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| **Document Title:** | **Pediatric Fracture Printing: Creating a Science of Statistical Fracture Signature Analysis** |
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***Pediatric Fracture Printing: Creating a Science of Statistical Fracture Signature Analysis***

In this research a forensic pathologist, a forensic anthropologist, a biomechanical engineer, and a pattern recognition engineer collaborated to address a gap in best practice that surrounds the interpretation of pediatric cranial fracture trauma. The study had three main objectives: (1) to **continue development** and gathering of data on an experimental animal model to help correlate input forces and fracture patterns; (2) to **initiate** the development of an automated pattern recognition method for pediatric 'fracture-printing' to be used in the identification of injury causation, initially based on "ground truth" data from the animal model; and (3) to **collect forensic case file data** on pediatric deaths involving cranial fracture and known blunt force impact scenarios from medical examiner offices across the country to **begin** to establish a human database. This database, named the "Pediatric Fracture Pattern Registry", was developed by consultant Dr. Steve Clark. An additional objective focused on adult human cranial fracture, as our pediatric cranial fracture initiation and propagation findings were inconsistent with the little that is understood about adult humans. Therefore, we experimentally impacted a small sample of adult human cadaver heads using the same parameters as our juvenile porcine impacts.

The purpose of this research was to provide medicolegal death investigation experts (such as forensic pathologists, coroners, forensic anthropologists, and medical examiner investigators), as well as child protective services professionals, the data needed to more accurately interpret pediatric cranial trauma and determine whether it is consistent with abusive or accidental injury. Because little experimental data on pediatric cranial fractures exists, medicolegal death investigators and child protective services professionals must rely on their own experiences or vague guidelines developed from clinical cases of children brought into other morgues and/or emergency rooms. A major weakness of these guidelines is that they are often limited by one's own experiences or based on anecdotal, unsubstantiated eyewitness accounts of causes and mechanisms of injury. As a result, there is a lack of consensus by experts in the field surrounding biomechanical causes of various pediatric cranial fracture patterns. This is especially problematic when these cases go to court. Due to the anecdotal nature of these guidelines, the scientific basis of expert witness testimony surrounding pediatric cranial fracture is often questioned at trial.

**Biomechanical Experiments: Design, Methods and Data Analysis**

***Porcine surface study:*** This study examined the effect of surface compliance on the pattern of skull fractures in head drop experiments onto the parietal bone with an immature porcine (*Sus domesticus*) model. The hypotheses of this study were: 1) head drops onto a rigid surface would produce more fracturing than drops onto a compliant surface; and 2) fracture patterns produced in high-energy head drops onto a compliant surface would have characteristic differences from patterns generated on a rigid surface, either at a high or low energy.

Specimen heads of a given age were dropped with a consistent orientation onto various surfaces at the same impact energy. The study was performed with specimens 2-19 days of age in controlled head drops onto a rigid surface and three carpeted surfaces. The rigid surface was an aluminum plate (n=32). "Carpet 1" covered the rigid surface with a thin, commercial-grade carpet (n=32), "carpet 2" added foam underlayment (n=32), and "carpet 3" used a plush carpet with underlayment (n=8). The resulting fracture patterns were recorded on a standard diagram and the location and length of each was documented as seen in figure 1.

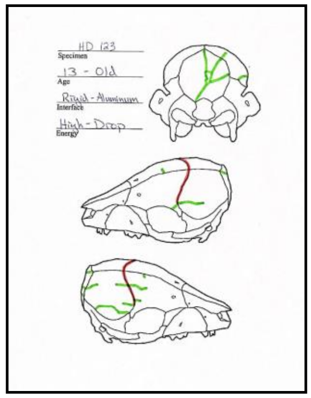


Figure 1. Example of porcine fracture diagram.

The total number of cranial fractures for impacts onto the rigid surface was statistically greater than for the carpeted surfaces (p<0.001 for each). There were also more fractures occurring in bones other than the impacted right parietal bone for the rigid interface than for each of the carpeted interfaces (p<0.001 for each). Furthermore, there was a statistically greater total length of cranial fractures from impacts onto the rigid surface than each of the carpeted surfaces (p<0.001 for each). This study showed that a head dropped onto a rigid surface would produce more extensive fracturing than one dropped onto a compliant surface for the same level of impact energy.

Carpets 1-3 data were compared to previously published low-energy drops onto a rigid surface. T*here w*ere *significantly more diastatic fractures produced in the low-energy rigid* drop *experiments than in high energy* drop experiments onto *carpets 2 (p=0.021) and 3 (p=0.022).* While the degree of fracturing was similar for high-energy drops onto the carpeted surfaces as low-energy drops onto a rigid surface, differences in diastatic fractures may allow these impact scenarios to be distinguishable post-trauma.

***Porcine shaped impact study*:** This study was conducted to understand biomechanical mechanisms and cranial fracture patterns from shaped surface impacts using an immature porcine model. The hypotheses of the study were: 1) heads dropped against surfaces with a large contact area would have fractures that mimic flat surface experiments with peripherally-initiated linear fractures; 2) as the contact area decreased, depressed fracturing would occur; 3) at some intermediate contact size and shape, there would be a combination of depressed and linear fractures; and 4) the energy and resulting contact force necessary to cause fracture initiation would decrease with the area of the impacting surface.

Porcine heads aged 1-20 days (n = 32) were dropped under controlled conditions onto 4 impact shapes: a 2" diameter hemisphere (n=8), a 1/16" edge (n= 9), a 5/8" diameter ball-bearing (n=7), and a ¼" flat-ended peg (n=8). As in the surface study above, biomechanical data were collected during each experiment and the heads were then processed and diagrammed.

The 2" diameter hemisphere represented a transition between flat and localized surfaces, as 5 specimens expressed both peripheral linear and local impact fractures. As hypothesized, when the implement contact area decreased the occurrence of depressed, localized fractures increased. Depressed fractures were generated with the 5/8" diameter ball-bearing, and the fracture patterns paralleled the shape of the impacting implement. The 1/16" edge impact shape generated linear fractures that extended along the contact surface and caused a creasing depression of the bone. The ¼" peg produced punctures through the bone and had the highest frequency of depressed fractures (7/8).

The study showed that depressed fractures that resembled impact shape were noted in cases of localized contact area, while linear fractures were generated in cases of more distributed contact force. The study showed that both peak contact force and kinetic energy to initiate cranial fracture decreased with contact area. For example, the impact energy needed to initiate cranial fracture in the parietal bone of the immature porcine skull against a rigid edge-shaped surface, simulating contact with a table or sink, was approximately one-quarter that needed to cause a cranial fracture against a flat, rigid surface.

***Human head impact study:*** The purpose of this study was to help clarify contrasting data in the trauma literature regarding the location of fracture initiation and direction of fracture propagation in blunt cranial impacts. High-speed cameras were utilized to record cranial fracture initiation, propagation, and sequencing in a variety of controlled impact experiments performed on adult cadaver heads.

Seven unembalmed adult male cadaver heads were impacted with various shaped aluminum implements attached to a 10 kg mass using a custom-built drop tower. Specimens were secured in a plaster of Paris bed and impacted once onto the center of the right parietal. Controlled impacts were performed with varying energies and shaped implements to investigate effects of these variables on cranial fracture initiation and propagation. Three heads were impacted at various energies using a flat, 3-inch diameter implement. Two heads were impacted with a flat, 1-inch square implement. One head was impacted with a 2-inch spherical implement. The final head was impacted with a 1-inch spherical implement. High-speed cameras recorded fracture events at 6,600 and 10,000 fps. One specimen head was CT scanned. The parietal bone geometry was utilized in producing a computational model investigating the distribution of impact-related stresses in the bone.

This study provided documentation of peripheral cranial fracture initiation in adult human subjects. Video footage clearly showed linear fractures initiating peripherally in all three impacts with the flat, 3-inch circular implement, one impact with the flat, 1-inch square implement, and the 2-inch spherical impact.

The outcomes of the impacts using the flat, 3-inch circular implement reflect variation in location of fracture initiation, direction of propagation, and fracturing sequence with impact energy. At the lowest energy (52.5 J), a single linear fracture initiated near the pterion and propagated back toward the impact site. The second experiment on another skull at a slightly higher energy (72.7 J) produced a peripherally initiating linear fracture, followed by concentric fracture around the point of impact and then a linear fracture propagating outward from the impact site. The highest energy impact on another skull (120.2 J) produced a similar fracturing sequence with more extensive damage.

The results also demonstrated implement shape effects. Both impacts with the 1-inch square implement produced linear fracture. However, initiation occurred at the impact site in one experiment, and peripheral to the impact site in the other. The 2-inch spherical implement produced a peripherally initiating linear fracture followed by concentric fracture around the impact site. The 1-inch spherical implement generated a shallow depressed fracture in the shape of the implement.

The stress distribution calculated in the computational model paralleled experimental observations of fracture initiation. The model showed a zone of circumferential-oriented tensile stresses in the parietal bone away from the impact site. These stresses could be responsible for radial-oriented fractures initiating peripheral to the impact site in areas of 'outbending.' With higher loads, the model indicated a zone of large circumferential and radial-oriented stresses at the impact site. These stresses could be responsible for concentric and radiating linear fractures initiating at the impact site.

**Development of the Fracture Printing Interface: Design, Methods and Data Analysis**

Using the porcine cranial impact data, an automated pattern recognition method was developed to classify cranial fracture patterns associated with different impact energy (high or low), constraint condition (entrapped or free-fall) and impact surface (rigid, compliant or carpet) for a given specimen age. The objective of this part of the research was to develop a method using machine learning in order to determine the statistical probability of a causative impact condition based on a cranial fracture pattern for a given age of specimen.

A total of 354 porcine cranial fracture samples have been generated in controlled biomechanical impact experiments. Subsequently the cranial fracture diagrams were uploaded to a user-friendly Fracture Printing Interface (FPI). The FPI was developed to automatically extract characteristic features of the fracture patterns. Given the specimen age and depending upon the user's particular request, the FPI is able to predict one or more class labels. The class labels, to date, are: (1) impact energy level (high or low), (2) head constraint condition (entrapped or free-fall), and (3) impact surface (rigid, compliant or carpet).

In the current research the performance of the FPI was evaluated in various subtasks. Each subtask was created by choosing a subset of fracture diagrams that share one or more class labels (e.g. constraint condition of free-fall), and performing classification for another class label (e.g. predicting impact energy) for various age groups (young, old and all). The experimentally controlled data enabled the researchers to use classification accuracy as a measure of performance for the FPI.

The FPI utilizes 20 different classifiers that come from 5 different families of classification methods: (1) decision trees, (2) discriminant functions, (3) Bayesian methods, (4) lazy learners, and (5) ensemble methods in order to categorize the porcine fracture patterns. The well-known 10-fold cross-validation technique was used to report the performance of the best performing classifier for each experimental case.

Overall, the FPI was successful in categorizing cranial fractures into classes based on constraint condition, impact surface, and impact energy with reasonably high levels of accuracy. For a fixed impact energy level the FPI showed an accuracy of being able to predict constraint condition 81-85% of the time for a compliant surface and 92-94% for a rigid surface. Moreover, in a situation of free-fall on a rigid surface, the FPI was able to accurately predict the associated impact energy level (high or low) 86-95% of time. The two constraint conditions in the FPI were dropped heads and entrapped heads. The impact surface variables were rigid, compliant and carpet. The impact energy variables were high energy and low energy. Low energy produced fracture initiation, and high energy produced significant fracture propagation in the porcine model. Both low and high energy impacts were generated by the force of gravity by changing the drop height of the head.

**Pediatric Forensic Case Data: Design, Methods, and Data Analysis**

This portion of the project was designed to collect data from medical examiner's case files on pediatric deaths (from birth to five years of age) that exhibited cranial fractures. Information on the decedent's age, descriptions of cranial injuries, cause of death, manner of death, history of injury and reliability of the history provided was collected along with photographs and/or diagrams of the cranial fractures.

A total of 15 office have provided data including the following facilities: Pima County Office of the Medical Examiner (Tucson, AZ), Harris County Institute of Forensic Sciences (Houston, TX), Tarrant County Medical Examiner's Office (Fort Worth, TX), Fulton County Medical Examiner's Office (Atlanta, GA), Hennepin County Medical Examiner's Office (Minneapolis, MN), Midwest Medical Examiner's Office (Anoka, MN), New York City Office of the Chief Medical Examiner (New York City, NY), Erie County Medical Examiner's Office (Buffalo, NY), Cook County Office of the Medical Examiner (Chicago, IL), Washtenaw County Medical Examiner's Office (Ann Arbor, MI), Genesee County Medical Examiner's Office (Flint, MI), St. Clair County Medical Examiner's Office (St. Clair, MI), Kent County Medical

Examiner's Office (Grand Rapids, MI), Sparrow Forensic Services (Lansing, MI), and Mayo Clinic (Rochester, MN). These 15 office visits meet the original goal of this project.

The dataset from the 15 medical examiner's offices currently contains 314 cases of pediatric deaths involving cranial fractures. The male and female distribution for each case type is generally even, however, there are more male than female deaths at ages 1.5-2 years-at-death, 2.5-3 years-at-death, and 3.5-4 years-at-death. The manner of death distribution is 176 accidents, 126 homicides, and 12 undetermined. The amount of homicides is highest in the youngest age-at-death category, from 0-6 months of age, and the numbers steadily decline as the age-at-death increases. The number of accidental deaths has a spike at the 1.5-2 years age-at-death category, which is likely due to the decedents' recent ability to walk and run.

A pilot study has also been conducted on 100 human pediatric cranial fracture patterns from these forensic cases. This initial study has shown that the models and algorithms from the Fracture Printing Interface, developed using the porcine data, were able to be transformed in order to classify human pediatric cranial fracture patterns into categories of homicides (cases in which the manner of death was ruled a homicide by the medical examiner/coroner) or high energy accidents (e.g. TVs crushing decedents, second story falls from windows) with an accuracy of 75%.

This information, along with standardized fracture pattern diagrams, was also uploaded into the secure National Cranial Fracture Registry created by Dr. Steven Clark. This database is currently 'offline', but has the capability of being shared with medico-legal death investigator professionals. This capability will not only allow death investigators to examine cases of similar fracture patterns and/or scenarios, but would also allow these professionals to upload their own cases to further contribute to the body of knowledge which has been gathered by current funding.

## Implications for Criminal Justice Policy & Practice in the US

The primary accomplishments of this research will have significant impact on criminal justice policy and practice in the United States. To begin, our experimental biomechanical work has generated foundational, ground-truth knowledge correlating known impact conditions with fracture characteristics, including predictable processes of cranial fracture initiation and propagation that were previously not understood. Secondly, the development of the Fracture Printing Interface, a new, automated system that classifies cranial fracture patterns with a high degree of accuracy as validated on an experimental porcine dataset and utilized in a pilot case-based human pediatric dataset, is important proof-of-concept necessary to take the next step in building the "Human Fracture Printing Interface". Additionally, we have established the "National Cranial Fracture Registry", a pediatric cranial fracture database that will serve as a resource for other forensic practitioners and researchers worldwide. Moving forward, it is envisioned that this database will be combined with the Human Fracture Printing Interface, thereby creating a tool that will automatically extract fracture features of an uploaded forensic case that can be compared to the known database and predict the most likely cause of the injury. This will provide medicolegal death investigators an analytical tool that will enable them to more effectively interpret cranial fracture patterns in pediatric deaths based on the ability to establish a statistical level of scientific certainty about injury causation. This will help close a tremendous and costly gap in the criminal justice system surrounding pediatric cranial fracture interpretation.

Appendix 1

**<u>List of Scholarly Products</u>:**

**Journal Publications in Progress**

1. Deland,T.S., Niespodziewanski,E., Fenton,T.W., Haut,R.C. The Role of Interface on the Impact Characteristics and Cranial Fracture Patterns Using the Immature Porcine Head Model. J. Forensic Sciences. (**In review with JFS**)
2. The effect of impact surface shape on the patterns and biomechanics of cranial fractures in the immature porcine model (**Almost ready to be submitted to JFS**)
3. Development of a Fracture Printing Interface to Classify Porcine Cranial Fracture Patterns (**Almost ready to be submitted to JFS**)
4. Statistical Discrimination of Porcine Cranial Fracture Patterns Using Ground Truth Experimental Data (**In Preparation**)
5. Fracture Initiation and Propagation in Pediatric Blunt Cranial Trauma (In Preparation)
6. Experimental and Computational Validations of the Initiation and Propagation of Cranial Fractures in the Adult Skull (**In Preparation**)

**Published Conference Abstracts**

1. DeLand, T., Niespodziewanski, E., Fenton, T.W., and Haut, R.C. A Forensic Pathology Tool to Predict Pediatric Skull Fractures - Part 4: Interface Effects on Head Drops. 2014 American Academy of Forensic Sciences Annual Meeting, Seattle, WA.
2. Isa, M.I., Fenton, T.W., Vollner, J.M., Niespodziewanski, E.R., Love, J.C., DeJong, J.L., DeLand, T.S., Haut, R.C. Fracture Initiation and Propagation in Pediatric Blunt Cranial Trauma. 2014 American Academy of Forensic Sciences Annual Meeting, Seattle, WA.
3. Vollner, J.M., Carpenter, K.A., Fenton, T.W., Haut, R.C. Pediatric Cranial Fracture Patterns in Cases of Head Trauma Resulting in Death. 2014 American Academy of Forensic Sciences Annual Meeting, Seattle, WA.
4. Vogelsberg, C.M., Vaughan, P.M., Fenton, T.W., Haut, R.C. A Forensic Pathology Tool to Predict Pediatric Skull Fracture Patterns- Part 5: Controlled Head Drops onto Shaped Impact Surfaces. Accepted for podium presentation at the 2015 Annual Meeting American Academy of Forensic Sciences, Orlando, FL.
5. Fenton, T.F., Isa M.I., Vaughan, P.M., Haut, R.C. Experimental and Computational Validations of the Initiation and Propagation of Cranial Fractures in the Adult Skull. Accepted for podium presentation at the 2015 Annual Meeting American Academy of Forensic Sciences, Orlando, FL.
6. Vollner, J.M., Bucak S., Fenton, T.W., Haut, R.W., Jain, A. The Fracture Printing Interface: Development of an Automatic Classification System for Cranial Fracture Patterns. Accepted for podium presentation at the 2015 Annual Meeting American Academy of Forensic Sciences, Orlando, FL.