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Development of a child head analytical dynamic model considering cranial nonuniform thickness and curvature – Applying to children aged 0–1 years old

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ABSTRACT

Background and objective: Although analytical models have been used to quickly predict head response under impact condition, the existing models generally took the head as regular shell with uniform thickness which cannot account for the actual head geometry with varied cranial thickness and curvature at different locations. The objective of this study is to develop and validate an analytical model incorporating actual cranial thickness and curvature for child aged 0–1YO and investigate their effects on child head dynamic responses at different head locations.
Methods: To develop the new analytical model, the child head was simplified into an irregular fluid-filled shell with non-uniform thickness and the cranial thickness and curvature at different locations were automatically obtained from CT scans using a procedure developed in this study. The implicit equation of maximum impact force was derived as a function of elastic modulus, thickness and radius of curvature of cranium.
Results: The proposed analytical model are compared with cadaver test data of children aged 0–1 years old and it is shown to be accurate in predicting head injury metrics. According to this model, obvious difference in injury metrics were observed among subjects with the same age, but different cranial thickness and curvature; and the injury metrics at forehead location are significant higher than those at other locations due to large thickness it owns.
Conclusions: The proposed model shows good biofidelity and can be used in quickly predicting the dynamics response at any location of head for child younger than 1 YO.

1. Introduction

Head injury is a leading cause of death or disability in young children [1,2]. The main causes of head injury are vehicle crashes, accidental falls, abuse etc., most of which are the impact-induced injuries [3]. Therefore, investigating young children's head dynamic response under impact condition is an important topic. Currently, the common methods are cadaver or volunteer experiment [4,5], Anthropomorphic Test Devices (ATD) tests [6,7], finite element (FE) simulation [8–13] and analytical model [14–18]. Among them, the analytical model has the advantage of quickly predicting the head global dynamic responses under varied impact scenarios [18].

In previous studies, Anzelius [14] first proposed a head analytical model that considered the human head as a rigid spherical shell filled with non-stick liquid. This model was further improved in Engin's study by assuming the head to be a fluid-filled elastic spherical shell [15]. Young [18] developed an analytic model of a spherical shell impacting with a solid sphere through combining the Hertzian contact stiffness and the shell contact stiffness. Based on Young's study, Heydari and Jani [16] assumed human head as an ellipsoidal shell to approximately reflect the variation of the curvature and compared the dynamic responses of ellipsoidal shell model with the original spherical shell model. Li et al. [17] further revised Young's model by adding energy loss terms. The model was used to analyze the blunt impact of a human head on the ground or an automobile and two football player's head collision. The dynamic responses predicted by the theory model are general consistent with the results of existing FE simulations.

Although above analytical models have provided encouraging results on investigating head dynamic responses under impact condition, none of the existing models can take the actual cranial thickness and curvature into consideration. Therefore, the primary

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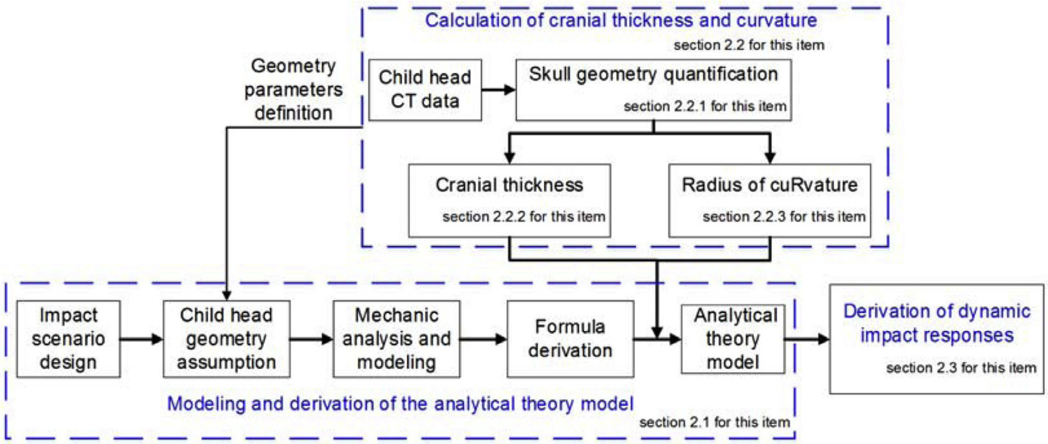

Fig. 1. Procedure of developing child head analytical model considering cranial thickness and curvature.

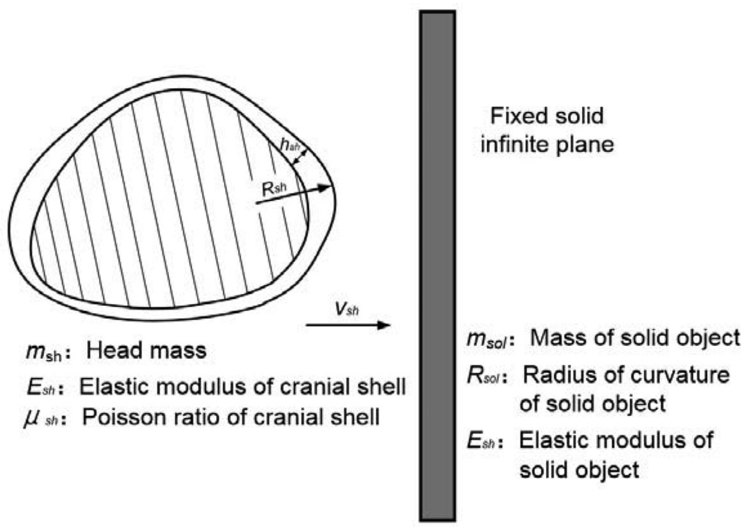

Fig. 2. Scenario of child head impacting with a fixed rigid plane at speed of v_{sh}.

motivation of the work is to (1) derive the impact force implicit equation as a function of cranial elastic modulus, thickness and radius of curvature etc.; (2) establish a procedure of accurately calculating the actual cranial thickness and curvature at any location from child head CT scans; (3) develop an analytical model incorporating actual cranial thickness and curvature for child aged 0–1YO and validate it against cadaver test result; (4) investigate the effect law of elastic modulus, cranial thickness and radius of curvature on child head dynamic response and the response variations at different head locations.

2. Methods

The procedure of developing child head analytical model considering cranial thickness and curvature are shown in Fig. 1. It primarily includes three parts: modeling and derivation of the analytical model, calculation of actual cranial thickness and curvature at any impact location and derivation of head dynamic impact responses.

2.1. Modeling and derivation of the analytical theory model

The analytical model in our study was to simulate the impact scenario of child head impacting with a fixed rigid plane at a speed of v_{sh}as shown in Fig. 2. According to Young [18], the cranial bone plays the most important role on the impact force and deformation and the influence of the bulk modulus of the inner fluid can be ignorable. However, it should be noted that the impact energy are still directly related with the fluid-filled mass [17], thus the child head was simplified into a fluid-filled irregular shell with the head mass m_{sh}. The thickness, radius of curvature (reciprocal of curvature), elastic modulus, and Poisson ratio of the irregular shell were denoted ash_{sh}, R_{sh}, E_{sh}, μ_{sh} respectively. The fixed solid object was assumed as an infinite rigid plane, in which the mass, radius of curvature, and elastic modulus were denoted as m_{sol}, R_{sol}, and E_{sol}, respectively.

Based on the theory of contact mechanics and energy conservation, the initial kinematic energy transformed into the Hertzian deformation energy, global shell deformation energy, and the residual shell bounding kinematic energy.

- Hertzian contact stiffness

In Hertz contact, the relationship between force and deformation was given as [19],

$$F_{\max} = k_H \Delta x_H{}^{3/2} \tag{1}$$

where $F_{\max}$ is the maximum force during impact, Δx_H is the summation of the deformations of the two objects, and k_H is the Hertzian contact stiffness expressed as,

$$k_H = \frac{4}{3} R^{*1/2} E^* \tag{2}$$