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Development/global validation of a 6-month-old pediatric head finite element model and application in investigation of drop-induced infant head injury

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ABSTRACT

Drop is a frequent cause for infant head injury. To date, finite element (FE) modeling was gradually used to investigate child head dynamic response under drop impact conditions, however, two shortages still exist on this topic: (1) due to ethical reasons, none of developed 6-month-old (6MO) head FE model was found to be quantitatively validated against child cadaver tests at similar age group; (2) drop height and impact surface stiffness effects on infant head responses were not comprehensively investigated. In this study, motivated by the recently published material properties of soft tissues (skull and suture, etc.) and reported pediatric head global cadaver tests, a 6MO child head FE model was developed and simulated results compared with the child cadaver experimental data under compression and drop conditions. Comparison of results indicated that the FE model showed a fairly good biofidelic behavior in most dynamic responses. The validated FE model was further used to investigate effects of different drop heights and impact surface stiffness on the head dynamic responses. Numerical results show that the pediatric head mechanical parameters (peak acceleration, HIC, maximal vonMises stress and maximal first principal strain of skull) keep increasing with the increase in drop height, and exhibit "logarithmic function" shapes at "fast–slow" trends with increase in impact surface stiffness. Based on above analysis, the regressions were conducted to describe the relationship between drop height and impact surface stiffness and head global injury predictors (head peak acceleration, HIC, etc.). This paper provides a fundamental study of child head injury mechanism and protection under drop conditions.

1. Introduction

Head injury is the leading cause of pediatric fatality and disability in the United States [1–4], in which drop/fall is one of the most frequent causes [5,6]. Finite element (FE) modeling has already been widely used to investigate the dynamic response of the adult head due to blunt impact. However, compared with the developed adult head FE models appeared in the literature, there are only a few 3D pediatric head FE models. Lapeer and Prager [7] developed an infant head FE model to simulate skull deformation during birth process. A 6MO head

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FE model developed by Klinich et al. [8] was used to investigate the skull injuries in reconstructing accidents that the infant sitting in rear-facing child restraint system (CRS) suffered from airbag deployment during motor vehicle crashes. Roth et al. [9,10] developed a 6MO child head model to simulate brain injuries due to shaking and impact conditions. The same research group also developed a 3-year-old [11,12] and a 17-day-old child head models [13], in which the 3YO child head model was mainly used to compare the intracranial injury metrics differences between this 3YO model and a scaled adult head model [11], and the 17-day-old model was used to simulate the pediatric skull fracture in reconstructing the real world head traumas [13]. Coats et al. [14] constructed a 1.5MO head FE model and conducted a parametric study to investigate the relative importance of brain material properties and the anatomical variations in suture and scalp on head responses under drop conditions. This model was also used to reproduce Weber's cadaver drop tests [15,16] resulting in bone fracture. Li et al. [17,18] developed a parametric pediatric head FE model and morphed a baseline model to a newborn, a 1.5MO, and a 3MO head model, in which only the newborn head FE model was validated against cadaver experiment. Parametric study was conducted on the material properties of different components to determine their respective parametric values that had significant effects on head response. Ruan et al. [19] developed a 6-year-old child head model based on a specific subject, but this model was only "validated" by comparing the head response with the adult cadaver test data under similar impact conditions.

Weber [15,16] dropped 50 children aged from 0 to 9 month old onto 5 different impact surfaces under the drop height of 82 cm, which provided valuable information for studying the skull fracture mechanism and criteria. However, no quantitative data, such as head acceleration and contact force were collected from the tests, and only the skull fracture patterns were reported in that study.

Even the aforementioned pediatric head FE models provided encouraging results for investigating child head injuries, only the 17-day-old (newborn) child head model developed by Roth et al. [13] and the newborn head FE model from Li et al. [17,18] were quantitatively validated against cadaver experimental data from corresponding age group. None of 6MO pediatric head models found in the literature was validated by cadaver test data from similar age group. Even drop is one of the most frequent causes for infant head injury; the effects of drop height and impact surface stiffness on child head injury were not comprehensively investigated in the literature. Therefore, the objectives of this study are: (1) to develop a biofidelic 6MO child head FE model based on the CT scans and validate it against the child cadaver experimental data at similar age groups; (2) to investigate the effects of drop height and impact surface stiffness on the head dynamic responses using this validated 6MO head FE model.

2. Model development

2.1. Head geometry

The geometries of different components of the present head FE model were extracted from an early version of the 6MO head FE model constructed by Klinich et al. [8]. The extracted surfaces of skull, suture, scalp, brain, dura, etc. were saved in iges format files and were imported into TrueGrid or Hypermesh software to conduct meshing. The extracted head geometries were remeshed with only high quality hexahedral solid elements and quadrilateral shell/membrane elements. The newly added components, pia, falx, and tentorium, were implanted into this model as shown in Fig. 2 and the brain was approximately divided into cerebrum, cerebellum, and brainstem according to the anatomical atlas. In addition, material properties of different components were updated as described in the section of Material properties.

The geometry in the previous model by Klinich et al. [8] was reconstructed from CT scans of a 27-week-old subject. No head trauma or skull abnormality was found after examination on the CT by a pediatric radiologist. The head breadth, head length, ear to top-of-head distance of the head CT were measured and compared with the statistical data from Schneider et al. [20], showing that this head model was within the normal range of head dimensions for this age group and can then be considered as a representative of a normal 6MO child. The detailed geometry information of this head can be found in the study of Klinich et al. [21].

2.2. Meshing

In this study, an inside-to-outside meshing procedure was adopted to mesh different components of the head geometry as shown in Fig. 1.

In order to obtain high quality meshes, first, the irregular brain volume was meshed with only hexahedral elements using TrueGrid 2.3.4 software (XYZ Scientific Application Inc., California), which is a specialized mesh generation software for the geometry with complex shape. The butterfly topology approach combined with the multi-block and projection strategies were adopted during meshing [22]. All the meshing work on brain was carried out using the commands scripts in TrueGrid. Then, the brain meshes were exported to the Hypermesh (Altair Engineering Inc.) as the basis to mesh other components outside the brain. The pia mater, cerebrospinal fluid (CSF), dura mater, skull and suture, and scalp were meshed respectively in sequence. The pia and dura mater were meshed with membrane elements with the thickness of 0.5 mm, CSF was meshed with solid elements with the thickness of 1.5 mm, and the skull (including face bone), suture, as well as the scalp were meshed with thick shell elements. The thickness of skull & suture were non-uniform, which were directly extracted from Klinich's head FE model, and the thickness of scalp was assumed constant with the value of 2 mm. As a result, there are 50,404 hexahedral solid and quadrilateral shell elements and 42,575 nodes in this model. Jacobian is a comprehensive criterion to evaluate the mesh quality. The Jacobian value ranges from −1.0 to 1.0, where 1.0 represents a perfectly shape element, as the element becomes more distorted, the Jacobian value approaches zero. The minimal jacobian of elements in this model was greater than 0.4 and 0.7 for solid and shell elements respectively.

The primary anatomical components constructed in this model include brain, craniums (frontal, parietal, occipital, and bascranium craniums), sutures (sagittal, coronal, squamous,