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Biomechanical Characterization of Video Recorded Short Distance Falls in Children

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PROJECT SUMMARY

Although injuries from accidental falls in children are common, history of a fall is also the most commonly stated false scenario provided by caregivers to conceal physical abuse; differentiation between the two is critical for both abuse victims and accidentally injured children. Determining *biomechanical compatibility* between injuries and stated cause is a key aspect in differentiating abusive from accidental injuries in clinical and forensic settings, and in obtaining truthful convictions in the judicial system. Unfortunately, the lack of evidenced-based data from witnessed short distance falls has led to controversy when assessing biomechanical compatibility between severe head injuries or fatalities and short distance fall histories.

MAJOR GOALS

The goal of our project was to improve accuracy in forensic biomechanical investigations of child abuse that seek to determine whether fatal or severe head injuries can result from pediatric short distance falls. Our goal was accomplished through the following aims:

Specific Aim 1: Characterize head impact biomechanics of video recorded pediatric falls.
Specific Aim 2: Characterize injury outcomes and determine the rate of severe head injury in video recorded pediatric falls.
Specific Aim 3: Develop a predictive model to estimate head impact acceleration and velocity based upon fall, environment, and child characteristics.
Specific Aim 4: Develop a searchable web-based knowledgebase of video recorded pediatric falls to facilitate biomechanical assessment of fall history and injury compatibility.

RESEARCH QUESTION

Our research question was to determine whether short distance falls involving children lead to fatal or severe head injuries.

RESEARCH DESIGN AND METHODS

This study provided evidence-based knowledge needed to address the gap in understanding of pediatric fall biomechanics by prospectively investigating childcare center falls using video recordings and *in situ* biometric measurements. Falls were video recorded while children equipped with wearable biometric devices were engaged in daily activities in 4 indoor classrooms and on an outdoor playground; 3 video cameras were installed in each monitored space. Biomechanical measures (linear and angular head acceleration and velocity) were obtained using a wearable accelerometer-gyroscope device (SIM G™) located within a headband worn by the children. Our goal was to capture and analyze 3000 video recorded falls and associated biometric data involving children between 12 - 36 months of age. Our innovative approach enabled us to capture fall characteristics, describe the relationship between child and fall environment factors and biomechanical outcomes, develop a searchable, web-based Pediatric Fall Biomechanics Knowledgebase and estimate of the rate of severe head injuries in short distance falls (Fig 1; Table 1).

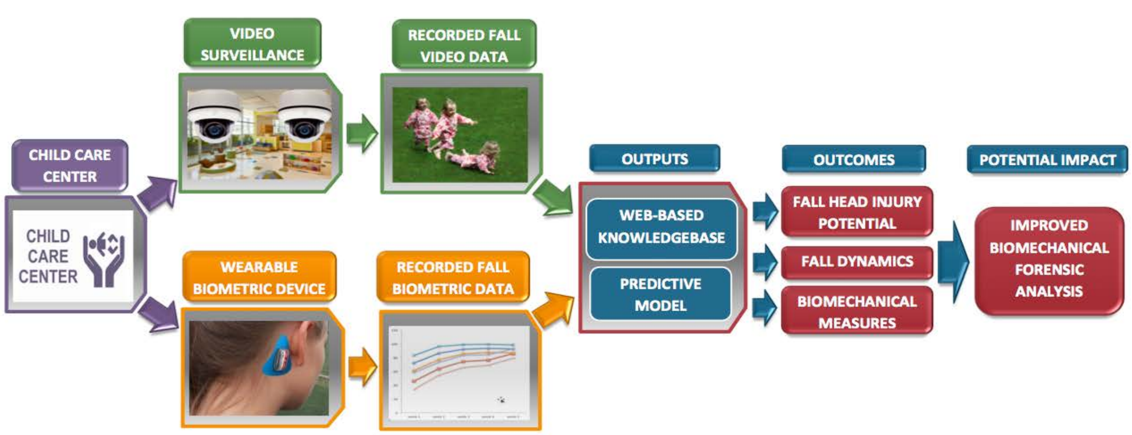

FIGURE 1. PROJECT METHODOLOGY.

Table 1. Data collected from falls

Child characteristics: age, gender, anthropometrics, mass
Fall characteristics: fall type (e.g. fall from standing, fall from elevated surface), initial position, fall height, initial action pre-fall (e.g. running, walking), fall dynamics (how child fell; rearward, forward, etc.), body region making 1st impact, object/s involved in fall, final landing position, impact surface
Head impact and injury outcomes: head impact (yes/no), region of head impact (e.g. frontal, left or right parietal, etc.), head injury (yes/no), location of head injury (e.g. frontal, parietal, etc.), type of head injury (e.g. skull fracture, subdural hemorrhage, etc.), other injuries, medical care sought (yes/no), first aid provided (yes/no), injury severity (scored using Abbreviated Injury Scale), abstracted medical record
Fall environment: Furniture, playground equipment and fixed cabinetry dimensions. Flooring/ground properties using a resiliency tester to measure coefficient of restitution (stiffness). Materials used in flooring, subflooring and playground surfaces
Head biomechanical measures: peak linear head acceleration/velocity, peak angular head acceleration/velocity, impact duration, direction of head impact force
Incident report: incident report filed (yes/no), if yes, report obtained and abstracted

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 the stated cause. Currently, biomechanical assessments often rely upon a combination of manual calculations, computer simulation and/or experiments using human surrogates to estimate the level of injury risk associated with the specific event in question. These methods are limited given assumptions and oversimplifications of fall victim and fall environment properties that must be made in manual calculations, surrogate experiments and computer simulations. Surrogates in many cases have limited biofidelity (how human-like), failing to provide an accurate representation of the fall victim. Additionally, fall studies in the scientific literature often referenced in expert testimony are largely based on unwitnessed falls. Our study provides knowledge that will likely influence the current practice used in forensic biomechanical investigations by describing injury outcomes, fall dynamics and *in situ* biomechanical measures of a large number of video recorded falls involving *actual children*. Knowledge from our study circumvents limitations undermining current forensic biomechanical investigations, which play a pivotal role in the prosecution of child abuse and defense of accidents involving a fall history.

The outcomes of this project have the potential to facilitate evidence-based forensic biomechanical assessments and address the ongoing controversy of whether short distance falls can cause fatal or severe head injury; a question that is continually tried in courts of law. Furthermore, the availability of *in situ* head impact measurements from falls in our study can inform the assessment of physical and computational surrogate biofidelity used in reconstruction of pediatric falls. This information has the potential to be transformative to the field of pediatric injury biomechanics given the scarcity of such data in infants and young children.

Participants and Other Collaborating Institutions

Dr. Gina Bertocci served as the project PI and Drs. Angela Thompson and Karen Bertocci served as the project Co-PI's. Research engineers, Craig Smalley, Dr. Nathan Brown and Dr. Raymond Dsouza were also critical to the project. Bioengineering graduate students also participated in data collection and post-processing. Dr. Mary Clyde Pierce from Lurie Children's Hospital was available to review medical records as needed.

Changes in Approach from Original Design and Reason for Change

There were no changes to the original study design. However, we were unable to develop a predictive head injury model as planned because there were no head injuries from falls. In order to develop a predictive head injury model, data from both falls leading to head injuries and falls without head injury are needed.

Outcomes

Activities/Accomplishments

- Anthropometrics were measured for 35 children ranging in age from 12-36 months.
- 3255 video recorded falls involving young children in a childcare setting were captured and analyzed.
- 3255 falls were characterized by initial conditions, fall dynamics, landing position, fall environment, head biomechanics (for SIM G^{TM} activated falls), and child anthropometrics. All data is stored in comprehensive searchable research database.
- Fall environment coefficients of restitution were measured for 45 different surfaces or objects.
- 174 video recorded falls met or exceeded the 12 g threshold activating the SIM G^{TM} device which recorded head biomechanical data for these falls.
- A web-based searchable Pediatric Fall Biomechanics Knowledgebase containing a subset of variables describing our 3255 falls was developed.

Results/Findings

35 children (age 22.6 ± 6.4 months; range 12.4-36 months) were enrolled in our study. 3255 video recorded falls were captured and analyzed. SIM G^{TM} devices were worn during 1021 falls (31%) and in 17% (n=174) of these falls the SIM G^{TM} device was activated. Overall there were 12.1 falls/observation hour, which equated to 3.1 falls/subject hour of observation.

No children had serious injuries resulting from falls. No children had multiple injuries and medical care was not sought for any falls. 4 children had a single soft tissue injury (3 lacerations and 1 nosebleed) scored as AIS 1 injuries, and 3 children had a single instance of erythema (red mark). Thus, only 0.2% of falls resulted in minor injuries. Incident reports were filed by childcare center staff for 5 of these fall events.

Only 20% of all falls were from a higher surface, with the majority of falls having no change in support surface height (e.g. tripping while walking or running). The maximum fall height was 1.2 m as measured to the head center of mass. The majority of falls occurred in the classroom and most had a forward fall dynamic (Fig 2).

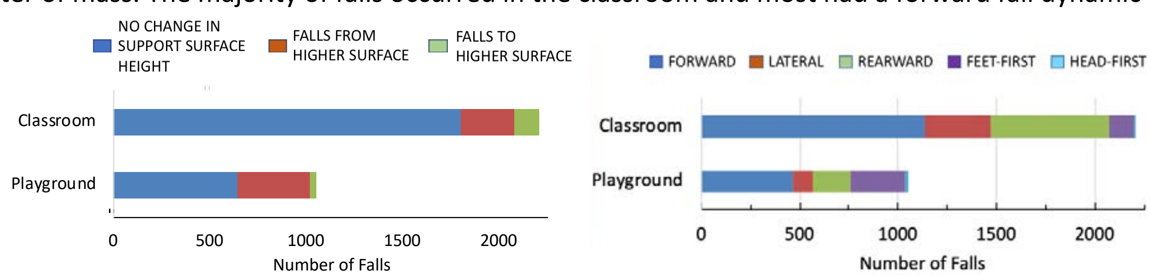

Figure 2. Distribution of fall types by location and distribution of fall dynamics by location.

Head impact occurred in only 6% of falls, most of which involved no change in support surface height (Fig 3).

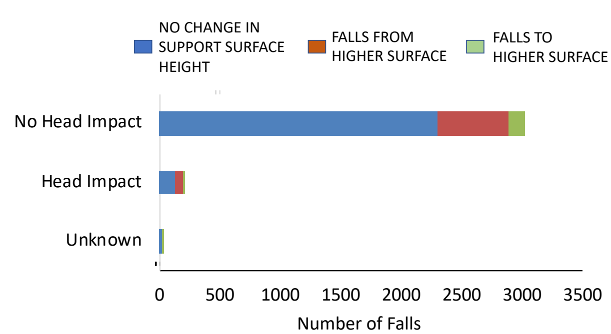

FIGURE 3. DISTRIBUTION OF FALL TYPES BY HEAD IMPACT STATUS.

SIM G™ activation in falls meeting or exceeding the 12 g linear head acceleration threshold occurred at a rate of 0.2 activations/subject hour overall, but at a rate of 0.4 activations/subject hour on the playground. The SIM G device was activated in 28% of falls from a higher surface when the SIM G™ was worn, 15% of falls with no change in support surface when the SIM G™ was worn, and in 12.5% of falls to a higher surface when the SIM G™ was worn. Head biomechanical measures were recorded in 174 falls, with a maximum linear head acceleration of 50 g and a maximum rotational head acceleration of 5388 rad/sec^2 (Table 2). This fall occurred when a child tripped and fell forward impacting his head on a wooden bookcase. No injury occurred and the child was observed playing shortly after the fall event.

TABLE 2. SIM G RECORDED HEAD BIOMECHANICAL MEASURES (N=174)

	Linear Head Acceleration (g)	Linear Head Velocity (m/s)	Rotational Head Acceleration (rad/s^2)	Rotational Head Velocity (rad/s)	Impact Duration (msec)
Median	15.3	1.9	1013	8.9	22.0
Range	12 - 50	0.5-3.8	377- 5388	2.6-21.6	6.0-34.0

There was no difference in linear head acceleration or rotational head acceleration across fall types (Fig 4) and head accelerations did not correlate to fall height (r=0.004 for linear head acceleration; r=0.102 for rotational head acceleration). However, head accelerations were significantly higher for falls where there was head impact (Fig 5).

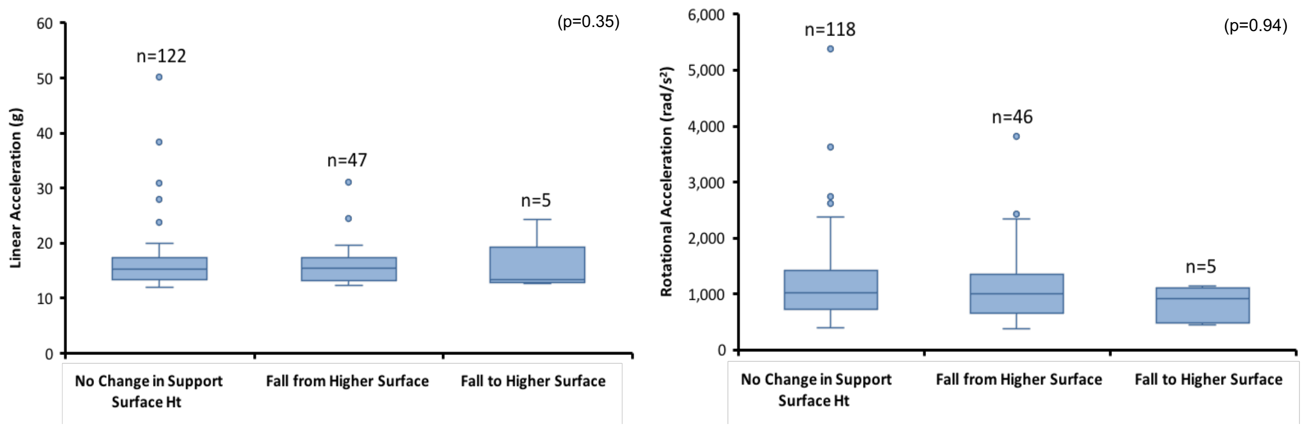

FIGURE 4. LINEAR AND ROTATIONAL HEAD ACCELERATION BY FALL TYPE.

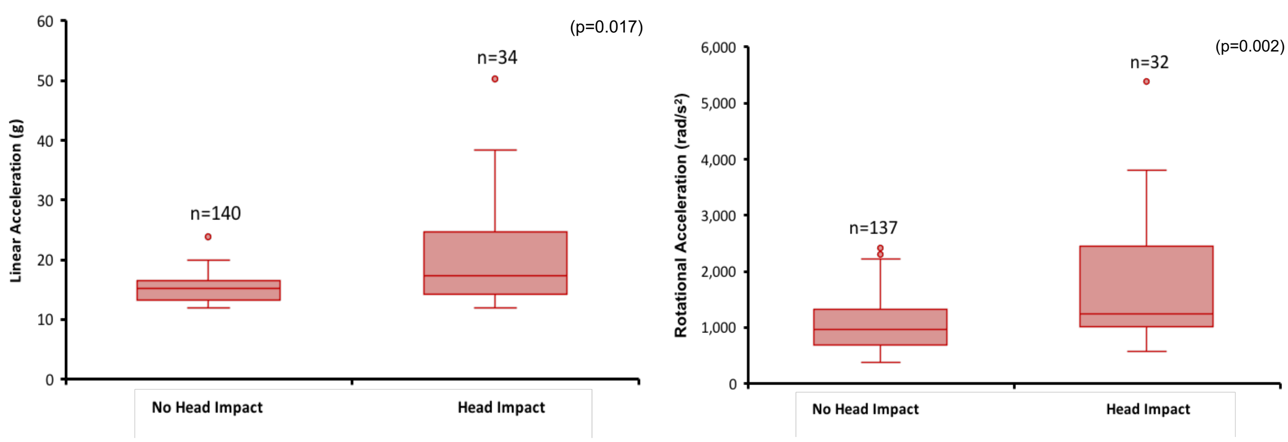

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FIGURE 5. LINEAR AND ROTATIONAL HEAD ACCELERATION BY HEAD IMPACT STATUS.

A subset of our variables describing all falls will be available to the public in a searchable, web-based Pediatric Fall Biomechanics Knowledgebase. (This website will go live once manuscripts describing our dataset are published.) This searchable Knowledgebase will enable users to conduct a quick search or to set search criteria to customize their query of de-identified falls data (Fig 6). Query results can then be exported to various applications (e.g. Excel, Word) to further analyze the data.

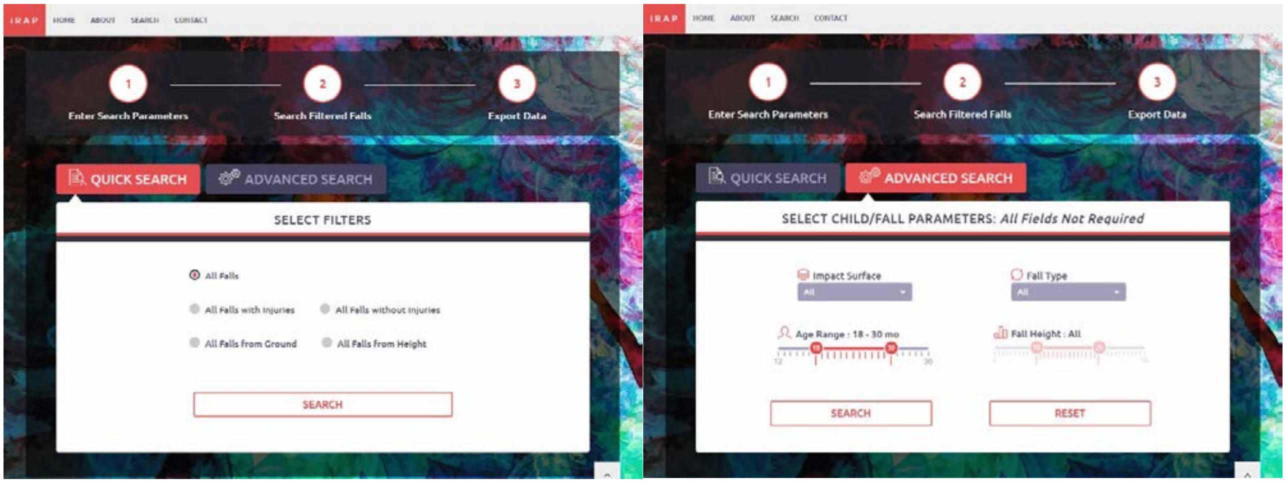
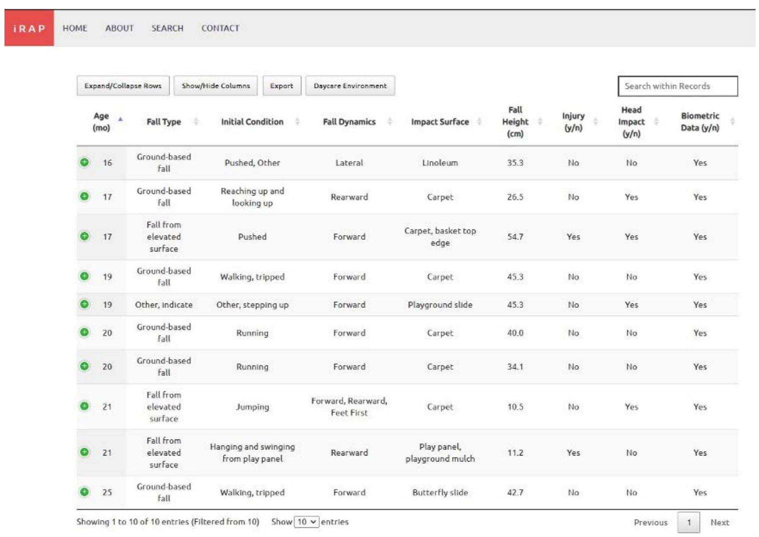


FIGURE 6. SEARCHABLE PEDIATRIC FALL BIOMECHANICS KNOWLEDGEBASE: QUICK SEARCH AND ADVANCED SEARCH ENABLING SELECTION OF CUSTOM SEARCH CRITERIA.



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Age (mo)	Fall Type	Initial Condition	Fall Dynamics	Impact Surface	Fall Height (cm)	Injury (y/n)	Head Impact (y/n)	Biometric Data (y/n)
16	Ground-based fall	Pushed, Other	Lateral	Linoleum	35.3	No	No	Yes
17	Ground-based fall	Reaching up and looking up	Rearward	Carpet	26.5	No	Yes	Yes
17	Fall from elevated surface	Pushed	Forward	Carpet, basket top edge	54.7	Yes	Yes	Yes
19	Ground-based fall	Walking, tripped	Forward	Carpet	45.3	No	No	Yes
19	Other, indicate	Other, stepping up	Forward	Playground slide	45.3	No	Yes	Yes
20	Ground-based fall	Running	Forward	Carpet	40.0	No	No	Yes
20	Ground-based fall	Running	Forward	Carpet	34.1	No	No	Yes
21	Fall from elevated surface	Jumping	Forward, Rearward, Feet First	Carpet	10.5	No	Yes	Yes
21	Fall from elevated surface	Hanging and swinging from play panel	Rearward	Play panel, playground mulch	11.2	Yes	No	Yes
25	Ground-based fall	Walking, tripped	Forward	Butterfly slide	42.7	No	No	Yes

Showing 1 to 10 of 10 entries (Filtered from 10) Show 10 entries Previous 1 Next

FIGURE 7. SEARCHABLE PEDIATRIC FALL BIOMECHANICS KNOWLEDGEBASE: QUERY RESULTS TABLE.

LIMITATIONS

Falls data is limited in terms of subject and fall environment variability since all data was collected at one licensed childcare center where children were supervised; however, it is the combination of child and fall characteristics that creates a diverse biomechanical representation of falls. The large number of falls is expected to create a diverse biomechanical representation of falls given that outdoor playground and indoor playroom environments were studied. The outdoor playground included climbing equipment that led to falls from elevated surfaces, although height was limited by age-appropriate playground equipment. However, we acknowledge that supervised childcare center falls may not be fully representative of falls occurring during unsupervised activities. Studying children ranging from 12-36 months of age with differing developmental levels also provided further diversity in fall biomechanics. Some children removed the SIM G headband for periods of time during data collection. The childcare center staff and research team observer replaced headbands on children when possible. However, at times children resisted wearing the SIM G device. Given the high rate of falls and large number of observation hours it did not inhibit our ability to meet data collection goals. Since all falls were video recorded and observed by a research team member, when children removed their headbands and threw them causing an "impact" to be registered, video recordings were able to identify this impact as a false event and it was removed from the data set.

ARTIFACTS

LIST OF PRODUCTS

- G Bertocci, C Smalley, N Brown, R Dsouza, A Thompson, K Bertocci, B Hilt, D Cory, K McKinsey, MC Pierce, Injuries and Biomechanics of Falls Involving Young Children in a Childcare Setting Obtained Through Video Recording and Wearable Biometric Devices, Shaken Baby Syndrome and Abusive Head Trauma Symposium, Sept 2020 (abstract and virtual presentation).
- D Cory, G Bertocci, A Thompson, B Hilt, C Smalley, N Brown, R Dsouza, K Bertocci, K McKinsey, Characterization of Video-Recorded Falls Involving Children in a Childcare Setting, Ohio State University Injury Biomechanics Symposium, May 2020 (abstract; presentation canceled due to COVID).
- *In Situ* Head Biomechanics of Video Recorded Falls Involving Children in a Childcare Setting - manuscript to be submitted Jan 2021 to *Nature - Scientific Reports*.
- Searchable Pediatric Fall Biomechanics Knowledgebase website - key variables describing 3255 falls. Website is complete and will go live once manuscripts are published.
- Pediatric Falls Research Database - maintained by the University of Louisville, Injury Risk Assessment and Prevention Laboratory directed by Dr. G Bertocci.

DATA SETS GENERATED

Our dataset consists of 3255 video recorded falls involving children in a licensed childcare center which have been described based on fall characteristics, child characteristics, and head biomechanics (when SIM G™ was activated). Additionally, our dataset includes screen grabs of fall initiation, mid-fall, and landing time points from video recordings. A subset of key variables describing all falls will be available to the public via our web-based, searchable Pediatric Fall Biomechanics Knowledgebase containing de-identified data. This website will be made available on the internet once we have published manuscripts describing our dataset.

DISSEMINATION ACTIVITIES

We have presented our study findings at the Shaken Baby Syndrome and Abusive Head Trauma Symposium, which is typically attended by clinicians, social workers, law enforcement personnel, judiciary personnel and victims' families. This 45 min presentation enabled the PI to provide an in-depth overview of our findings. We have also drafted our first manuscript which will be submitted to *Nature - Scientific Reports*, an open source journal, freely accessible to the public. Subsequent manuscripts will also be submitted to open source journals. Additionally, once manuscripts describing our dataset have been published, our completed Pediatric Fall Biomechanics Knowledgebase website will be released on the internet. This will enable anyone with internet access to search a subset of variables describing our 3255 pediatric falls. We will also implement search engine optimization using key words and features to increase the quantity and quality of traffic to our website.