Risk Factors Associated with Fall-Induced Paediatric Head Injuries for Children 0-3 Years Old

Yuxin Xuan, Lingsheng Meng, Yelan Tao, Jingwen Hu

I. INTRODUCTION

Falls are one of the leading causes of paediatric head injuries, and a common false-case history for child physical abuse cases. Establishing whether a head injury to a child was the result of a fall or abuse is a fundamental problem in forensic investigation. It is especially difficult for infants or young children, because they may be too young, afraid, or injured to describe the scenario.

As paediatric heads change rapidly in size, shape, and anatomical composition, i.e., suture and fontanelle, during growth in the first three years of life, accurate assessment of head injury risks for infants and young children is extremely challenging. With the rapid advances in parametric finite element (FE) human modelling in the recent years, it will be valuable to be able to develop subject specific paediatric head FE models for evaluating the head injury risks and the associated risk factors in fall related forensic investigations. In the past few years, our research group has conducted a series of studies for developing statistical geometry models of paediatric skulls [1], using mesh morphing methods to change a baseline paediatric head FE model into target geometries [2], and applying the morphed models in post-mortem human subject tests and paediatric fall reconstructions [3]. However, those models were limited by low CT resolutions, and risk factors associated with fall induced paediatric head injuries were never systemically simulated.

Therefore, the objectives of this study were (1) to develop anatomically accurate parametric paediatric head FE models for 0-3 year-old (YO) children based on high-resolution CT scans; and (2) to investigate the effects of age, ground material, and impact location/orientation on skull and brain injury measures using multiple age specific paediatric head FE models.

II. METHODS

In this study, we used a series of well-established methods to develop a parametric paediatric head FE model representing 0-3 YO children, which includes CT image processing and segmentation, landmarking, template mesh morphing and mapping, statistical analysis, and automated mesh morphing for generations of age specific head FE models. These methods have been used previously in building parametric models for the femur [4] and ribcage [5] as well as parametric whole-body human models [6]. In this study, five head FE models corresponding to 0, 0.5, 1, 2, and 3 YO children were generated based on the statistical geometry model developed in this study; and a total of 60 fall impact simulations were conducted under a 4.7m/s impact velocity with varied ground material and impact location/orientation.

CT Image Processing and Segmentation

High-resolution head CT scans (512x512 with 0.625mm slice thickness) from 92 0-3 YO children were obtained from the University of Michigan Hospital System based on a protocol approved by the Institutional Review Board in the University of Michigan. Among the 92 cases, the head circumferences of three subjects fell outside three standard deviations from the 50th percentile value based on the CDC Growth Charts in the United States [7], which were excluded from the analysis. Gantry tilt correction was first conducted for the remaining 89 CT scans. CT segmentation was then performed for each subject using Mimics (Materialise, Belgium) by creating separate masks for the inner and outer skull surfaces in each CT slice. These masks were then reconstructed into 3D surfaces through 3D interpolation and mesh smoothing. The 3D surfaces were then output as .STL files as the subject skull geometry.

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Landmarking and Template Mesh Morphing/Mapping

A previously developed 6 month-old head FE model [2] was used in this study as the template mesh to be mapped onto the geometry for each subject. To do so, a set of 142 landmarks were first identified on the skull for each subject. Among all the landmarks, six were placed on the left and right points at the upper margin of each ear canal (Porions), infraorbital, and supraorbital of the skull, which were used to define the Frankfort plane and the anatomical coordinate system. The other landmarks were then identified along the suture-bone boundaries. If the suture was completely ossified, corresponding landmarks could be partially skipped as long as the remaining landmarks were able to capture the skull surface geometry. Consequently, the number of landmarks varied among subjects. To obtain a homologous set of landmarks in all subjects, the landmark data were fitted by cubic splines and new landmarks were sampled evenly on these splines, resulting in a new set of 190 landmarks. After the homologous set of landmarks were achieved, a landmark based mesh morphing was conducted for each subject using a radial basis function (RBF) followed by mesh mapping to project the inner and outer skull surfaces of the morphed template mesh onto the subject skull geometry. Fig. 1 shows an example of the subject specific FE model overlaid onto the CT segmented subject skull geometry.

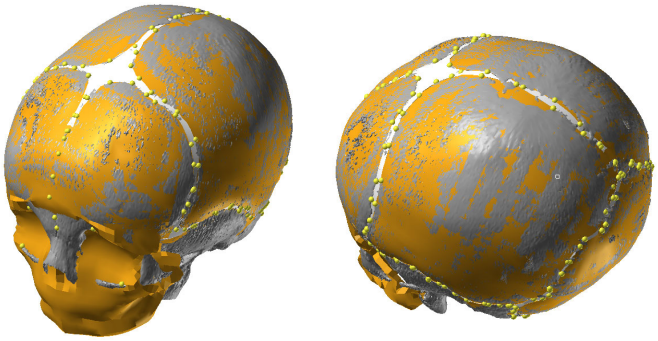


Fig. 1. A 6 month-old subject-specific FE model (in orange) overlaid onto the subject skull geometry (in grey) Landmarks are illustrated as yellow dots

Statistical Analysis

All 89 subject specific head FE models based on the same template mesh were generated and aligned using Generalized Procrustes Alignment (GPA). The statistical head geometry model was then developed through Principal Component Analysis (PCA) and multivariate regression analysis. A total of 5,431 nodes on each subject model were aggregated to form the geometry matrix with a dimension of 89×16,293. The matrix was analysed using PCA, and PC scores were then predicted by age and head circumference using a regression model. The regression model can be expressed as $S_{89x1}=C_{89x3}F_{3x1}+\varepsilon_{89x1}$, where S_{89x1} is the PC score vector, F_{3x1} is the predictor vector [age, head circumference, 1], C_{89x3} is the regression coefficient matrix, and ε_{89x1} is a vector of residual errors that follows $N(0,\sigma)$.

Rapid Development of Age Specific Head FE Models

With the statistical model, five skull geometry targets at the age of 0, 0.5, 1, 2, and 3 YO with 50th percentile head circumference at each age were predicted. These geometry targets provided both inner and outer skull surfaces, and suture width distributions corresponding to those specific ages. However, when the suture is closed or nearly closed, the elements representing these areas are often squeezed, resulting in bad mesh quality. Therefore, in this study, regional mesh smoothing plus material property change from suture to bone were applied to closing or closed sutures. Other components of the head models, including facial bones, scalp and brain tissues, were morphed using the skull surfaces as the landmarks. The whole process of generating age specific head FE models has been automated, and can generate a paediatric head FE model with any given age within 0-3 YO and the associated head circumference. Detailed material properties of all components in the paediatric head can be found in [3], and the same parameters were used in all morphed models.

Parametric Simulations on Risk Factors in Paediatric Falls

To investigate the effects of age, ground material, and impact location/orientation on paediatric head injury risks in falls, a parametric study was conducted. The aforementioned five age specific head FE models, three ground materials and four impact locations/orientation were varied, which resulted in a total of 60 (5 models x 3 ground materials x 4 impact orientations) simulations. Table 1 describes the thickness and material properties

associated with the three ground materials (i.e. carpet, wood, and concrete) used in this study. Four impact locations/orientations were simulated as shown in Fig. 2. All simulations were performed under an impact velocity of 4.7m/s, which was derived based on an average fall height from 65 in-depth investigated paediatric fall cases from our previous study (unpublished yet). Maximal von Mises stress in the skull and maximal principal strain in the brain were used as injury measures to evaluate skull and brain injury risks, respectively. Analysis of Variance (ANOVA) was conducted to evaluate the statistical significance of each parameter.

Table 1. Material parameters for different impact surfaces

Impact surfaces	*Elastic modulus (MPa)*	*Density (kg/m^3)*	*Poisson's ratio*	*Thickness (mm)*
Carpet (two layers)	2.5	9.45E2	0.3	8
	279.92	1.14E3	0.3	5
Concrete	2.10E+05	7.80E3	0.3	13
Wood floor	300	3.50E3	0.35	13

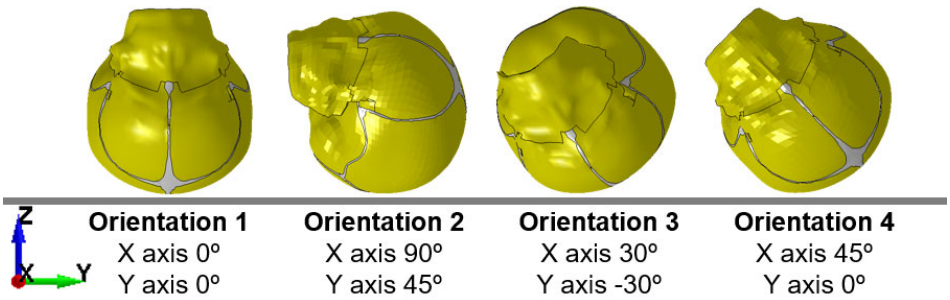


Fig. 2 Four impact locations/orientations

III. INITIAL FINDINGS

It was found that age and head circumference can effectively account for most variances among the dataset with a R^2 is 0.78. Suture width became extremely small after two years of age and completely closed for three years olds. Fig. 3 shows five age specific paediatric head models with 50th percentile head circumferences at respective ages, which were used for the parametric simulations. The mesh quality is comparable to the baseline FE model and is suitable for impact simulations.

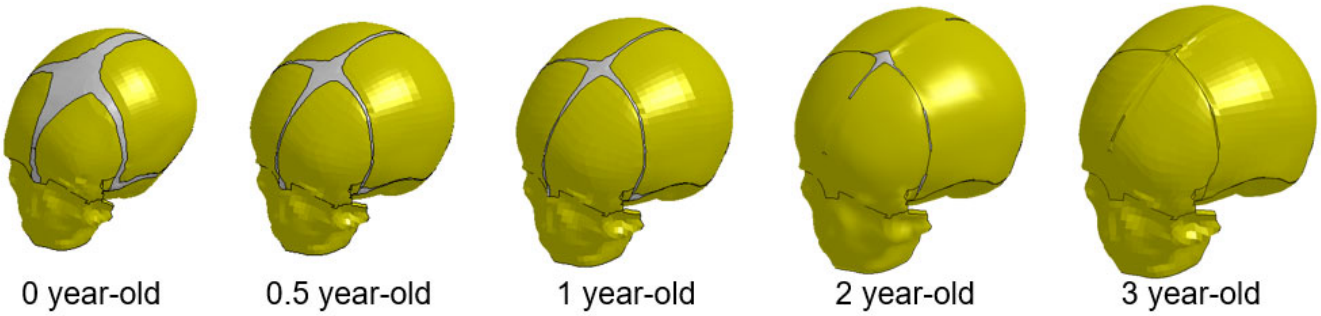
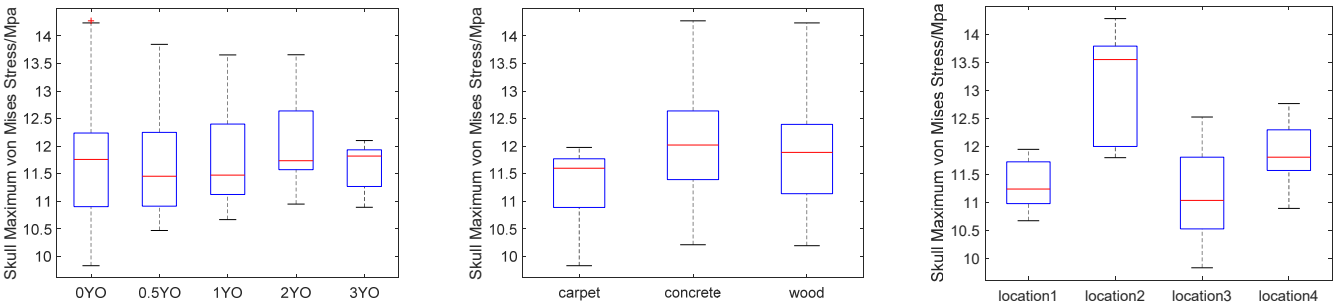


Fig. 3. Five age specific paediatric head models with 50th percentile head circumference

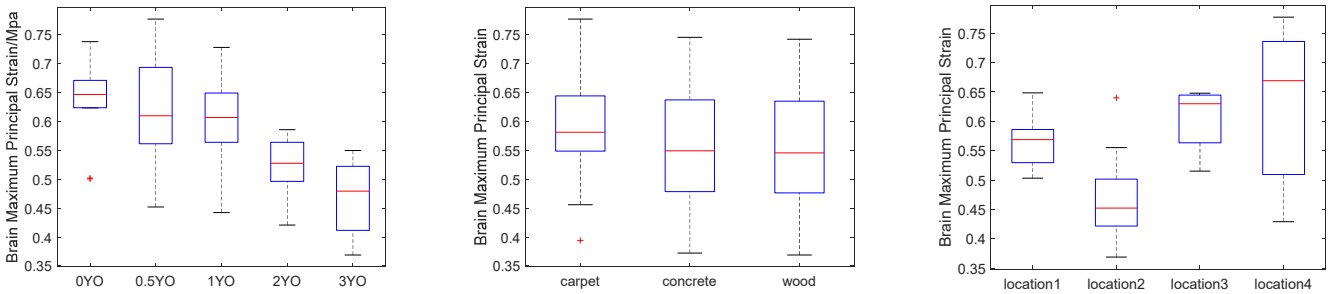
Fig. 4 and Fig. 5 show the factor effects on 95th percentile skull maximal von Mises stress and 99.75th percentile brain maximal first principal strain, respectively. The purpose of using top percentile strain/stress instead of the absolute maximal values is to filter out the single element outlier. Impact location/orientation and ground material are significant ($p<0.05$) in terms of skull fracture, and impact location/orientation and age are significant ($p<0.05$) for predicting brain injury. More specifically, we found that impact location/orientation is the most dominant factor among the three selected factors for both the skull fracture and brain injury. It is interesting that ground material is significant for predicting skull fracture, but its effect is quite small for predicting brain injury. Although age is not statistically significant for the skull fracture, it is significant for brain

injury. In addition, we anticipated that the impact orientation effects would have been related to the suture distributions, which is related to age as well.



(a) Age (p=0.857) (b) Ground Material (p=0.010) (c) Impact Orientation (p=0.000)

Fig. 4. Factor effects on maximum von Mises stress in the skull



(a) Age (p=0.000) (b) Ground Material (p=0.388) (c) Impact Orientation (p=0.000)

Fig. 5. Factor effects on maximum first principal strain in the brain

IV. DISCUSSION

Compared to previous studies on paediatric skull geometry models [1], this study used a larger sample size, higher resolution of the CT scans, and more landmarks in geometry mapping, which resulted in more accurate skull geometry prediction. By applying an automated mesh smoothing and material changing method, we were able to generate head FE models accounting for the significant variations in size, shape, and suture width among paediatric heads between newborn and 3 YO. This method has the potential to be applied to subject specific injury pattern reconstructions in various impact conditions.

Our parametric simulation results suggested that impact location/orientation has a dominant effect on skull fracture and brain injury, while ground material is sensitive to the skull fracture but not brain injury. It should be noted that the same material properties were assigned for all the paediatric head models, all ground materials were set as 13 mm in thickness, and the impact velocity was set at 4.7 m/s. Therefore, the simulation results are limited to only these conditions. It is reasonable to expect that lower impact velocities may result in different effects from the ground material, as the current ground material and thickness may not be enough to absorb all the energies from a high speed impact. Furthermore, we did not consider different injury tolerance criteria for different ages due to the lack of paediatric experimental data, which may affect the injury risks substantially. Also, our simulations did not consider the body mass effects on head impact responses in the drop condition. Such effects may need an accurate cervical spine model to capture, which could be a good future work. Nevertheless, this study demonstrated the capability of the parametric paediatric head FE models. Future work may expand the parametric simulations to include whole-body drop analysis, more risk factors and conditions.

V. REFERENCES

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