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# Development of a Paediatric Head Model for the Computational Analysis of Head Impact Interactions

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***Abstract*****—**Head injury in childhood is a common cause of death or permanent disability from injury. However, despite its frequency and significance, there is little understanding of how a child's head responds during injurious loading. Whilst Infant Post Mortem Human Subject (PMHS) experimentation is a logical approach to understand injury biomechanics, it is the authors' opinion that a lack of subject availability is hindering potential progress. Computer modelling adds great value when considering adult populations; however, its potential remains largely untapped for infant surrogates. The complexities of child growth and development, which result in age dependent changes in anatomy, geometry and physical response characteristics, present new challenges for computational simulation. Further geometric challenges are presented by the intricate infant cranial bones, which are separated by sutures and fontanelles and demonstrate a visible fibre orientation. This study presents an FE model of a newborn infant's head, developed from high-resolution computer tomography scans, informed by published tissue material properties. To mimic the fibre orientation of immature cranial bone, anisotropic properties were applied to the FE cranial bone model, with elastic moduli representing the bone response both parallel and perpendicular to the fibre orientation. Biofiedility of the computational model was confirmed by global validation against published PMHS data, by replicating experimental impact tests with a series of computational simulations, in terms of head kinematic responses. Numerical results confirm that the FE head model's mechanical response is in favourable agreement with the PMHS drop test results.

***Keywords*****—**Finite element analysis, impact simulation, infant head trauma, material properties, post mortem human subjects.

## I. Introduction

TRUMATIC brain injury (TBI), as a result of a fall or motor vehicle interaction is the leading cause of death and permanent disability from injury in the paediatric population [1], [2]. The causes of paediatric traumatic events are typically characterised as 'accidental' or 'non-accidental' and an ability to make early diagnoses will help to inform clinical management and develop injury prevention strategies. Currently, one of the most significant challenges is discriminating between accidental fall related head injuries and physical abuse.

FE analysis has become an effective way to study head injury mechanics and evaluate head injury risk. There is a significant disparity between the number of paediatric and adult FE models head where those of adult [3]-[10] used to investigate the neurological injuries and the presence of skull fracture, however, with paediatric FE model these analysis are very limited.

Paediatric head FE model development is constrained by the limited availability of material property data, quantitative age-dependent anatomical data and paediatric impact response data. The biofidelity of the FE head model, subjected to impact loading, requires validation from impact response data acquired by experimental impact testing on PMHSs, which is also limited.

With regard to the adult head, there are several experimental studies, which are used to validate the adult FE head models, providing pressure [11], brain displacement [12] and skull fracture [13] correlations. However, due to social and ethical concerns, there is a limited number of child head cadaver experiments used to investigate head injury mechanics and the material properties of the complex paediatric head tissues.

This study aims to develop and validate a previously constructed FE paediatric head model [14] to improve its biofidelity by producing orthotropic structures with characteristic anisotropic properties and an optimised FE mesh refinement to produce accurate results, whilst requiring the minimum computational time. The FE head model will be subjected to global validation against paediatric published PMHS impact response data, by implementing a series of computational simulations that replicate the experimental impact tests in terms of head kinematic responses.

## II. Paediatric Head Model Development

### A. Data Set and Geometrical Acquisition

The geometric model developed in this work is based on a previous model by Khalid et al. [14], from high-resolution computerised tomography (CT) scans of a 10 day old infant selected to represent the skull geometry of the cranial bones (parietal, occipital, and frontal bones) with sutures and fontanelles using Mimics Software (Materialise; Leuven, Belgium). Mimics software uses grey scale values from CT scans to segment the model into regions by defining a threshold value. Different segmentation tools were used to mask the parts of the infant's head based on the different

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threshold values of these parts. However, some parts, for example the fontanelle and sutures, had grey scale values close to other parts, thus, requiring more advanced segmentation tools. Mimicking the PMHS tests, the cervical vertebrae and mandible were discarded. The reconstructed three dimensional (3D) computer-aided design (CAD) head model was meshed successfully with Mimics remesher (3-matic v10) for use in a FE analysis solver. Mesh convergence was used to ascertain the solution convergence of the FE head model. A number of high quality second order tetrahedral elements, shown in Fig. 1, were used to provide accurate results with minimal computational time.

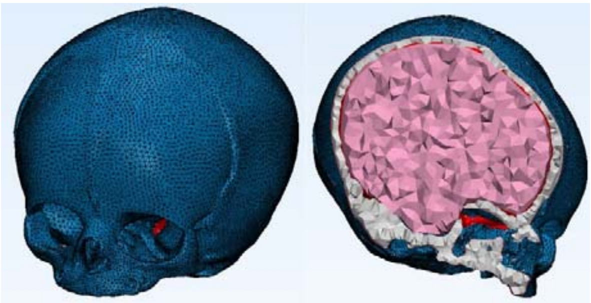

Fig. 1 Major tissues within the paediatric head

*B. Material Properties*

To improve the geometric configuration and physical response biofidelity of the paediatric FE head model, the meshed FE head model [14] utilised low strain rate material data from infant specimens to provide a “real” physical response for complex head tissues. The tissue data were obtained from Coats & Margulies [15]. This FE head model, shown in Fig. 2, overcame previous limitations [8], [9], [16] using homogenous and isotropic material properties to provide validation with PMHS tests [19]. However, McPherson & Kriewall [17] reported the orthotropic fibre orientation as a key anatomical feature in the cranial bones. Furthermore, to confirm McPherson & Kriewall's [17] findings, the experimental material testing of parietal and occipital bones showed a difference in stiffness properties [15]. Given the variance in the elastic modulus between fibres of parallel and perpendicular specimens, the cranial bones of the FE head model were given an orthotropic response, in the direction of fibre orientation. The sutures of the FE head model were modeled as elastic-isotropic [15] and the brain modeled as a gelatin substance [18].

*C. FE Simulation*

This study exploits the greater availability of software that converts radiological images into 3D computer models. Mimics was used to produce a CAD model, which was subsequently exported as a stereolithography (STL) file by Mimics re-mesher and then meshed utilising the various mesh types and sizes available to run successfully in an FE software.

Abaqus/Explicit 6.12 (Dasault Systèmes, Vélizy-Villacoublay, France) used as a FE solver, where the meshed FE head model was imported and assigned material properties, according to built-in material models for different parts of the head model as reported in Khalid et al. [14]. General contact sliding, with a frictional contact coefficient of 0.2 [6], was applied for the interaction between the FE model and rigid plate [14]. The interaction between head tissues was implemented using tie constraints.

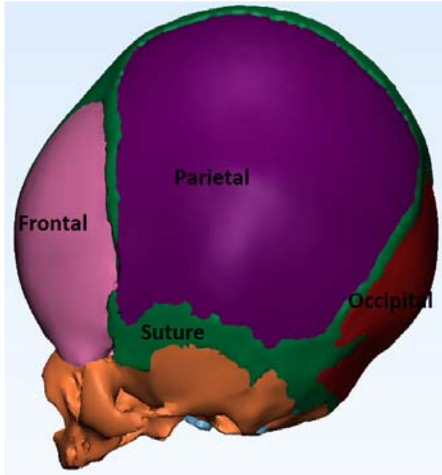


Fig. 2 Major structures of the skull demonstrate different material properties

## III. Paediatric Head Model Validation

*A. Post Mortem Human Subject Tests*

Prange et al. [19] performed drop and compression loading tests on paediatric PMHSs aged 1, 3 and 11 days old. During the drop tests, the infant’s heads were dropped onto a hard flat steel uniaxial force plate at five different locations (vertex, occiput, forehead, left and right parietal) from two different heights, 0.15 and 0.3 m. Prior to testing, the cranial cavity was filled with water and sealed, the mandible was removed and the head assumed to be symmetrical [19]. From the different impact tests, impact force was measured and acceleration was calculated, to provide the first mechanical response data from a paediatric PMHS. After completion of the tests, dissection and visual inspection determined that no skull fracture or permanent deformation was produced. The calculated average peak acceleration and Head Injury Criterion (HIC) were not significantly different across all impact locations [19].

*B. FE Model Validation under Impact Drop Conditions*

The previously constructed infant FE head model [14] was validated against the findings of the PMHS drop tests [19], by simulating the test methodology. The model was subjected to a series of simulated impacts onto a hard flat steel uniaxial force plate at five different locations (vertex, occiput, forehead, left and right parietal) from two different heights, 0.15 and 0.3 m. The initial velocity of the FE head model was 1.715 m/s and 2.425 m/s, in accordance with the drop heights reported in the Prang’s study [19] by using the acceleration due to gravity and Newton’s laws of motion, which is outlined in (1):

$$V = \sqrt{2gh} \tag{1}$$

where $V$ is the impact velocity, $g$ is the gravitational acceleration and h is the impact height. During the FE simulation, the numerical acceleration was also obtained by dividing the impact force by the head mass, as in Prang's test [19]. The mass of the present FE head model was close to the mass of Prang's PMHS head.

## IV. Results

Out of technological necessity, the methodology undertaken during the PMHS impact tests [19] required the impact accelerations to be derived by calculation, dividing the impact force by the head mass. This approach requires the head being assumed to be a rigid body, producing a "generalised global response" rather than a deformable structure which may produce localised responses.

For the purpose of validation, the global response of the FE head model was compared with Prang's PMHS tests. The peak numerical acceleration was calculated by the same procedure. The global response of both Prang's PMHS head tests [19] and the FE model tests, can be seen in Fig. 3 to be similar to those reported in Prang [19].

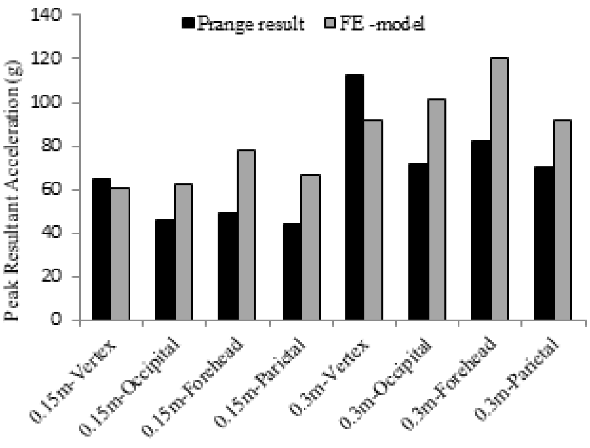


Fig. 3 Peak resultant acceleration with drop heights of infant PMHS and FE head model impact tests

## V. Discussion

There is a need to better understand the mechanical behavior of an infant's head when subjected to impact loading. Accidental falls are currently the leading cause of non-fatal injury in infants less than one-year-old [20].

An understanding of head impact biomechanics is essential for physicians, child protection and law enforcement personnel for discriminating between accidental and inflicted head injury scenarios. Furthermore, paediatric kinematic head response values are an essential prerequisite for implementing child injury mitigation strategies such as helmets, child seats and playground surfaces. Access to paediatric PMHS heads is extremely limited as a result of societal and ethical considerations and out of experimental necessity; researchers [3]-[10] have attempted other approaches.

This study further demonstrates the potential of FE modelling to fill this void and provide an estimate of the kinematics of the paediatric head response. These paediatric FE head models require both accurate geometric data and relevant material properties for head tissues, including the scalp, skull, sutures and brain to provide a valid biofidelic impact response.

Following the preliminary work presented by Khalid et al. [14] produced a newborn FE head model from high-resolution CT scan images of a 10-day-old infant. Khalid et al. [14] worked on the grey scale values of different parts of the head utilising different segmentation tools, to reconstruct the cranial bone, suture, fontanelle and brain models followed by successful meshing in 3-matic remesher.

This paper reports improvements to the biofidelity of this FE model by producing orthotropic structures, utilising the reported material property data and using the built-in material models in the FE software. Furthermore, it was validated using 'global' impact response values reported by PMHS experimental drop test data [19], in terms of the acceleration-time response of the head under impact conditions.

Fig. 3 shows that peak resultant accelerations, for all the drop tests, produce a good correlation for all the conditions, except the impacts to the occipital and forehead regions at both 0.15 and 0.30 m, which are seen to be slightly greater than those in the PMHS experiments.

Comparing the results and variance between the different tests, it can be seen that the responses of paediatric FE head model are in favorable agreement with Prang's PMHS results [19] under drop impact conditions. The peak resultant accelerations vary significantly between different drop heights but not between different impact locations.

## VI. Conclusion

An improved FE model of a 10 day old infant was developed, based on a reported preliminary FE model from high-resolution CT scan images. All the reported paediatric FE models represented the cranial bone homogenous and isotropic, however, there is a trabeculae in the centre of each cranial bone appeared with fibres oriented from these trabeculae. The FE model successfully implemented published cranial bone response data and behaved both orthotropically and inhomogeneously, such that the stiffness of the parallel fibres were different to those of the perpendicular fibres. The model's biofidelity was confirmed by global validation against published PMHS data, by replicating experimental impact tests with a series of computational simulations, in terms of head kinematic responses. The impact response of the FE head model shows a good correlation with PMHS' test response.

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