recognition of associated TBIs remains an important part of initial assessment and treatment planning in facial trauma patients and could significantly reduce morbidity and mortality associated with these life threatening injuries. Several earlier studies (Gwyn et al., 1971; Luce et al., 1979; Lee et al., 1987; Lim et al., 1993; Chang et al., 1994; Pappachan and Alexander, 2006) had been conducted in evaluating the incidence of facial injuries and associated injuries. However, there is paucity of information in the literature regarding the correlation between facial injuries and TBIs. Various schools of thought arise among the reported studies; the traumatic energy is largely absorbed by the facial skeleton which acts as shock absorber in protecting the brain from injury (Lee et al., 1987; Chang et al., 1994), whereas proponents of opposing viewpoints advocate that the traumatic energy which is sufficient to cause facial injuries would have the potential for concomitant facial and brain injuries (Davidoff et al., 1988; Keenan et al., 1999; Martin et al., 2002). Prior statistical findings from retrospective clinical cases reported a wide range of incidence rates of brain injuries associated with facial fractures; with the lowest rate as 5.4% (Lim et al., 1993) whereas some rates as high as 80% (Martin et al., 2002; Hayter et al., 1991). Despite the bulk of valuable statistical information provided by these retrospective clinical studies regarding the correlation of facial injuries and brain injuries, these studies not only being time-consuming in collecting medical histories of the

---

* Corresponding authors at: Department of Mechanical Engineering, National University of Singapore, 9 Engineering Drive 1, 117576 Singapore. Tel.: +65 65168934 (Tse, KM)/65162235 (Lee, HP).
E-mail addresses: tsekm.research@yahoo.com, tsekm@nus.edu.sg (K.M. Tse), mpeleehp@nus.edu.sg (H.P. Lee).

http://dx.doi.org/10.1016/j.aap.2015.03.012
0001-4575/© 2015 Elsevier Ltd. All rights reserved.

population over a long period of time, but also raised concerns such as conflicting and biased data due to population samples and non-standardized methodologies. Finite element analysis (FEA) offers a cost-effective alternative in modern scientific investigations of traumatic situations through numerical simulations in a virtual environment. FEA has becoming increasingly popular in the biomedical field, particularly in investigations on biomechanical simulations of traumatic brain injury (TBI) (Ruan et al., 1994; Kleiven and Hardy, 2002; Horgan and Gilchrist, 2004; Willinger and Baumgartner, 2003; Mao et al., 2013). Besides the 50th percentile Wayne State University Brain Injury Model (WSUBIM) (Ruan et al., 1994; Mao et al., 2013) and the established Global Human Body Models Consortium (GHBMC) (Global Human Body Models Consortium, 2007), with the recent advance of medical images based modeling techniques, a number of finite element (FE) studies using patient-specific head models have been performed in investigating maxillofacial injuries (Autuori et al., 2006; Wanyura et al., 2011; Schaller et al., 2012) and TBI (Ho et al., 2009; Chen and Ostoja-Starzewski, 2010; Bar-Kochba et al., 2012; Wright et al., 2013). Nevertheless, with the variations in primary focus, these previous FE head models are inappropriate for analyses of concomitant facial and brain injuries as either the facial skeletal features were oversimplified (Ruan et al., 1994; Kleiven and Hardy, 2002; Horgan and Gilchrist, 2004; Willinger and Baumgartner, 2003) or both the mandible and the intracranial contents which constitute approximately one-third of the head's mass (Saladin, 2007) were completely neglected (Autuori et al., 2006; Wanyura et al., 2011; Schaller et al., 2012). In contrast to the clinical importance mentioned previously, there has been, to the authors' knowledge, no FE study regarding investigation of the association of brain injuries with facial trauma.

In the present study, a subject-specific FE model of human head, with detailed anatomical features in its intracranial and extracranial contents, is employed and used to simulate nine common impact scenarios of facial injuries. Evaluation and analyses of the nine scenarios, in terms of the biomechanical parameters of the skeletal skull and intracranial tissues, are performed to determine whether facial injury is associated with severity of TBI. Also, investigation of the association of the TBI with its mechanisms following facial trauma would be conducted, with the individual stress wave propagation paths to the intracranial contents through the facial and cranial skeleton being discussed thoroughly.

2. Methods and materials

2.1. FE head model

In our study, geometrical information of the human skull and brain were obtained from axial computed tomography (CT) and magnetic resonance imaging (MRI) images, with high in-plane resolutions, of a middle-aged male subject (Fig. 1a–c). These medical images were imported into Mimics v13.0–v14.0 (Materialise, Leuven, Belgium) for segmentation and reconstruction of the FE model of human head and brain, which comprises a cranial skull with detailed facial bone features, teeth, cervical vertebrae, nasal septal cartilage, nasal lateral cartilages; brain tissues as well as the cerebrospinal fluid (CSF) separating the skull and the brain (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 1.35 mm and aspect ratio of 1.75. The entire FE model of human head, weighing 4.82 kg, consists of 483,719 nodes and 403,176 linear hexahedral elements. Further details on the development of the model can be referred to Tse et al. (2014). All the above mentioned nine impact simulations were performed using the explicit codes in Abaqus v6.10 (SIMULIA, RI, USA) with a 8-cores workstation and each simulation takes approximately 2–3 days to run. It should be noted that this subject-specific head model had been validated against three cadaveric experiments (Tse et al., 2014), whereas one of which was the experimental impact on frontal bone in Nahum's et al. (1977) study. Following Mao's et al. (2013) validation of the skull, the present study employed this FE skull–brain model without facial tissues to replicate various blunt impact locations such as nasal bone, maxillary bone and mandibular bone in Cormier's (2009) experimental work on the cadaveric heads with facial fresh. All the impact force histories were found to agree well with Cormier's (2009) experimental work except for that of the mandible impact (Fig. 2).

2.2. Material properties

From the biological perspectives, bone is microscopically considered as a complex, multiphasic, heterogeneous and anisotropic structure (Doblaré et al., 2004). However, most previous FEHMs considered it to have homogeneous and isotropic behavior

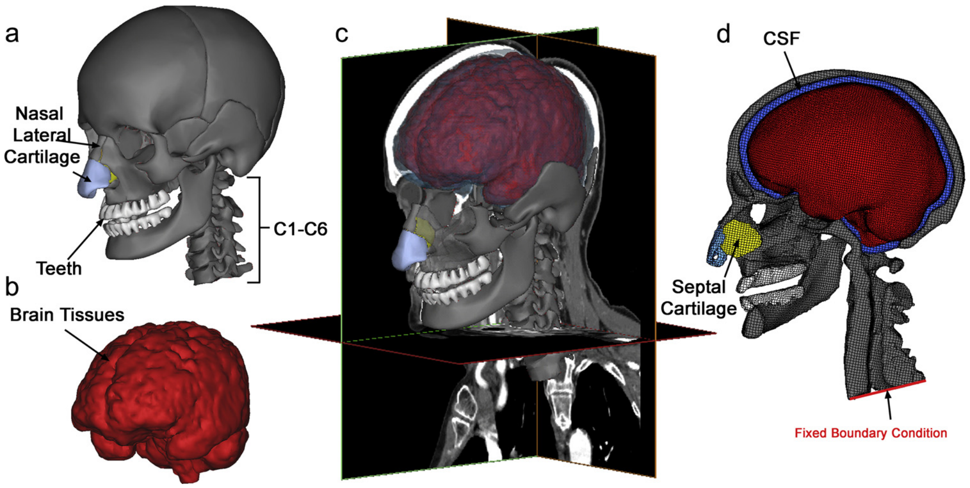

Fig. 1. Various components of a subject-specific model of (a) human skull and (b) brain segmented from (c) CT and MRI data by Mimics. (d) The meshed model on the right shows the mid-sagittal view of the skull and CSF except the brain.