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# Numerical simulations of the 10-year-old head response in drop impacts and compression tests

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A B S T R A C T

*Background and objective:* Studies on traumatic injuries of children indicate that impact to the head is a major cause of severe injury and high mortality. However, regulatory and ethical concerns very much limit development and validation of computer models representing the pediatric head. The purpose of this study was to develop a child head finite element model with high-biofidelity to be used for studying pediatric head injury mechanisms.

*Methods:* A newly developed 10-year-old (YO) pediatric finite element head model was limitedly validated for kinematic and kinetic responses against data from quasi-static compressions and drop tests obtained from an experimental study involving a child-cadaver specimen. The validated model was subsequently used for a fall accident reconstruction and associated injury analysis.

*Results:* The model predicted the same shape of acceleration–time histories as was found in drop tests with the largest discrepancy of −8.2% in the peak acceleration at a drop height of 15 cm. Force–deflection responses predicted by the model for compression loading had a maximum discrepancy of 7.5% at a strain rate of 0.3 $s^{-1}$. The model-predicted maximum von Mises stress ($\sigma_v$) and principal strain ($\varepsilon_p$) in the skull, intracranial pressure (ICP), maximum $\sigma_v$ and maximum $\varepsilon_p$ in the brain, head injury criterion (HIC), brain injury criterion (BrIC), and head impact power (HIP) were used for analyzing risks of injury in the accident reconstruction.

*Conclusions:* Based on the results of the injury analyses, the following conclusions can be drawn: (1) ICP cannot be used to accurately predict the locations of brain injury, but it may reflect the overall energy level of the impact event. (2) The brain regions predicted by the model to have high $\sigma_v$ coincide with the locations of subdural hematoma with transtentorial herniation and the impact position of an actual injury. (3) The brain regions with high $\varepsilon_p$ predicted by the model coincide with locations commonly found where diffuse axonal injuries (DAI) due to blunt-impact and rapid acceleration have taken place.



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## 1. Introduction

Traumatic head injury has become one of the most severe threats to children's lives, due to its high incidence and fatality rate. In the U.S., approximately 19% of all traumatic pediatric deaths result from head injury [1], as do approximately 75% of trauma-related hospitalizations of children [2]. Early-age head injuries may lead to mental problems that can last for a lifetime, and this brings heavy burdens to families and society. Additionally, it has been reported that at similar impact loading conditions, children will sustain more severe injury outcomes than adults [3]. Therefore, studies on pediatric head injury mechanisms and corresponding protective means have been popular in recent years.

Mechanisms of injury for children's heads are different from those of adults, and information for adequate description of these differences has been insufficiently available and difficult to obtain. While a number of studies using cadaveric tests and computer simulations have been conducted to elucidate mechanisms of injury in adult heads subjected to falls, impacts, and blast waves [4–10], ethical concerns have limited the availability of child-cadaver specimens for the same types of tests. In the available literature published since 1980, there have been only six experimental studies on the mechanical responses of pediatric heads. Included in these studies are tests conducted by McPherson and Kriewall [11], Margulies and Thibault [12], and Davis et al. [13], which focused on the properties of pediatric cranial bones, and tests by Weber [14,15], Prange et al. [16], and Loyd [17], which focused on overall head responses.

Despite difficulties in obtaining sufficient numbers of cadaveric specimens of children, great progress has been made in the development of numerical models of pediatric heads representing children of many ages. To date, a number of reports have been published regarding models representing heads of infants and children from 0 to 3 years of age. For example, Klinich et al. [18] built a finite element model (FEM) representing the head of a 6-month-old (MO) infant. This model was used for investigation of skull injuries incurred during usage of backward child-restraint systems. To study brain injuries due to shaking, falling, and impact, Roth et al. [19–21] developed a series of FEMs for children 17 days, 6 months, and 3 years of age. Li et al. [22] used principal component analysis and regression analysis to establish parameterized geometric models representing the heads of newborn, 1.5-MO, and 3-MO infants. These models could be applied in studies of accident reconstructions. The same authors developed a model representing the head of a 6-MO to analyze young children's injuries due to falls [23].

Mizuno et al. [24] constructed a 3-year-old (YO) full-body FE model with a rigid head by scaling the 50th percentile-adult model of the Total Human Model for Safety (THUMS). Using CT images, Ruan et al. [25] developed a 6-YO, full-body model that included a head with anatomical details. To the best of our knowledge, no head models for 9- to 15-YOs are available. Within this age range, the sizes of the heads of 12- to 15-YO children are similar to those of fifth-percentile females. Thus, 12- to 15-YO pediatric heads can be approximated by using the fifth-percentile female model, such as the THUMS 5th percentile female model and the female model being developed by the Global Human Body Modeling Consortium (GHBMC).

Heads for 9- to 11-YO children cannot be replaced by heads of children of other ages nor of adults. Furthermore, 9- to 11-YO children have higher chances of injury during traffic accidents. Knowledge of this higher incidence has resulted in particular regulations regarding testing and protective means for this age group [26]. Therefore, there is a great need for a high-biofidelity head model representing 9- to 11-YO children.

To improve the safety of children in the aforementioned age range, Wayne State University (WSU), under a financial sponsorship of Toyota Motor Corporation, developed a high quality, 10-YO full-body FEM, which was named Collaborative Human Advanced Research Model-10 YO (CHARM-10). Models for some of the main body parts, such as the neck, chest, and extremities, have been validated [26–28]. However, validation for the head model remains incomplete. In this study, the mechanical responses of the CHARM-10 head FEM were validated against results obtained from compression and drop tests on cadaveric specimens in the age range of 9 to 10 years. Additional analyses were conducted regarding injuries predicted by the model in drop-loading conditions.

## 2. Methods

### 2.1. *The finite element model*

The CHARM-10 head model used in this study was based on the model originally developed at WSU [29–31]. The dimensions of the head (perimeter, length, width, height, and brain volume) were compared with statistical data reported by Dekaban [32] as shown in Table 1. From this table, one can see that the key dimensions of the model closely match Dekaban's data. The largest discrepancy is in the head width, where the difference is 2%. Such a slight discrepancy demonstrates that the model can well represent the geometric features of a 10-YO child.

A multi-block approach, achieved through an edge projection method, was used for the original model developed at WSU. The curved contours of brain surfaces observed in clinical images were simplified with flat surfaces formed by grid lines, as shown in Fig. 1(a). The mesh generated from these grids, shown in Fig. 1(b), has the same flat surfaces as observed in the blocks. The current study is based on an approach

**Table 1 – Comparisons of measurements of 10-YO heads with reported anthropometric data for 9- to 10-YO children [32].**

| Head region | Perimeter (cm) | Length (cm) | Width (cm) | Height (cm) | Brain volume (cm$^3$) |
|---|---|---|---|---|---|
| 10-YO model | 52.8 | 18.3 | 14.1 | 12.1 | 1369 |
| Anthropometric external dimensions (9- to 10-YO) | 53.5 | 18.6 | 14.4 | 12.3 | 1384 |
| Deviation (%) | −1.3 | −1.6 | −2.0 | −1.6 | −1.0 |