Journal of Biomechanics 43 (2010) 2887–2896

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Study of an infant brain subjected to periodic motion via a custom experimental apparatus design and finite element modelling

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ARTICLE INFO

Article history:
Accepted 19 July 2010

Keywords:
Shaken baby syndrome
Head injury
Experimental apparatus
Finite element
Fluid structural interaction (FSI)
Brain–skull interface
Anterior fontanelle
Arbitrary-Lagrangian–Eulerian (ALE)

ABSTRACT

This paper presents a rig that was specifically designed to simulate the shaking of mechanical models of biological systems, especially those related to shaken baby syndrome (SBS). The scope of this paper includes the testing of an anthropomorphic model that simulates an infant head and provides validation data for complex finite element (FE) modelling using three numerical methods (Lagrangian, Arbitrary-Lagrangian–Eulerian (ALE) and Eulerian method) for fluid structure coupling.

The experiments for this study aim to provide an understanding of the influence of two factors on intracranial brain movement of the infant head during violent shaking: (1) the specific paediatric head structure: the anterior fontanelle and (2) the brain–skull interface.

The results show that the Eulerian analysis method has significant advantages for the FSI modelling of brain–CSF–skull interactions over the more commonly used methods, e.g. the Lagrangian method. To the knowledge of the authors, this methodology has not been discussed in previous publication.

The results indicate that the biomechanical investigation of SBS can provide more accurate results only if the skull with paediatric features and the brain–skull interface are correctly represented, which were overlooked in previous SBS studies.

1. Introduction

Shaken baby syndrome (SBS) is a form of child abuse caused by violent shaking. Almost 200 babies in the UK die annually from injuries related to SBS, whereas twice that number of babies survive with permanent brain damage or visual impairment.

An early biomechanical study of SBS focused on measuring the shaking acceleration by using either a dynamic rigid anthropomorphic shaking dummy (Duhaime et al., 1987; Prange et al., 2003; Cory and Jones, 2003) or mathematical dynamic modelling (Wolfson et al., 2005). However, the results are contradictory to pathological evidence. The explanation of the mechanism of injury remains unknown (Goldsmith and Plunkett, 2004; Shannon and Becker, 2001; Ommaya et al., 2002).

Meanwhile, a considerable number of experimental studies was performed related to impact head injuries. Margulies et al. (1990, 1992) constructed mid-sagittal plane skull models that were excited by traffic collision whiplash to study the diffused axonal injury (DAI). Ivarsson et al. (2000) constructed a physical model of a parasagittal human head to establish whether cerebral ventricles could relieve the shearing deformation to protect the brain from rotational injury. Bradshaw et al. (2001) created a model of a coronal plane to investigate the DAI induced by coronal impacts. Finite element (FE) methods were also used to model head injury. Kleiven and Holst (2002) studied the size of the head and intracranial response under impact loading by using a 3D FE model. Margulies and Thibault (2000), Lapeer and Prager (2001) and Cheng, et al. (2005) used an FE model to demonstrate that an infant's skull with fontanelle shows a significantly larger cranial deformation and stress distribution to the brain. Additionally, an FE study by Omori et al. (2000) indicated that the protruded vasculature tissue inside of the CSF affected the stress distribution on the brain surface during rotational loading. However, a combination of the experimental testing and FE modelling has not been previously reported for the study of SBS.

The aim of the present study is to investigate an innovative test apparatus and to compare reliable test data to FE models for the study of SBS. The motion of an infant brain is explored with and without anterior fontanelle (Fig. 1) and its protrusion into the fluid. The FE modelling of the brain–skull interface was compared to the traditional Lagrangian algorithm and the fluid–structure–interaction (FSI).

2. Experiment methodology

2.1. Description of method

Fig. 2 shows the configuration of the experiment and the numerical simulation. The method consisted of the design of the experimental apparatus and the anthropomorphic infant head models with an open circle covered with membrane, which is used to simulate the anterior fontanelle. The FE models were

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0021-9290/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jbiomech.2010.07.023

used to validate the test results, and the experimental output (displacement vs. time) was used as input to the models.

Table 1 shows the results from the experiment and the FE models. For simplicity, the experimental models consisted of only the anterior fontanelle, CSF, skull and brain. To result in a meaningful evaluation of the fontanelle and the fluid boundary, four difference scenarios (Fig. 2) were considered. First, a "restrained open" model consisted of an initial pre-stretch on the membrane and a protrusion inside of the fluid. Second, a model consisted of a loose membrane and a protrusion inside the fluid. Third, an ideal model consisted of a loose membrane and no protrusion inside the fluid. Finally, a model consisted of a fully enclosed structure with neither membrane nor protrusion. In each of the scenarios, the brain–skull interface was modelled by using three numerical coupling methods: Lagrangian, ALE and Eulerian algorithm.

The experimental model provided a comparison between the first and final scenarios, whereas the FE model extended the comparison to all four of the scenarios.

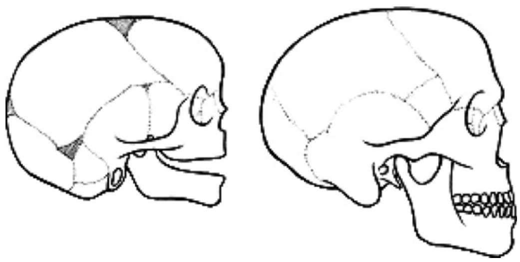

Fig. 1. The difference in size and proportions of the infant and adult skulls (Berkovitz and Moxham, 1988). The infant on the left has a fontanelle on the top of the skull.

2.2. Experimental apparatus

The rig simulates the shaking of mechanical models related to SBS. The experimental apparatus consists of three units (Figs. 3 and 4). Their objectives are given as follows:

- Dynamic shaking unit: to provide a stable and adjustable linear repetitive motion to mimic the observations from a dummy shaken by the volunteer adults.

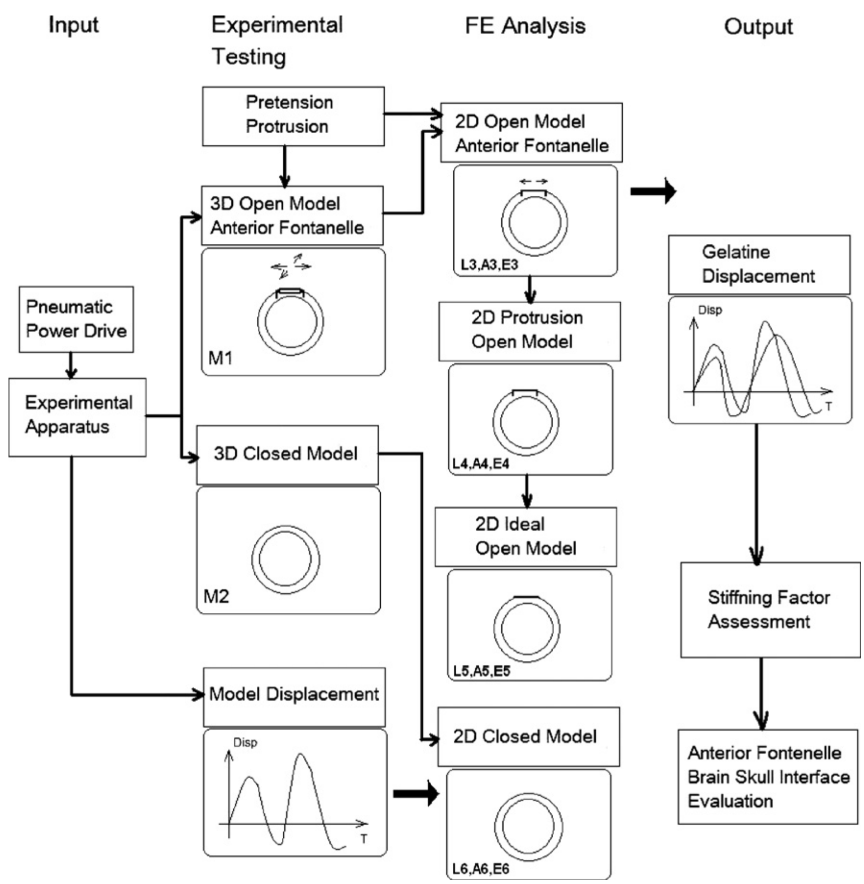

Fig. 2. The flow chart of the experimental test and simulation procedure.

Table 1
The experimental and FE model of Lagrangian, ALE and Eulerian coupling.

Test or FE	Model			Paediatric features	Stiffening factors	Representation of infant head
Test	M1			Fontanelle	Pre-stress and protrusion	Stiff infant head
	M2			Closed	–	Closed scaled adult skull
FE	LAG	ALE	EUL			
	L3	A1	E1	Fontanelle	Pre-stress and protrusion	Stiff infant head
	L4	A2	E2	Fontanelle	Protrusion only	Partial stiff infant head
	L5	A3	E3	Fontanelle	No	Ideal flexible head
	L6	A4	E4	Closed	–	Closed scaled adult skull