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Development of a Probability Model to Predict Head Injury Risk in Pediatric Falls

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Project Summary

Accurate differentiation between abuse and accident is critical for both abuse victims and accidentally injured children; abuse victims must be removed from unsafe environments and accident victims must remain with their innocent families. Often a central question in discriminating abuse from accident is whether severe head injuries or fatalities can result from a caregiver provided fall history. Determining biomechanical compatibility between head injuries and a caregiver fall history is a key aspect in discriminating abuse from accident. Biomechanical reconstruction of falls is critical in forensic investigations but is greatly limited by the lack of evidenced-based head injury thresholds suitable for use in predicting risk of pediatric head injury. Our research goal was to develop an evidenced-based statistical model capable of predicting probability of head injury in young children involved in falls to improve forensic biomechanical investigations. Our probability model is based on falls data previously collected through video monitoring of children with wearable head accelerometers in a childcare center (CCC; NIJ#2017-DN-BX-0158), combined with data collected on children presenting to a pediatric emergency department (PED) with a detailed fall history and head injury. When feasible PED falls were reconstructed using physics-based computational modeling to determine associated head acceleration/velocity. Combining data from falls with and without head injury allowed us to develop pediatric head injury probability models based on head acceleration. These injury probability models can aid in determining biomechanical compatibility between a child's head injury and stated fall history.

Major Goals

The goal of our project was to develop evidence-based statistical models capable of predicting the probability of head injury in young children involved in falls to improve forensic biomechanical investigations. Our goal was accomplished through the following aims:

Specific Aim 1: Describe fall, child and injury characteristics associated with pediatric falls resulting in head injury.

Specific Aim 2: Develop and validate a biofidelic 3D human child computer model used to determine head accelerations in simulations of reconstructed common pediatric fall scenarios.

Specific Aim 3: Develop evidence-based statistical models to predict probability of head injury associated with falls involving young children.

Research Question

Our research question was to determine the probability of head injury from short distance falls involving young children.

Research Design and Methods

Our research goal was to develop evidence-based statistical models capable of predicting the probability of head injury in young children involved in falls to improve accuracy in forensic biomechanical investigations. This study will provide knowledge to address a major gap when attempting to determine biomechanical compatibility between a child's head injury and given fall history by combining previously collected data from video recorded falls (NIJ #2017-DN-BX-0158) occurring in a childcare setting with prospectively investigated falls from the PED that have resulted in head injury to develop injury probability models. Data was collected from PED falls via in-hospital caregiver interviews and virtual follow-up interviews to verify fall details and capture fall environment characteristics. Our directly measured head accelerations from CCC falls were combined with head accelerations determined through modeling of PED falls to develop head injury thresholds for young children (Fig 1). The following methodology was employed to meet our specific aims and overall project goal.

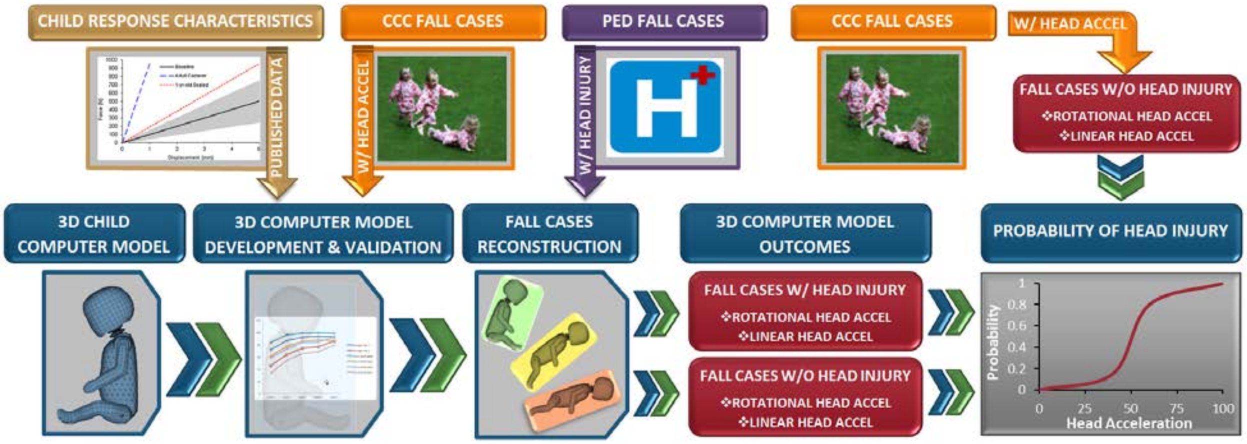

FIGURE 1. RESEARCH METHODOLOGY SCHEMATIC.

Table 1. KEY DATA COLLECTED FROM PROSPECTIVE PED FALLS

Child characteristics: age, gender, race, ethnicity, child's developmental capacities and anthropometrics
Fall characteristics: detailed description of fall event, initial position, fall height, fall type (e.g., child alone, child and other person, stair fall), initial action pre-fall (e.g., running, walking, standing), fall dynamics (how child fell), body region making 1st impact, object/s involved in fall, final position, impact surface, post-fall child behavior/ action, post-fall caregiver behavior/action, time sequence of events
Detailed injury/clinical findings: injury/skin findings will be described by anatomical location, plane and side of body. Diagnostic imaging and radiology report, and photo documentation of skin findings will be obtained pending caregiver consent. Injury severity will be scored using both the AIS and MAIS.[1*]
Fall environment: photos of fall scene including measuring device positioned adjacent to elevated surface (if applicable), furniture involved, impact surface and/or object/s as applicable.

* **AIS** describes injury severity on a 6-point scale (1=minor; 2=moderate, 3=serious, 4=severe, 5=critical, 6=maximal (untreatable) based on body region, type (e.g. skeletal, vascular, muscular) and severity.[22] Additionally, the maximum (**MAIS**) will be determined for each subject across all injuries.

EXPECTED APPLICABILITY OF RESEARCH

Biomechanical experts are frequently called upon to testify in pediatric injury/child abuse cases regarding the compatibility of a child's injuries with a stated cause. In cases where a fall is the stated cause, a biomechanical analysis may be conducted which includes reconstructing dynamics of the fall history and calculating or measuring biomechanical outcomes such as head accelerations, velocities, and impact forces. These outcomes are then compared to injury thresholds to determine the likelihood of injury. However, a limitation of forensic biomechanical investigation involving falls is the paucity of pediatric specific head injury thresholds. Using head injury thresholds that are scaled from adults or primates can lead to inaccurate conclusions regarding whether a fall can generate serious or fatal head injury in a child given anatomical and physiological differences. Since biomechanical analysis is a critical component in cases involving a fall history, these inaccuracies may translate into errors in expert testimony leading to failure to prosecute a guilty perpetrator or failure to acquit an innocent defendant.

In our study we developed evidence-based pediatric specific head injury probability models to aid in determining the likelihood of head injury in falls involving young children. These probability models are needed to improve confidence when attempting to predict likelihood of head injury in fall reconstruction, a key element in biomechanical forensic investigations.

Participants and other collaborating institutions

Our collaborative multidisciplinary research team consisted of engineers from the University of Louisville (U of L) and a pediatric emergency medicine physician and clinical research personnel from Lurie Children's Hospital (LCH). Subject enrollment and collection of PED data was conducted by LCH personnel, while fall assessment and engineering analysis were conducted by U of L personnel. Both U of L and LCH personnel participated in follow-up interviews with caregivers to collect fall characteristics and fall environment details. Dr. Gina Bertocci (U of L) and Dr. Mary Clyde Pierce (LCH) served as the project MPIs, and Dr. Raymond Dsouza (U of L) and Dr. Angela Thompson (U of L) served as the project Co-PI's. Additional key personnel at U of L included Craig Smalley and Dr. Karen Bertocci. LCH key personnel included Danielle Cory, Kelsey Julian, Kim Kaczor, and Jillian Benedetti.

Changes in approach from original design and reason for change

There were no substantial changes to the original study design, but to enable us to achieve the required sample size, inclusion criteria were expanded to include: 1) younger children, 2) cases that were referred to Lurie Children's Child Protection Team for a social work consult where injuries were determined to be due to accidental cause, and 3) children with loss of consciousness and no other head injury. Additionally, 3D computer modeling for a subset of PED falls was complemented by 2D physics-based modeling to reconstruct falls to determine biomechanical outcomes.

Outcomes

Activities/Accomplishments

- A comprehensive searchable Pediatric Fall Assessment Research Database containing patient demographics and relevant medical history, fall characteristics, fall environment details, follow-up interview details including fall scene photos and measurements, injury outcomes, skin assessment body diagram, head injury details, imaging data, biomechanical outcomes of fall, and accident vs. abuse determination was developed.
- 1266 children presenting to the LCH PED with a fall history and complaint of a potential head injury were screened; 140 of these children (11%) were eligible for our study. From this pool of potential subjects 101 children were enrolled in our study; 2 cases were subsequently deemed to be *indeterminate* for accidental cause, leading to 99 remaining subjects with a head injury due to an accidental fall. For these children patient demographics and relevant medical history, fall characteristics, fall environment details, injury outcomes, skin assessment body diagram, head injury details, imaging data, biomechanical outcomes of fall, and accident vs. abuse determination were documented in our Pediatric Fall Assessment Research Database.
- 52 video-conferenced or phone follow-up interviews were conducted with caregivers to obtain further details related to their child's fall and fall environment (including key measurements and photos as applicable), presence/absence of evidence of impact following the fall (e.g., bruise, swelling), and a description of their child's response and the caregiver's response after the fall.
- A 3D Madymo rigid body computer model of a 12-month-old child was developed and validated for use in falls reconstruction.
- 2D physics-based models were developed, calculations were automated and standardized by fall type.
- Overall, 80 PED falls were able to be reconstructed to obtain biomechanical outcomes.
- Using data from PED falls and previously collected CCC falls, head injury probability models were developed based on linear and rotational head accelerations.

Results/Findings

Specific Aim 1: Describe fall, child and injury characteristics associated with pediatric falls resulting in head injury.

Ninety-nine (99) children (age 17.2$\pm$12.6 months) having a head injury from an accidental fall were enrolled in our study. This represented only 7.8% of 1266 children presenting to the PED with a fall history and complaint of potential head injury. (When considering only those with a head injury documented through imaging (i.e., excluding those with loss of consciousness or altered mental status), this number is reduced to 6.9% of screened cases.) No fatalities resulted from these falls, and children had the following head injuries resulting from falls:

- 5 had loss of consciousness without other documented injury
- 6 had altered consciousness without other documented injury
- 44 had an isolated skull fracture
- 8 had an isolated intra-cranial hemorrhage (ICH)
- 33 had both, a skull fracture and ICH
- 3 had a facial bone fracture

Characteristics of injuries resulting from falls include the following:

- 90.9% of skull fractures were linear skull fractures; non-linear skull fractures were associated with specific fall histories compatible with fracture type (e.g., depressed skull fractures occurred with head impact onto corners of structures or furniture).
- 83% of ICHs were focal; non-focal ICHs were predominantly associated with occipital or frontal head impact.
- Only 2 children had an extra-axial (i.e., non-head) injury (1 humerus fracture and 1 metacarpal fracture).

The distribution of fall types associated with these head injuries is provided in Figure 2.

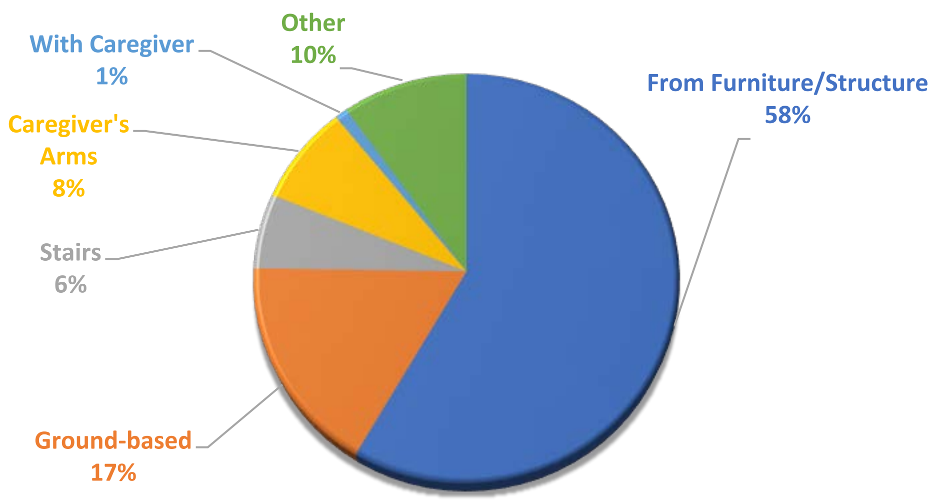

FIGURE 2. DISTRIBUTION OF FALL TYPES (N=99).

SPECIFIC AIM 2: DEVELOP AND VALIDATE A BIOFIDELIC 3D HUMAN CHILD COMPUTER MODEL USED TO DETERMINE HEAD ACCELERATIONS IN SIMULATIONS OF RECONSTRUCTED COMMON PEDIATRIC FALL SCENARIOS.

To develop a 3D child computer model for use in reconstructing falls, we utilized pediatric biomechanical properties from the scientific literature to modify the CRABI-12 anthropomorphic test device (ATD) model within Madymo software. Modifications were made to properties of the head, neck, and joints. Using this modified child model, we recreated the fall environment and properties, along with the initial position of the child to reconstruct a forward fall from the base of a slide onto rubber playground mulch (Fig 2; fall that occured in our CCC study). The model was then tuned to achieve the fall dynamics observed in the video recording and key biomechanical measures were then compared (Fig 3). As an example, linear head acceleration recorded from the child's wearable accelerometer showed good agreement with that predicted by the computer model (Fig 3). To further validate the computer model, other childcare center falls with wearable head accelerometer data and video recorded fall dynamics were reconstructed and outcomes were compared. Given reasonable agreement between actual falls and computer simulations, the 3D computer model was deemed to be validated and ready for use in predicting biomechanical outcomes in PED falls. To expand the number of reconstructed falls, 2D physics-based models were also used to predict biomechanical outcomes in PED falls.

FIGURE 2. VIDEO-RECORDED CHILDCARE CENTER FORWARD FALL FROM BASE OF SLIDE.

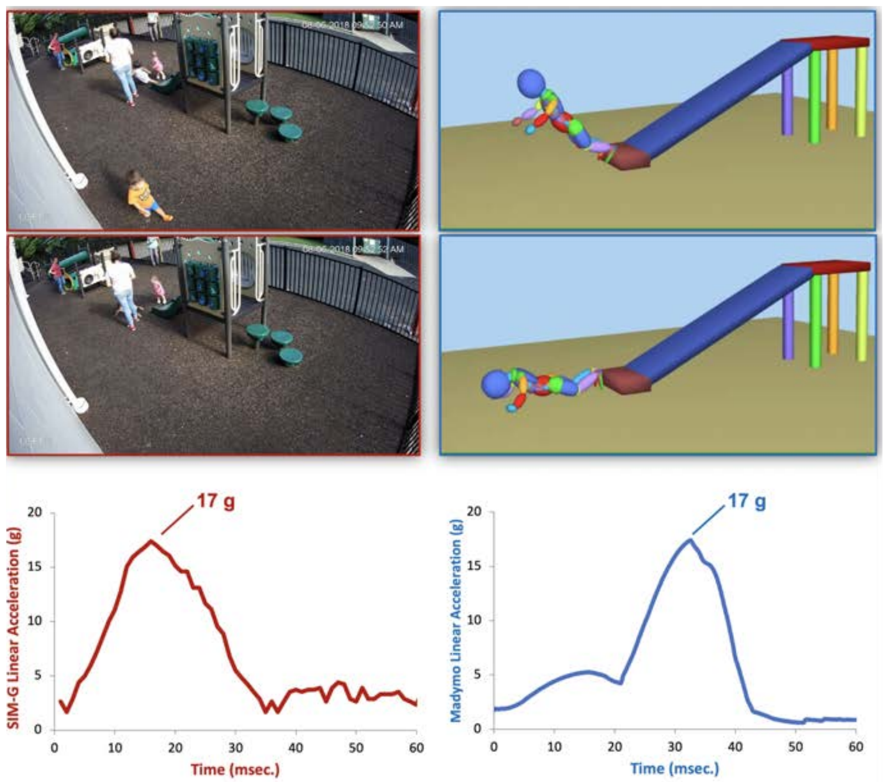

FIGURE 3. RECONSTRUCTION OF CHILDCARE CENTER FALL FROM BASE OF SLIDE USING DEVELOPED 3D CHILD COMPUTER MODEL. LINEAR HEAD ACCELERATION RECORDED USING A WEARABLE ACCELEROMETER IN THE CHILD'S HEADBAND (LOWER LEFT PANEL) WAS COMPARABLE TO THAT PREDICTED BY THE 3D COMPUTER MODEL (LOWER RIGHT PANEL).

SPECIFIC AIM 3: DEVELOP EVIDENCE-BASED STATISTICAL MODELS TO PREDICT PROBABILITY OF HEAD INJURY ASSOCIATED WITH FALLS INVOLVING YOUNG CHILDREN.

By combining data from CCC falls where no head injury occurred with reconstructed PED falls leading to head injury, probability models of head injury were developed based on head accelerations (Fig 4). These probability models can serve as an aid to understanding the likelihood of head injuries associated with falls involving young children. For example, when a child's exposure to linear or rotational head acceleration has been determined for a given fall, probability models can be utilized to determine the likelihood of moderate or serious head injury associated with that specific fall. However, it is important to note that probability models are not an indicator of head injury characteristics or extent of injury, and therefore cannot be used as the sole tool to determine biomechanical compatibility. Head injury probability models are a quantitative tool that must be used in conjunction with a qualitative assessment of the constellation of injuries, injury characteristics, and extent of injuries to determine biomechanical compatibility with the stated cause.

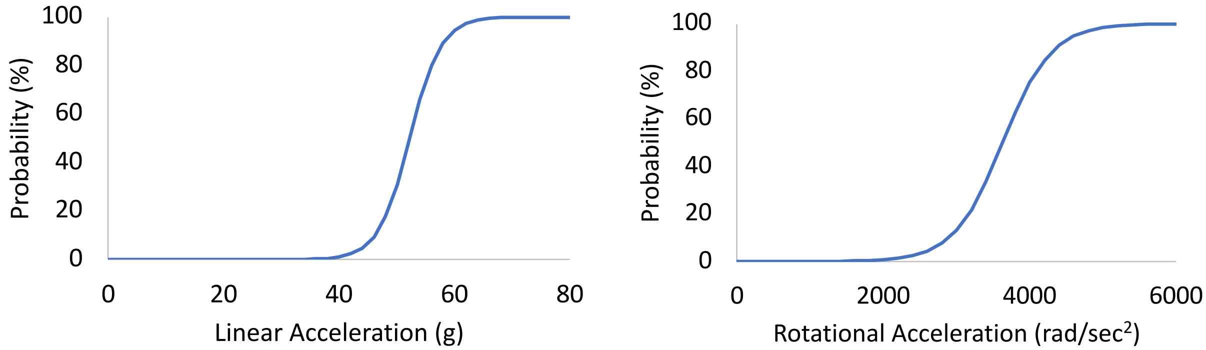

FIGURE 4. PROBABILITY OF AIS 2 (MODERATE) OR AIS 3 (SERIOUS) HEAD INJURY BASED ON LINEAR HEAD ACCELERATION AND ROTATIONAL HEAD ACCELERATION.

LIMITATIONS

Limitations of our study include the following:

- Subjects were enrolled from a single geographic area through one PED.
- Follow-up interviews were conducted for a subset of falls (52 of 100 falls); thus, for some falls from elevated surfaces measurements of fall height were estimated.
- Fall characteristics are based upon caregiver description of the incident.
- Head injury probability models cannot be used as the sole indicator to determine biomechanical compatibility between head injury and stated cause of injury. A qualitative biomechanical assessment must also be conducted to determine compatibility between the constellation of injuries, injury characteristics, and extent of injuries and the stated cause of injury.
- Head injury probability models do not predict the characteristics or extent of head injuries.
- Probability of head injury models rely upon biomechanical measures that were predicted using computational modeling for PED falls.
- Probability of head injury models do not account for cranial bone impacted, which can influence likelihood of fracture given differences in thickness and ultimate strength of cranial bones.
- Differences in skull anatomy and biomechanical properties exist across the age range of children in our study (7 to 48 months). Age-related properties have been shown to influence likelihood of fracture and fracture characteristics.

ARTIFACTS

LIST OF PRODUCTS

- G Bertocci, A Thompson. Head Injury Biomechanics in Falls Involving Young Children (keynote presentation), *International Shaken Baby Syndrome/Abusive Head Trauma Symposium*, Philadelphia PA. Oct 2022.
- Pediatric Fall Assessment Research Database - maintained by the University of Louisville, Injury Risk Assessment and Prevention Laboratory directed by Dr. G Bertocci.
- 3D rigid body model of 12-month-old child used to simulate common household falls and determine associated biomechanical measures of the head.

DATA SETS GENERATED

Our dataset consists of 99 falls involving young children with a head injury (88 with head injuries documented on imaging) who have presented to the LCH ED. Each fall contains descriptions of patient demographics, anthropometrics, and relevant medical history, fall characteristics, fall environment details, injury outcomes and severity, a skin assessment body diagram, head injury details, imaging data, biomechanical outcomes of fall (for 80 falls), and accident vs. abuse determination. Follow-up interview details including fall scene photos and measurements (as applicable) are included for 52 falls.

Dissemination Activities

We have presented our study findings at the International Shaken Baby Syndrome and Abusive Head Trauma Symposium, which is attended by clinicians, social workers, prosecutors, defense attorneys, law enforcement personnel, judiciary personnel, and victims' families. This 1 hr presentation enabled Drs. Bertocci and Thompson to provide an in-depth overview of our findings. Dr. Bertocci has previously presented on *Injury Biomechanics in Abusive Head Trauma* for the Army's Judge Advocate General (JAG) Child Abuse Training and will present findings from our study at subsequent JAG Training sessions. Manuscripts resulting from this study will be submitted to an open-source journal, freely accessible to the public. Once manuscripts describing our dataset have been published, data for a subset of key fields contained within our Pediatric Fall Assessment Database will be available upon request. Notice of availability of the dataset will be included on our Injury Risk Assessment and Prevention website (https://louisville.edu/research/injury-risk-assessment/), as well as in our published manuscript(s).