Document Title: Development and Validation of A New Pediatric Head Injury Assessment Tool For Possible Child Abuse Cases Considering Subject-Specific Child Head Anatomy

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Document Number: 254134

Date Received: October 2019

Award Number: 2012-DN-BX-K045

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1 Purpose of the project

Head injury is the leading cause of pediatric death, disability, and health-care costs in the United States [1,2], and child abuse is the leading cause of head injury in infants [3] and trauma-related death in children under 4 years of age [4]. Short-distance falls of less than 3 feet are a common false-case history for a child abuse case [5], and short falls are also extremely common events in infants and young children as they learn to roll, climb, and walk.

Establishing whether a head injury to a child was the result of a short fall or abuse is a fundamental problem in forensic investigation. Current injury assessments on possible child abuse cases are mainly based on clinical evidence and experts' professional experiences. The history of the injury, site, injury type, developmental stage of the child, and even the anthropometry and head anatomy of the specific child all need to be considered to assess the cause of head injuries, but individualized experiences vary significantly in terms of all these aspects. For this reason, expert opinions regarding how a head injury occurred in a child are sometimes in direct conflict, which can result in a wrongful legal action [6].

In the injury science literature, the pediatric head injury assessment tools, including the anthropomorphic test devices (ATDs) and computational human models, are either scaled-version of adult ATDs or only represent a head at a single age with single head geometry, hence they cannot account for the biomechanical differences/variations among the child population. To accurately assess the injury, subject-specific head finite element (FE) model representing the real patient head geometry is needed. However, due to the complexity, the process for developing such a model generally takes months, which makes it inefficient and almost impossible for any forensic applications for criminal justice purposes.

Given the limitations of current pediatric injury assessment tools, the goal of this research is to establish a new paradigm for developing and using subject-specific pediatric head FE models to provide objective and accurate assessments for judging the consistency of head injuries and the stated causes in infants or young children. The FE model-based injury assessment tool is designed to evaluate whether a non-abusive injury cause, such as a fall, described by the parents or caregivers can or cannot cause the medically observed head injury. The final product of this project is a model-based head-injury assessment tool for 0-3 year-old (YO) children. Users only need to input patient’s basic information, such as age, weight, height, head circumference, and/or head CT images to rapidly generate the subject-specific head FE model. If incident conditions, such as fall height, fall angle, and impact surface material and thickness, are also defined, the model will be able to predict a range of skull/brain injury risks based on model-calculated results, and will provide a statistical assessment to whether the existing head injury is consistent with the stated injurious event. The pediatric head-injury assessment tool developed in this study can provide a more objective, accurate, and cost-effective way for forensic science researchers, practitioners, and policymakers in the criminal justice system to evaluate the consistency of a head injury with the stated cause in an infant or a young child.

2 Project design, methods and data analysis

The objectives of this study were 1) to develop a method that can rapidly construct subject-specific head FE models for 0-3 YO children with accurate geometry and appropriate material properties for different anatomical regions, including skull, suture, fontanelles, and brain, and 2) to validate and optimize the injury assessment accuracy of this method using pediatric cadaver drop tests and reconstructions of real-world short-fall cases for children. Five specific aims were proposed in this study:

1) to develop a statistical model that describes head geometry of 0-3 year-old (YO) children based on CT images, accounting for head size and shape, suture width, and skull thickness;
2) to conduct dynamic pediatric brain material-property tests using porcine brain tissues and quantify the age effects on brain material properties under impact loading conditions;
3) to develop a fast and efficient method to automatically generate subject-specific pediatric head FE models capable of representing developmental changes during child growth;
4) to computationally reconstruct 50 infant cadaver drop tests for model validation/optimization and development of a skull-fracture injury criterion for 0-1 YO children; and
5) to prospectively collect clinical data and computationally reconstruct 60 head-first short-fall cases for further model validation/optimization and development of a traumatic brain injury criterion for 0-3 YO children.

The overall technical schematic of this project is shown in Figure 1 in the Appendix. The first two specific aims were to develop statistical geometry and material property models, which are the two key components of an accurate FE model. The third specific aim is to develop a method to rapidly generate subject-specific head FE models for a 0-3 YO children with information provided by the first two aims. The last two specific aims are to validate, improve, and optimize the models developed in aim 3, so that an objective and accurate head injury assessment can be achieved to help judge the consistency of a head injury and its stated cause.

2.1 Statistical geometry model of 0-3 YO pediatric skull

To quantify the pediatric skull geometry, head CT scans from 158 0-3 YO children were obtained from the University of Michigan hospital system following a protocol approved by an institutional review board at the University of Michigan. Several steps were involved for CT image processing using Mimics (Materialise, Plymouth, MI) and in-house programs, including gantry tilt correction, skull geometry segmentation, landmark identification, skull thickness measurement, and landmark reprocessing and alignment. Principal component analysis (PCA) and regression analysis were used to build the statistical model of skull geometry. PCA was used to express the geometry data on an orthogonal basis that can be more readily analyzed and to quantify the data variance in a more efficient way. In this study, the three-dimensional skull geometry with landmarks defining head size/shape, skull thickness, and suture width can be predicted by the regression model, when age and head circumference are given. A linear mixed model was also used to test whether the skull thickness values were significantly affected by the subject age, head circumference, and location.

Figures 2 and 3 in the Appendix show the skull size/shape, suture width, and skull thickness distributions for children at different ages based on the statistical model. The skull size increases markedly from newborn to 3 YO, but the growth speed slows down toward 3 YO, while the suture closing speeds are very different across the skull. In particular, the squamosal suture, the inferior region of lambdoid and coronal sutures, and the sagittal sutures near the frontal cranium close more rapidly than other parts of the sutures. For children from newborn to 3 month-old, none of the sutures were closed, while for children older than 2 YO, all sutures and fontanels are closed. Regarding the skull thickness, it is non-uniformly distributed across the skull. In particular, the skull thickness values in the occipital region are much higher than those in the frontal and parietal regions. More detailed results can be found in the paper published by Li et al. [7].

In summary, the size and shape of the pediatric skull change significantly with age and head circumference. The skull thickness and suture width vary with age and location, which will have important effects on skull stiffness and injury prediction. The statistical geometry model developed in this study can provide a geometrical basis for the development of child anthropomorphic test devices and pediatric head FE models.

2.2 Tissue testing for quantifying age effects on brain properties

Age dependency on porcine brain material properties was studied under compression and shear loading conditions at three strain rates (0.01, 1, and 100 s^{-1}). Porcine brain specimens were obtained in four age groups (1-, 4-, 10-, and 20-week) to represent different human developing stages from infant to adolescent. A total of 156 brain tissue specimens were tested with 6 specimens for each age-loading-rate combination, except for specimens at 20-week (8 for each testing condition). The stress-strain relationship was obtained under constant strain rate, uniaxial compression and shear loading, with a maximum strain of 50%. Testing configuration is shown in Figure 4 in the Appendix. Maximum stress at 50% strain was determined, and one-way ANOVA was applied to examine significant levels of the age and strain rate dependency.

Results from the current study clearly demonstrated the age and strain rate dependency in porcine brain material properties (Figures 5 and 6 in the Appendix). In particular, maturation in the pigs is accompanied with a significant increase in elastic and shear moduli of brain tissues. The 20-week porcine brain tissue is 3-4 times stiffer than the immature groups (1- 4-, and 10-week), and this observation is in good agreement with the results of a previous study on human infant brain tissues by Chateline et al. [8].

The data reported from the current study revealed the age-dependent change in porcine brain material property during its early developmental stage from infant to adolescent. Given the fact that the biological basis and neuro-architecture for porcine brain and human brain are close, we applied this age-dependency into scaling law to translate animal results to human. Combining results from the current study and the published study on human infant brain properties [8] (Figure 7), we found a good agreement of the brain properties between the age-scaled porcine and the human infant in the static shear modulus with age. Experimental results and the scaling law from the current study provide useful information to better understand the brain tissue biomechanics at its early developmental stage and will further help develop accurate constitutive equations for infant brain tissues.

2.3 Method for rapid development of subject-specific pediatric head FE models

A schematic of the approach for developing the subject-specific pediatric head FE model is shown in Figure 8. The foundations of this new modeling concept are statistical models of human geometry that describe morphological variations within the target population as functions of human parameters (age, stature, head circumference, etc.) and a mesh morphing method that can rapidly morph a baseline human model into other geometries while maintaining high geometry accuracy and good mesh quality.

In this study, Radial basis functions (RBFs) were used to morph the nodal locations of a baseline 6 month-old head FE model to target geometries specified by the statistical skull geometry model. RBFs have been widely used in image processing and neural networks, but in the present study RBFs were used for 3D interpolation and smoothing. Corresponding landmarks were identified on both the statistical geometry model and the baseline human FE model, so that nodal displacement at each landmark location can be calculated. Using RBFs, a 3D displacement field throughout the entire space of the human geometry is calculated based on the landmark displacements. By applying this displacement field to the baseline FE mesh, a new model with new geometry can be achieved. The RBF method can effectively change the baseline FE model into a different geometry without reducing the mesh quality [9]. Since mesh morphing is an automated procedure, pediatric head models at any age from 0-3 YO can be rapidly developed with the statistical pediatric skull geometry model and the RBF mesh morphing tool, which can provide valuable information on future investigation of age effects on pediatric head injuries.

A user interface has been made (shown in Figure 9) to facilitate the process of building subject-specific pediatric head FE models. The users only need to input the age and head circumference of the subject, and a subject-specific head FE model can be rapidly generated. Examples of the target skull geometry from CT scans and the morphed FE models based on statistical geometry model are shown in Figure 10. Reasonable match can be achieved between the morphed FE models and the geometry targets regarding the skull size, shape, and suture width.

2.4 Cadaver drop test reconstruction and skull fracture injury risk curves

In a series of studies reported by Weber [10,11], 50 cadaver subjects aged from 0 to 9 months were dropped onto five impact surfaces with different stiffness levels at the height of 82 cm. In this study, all these 50 tests were reconstructed using the subject-specific pediatric head FE models, which were morphed into subjects with ages, head sizes/shapes and skull thickness values reported in the tests. To accurately simulate the stiffness levels of five impact surfaces, headform drop tests, FE simulations and material inverse optimizations were conducted. For the 20 cadaver tests with skull fracture, the head impact locations in the reconstruction simulations were adjusted around the occipital-parietal area until the maximal von Mises stress distribution appeared to be similar to the skull fracture location and orientation reported in the tests. Because the head impact locations were not reported for the 30 cadaver subjects without skull fracture in Weber's tests, four impact locations around the occipital-parietal area were simulated to account for the uncertainty of the contact location. The model-predicted strain and stress responses as well as the global kinematic-based injury measures were output from all the simulations for test reconstructions. The skull fracture risk curves for infants from 0 to 9 months old were developed based on the model-predicted head injury measures through logistic regression analysis with age as a covariate. Wald statistic and ominous tests were conducted for statistical significance.

The reconstruction results for the 20 cadaveric tests with skull fracture are shown in Figure 11. The maximal von Mises stress distributions matched reasonably well with the skull fracture patterns reported in the tests. All the six selected injury predictors are significant of skull fracture. In general, the model-predicted stress responses were better predictors (skull maximal von Mises stress, maximal shear stress and maximal first principal stress) than global kinematic-based variables (peak head acceleration, HIC) in predicting skull fracture in terms of the goodness of fit and accuracy rate. The injury risk curves as well as the thresholds associated with each injury predictor can be found in the paper published by Li et al. [12].

2.5 In-depth pediatric fall case investigation and reconstruction

A total of 162 0-3 YO patients, who were reported to be involved in witnessed fall, have been enrolled to participate the fall investigation study in the pediatric emergency department at the University of Michigan and Michigan Children’s Hospital. To collect the fall data, informed consent were first obtained from subject’s legal guardian following the protocol approved by an institutional review board at the University of Michigan and Wayne State University. Then detailed fall conditions were gathered through guardian interview and the in-depth fall site investigation. Among all the consented subjects, fall site investigations have been conducted for 62 patients, in which no suspicious child physical abuse case was found. The fall conditions collected in the site investigations included fall mechanism, fall height (foot and head), landing posture/angle, first impact location, and impact surface material composition and thickness. Patient information included, age, weight, height, head circumference, documentation of head injuries, and CT scans if available. Examples of site investigations are shown in Figure 12.

To reconstruct fall cases with in-depth investigations, a database of impact surface characteristics related to the collected fall cases were generated through headform drop tests, FE simulations, and material inverse optimizations. The whole-body kinematics of each fall case was estimated using MADYMO (TASS, Netherlands). By varying the initial fall conditions, a range of head-to-ground contact velocities were estimated for each fall case. The impact surface properties and the impact velocities were used as the boundary conditions in the FE simulations with the subject-specific FE models for fall reconstructions. An example of the MADYMO simulation and FE simulation results is shown in Figure 13, in which multiple MADYMO runs were conducted. The impact velocity was not affected by the initial condition much as long as the fall height was controlled as the same. The simulated FE results showed a good potential for injury pattern prediction compared to the actual skull fractures.

3 Scholarly products produced or in process

3.1 Peer-reviewed journal articles and conference papers

- Hu J et al. (2014) “Parametric Human Modeling To Predict Injuries For Various Vulnerable Populations” *Proceedings of WSU 75th Anniversary Symposium, Injury Biomechanics, Prevention, Diagnosis & Treatment*, Detroit, MI, USA.
- Fan H et al. (2014) “Age dependent material properties of infant and adolescent porcine” *Proceedings of WSU 75th Anniversary Symposium, Injury Biomechanics, Prevention, Diagnosis & Treatment*, Detroit, MI, USA.
- Li Z et al. (2015) "A Statistical Skull Geometry Model for Children 0-3 Years Old" *PLOS ONE*, 10(5):e0127322, DOI: 10.1371/journal.pone.0127322.
- Li Z et al. (2015) "Prediction of Skull Fracture Risk for Children 0-9 Months Old through Validated Parametric Finite Element Model and Cadaver Test Reconstruction" *International Journal of Legal Medicine*, 129(5):1055-66.
- Park BK et al. (2016) "Skull Fracture Prediction Using A Parametric Skull Model for Children 0-3 Years Old" *IRCOBI Asia Conference*, Seoul, South Korea.
- Hu J et al. (2015) “Developing Parametric Human Models Representing Various Vulnerable Populations in Motor Vehicle Crashes” *won the “2015 Mimics Innovation Awards*”. The paper is published online at http://biomedical.materialise.com/mimics-innovation-awards-winners-2015.
- Hu J (2016) "Height of Head Centre of Gravity Predicts Paediatric Head Injury Severity in Short-Distance Falls" Evidence-based Medicine, Commentary, PII: ebmed-2016-110558. DOI: 10.1136/ebmed-2016-110558.
- Jin X et al. (2018) “Age dependent material properties of infant and adolescent porcine brain under compression and shear loading.” *Journal of Biomechanics*, In progress.

3.2 Presentations and Webinars

- A presentation “A New Pediatric Head Injury Assessment Tool for possible child abuse cases considering subject-specific child head anatomy”, has been made at the 2014 NIJ R&D Grantees Meeting, Seattle, WA.
- Three Webinar lectures entitled “New Pediatric Head Injury Assessment Tool for Possible Child Abuse Cases Considering Subject-Specific Child Head Anatomy” have been made through the NIJ Grantees Live Seminar Series “Map it Out: Models in Forensic DNA & Pathology – Part II”.
- A presentation entitled “Developing Parametric Human Models Representing Various Vulnerable Populations in Motor Vehicle Crashes” was made at the Mimics Innovation Conference, Tampa, FL in 2016.
- A presentation entitled “Accuracy of Parental Estimates of Fall Height in Young Children” was made at the Annual Meeting of the Society for Academic Emergency Medicine in Orlando, FL and at the Pediatric Academic Societies Meeting in Toronto, Canada in 2017.
- A presentation entitled “A New Pediatric Head Injury Assessment Tool for Forensic Investigations” was made The 6th SAVIR National Conference, Ann Arbor, MI in 2017.

4 Summary of major findings and product related to criminal justice practice

This project developed a novel process for rapid development of subject-specific pediatric head FE models and applying these models for head injury assessment. Better understanding of the age effects on pediatric skull geometry and brain material properties has been achieved, real-world pediatric fall cases with in-depth investigations have been collected, and cadaver test and real-world fall reconstructions have been conducted for the purpose of validating the models and developing injury risk curves. The models and simulation procedures developed in this study can provide a more objective, accurate, and cost-effective way for forensic science researchers, practitioners, and policymakers in the criminal justice system to evaluate the consistency of a head injury with the stated cause in an infant or a young child.

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3. Greenes DS, Schutzman SA (1999) Clinical indicators of intracranial injury in head-injured infants. Pediatrics 104: 861-867.
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9. Li Z, Hu J, Zhang J (2012) Comparison of Different Radial Basis Functions in Developing Subject-Specific Infant Head Finite Element Models for Injury Biomechanics Study. ASME 2012 Summer Bioengineering Conference Fajardo, Puerto Rico.
10. Weber W (1984) Experimental study of skull fractures in infants. Z Rechtsmed 92: 87-94.
11. Weber W (1985) Biomechanical fragility of skull fractures in infants. Z Rechtsmed 94: 93-101.
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Appendix

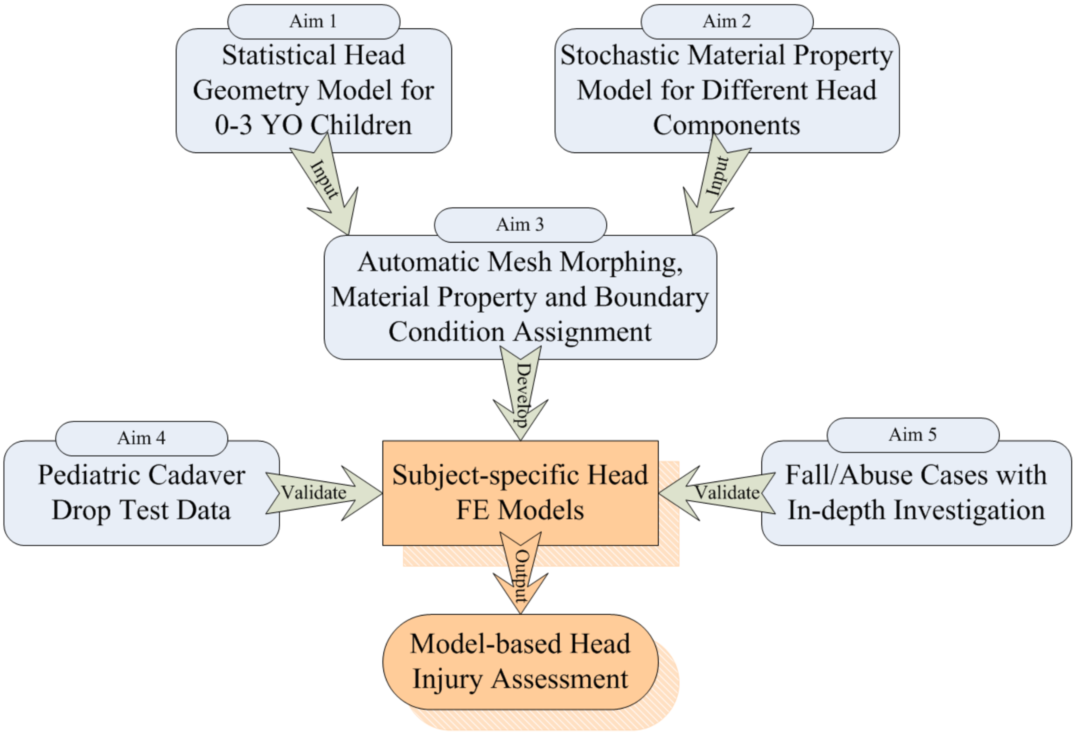


Figure 1: Overall technical schematic for developing and validating subject-specific pediatric head FE models

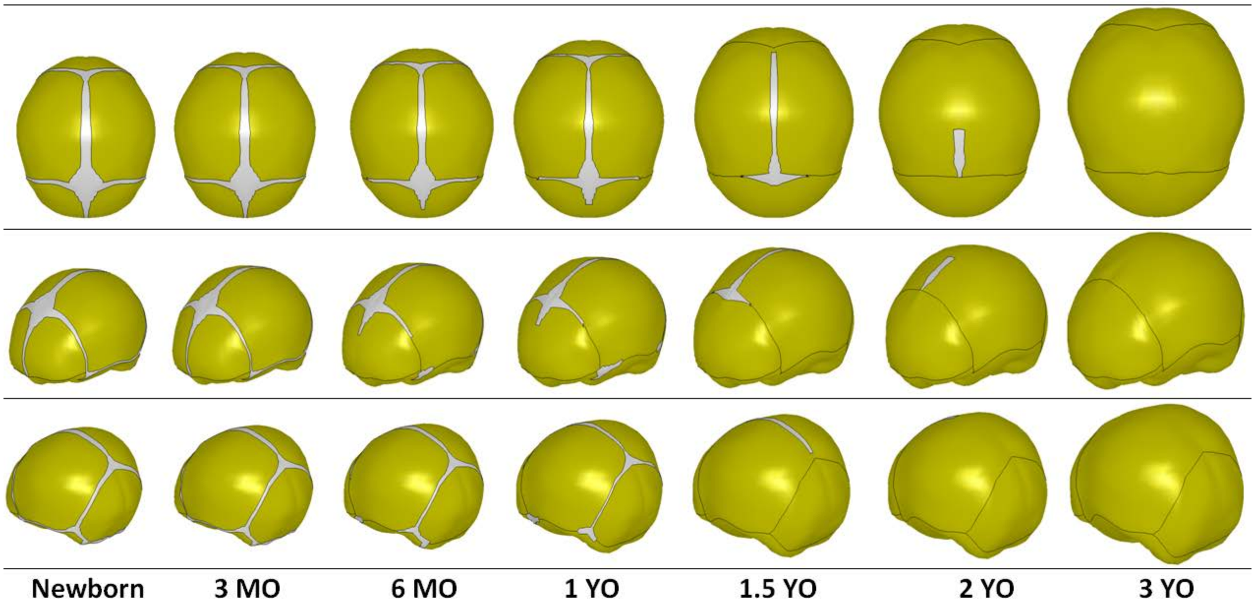


Figure 2: Skull size/shape and suture changes by age

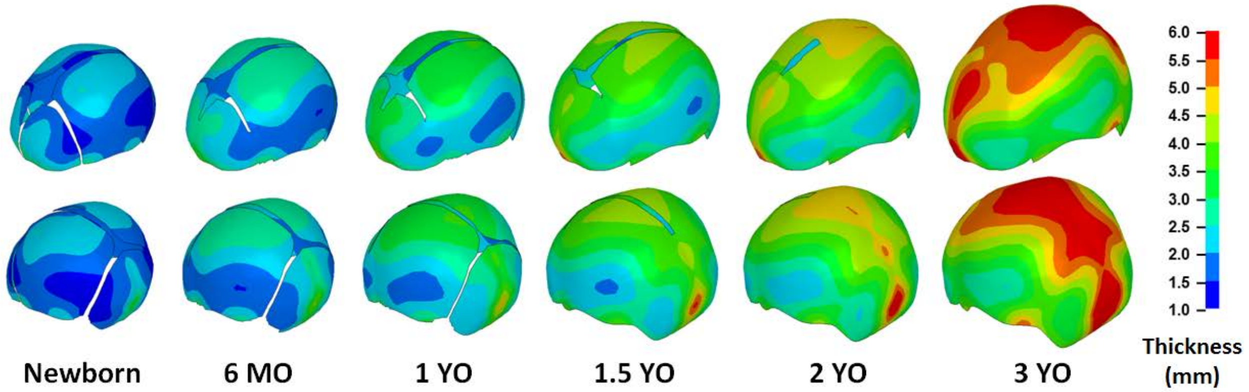
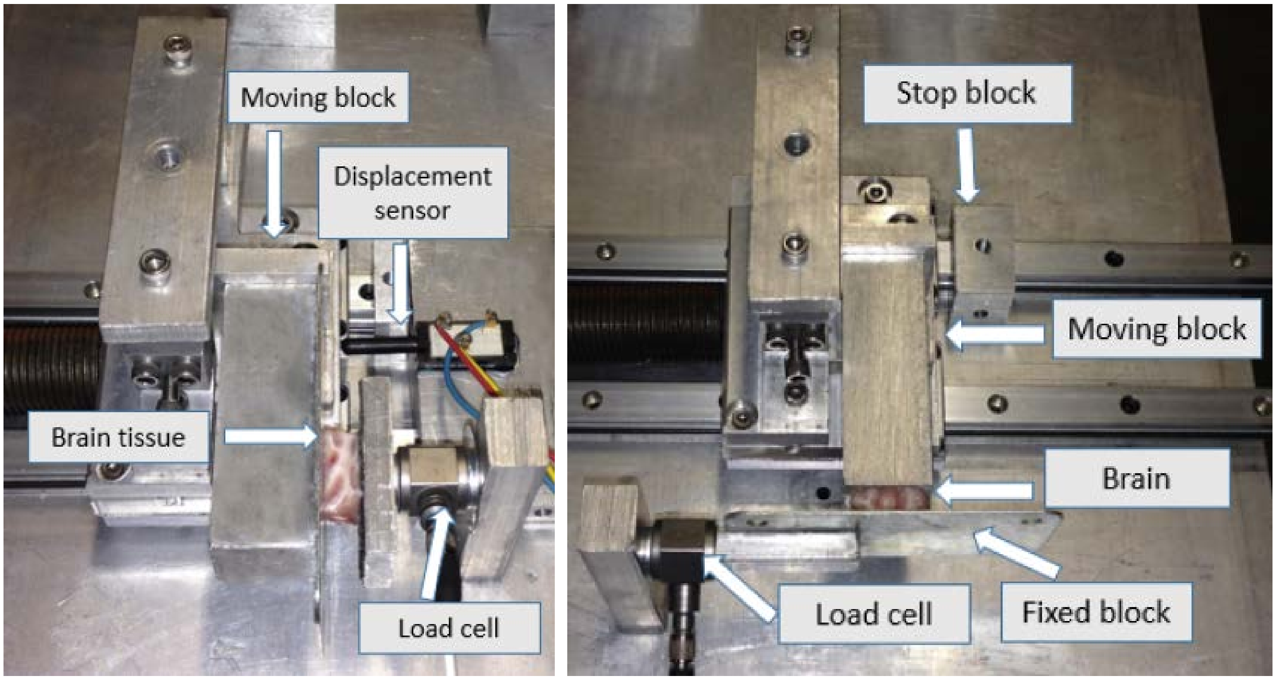
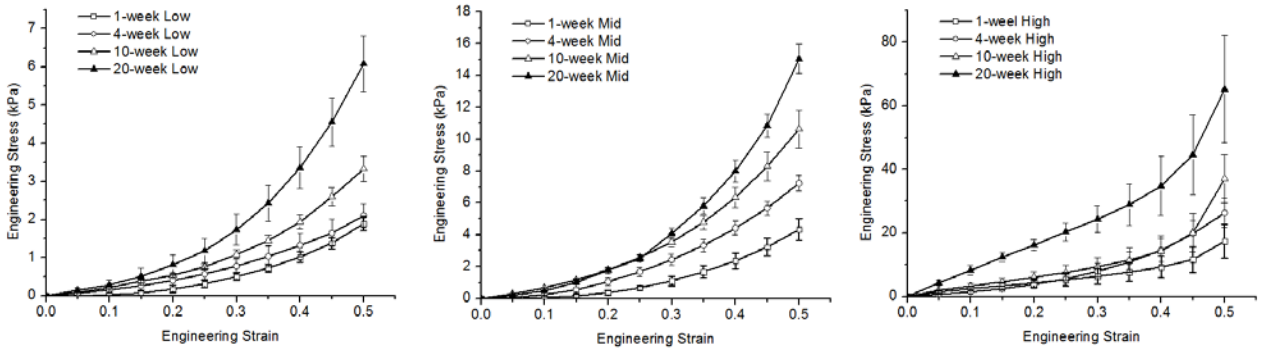


Figure 3: Skull thickness distribution by age



(a) Compression test fixture (b) Shear test fixture

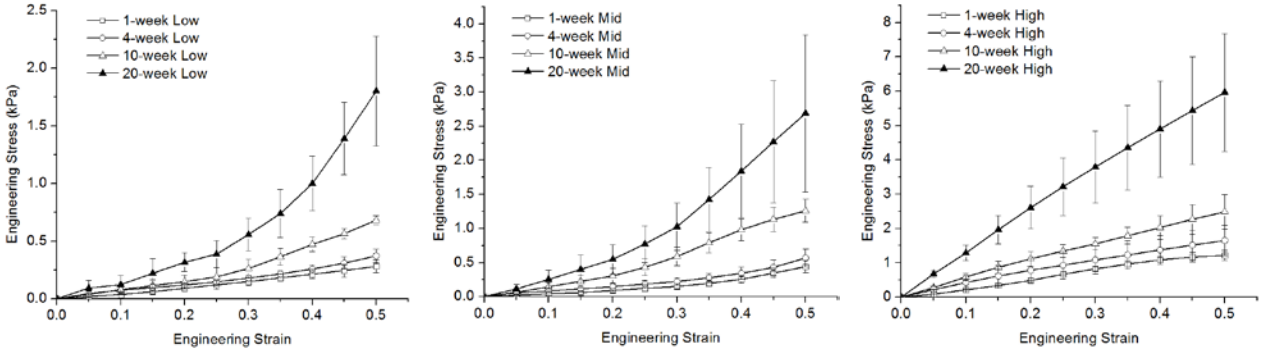
Figure 4: Testing configuration of (a) compression and (b) shear tests



(a1) Compression -
Low strain rate

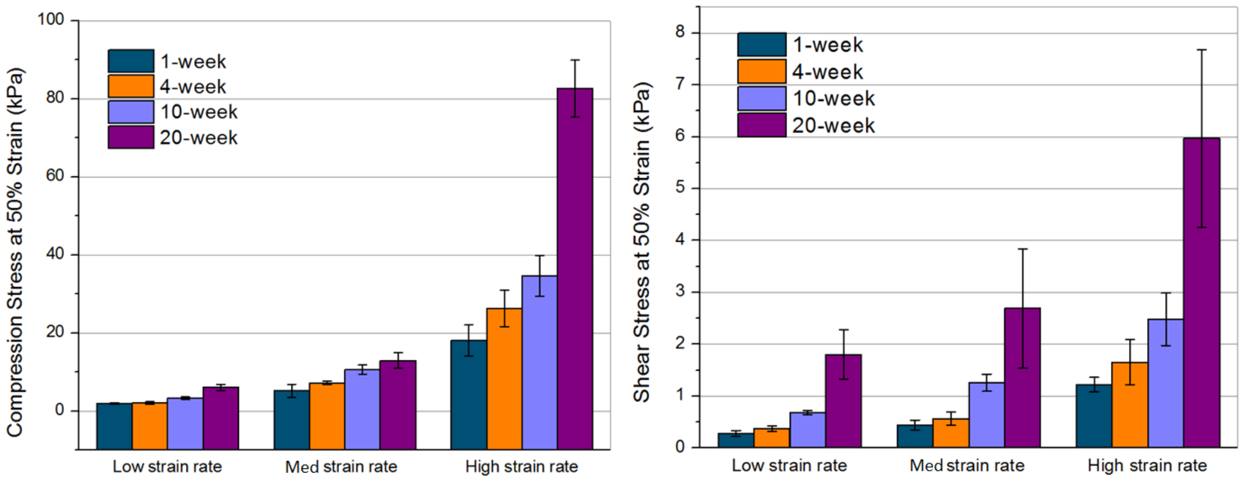
(a2) Compression -
Mid strain rate

(a3) Compression -
High strain rate



(b1) Shear - Low strain rate (b2) Shear - Mid strain rate (b3) Shear - High strain rate

Figure 5: Stress-strain relationships of brain material for four age groups at varying strain rates



(a) Compression (b) Shear

Figure 6: Brian material mean stress at 50% strain of four age groups at three strain rates

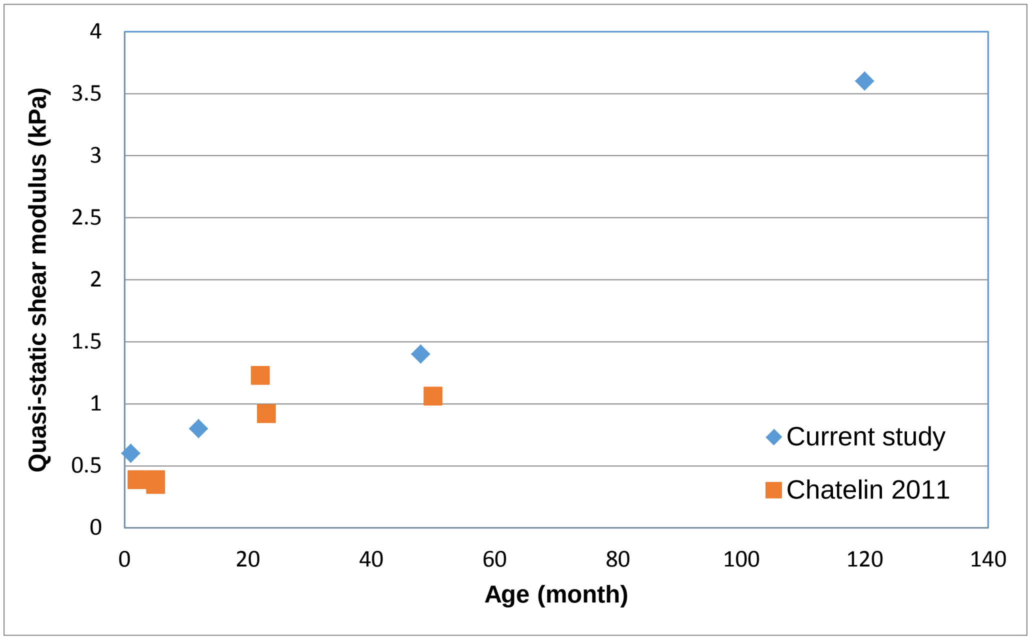


Figure 7: Comparison of experimental results of the scaled-age porcine data to the published human infant data

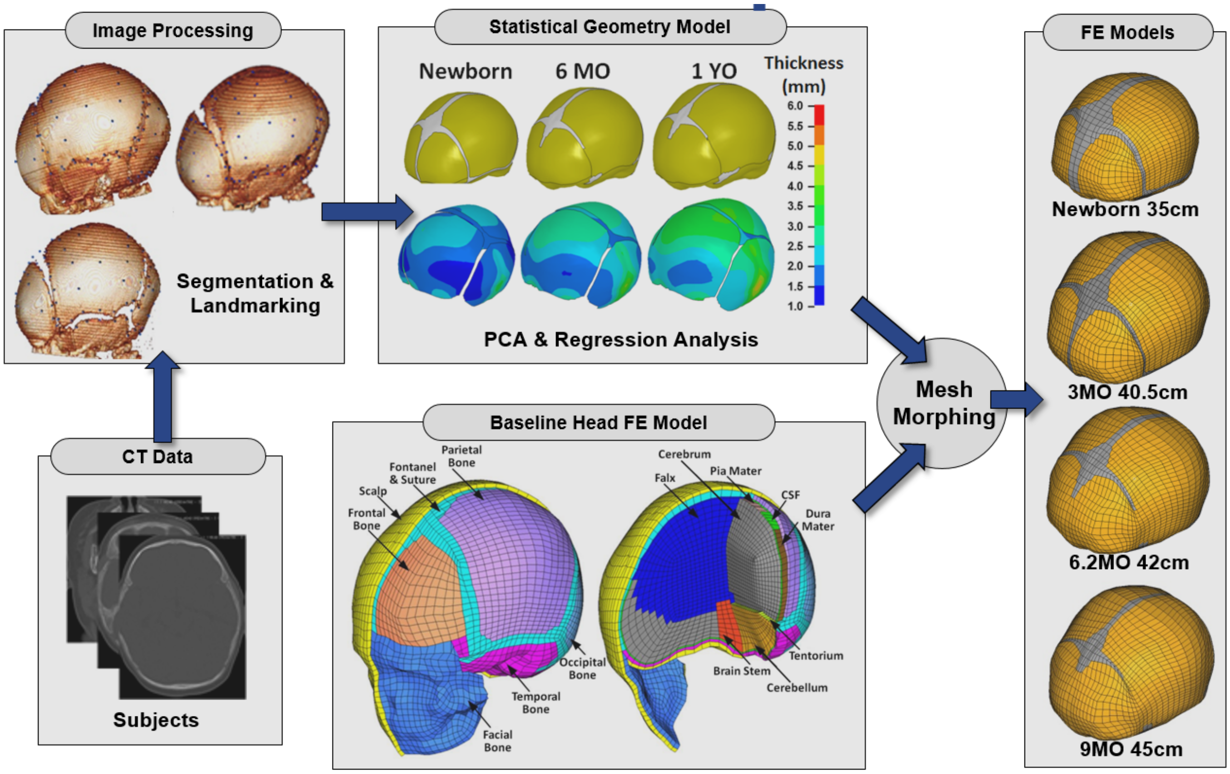
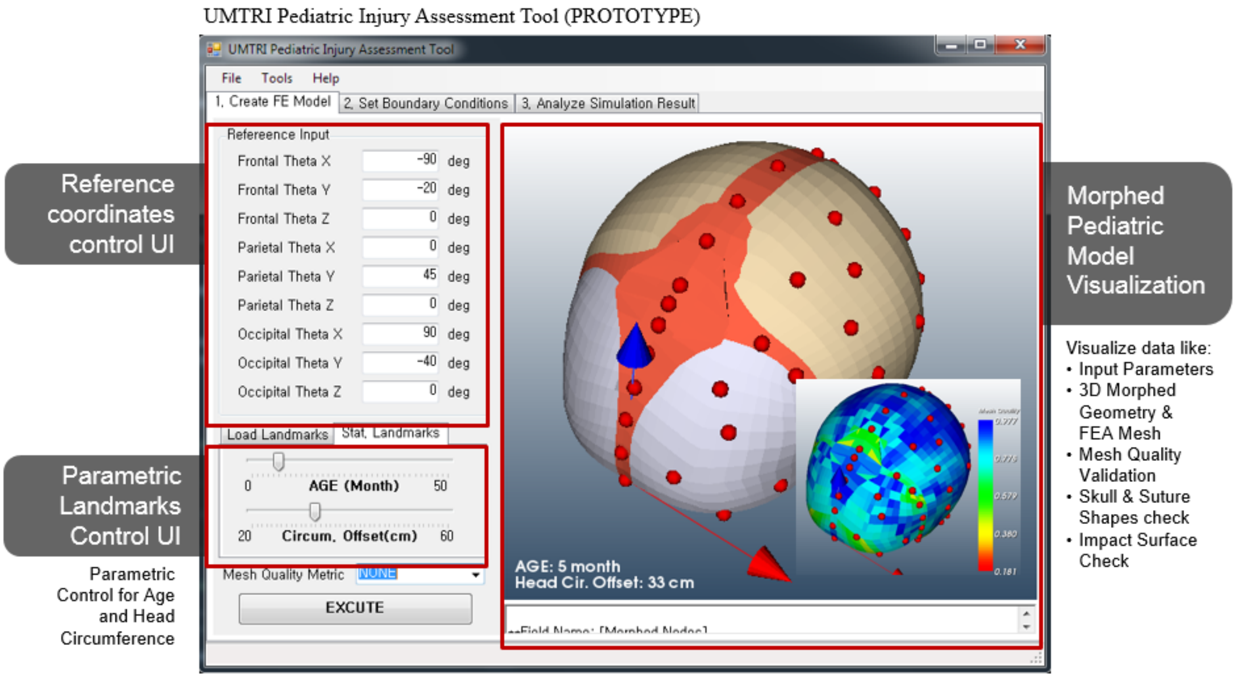


Figure 8: Process for developing subject-specific pediatric head FE models



Frontal Theta X -90 deg
Frontal Theta Y -20 deg
Frontal Theta Z 0 deg
Parietal Theta X 0 deg
Parietal Theta Y 45 deg
Parietal Theta Z 0 deg
Occipital Theta X 90 deg
Occipital Theta Y -40 deg
Occipital Theta Z 0 deg

AGE (Month) 0 – 50
Circum. Offset(cm) 20 – 60
Mesh Quality Metric NONE

AGE: 5 month
Head Cir. Offset: 33 cm

--Field Name: [Morphed Nodes]

Reference coordinates control UI

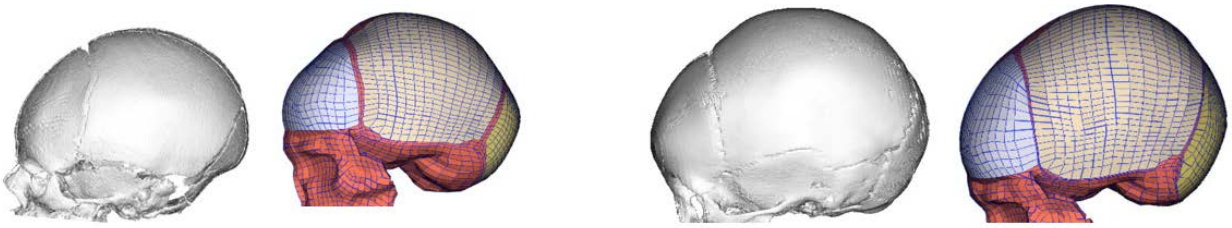
Parametric Landmarks Control UI

Parametric Control for Age and Head Circumference

Morphed Pediatric Model Visualization

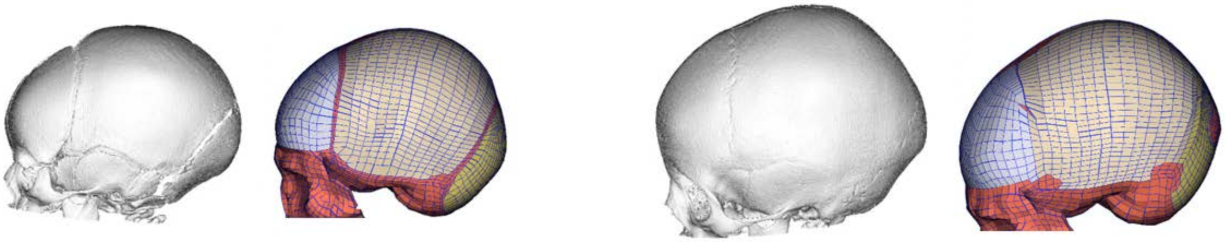
Visualize data like:
- Input Parameters
- 3D Morphed Geometry & FEA Mesh
- Mesh Quality Validation
- Skull & Suture Shapes check
- Impact Surface Check

Figure 9: User interface for developing subject-specific pediatric head FE models



Age: 0.01 Month
Head Circumference: 33.43 cm

Age: 7.2 Month
Head Circumference: 42.37 cm



Age: 1.44 Month
Head Circumference: 38.47 cm

Age: 18.6 Month
Head Circumference: 48.88 cm

Figure 10: Examples of morphing the baseline FE head model to match the geometry targets from CT scans

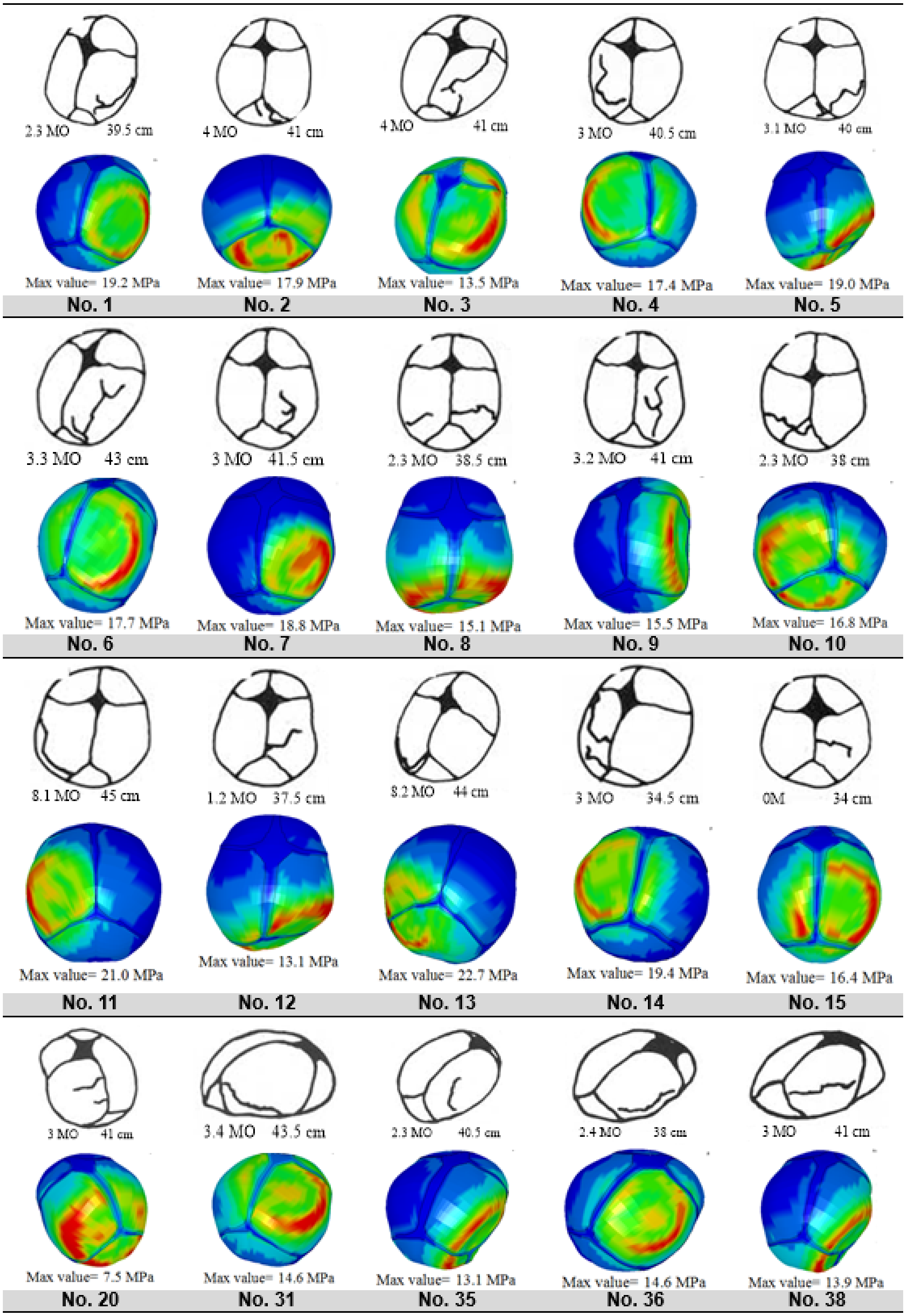


Figure 11: Fracture pattern comparison between tests and simulations

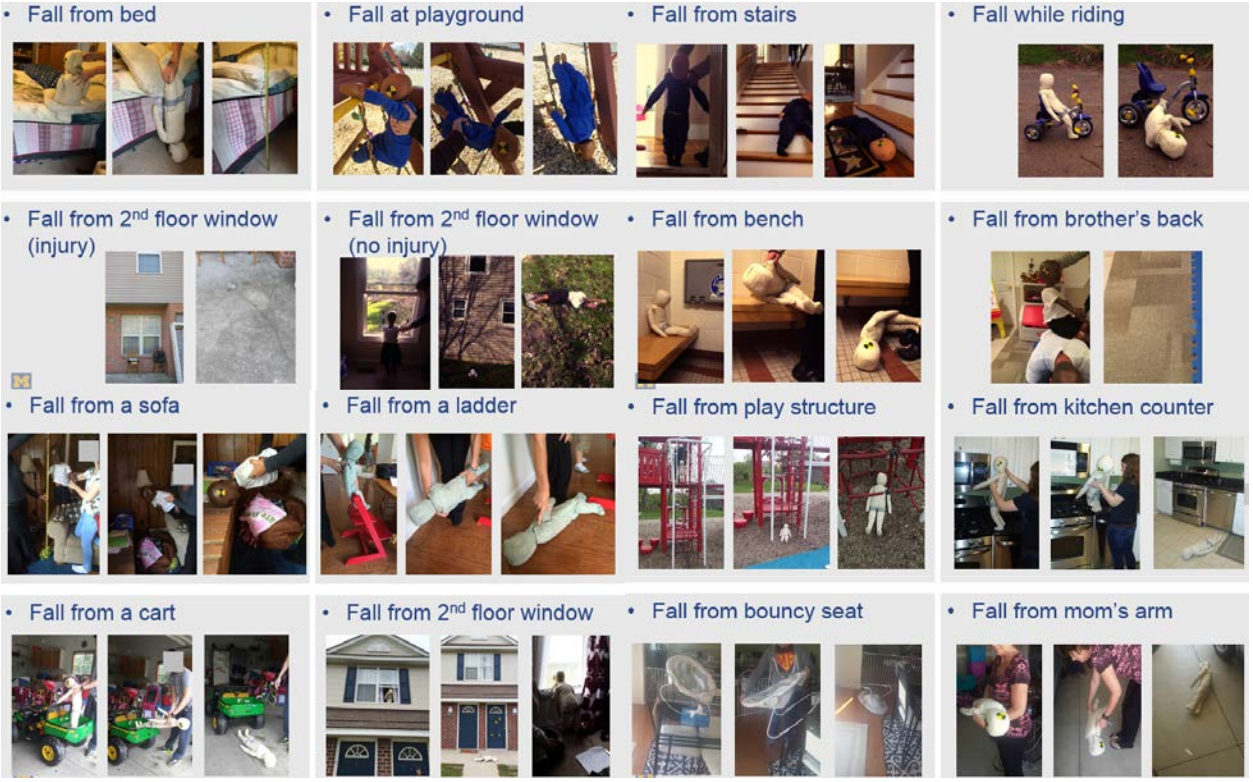


Figure 12: Examples of pediatric fall investigations

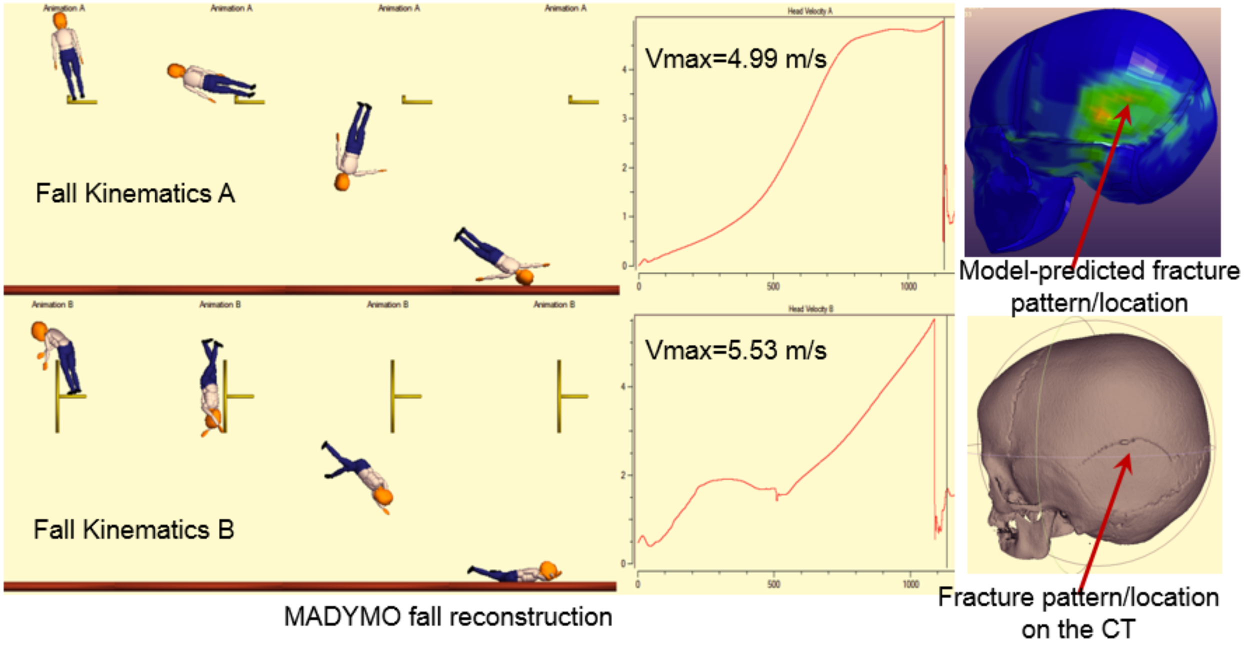


Figure 13: An example of fall reconstructions