

March 2020

A Multidisciplinary Approach to Trauma Analysis in Cases of Child Fatality

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A Multidisciplinary Approach to Trauma Analysis in Cases of Child Fatality

by

Jaime D. Sykes

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Arts in Applied Anthropology
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Date of Approval:
March 19, 2020

Keywords: Finite Element Modeling, Skeletal Biology, Forensic Anthropology, Cranial Fracture

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DEDICATION

This thesis is dedicated to my wonderful parents, Paul and Linda Sykes, for their never-ending encouragement and support throughout my education. I love you both more than words could possibly express! I also dedicate this work to my brother, Charlie Sykes, for encouraging me to keep going when I hit snags in the road. You are the best brother I could ever ask for! To Hannah Ayers and Emily Baker, my best friends and two brilliant human beings who always provided a willing ear to my incessant chatting about this thesis. To my classmates and friends from USF and the many professors who nurtured my development as an academic, thank you all! Finally, to the love of my life, Beck Seiverd. You provide so much support and encouragement for my desires and aspirations. I am so lucky to have had you by my side throughout this journey, and I cannot wait to see our life together unfold.

ACKNOWLEDGMENTS

I offer my sincerest thanks to my advisor Dr. Erin H. Kimmerle for her incredible mentorship throughout these last few years. Thank you for the endless opportunities and always helpful advice as I work towards my professional goals. Thank you for allowing me to find my footing in the field in my own way while simultaneously guiding me through the process of becoming a biological, forensic, and applied anthropologist.

Special thanks to my committee member Dr. Daniel Simkins for taking on an anthropologist and trusting me to do my best as a fumble my way through the engineering world. Thanks to my committee members Dr. Lorena Madrigal and Dr. Christian Wells for providing me with their valuable perspectives and feedback. Thanks to Dr. Simkins' Ph.D. students James Olliff and Brad Alford for their invaluable work and assistance on this project.

My deepest thanks to my friends and colleagues Kelsee Hentschel-Fey, Gennifer Goad, Kirsten Verostick, and Dr. Cate E. Bird for their encouragement and support throughout the duration of this project. Thanks to the numerous faculty in the University of South Florida's Department of Anthropology who have contributed immensely to my growth and development as an anthropologist. Additional thanks to my cohort for their support as we go through this process together.

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ABSTRACT

Child fatality is an issue of social and forensic significance. Due to the complex nature of these cases, it can be difficult to determine the cause and manner of death (referred to as equivocal death), particularly when differentiating between accidental and inflicted traumatic fatalities. Finite Element Modeling is a tool typically used to elucidate the etiology of fractures. This thesis utilizes a multidisciplinary approach to research the frequency of equivocal deaths among juveniles and the usefulness of FEM as a solution to diagnosing skeletal trauma. The first component examines the problem of misdiagnosed manner of death through retrospective case examinations in Pasco County, Florida, and the second aspect of the study examines the efficacy of Finite Element Modeling in trauma research by comparing two simple hemispherical models that approximate the neurocranium. The child fatality study examines 84 cases of child fatalities in Pasco County, Florida, and finds that the demographic characteristics of the decedents given their relationship to the perpetrator closely mirrored those findings in the published literature. Similarly, the age breakdown of decedents mirrors other studies on child fatalities, where infants and teenagers are most at risk of violent deaths. Most importantly, equivocal deaths were more present in the dataset than previously thought, and nine cases were possibly misdiagnosed in terms of manner of death. The modeling component of this study demonstrates that FEM may not be the most appropriate method of computational modeling due to the restrictiveness of the meshes that are used to create the individual elements in the model. Experimentation with meshfree modeling techniques that allow for more realistic fracture propagation are needed, as well as patient-specific modeling. Finally, skeletal surveys through direct observation and other

modes of anthropological analysis in the autopsies of child fatalities are highly encouraged given the results of this study.

CHAPTER ONE:

INTRODUCTION

Forensic anthropologists make numerous contributions to medicolegal death investigations by establishing biological profiles of unidentified individuals, leading exhumation or body location efforts using archaeological excavation and survey techniques, estimating the postmortem interval in decomposed cases, and examining skeletal remains for evidence of disease or trauma (Byers 2008; Komar and Buikstra 2008; Tersigni-Tarrant and Shirley 2013; Wedel et al. 2014). Trauma analysis, which is the application of the anthropologist's knowledge of skeletal biology to the study of how fractures propagate under various mechanisms of injury, has become a particularly important part of forensic anthropological casework (Kimmerle and Baraybar 2008; Kroman 2007; Kroman et al. 2011; Wedel et al. 2014). Trauma analysis is a vital component of both domestic homicide cases and international human rights investigations (Berryman et al. 2013; Byers 2008; Kimmerle 2013; Kimmerle and Baraybar 2008; Komar and Buikstra 2008; Kroman 2007; Kroman et al. 2011; Wedel et al. 2014). Additionally, forensic anthropologists have increasingly turned their attention to the study of skeletal fractures in the juvenile skeleton to shed light on abuse-related deaths in children and infants (Lewis 2007; Love et al. 2011; Ross and Abel 2009; Ross and Abel 2011; Ubelaker and Montaperto 2011; Wheeler et al. 2013).

The study of skeletal trauma in incidents of child homicide and infanticide is not only an increasingly important area of study in forensics, but is also of interest in a diverse array of subdisciplines of biological anthropology. Studies have uncovered possible instances of child abuse in the archaeological record by examining fracture patterns and healing rates in juveniles at various sites (see Blondiaux et al. 2002; Gaither 2012; Lewis 2007; Lewis 2010; Wheeler et al. 2013). Similarly, trauma analysis has been used to examine the practice of infanticide among nonhuman primates, such as chimpanzees (see Eriksen et al. 2014). For forensic anthropologists, examining the juvenile skeleton to document skeletal trauma and interpret mechanism of injury is an important role in casework, as increased academic and scientific interest in issues relating to child homicide and infanticide reflects increasing public awareness of and concern for child maltreatment in the United States (Korbin 1987; Ross and Abel 2009; Ubelaker and Montaperto 2011).

Problem Statement

Child homicide is a widespread problem in the United States (Boudreaux et al. 2001; Ewigman et al. 1993; McClain et al. 1993) with an average of four children dying per day in 2013 from caregiver abuse or neglect (CAN) (Children's Bureau Report 2015). Research indicates that these numbers are also underreported (Billmire and Myers 1985; Boudreaux et al. 2001; Carty and Pierce 2002; Ewigman et al. 1993). This poses a diverse array of issues for investigators, as these types of deaths are hard to define, investigate, and prosecute (Boudreaux et al. 2001). Additionally, child fatalities are more often misclassified as accidental or

undetermined in cases of homicide (Ewigman et al. 1993). As an overwhelming majority of deaths due to abuse are perpetrated by a caregiver, there are often no witnesses outside of the family unit who know what happened to the child. Added to this problem is a lack of documented timelines for injury occurrence given who was alone with a child, making it challenging to determine the manner of death and at times leading to misdiagnosis (Boudreaux et al. 2001; Ewigman et al. 1993; McClain et al. 1993; Wilczynski 1994; Ziegler et al. 2005). In addition, many nonfatal symptoms of child abuse go undetected by the medical community until the child is admitted to emergency services immediately before death, even when the child was evaluated by health care professionals for reasons potentially attributable to maltreatment shortly preceding the fatal incident (King et al. 2006).

The problem of misdiagnosed manner of death is of extreme importance to forensic anthropologists engaged in trauma research, as it can be difficult for medical examiners to distinguish between accidental and inflicted trauma at autopsy. Blunt trauma can be particularly difficult to interpret, creating a need for trauma researchers to develop studies that experimentally model how bone responds to strain (Wedel et al. 2014). In particular, blunt trauma to the cranium in young children is an important focus of this research as infants are of higher risk for fatal abuse (Abel 2011; McClain et al. 1993; Mulpuri et al. 2011), and cranial trauma is a high cause of morbidity in abused children (Abel 2011).

The etiologies of injuries to skeletal tissue can be difficult to interpret, as no single fracture type is a precise indicator of either an accidental or inflicted traumatic episode (Abel 2011; Galloway and Wedel 2014b; Kemp et al. 2008). Devising improved methods for distinguishing between accidental and inflicted injuries, particularly in the crania of young children, is therefore an increasingly important area of inquiry in both pediatrics and forensic

anthropology. This study aims to respond to the societal problems of child homicide and infanticide by addressing gaps in scientific understanding of inflicted and accidental fracture patterns. This will be accomplished through retrospective case review and by critically evaluating the efficacy of existing trauma modeling methods. This will provide directions for further study on modeling blunt force injuries to the cranium by utilizing theories in biomechanics and methods from engineering.

Research Objectives

- A. The first component of this study addresses the issues of underreporting child homicides and infanticides by identifying opportunities for improved investigative procedures through case examination. All data for this project were collected at the Pasco County Sheriff's Office in Florida.

Research questions: 1. How does child fatality data in Pasco County, Florida compare to child fatality data from previous studies and in other parts of the United States? 2. Is there potential under or overreporting of child homicides in this area?

Hypotheses: 1. It is hypothesized that Pasco County cases will have similar patterns in child homicides from previous studies, such as frequencies of victim age groups, sex, and relationship to the offender. 2. It is also hypothesized that there may be some potentially misclassified cases in the dataset, as reported in previous literature from other jurisdictions in the United States (Billmire and Myers 1985; Boudreaux et al. 2001; Carty and Pierce 2002; Ewigman et al. 1993).

To test these hypotheses and address these questions, categorical data were collected from the examined cases to better understand how children are dying in Pasco County and identify patterns in child maltreatment. These hypotheses were tested through statistical analysis.

- B. This thesis also aims to launch the first of what will foreseeably be a series of studies conducted by forensic anthropologists and civil engineers regarding the efficacy of computational modeling in trauma research. Prior computational work in biological anthropology has relied on the Finite Element (FE) method for constructing models, which can be a powerful tool for many questions (see Ledogar et al. 2016; Panagiotopoulou 2009; Zhang et al. 2016), but is problematic when studying crack propagation due to the restrictiveness of the mesh that is required to construct the model. FE models will be discussed in more detail later in this thesis.

Research questions: 1. In what ways is computational modeling useful to trauma analysis researchers who are interested in elucidating the differences between accidental and inflicted injury? 2. What are potential caveats that forensic anthropologists should be wary of when utilizing FEM in trauma analysis? 3. Are there alternative methods for modeling crack propagation for trauma research?

Hypotheses: 1. This study hypothesizes that FE models are not the best method for studying fracture propagation; not only due to the restrictiveness of the mesh in FE models (Yreux and Chen 2017), but also because slight adjustments to boundary conditions or other model variables could drastically influence results, and if an expert is not present to assure the validity and interpretation of the models, improper conclusions may be reached. As the majority of anthropologists are not experts in civil or structural

engineering, slight missteps in the code that the trauma analyst is not equipped to catch while testing could provide inaccurate results in high stakes medicolegal contexts. This hypothesis will be tested by examining the difference between two simple FE models that are identical with the exceptions of the boundary conditions (one with fixed and one with sliding boundaries). Potential new directions for trauma modeling and the importance of acquiring basic knowledge of engineering principles for forensic scientists embarking on this work will then be discussed.

Research Significance

By retrospectively examining case studies the medico-legal community will be provided with tools to create an improved standard of protocol for child death investigations, contributing to higher homicide clearance rates. The identification of investigative issues coupled with an enhanced understanding of the etiology of violence against children through retrospective case review will not only assist law enforcement in improving investigations, but will also establish clear directions for both law enforcement and applied anthropologists in developing effective community intervention strategies that may help prevent child abuse or accidental child fatalities.

Similarly, by reviewing best practices for computational modeling in trauma research, medical examiners and prosecutors will be able to practice more effectively. Medical examiners could be able to more confidently establish a cause (how the death occurred such as ‘blunt force trauma’ or ‘gunshot wound’) and manner of death, leading to enhanced confidence in cases that may have previously been considered more ambiguous. The medical community may also

benefit from this project through increased understanding of common risk factors at play for child abuse, and potentially through future improvements in scientific knowledge regarding accidental and inflicted trauma.

Improved computational modeling will also reduce many of the issues present in cadaver experiments such as reduction in bone integrity, lack of access to cadavers at some institutions, and ethical issues that can arise from conducting trauma studies on cadavers. Computational analysis allows the trained anthropologist to experimentally compare fracture patterns in possible child abuse cases, assisting in establishing whether the injuries could have been sustained during an accidental or abusive incident. Similarly, anthropological knowledge of skeletal biology and evolutionary theory could prove useful to engineers by providing knowledge of human variation that is related to sociocultural and biological factors that may not be accounted for in current models. Forensic anthropologists can assist engineers who are not using patient specific data to create their models, ensuring that population specific and individual level factors that affect the skeleton are taken into consideration during model construction.

Finally, anthropologists and trauma analysts benefit from working closely with engineers not only for the integrity of the created models, but also to ensure the anthropologist fully understands the work they are doing and the physical principles that are integral to their construction. More generally, this thesis adds to the body of work that demonstrates the potential for multidisciplinary work in trauma research.

CHAPTER TWO: LITERATURE REVIEW

The criminology literature briefly explored in the first chapter of this thesis provides some helpful context; however, the evolutionary and cultural anthropological perspectives that may illuminate the complex reasons that humans engage in infanticidal behavior must also be explored to achieve a holistic understanding of such practices. This chapter will contextualize child homicide from a biocultural perspective.

Secondly, this chapter provides examples of experimental research in skeletal trauma analysis that have been conducted in forensic anthropology, which sets a foundation for the modeling utilized in this thesis. The research methods are discussed, and improvements in the methodology considered for future extensions of this project are also explained.

The properties of bone are discussed at length, as the material properties of any structure to be modeled must be understood to create an accurate prediction of fracture propagation. Current literature in anthropological trauma analysis is explored as current scientific knowledge of fracture propagation in the forensic literature must be used to further inform any model created on this topic.

Finally, the tools provided by the fields of biomechanics and engineering relevant to forensic investigations of fracture analysis are summarized, and the importance of understanding the basics of solid mechanics to create better models in trauma analysis are highlighted.

Biocultural Perspectives on Child Homicide

Due to the complex and taboo nature of infanticide and child maltreatment, few cultural anthropologists have documented or published accounts of child abuse or infanticide in their field sites, at least domestically. Early studies have noted that infanticide is practiced differently across cultures and is often considered justifiable in certain culturally-specific contexts (Korbin 1987). For example, the Machiguenga of South America believe that women are committed to raise a child only after she begins breastfeeding (Johnson 1981; Korbin 1987). Their culture reviles anger, and infants born from difficult labors and unruly toddlers are at higher risk of infanticide or maltreatment (Johnson 1981; Korbin 1987). Informants from other cultures also reported infanticide as acceptable in cases of extramarital births (Korbin 1987). Similarly, researchers examined the prevalence of female infanticide in male-preferential cultures and found prevalent sex discrimination in infanticide and child maltreatment (see George 1997; Oomman and Ganatra 2002).

Jill Korbin (1987) noted the importance of dissecting infanticide in a culturally-specific way, as what constitutes maltreatment varies in different societies. For example, many societies view the lack of co-sleeping in Western societies as abusive (Korbin 1987). She argued that it is important to understand diverse childrearing practices, as cultural misunderstandings may translate into disproportionate reporting of non-Western families to child services, as was the case for the Maori in New Zealand who commonly relied on older children to care for young siblings (Korbin 1987). As globalization and colonization pushed the Maori into the cities, many Maori parents were reported for child neglect as their childrearing practices were considered to

be maltreatment by White citizens (Korbin 1987). These and other studies paved the way for more recent cultural discourse on infanticide.

One such study conducted by de Hilari and colleagues in 2009 investigated the practice of infanticide in two indigenous Bolivian communities. The researchers utilized community surveillance systems already in place along with verbal autopsy questionnaires to collect data on infant mortality at two sites (de Hilari et al. 2009). While the research team was not composed of anthropologists, they also employed ethnographic methods to collect their data (de Hilari et al. 2009). Researchers conducted semi-structured interviews and focus groups in which they questioned community members about how infanticide was practiced within their community to determine in what situations infanticide was deemed justifiable (de Hilari et al. 2009).

Informants in the first community all stated that they had heard of infanticide being practiced (de Hilari et al. 2009). Most infants were smothered shortly after birth, and it was generally grandparents and the men of the family who determined whether an infant should be killed (de Hilari et al. 2009). One justification of infanticide was if the child was considered to be possessed of an evil spirit (de Hilari et al. 2009). Physical deformities in children and fraternal twins (particularly twinsets composed of one male and one female child) were considered evidence of possession (de Hilari et al. 2009). Other times, infants may be killed if the family already has too many children or too few resources to raise the child. Some community members considered it a better alternative for the infant to die early than to suffer later in life (de Hilari et al. 2009).

In the second community, infanticide was more passive, as infants who could not be taken care of were generally neglected until they eventually passed (de Hilari et al. 2009). This community also expressed that infanticide was acceptable if twins were born, much like in the

first community (de Hilari et al. 2009). They also noted that infanticide was sometimes justified if the conception of the child was not culturally legitimate (de Hilari et al. 2009).

The authors highlighted the importance of understanding infanticide within a cultural context to learn what is deemed acceptable (de Hilari et al. 2009). They also noted that in many similar societies, it may take years before a child is granted personhood, as they must traverse through ritual and symbolic rites of passage before they are considered full members of the community, leaving them at risk of maltreatment from the Western point of view (de Hilari et al. 2009).

They also noted that infanticide can be considered through either an activist or adaptationist perspective (de Hilari et al. 2009). Activists may argue that all human life must be protected regardless of age or physical deformity, while the adaptationist may consider infanticide to be necessary in a few unfortunate contexts, such as when competition for resources is fierce (de Hilari et al. 2009). Ultimately, the team aligned themselves as activists, stating that while they do not place moral judgements on their informants, they would like to inform policy that would curb child mortality due to infanticide (de Hilari et al. 2009).

This article poses some important and interesting ethical considerations regarding the need for culture-specific studies of infanticide (de Hilari et al. 2009), but is somewhat problematic. The ways in which researchers collected their data do not appear to be fully ethical nor without causing discomfort or harm to the informants. The authors noted that during focus groups, community members would signal to each other not to be open with their responses and frequently became uneasy (de Hilari et al. 2009). While studying infanticide ethnographically can be tricky, there are likely ways in which the researchers may have mitigated the discomfort felt by the participants by asking questions that elicit fruitful responses without directly asking

them when infanticide is acceptable in front of others from the community. What is accepted as a general practice may not be openly discussed in front of a diverse group, thereby resulting in biased responses of data is collected in a public forum.

Another problem with this study is the false dichotomy posed by the authors, who separate those who see the adaptive advantages of infanticide from those who aim to prevent the practice (de Hilari et al. 2009). These ideas are not mutually exclusive, and for activists, they cannot be separated. It is of vital importance that anthropologists who work to decrease infant mortality due to infanticide understand the reasons why it may be practiced from both an evolutionary and cultural perspective.

In another study Aaron Denham and colleagues discussed justifications for infanticide among the Nankani in Northern Ghana (2010). This study revealed that episodes of infanticide and child homicide generally occur if the victim suffers from a deformity or illness at birth, if the birth occurs simultaneously with a tragic event, or if the child possesses unusual abilities (Denham et al. 2010). The members of this community believe that these children are not actually people, but spirits in disguise who will wreak havoc in the community and harm their family (Denham et al. 2010). The community believes that spirit children are commonly produced through taboo sexual activities such as adultery or sexual intercourse outdoors (Denham et al. 2010). To identify the prevalence of this phenomenon, the research team designed a large-scale study that took place over the course of three years (Denham et al. 2010).

Previous research on the topic within the community had been inadequate and contradictory, leading Denham and colleagues to attempt a more holistic study that incorporated ethnographic methods with demographic data (2010). The methods included in this study were semi-structured interviews of community members and local health workers, and participant

observation (Denham et al. 2010). These data were supplemented with verbal autopsy questionnaires that aimed to examine the frequency of spirit child infanticides (Denham et al. 2010).

The study found that some community members considered other structural issues such as poverty and the lack of accessible healthcare as instrumental in a spirit child diagnosis, with poorer families more likely to produce spirit children (Denham et al. 2010). They also emphasized that before a child can be identified as a spirit child, it must present with abnormal physical characteristics (e.g. deformed limbs or neonatal teeth) or behavioral patterns, such as those caused by physical disabilities, a loss of appetite, or infants who excessively cried were thought to desire the destruction of the family and murder of the parents (Denham et al. 2010). Similarly, children and infants who did not frequently make eye contact were considered to be attempting to hide their true spirit identities (Denham et al. 2010). To prevent the spirit child from causing illness, death, infertility, or poor harvest, the child is killed, usually within the first day or two of life (Denham et al. 2010).

The process to determine whether a child is indeed a spirit child takes time, and does not rest on rumor or conjecture alone (Denham et al. 2010). Multiple spiritual heads and the family patriarch will be consulted multiple times before a diagnosis is definitively made (Denham et al. 2010). Children born with disabilities or illnesses are not always diagnosed as spirit children during this process (Denham et al. 2010). Denham and colleagues note that maternal reactions to spirit child diagnoses varied, and this variation could be explained when factors such as poverty, previous number of children, family conflict, religious beliefs, age, and education were considered (2010). These complexities; however, were not fully discussed in this paper (Denham et al. 2010).

After interpretation of the autopsy questionnaire data, it was noticed that spirit children did not all die from infanticide, a fact that was missed in previous literature (Denham et al. 2010). Some children who were diagnosed as spirit children died of an illness (around 36 percent of all spirit child deaths), and the authors emphasized that the spirit child diagnosis most accurately describes why a child had passed away, not how the death physically occurred (Denham et al. 2010). The majority of spirit child deaths were due to poisonings that were administered by concoction men in inconsistent amounts and differing chemical compositions (Denham et al. 2010).

The main conclusion of the study is that families sought multiple treatment options for ailing children and were relieved when a child was not diagnosed as a spirit child, and that when a spirit child was killed, the family did not perceive the death as a murder, as the child was a spirit and not a true person (Denham et al. 2010). The authors also noted that the death of a spirit child often occurs to protect other children and allow for continued growth of the family (Denham et al. 2010). Most importantly, the team emphasized that the spirit child phenomenon in this community is complex and multifaceted, despite past literature to the contrary (Denham et al. 2010). Finally, they hypothesized that incidents of spirit child infanticides will decrease if structural issues related to maternal and child healthcare are addressed in the community (Denham et al. 2010).

Overall, the study conducted by Denham and colleagues is an example of how thorough anthropological research can shed light on complex cultural phenomena (2010). It is particularly useful, as it successfully navigates a generally avoided topic in anthropological research and provides useful insight into the causes of infanticide in a culturally specific manner. This study also improves upon the ethical concerns raised by the first study, as the researchers seemed to

have created strong rapport through participant observation before delving into the interview process.

The studies conducted by de Hilari and colleagues in 2009 and Denham and colleagues in 2010 shed light on how infanticide is practiced and justified in two different cultural contexts. To fill in some of the gaps and elucidate a more interesting and multifaceted discussion of infanticide, a review of the evolutionary literature is added to the discussion.

The body of evolutionary-based literature regarding infanticide is larger, with researchers applying evolutionary concepts to examine infanticidal behavior in nonhuman primates (Fruteau et al. 2010; Hiraiwa-Hasegawa 1988; Lyon et al. 2011; Stumpf and Boesch 2010) and humans (see Daly and Wilson 1980; Daly and Wilson 1984; Hausfater and Hrdy 1984; Hrdy 1999; Hrdy 2016; Temrin et al. 2011) alike. This approach when considering humans, particularly as taken by earlier researchers on the subject, is problematic and far too simplistic to accept at face value considering how culturally complex human beings are. When coupled with contributions from cross-cultural research; however, these evolutionary papers provide new insight into the phenomenon of infanticide in various ways.

Earlier scholarly contributions generally tended to describe child homicide as an event that was perpetrated by stepparents, particularly stepfathers, and parents who neglect or abuse children that hinder their long term fitness to focus on rearing or producing offspring that would be more successful later on (refer to Daly and Wilson 1980; Daly and Wilson 1987; Hausfater 1984). For example, Daly and Wilson argued that because it is energy-costly to raise children, it is maladaptive to raise offspring that are not genetically related to the caregiver (1980). They stated that this explains higher rates of child abuse and homicide in families with at least one non-genetically related parent (Daly and Wilson 1980). Further, they argued that birth defects,

prematurity, and disabled children are more likely to be victimized by parents because they are more costly to care for, lowering the parents' reproductive fitness further than if they rid themselves of the child and reproduce again (Daly and Wilson 1980). Researchers also argued that mothers who are separated from their children after birth are more likely to maltreat the child, as the first few hours are critical for maternal bonding (Daly and Wilson 1980). Finally, they argued against the notion that adoption is anomalous, as adoptions most frequently occur within kin groups or by infertile couples, therefore, there is less likely to be maltreatment in those homes as the adoptive parents are either biologically related to the child or are unable to reproduce themselves (Daly and Wilson 1980).

There are several fundamental problems with the paper put forth by Daly and Wilson (1980). First, the authors explicitly made these generalizations under the false assumption that all humans are monogamous with male bread-winners (Daly and Wilson 1980). They fail to adequately cite the research that supposedly supports these assertions, and had anthropological research been considered, the authors would have been alerted to the fact that human cultures are extraordinarily diverse, and many do not fit Western mating ideals or family structures. Second, the authors did not mention whether the child victims in stepparent homes were more frequently victimized by the nongenetic parent, and they simply stated that infanticide and child homicide were more frequent in these households (Daly and Wilson 1980). Finally, in regard to their argument concerning adoptive parents as kin, they include stepparents as potential adopters (Daly and Wilson 1980), directly contradicting their earlier argument that stepparents would be more likely to kill children that are unrelated to them. Daly and Wilson's paper is a good representation of how early literature regarding infanticide in humans from an evolutionary

perspective is insufficient to consider the vastness of human diversity, and why a biocultural approach should be employed in this type of work (1980).

A more recent study by Temrin and colleagues (2010) directly challenged the assertions regarding stepparents made by Daly and Wilson (1980). The researchers combed through statistical datasets from Sweden that examined the frequencies of child homicides in stepfamilies and biological families, and then examined whether stepparents who committed infanticide discriminated between genetically and nongenetically related children (Temrin et al. 2011). They agreed with Daly and Wilson (1980) that there are more incidents of child homicide in stepfamilies, but found that stepparents did not more commonly kill an unrelated child when the data were analyzed with a chi-square test (Temrin et al. 2011). The authors put forth a new hypothesis for the higher rates of infanticide in stepfamilies: that individuals with higher rates of criminality and anti-social behavior are selected into stepfamilies because they are less able to maintain lasting pair bonds with mates (Temrin et al. 2010).

While this hypothesis is also perhaps too generalized, it better explains why stepparents are more likely to perpetrate infanticide than the arguments posed by Daly and Wilson (1980). The authors suggest that other countries should conduct similar studies to evaluate the hypothesis cross-culturally (Temrin et al. 2011), which signifies that newer researchers are at least considering the complexities of human culture and rejecting biological determinism. This paper is an important step towards a biocultural approach to infanticide.

Another paper written by Sandra Hrdy (2016) considered the prevalence of infanticide among modern humans. She noted that humans are the outliers amongst great apes not only due to their faster breeding abilities and larger brains, but also because they are the only hominoids who kill their own offspring (Hrdy 2016). There are documented cases of apes killing infants that

they are unrelated to, particularly males who are limiting competition for their future offspring (Hausfater and Hrdy 1984; Hrdy 2016; Parmigiani and vom Saal 1994; van Shaik and Janson 2001). In humans; however, it is widely found that mothers are the most frequent perpetrators of infanticide (Hrdy 2016). It is also important to understand that postpartum responses to infants vary among human mothers far more than they do among the great apes (Hrdy 2016). Hrdy argues that a basic reason for these curious human particularities is found when one gazes back into the early days of hominin evolution (2016).

New research suggests that as early as the Pleistocene, hominins likely required assistance from alloparents to successfully raise their children while providing adequate nutrients for their metabolically expensive brains and reproductive systems (Hrdy 2016). Hrdy points to marmosets and tamarins as two other species of primate who practice alloparenting and kill their own offspring (2016). When marmoset mothers finish feeding, they often call for a male to relieve them of the infant (Hrdy 2016). If another marmoset does not oblige, a frustrated mother may go as far as to bite off the infant's hands to rid herself of it, causing it to fall from the trees (Epple 1970; Huck and Frenandex-Duque 2013; Hrdy 2016; Ross et al. 2007). Further, tamarins and marmosets that have low assistance from alloparents have been found to kill and even cannibalize their own offspring (Hrdy 2016). The author argued that human mothers with perceptions of lower alloparenting resources are more likely to maltreat their young, as they have evolved a lower postpartum maternal response due to their adaptation for obligate alloparenting in their evolutionary history (Hrdy 2016).

Hrdy's assertion suggests that lower instances of infanticide would be seen in cultures with more involved community parenting, which has been noted in previous studies (Hrdy 2016; Korbin 1987). Hrdy also acknowledged that this comparison can only go so far, as humans are

extremely different from marmoset and tamarin parents due to the very different sensory worlds they inhabit (2016). Similarly, she noted that studying infanticide in humans is very complicated due to their "...extraordinarily flexible family systems, capacities for coordinated endeavors, and culture generated adaptability to a range of habitats..." (Hrdy 2016: 280). Still, she argued that even human parents may have their choices directed in some small way by the past evolution of their species (Hrdy 2016).

Hrdy's (2016) paper provided an alternative hypothesis for the prevalence of infanticide in humans, but still has one major limitation that was not discussed by the author. It can be difficult to test hypotheses such as these, as there is no way to directly find evidence for the presence of behaviors such as alloparenting and food-sharing in extinct human ancestral groups. That being said, there are data that support this possibility when applied to modern humans, such as a higher frequency of mothers as perpetrators of infanticide and higher incidence rates among parents with less social support (Hrdy 2016; Korbin 1987).

Experimental Research

Forensic anthropologists have generally utilized two main methods for experimental trauma research: human cadaver and porcine model studies (Zephro et al. 2014). Porcine studies utilize pig cadavers as proxies for humans, and are generally conducted due to the difficulties in obtaining, storing, and experimenting with human cadavers (Zephro et al. 2014). This can be problematic; however, as the usefulness of pigs and their applicability to humans have yet to be truly elucidated in the literature (Zephro et al. 2014). It is also an issue because non-human

mammalian bone is histologically different from human bone, containing more plexiform bone than humans whose cortical tissue is generally comprised of lamellar bone (Zephro et al. 2014). As fracture properties have not been compared between various species experimentally, it is important that forensic anthropologists use human cadavers when possible until further research is conducted that demonstrates the efficacy of porcine trauma studies (Zephro et al. 2014).

Cadaver experiments have been used to dispel old myths regarding fracture propagation. For example, Anne Kroman and colleagues (2011) found that studies by Gurdjian and colleagues, conducted in the middle of the twentieth century and frequently cited by forensic anthropologists, were inaccurate in their assertion that fractures do not radiate from the point of impact (Gurdjian et al. 1953; Gurdjian 1975). Kroman's team found that radiating fractures do originate from the point of impact, and that Gurdjian's results were likely confounded by his use of a lacquer coating on his study skulls (2011).

Similarly, Kroman's (2007) dissertation used multiple cadaver experiments to better understand the biomechanics of the adult human skeleton in its entirety, advocating for the consideration of trauma classifications as a continuum, and demonstrating the importance of engineering variables in anthropological assessments of trauma. Other cadaver studies have directly considered the complicated issue of inflicted versus accidental trauma in children.

In 2005, anthropologist Per Holck at the University of Oslo conducted an experiment that aimed to clarify whether the mechanism of trauma in an infant fatality case was accidental or inflicted. The newborn child was admitted to the hospital very late at night by the child's father (Holck 2005). The father told the medical staff that he was carrying the child when he slipped, dropping the child onto the carpet and subsequently falling himself, causing his left thigh to land

on the child (Holck 2005). The father said that he immediately brought the child to the hospital and arrived within 15 minutes of the incident (Holck 2005).

In the initial medical examination, the anterior fontanelle was found to be depressed, and a neurosurgeon was notified (Holck 2005). A computed tomography (CT) scan of the head showed the presence of both epidural and subdural hematomas and brain edema as well as fractures on the left side of the skull (Holck 2005). These findings were followed up with a full radiological skeletal survey, and no other fractures were discovered anywhere else in the body (Holck 2005). The child did not survive the sustained injuries and passed away 29 hours after admission to the hospital (Holck 2005). An autopsy was subsequently performed.

When the head was examined, a large pool of fresh blood was found on the left side of the skull and a smaller pool of blood behind the right ear was observed (Holck 2005). The medical examiner also noted fractures on the right side of the head that were not found on the CT scan and were different from the fracture patterns seen on the left side of the skull (Holck 2005). The left parietal bone had three fracture lines that radiated from the ossification center, while the fractures on the right side of the cranium radiated from the posterior fontanelle, with one anterior fracture that extended across part of the occipital bone and over the entire right parietal bone (Holck 2005). The autopsy also revealed retinal iron deposits that indicated that the child may have suffered a shaking injury a few days prior to death (Holck 2005). Due to the medical examiner's suspicion that the trauma patterns were too severe to have been caused by the father's scenario, the author designed an experiment that used the cadaver of a stillborn child to test how much force it would have required for the child to have such severe injuries (Holck 2005).

The head of the cadaver was laterally set on a power cell and covered with a rubber pad that was meant to simulate the father's thigh (Holck 2005). An iron weight was dropped onto the

skull from different heights and with varying amounts of force (Holck 2005). The skull remained undamaged until the force reached 1000 N which would usually occur in an infant from a 1.5 m fall (Holck 2005). The maximum height of the infant in the investigated case was calculated to be 115 cm after the father reconstructed the events using a doll (Holck 2005). Not only did the amount of force required to cause such incredible damage to the child's cranium and brain not equate with the father's account, but the fracture patterns of the cadaver were also dissimilar from the investigated case (Holck 2005). The cadaver displayed fractures on both sides of the skull that were similar to the fractures described on the autopsied infant's left parietal bone (Holck 2005). The different fracture pattern on the autopsied infant's right side was determined to be more consistent with a concentrated force from a sharp instrument (Holck 2005). This additionally discredited the father's explanation, and demonstrated how trauma analysis and experimentation can shed light on the events surrounding possible child abuse.

This study has limitations, such as cadavers are not as solid as fresh bodies and the test could not perfectly mimic the story provided by the father (Holck 2005), but it is important to this research. This study shows how the anthropologist's expert knowledge of trauma can assist in the resolution of cases which may have been misidentified. Holck's study also shows how experiments may be conducted to test the validity of specific scenarios of cranial trauma, which will be done using computational modeling in this project (see Bandak et al. 1995; Baumer et al. 2010; Chen and Ostoja-Starzewski 2010; Horgan and Gilchrist 2003; Khalil and Hubbard 1977; Lapeer and Prager 2001; Tse et al. 2015; Yan and Fittock 2011 for studies using FE modeling).

Other researchers have begun to utilize the Finite Elements (FE) method for trauma experimentation. The FE method utilizes differential equations to approximate the values of some points of a shape, then linearly interpolates them to create an approximate model of the

desired geometry, or “domain.” FE is a mesh-based modeling method, meaning that the models are constructed using polygons such as triangles to approximate the geometric shape that is being modeled (e.g. a skull).

For example, in 2010, Baumer and colleagues conducted a study that examined the effects of compression forces on juvenile skulls by creating simple FE models and comparing simulated fracture patterns to those from known cases. The results of the study indicated that FE models are useful in predicting fracture characteristics, and the authors encouraged researchers to further improve the use of this method in forensic anthropology as it could become an invaluable tool for understanding perimortem traumatic injuries (Baumer et al. 2010).

To validate this approach, a study that compared head trauma in FE models of human heads to human cadaver experiments found that patterns were largely consistent (Tse et al. 2014). The validation of this method against cadaver experiments and its initial success in the forensic arena renders FE modeling a promising avenue for forensic scientists seeking to improve scientific understanding of inflicted and accidental trauma.

Finite elements have their limitations as well; however, and it is important that forensic anthropologists understand the methods that they are using when they engage in this type of experimental research. The issue with this method in trauma analysis is that meshes do not replicate smooth geometries, such as cranial vaults, very well. When a FE model of a skull is constructed, the researcher will generally have to sacrifice either the geometry of the model, or the aspect ratios of the polygons they are using to construct their mesh. If the researcher chooses to manipulate the aspect ratios of the polygons they are using to construct their mesh, the mesh may no longer be analysis suitable. Also importantly, good meshes take a great deal of time and peoplepower to construct.

Similarly, FE models are not ideal for studies that examine crack propagation, as each vertex of the polygon, or node, may only interact with nodes within the same polygon, or element. In FE models, these polygons cannot overlap (they are disjoint), and cracks that are allowed to propagate freely will alter the shape of the polygons. To fix this, the researcher may choose to re-mesh to follow the fracture, but the issue with this is that FE models generally do not allow for a mixture of arbitrary shapes. Further, re-meshing becomes complex as any changes made to the affected area need to be implemented to the rest of the model, taking more peoplepower and funds.

Due to these issues, researchers generally avoid re-meshing by restricting cracks to only move along the edges of each element, causing fractures that propagate to simply open a gap between elements. This is what is referred to as a “cohesive crack model.” This is similarly problematic, as cracks are no longer able to freely propagate where they would and are forced to move along the edges of the mesh. Mesh dependency is only suitable for an analysis if the researcher knows where the crack will propagate, or runs multiple simulations with various meshes to attempt and approximate where the crack will likely go. This is also time-consuming and expensive, and is not an ideal way to study fracture propagation.

For these reasons, this thesis aims to lay the groundwork for meshfree modeling research in trauma analysis. Meshfree methods reduce these issues as it does not utilize a polygon-based mesh. Instead, meshfree methods simply use particles, or unconnected nodes that interact with other particles within their support, which is essentially their neighborhood of influence, to create the domain. Similarly, to FE models, nodes may only interact with other nodes within their support; however, in meshfree models, supports overlap, allowing for smoother crack propagation. Instead of having to re-mesh when a crack propagates, the researcher may simply

remove shape functions on the other side of the crack, creating a hole in the domain after interpolation that is more representative of how the crack would propagate in the real world.

Meshfree methods are not perfect; however, as there is no explicit boundary to the domains like there are in Finite Element models, due to the lack of a mesh. This problem is solvable; however, as Joseph Alford's dissertation (2016) provides a framework for creating an explicit boundary in meshfree models.

Before improved computational models can be created; however, the mechanical properties of bone and classifications of skeletal trauma must be explored.

Mechanical Properties of Bone

Osseous tissue is comprised of both inorganic materials such as calcium hydroxyapatite ($\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})$), and organic materials such as collagen and other proteins, as well as water and blood vessels (Titora and Nielson 2012; White and Folkens 2005; Zephro and Galloway 2014). These materials make up two different types of bone: cortical bone and trabecular bone (Kroman 2007; Titora and Nielson 2012; White and Folkens 2005; Zephro and Galloway 2014).

Cortical bone is not as strong as trabecular bone, and can withstand less force before failure than trabecular bone (Kroman 2007; Nordin and Frankel 2001). Trabecular bone is more porous (Kroman 2007; Titora and Nielson 2012; White and Folkens 2005; Zephro and Galloway 2014), and is able to withstand strain values of seven percent versus cortical bone, which can only withstand two percent (Kroman 2007).

Bone is also an anisotropic material, meaning its properties differ in regards to direction (Kroman 2007; Turner and Burr 1993; Ubelaker and Montaperto 2011; Zephro and Galloway 2014). Cortical bone is transversely isotropic because its Young's modulus is the same transversely but differs longitudinally (Kroman 2007; Turner and Burr 1993). Bone is better able to withstand force longitudinally, and has a higher threshold to endure compression than other forces (Kroman 2007). Bone is also viscoelastic, which means its behavior is dependent upon the strain rate, which is the length and rate a load is applied to an object (Kroman 2007). It is important to know this when interpreting trauma, as fracture patterns are dependent upon strain rate (Keaveny and Hayes 1993; Kroman 2007).

The cranium specifically is composed of trabecular bone (commonly referred to as diploe) sandwiched in between two layers of cortical bone (Galloway and Wedel 2014a; Kroman 2007). When the cranial vault is subjected to a load, linear fractures radiate from the point of impact (Galloway and Wedel 2014a; Kroman 2007; Kroman et al. 2011). Under impact, a small amount of in-bending will occur with out-bending surrounding the impact site (Galloway and Wedel 2014a; Gurdjian et al. 1953; Gurdjian 1975; Rogers 1992). In the infant cranium, sutures have not yet closed, leading to the termination of radiating fractures when they come into contact with fontanelles (Galloway and Wedel 2014a). In addition to this, there are many other ways in which juvenile bone differs from that of adults.

In contrast to adult bone, the bones of infants and young children are more cartilaginous, meaning they have more collagen fibers than calcium hydroxyapatite, causing them to have lower elastic, but higher plastic thresholds than adult bones, hindering fracture propagation in juvenile bones (Lewis 2007; Ubelaker and Montaperto 2011). Juvenile bone also may endure higher strain than adult bone due to its plasticity and porous nature (Humphries 2011; Lewis

2007). It should be noted; however, that it requires less force to fracture juvenile bone than adult bone, and greenstick fractures and compression fractures are more common in children (Ubelaker and Montaperto 2011). As a child develops, their bones mature and become less elastic until they reach skeletal maturity.

Trauma Analysis

Trauma analysis is essential in forensic anthropological casework (Kroman 2007; Kroman et al. 2011; Wedel et al. 2014), as interpreting fracture patterns can assist in establishing cause and manner of death (Kroman et al. 2011). For trauma analysis to be interpreted properly, and for experimental models to most accurately reflect how various fracture patterns manifest in the skeleton a review of prior literature in trauma analysis and experimentation is vital.

Historically, trauma types have been divided into blunt force, sharp force, ballistic or projectile, and sometimes mixed or miscellaneous (Kroman 2007). Blunt trauma is commonly defined as an impact to a wide area of the bone caused by a blunt instrument or a fall, resulting in abrasions, contusions, and/or radiating skeletal fractures (Byers 2008; Komar and Buikstra 2008; Loe 2009). Sharp trauma; however, is classified as a shearing or compression force applied over a small area of bone, often dividing tissues from each other (Byers 2008; Komar and Buikstra 2008; Loe 2009), while projectile or ballistic trauma is considered to be created by a compressive or bending force applied by an object traveling at a high velocity (Byers 2008; Loe 2009). Sometimes, these categories overlap, as some sharp force injuries may create radiating fractures for example (Kroman 2007). Due to the complexities of trauma classification, some have argued

that fractures should be classified on a continuum, instead of strictly as discrete categories (Kroman 2007). This critique is useful in allowing forensic anthropologists to more thoroughly describe injuries; however, classifying trauma by mechanism of injury can still be useful when communicating trauma interpretation to others such as juries or law enforcement officers who are likely familiar with those terms. Blunt force trauma, for the purposes of this research is most notable, as children frequently sustain blunt injuries from falls or abusive episodes.

Interpreting blunt force injuries in juvenile crania is not an uncommon undertaking for forensic anthropologists and pathologists who are attempting to determine whether an injury was the product of an abusive or accidental traumatic event. The cranial vault is a frequently impacted area during fatal abusive events, with two-thirds of child homicides including blunt force trauma to the cranium (Abel 2011). Typically, current research into inflicted cranial trauma has found that simple linear, concentric, complex, diastatic, depression, and growing fractures are common in child homicide victims (Abel 2011).

Simple linear fractures occur when the cranial vault is impacted with a large, flat object such as the floor or a wall (Abel 2011). While these fractures may occur in children who are abused, it is common for children who sustain an accidental injury such as a fall to present with a simple linear fracture (Abel 2011). It is noteworthy; however, that children who fall accidentally rarely die from the episode and generally do not incur serious intracranial injuries (Abel 2011; Billmire and Myers 1985). According to the Center for Disease Control and Prevention, infants and young children who die accidentally are most likely to suffocate, die from an automobile collision, or unintentionally drown (National Center for Health Statistics 2018). Unintentional falls were only listed as a top ten cause of death in infants under one year old in 2018, ranked only above accidental fatal blows (National Center for Health Statistics 2018). Accidental linear

fractures also tend to occur on the parietal bones, and linear fractures that manifest elsewhere in the cranium may be indicative of abuse (Galloway and Wedel 2014b).

Concentric fractures differ from simple linear fractures because they occur from a higher velocity impact and from an impact that affects a smaller surface area of the body (Abel 2011). Concentric fractures surround the site of impact and are often accompanied by radiating fractures. Concentric fractures may occur from a blow to the head with an instrument such as a baseball bat or metal tube.

Complex fractures can be very difficult for anthropologists to interpret, as they generally occur from multiple impacts in episodes of severe violence (Abel 2011). Complex fractures are a powerful indicator of abuse, as multiple injuries are more frequently incurred in abusive incidents than from accidental falls (Abel 2011; Galloway and Wedel 2014b).

Diastatic fractures occur within the sutures and are common in infants and young children, as the sutures have not yet closed to any significant degree (Abel 2011). These fractures may occur in children that are birthed with the assistance of an instrument, such as a vacuum cleaner (Galloway and Wedel 2014b). These fractures may continue to grow, and may be labeled as growing fractures (Galloway and Wedel 2014b).

Depression fractures occur when a smaller instrument impacts the skull at a high velocity (Abel 2011). These fractures differ from concentric fractures because they tend to collapse the bone at the point of impact due to the smaller mass of the object. A depressed fracture may occur from a blow to the head with the metal handle of a cane or similar object.

While it is important to note that not one specific fracture type is indicative of a traumatic event, cases that present with multiple or bilateral injuries, or fractures that cross over suture lines are generally thought to be associated with abusive events (Abel 2011; Galloway and

Wedel 2014b; Kemp et al. 2008). It is also extremely important to understand that fractures alone are not good indicators of whether abuse has occurred (Galloway and Wedel 2014b). Forensic anthropologists must examine the context of the case and the presentation of injuries to make a diagnosis and prevent both under and over diagnosis of child abuse. This issue of determining the etiology of injuries highlights the importance of experimental research for trauma analysis to understand how accidental and inflicted injuries may be better differentiated.

Biomechanics and Basic Engineering Principles

Anthropologists engaged in trauma interpretation or experimentation should have an understanding of bone biomechanics, meaning they can diagnose how bone reacts to an impacting force and how the mechanical and structural properties of bone influence this reaction (Gonza 1982; Kroman 2007; Ubelaker and Montaperto 2011). Before fully delving into the mechanical properties of bone and how adult and juvenile bones differ, an introduction to some basic concepts in engineering and biomechanics as well as relevant definitions are provided including terminology in statics, solid mechanics, and biomechanics to create representative models and accurate interpretations of fracture patterns.

In engineering, scalars are defined as quantities that only have magnitudes. For example, the mass of an object is considered to be a scalar quantity. Vectors are quantities that have both magnitude and direction. Force and velocity are examples of vectors. Tensors are quantities that have both magnitude and two directions. Tensors are particularly important in biomechanics, as stress and strain (both of which will be defined in this section) are both tensor quantities. Also of

vital importance to experimental work in trauma analysis are Newton's three laws and the concept of force.

Force is defined as anything that alters an object's state of motion (Kroman 2007; Low and Reed 1996; Zephro and Galloway 2014). As previously noted, it is generally expressed as mass multiplied by acceleration when the mass of the object remains constant. More specifically; however, the net force should be calculated as a summation of all possible forces and can be described using summation notation:

$$\sum_i \underline{F}_i = m\underline{a}$$

Newton's first law of motion states that if an object is not acted upon by a force, its velocity will remain constant. Newton's second law demonstrates how the impacted object's acceleration is dependent upon the object's mass. When the mass of an object does not change, this concept is expressed formulaically as:

$$\underline{F} = m\underline{a}$$

where \underline{F} denotes force and \underline{a} is acceleration. Both force and acceleration are expressed with underbars because they are vector quantities. Mass (m) is a scalar quantity, and is expressed without an underbar. Newton's third law of motion states that for every action there will be an equal and opposite reaction. For example, when a ball hits the ground, the ground exerts a force on the ball. Simultaneously, the ball exerts an equal and opposite force on the ground during impact. Now that force and Newton's three laws have been defined and the concept of force has been introduced, a more thorough discussion of other variables is possible.

Velocity (\underline{v}) is a vector quantity that describes the rate at which an object changes position (\underline{x}) over time. Velocity can be either positive or negative, indicating direction on a coordinate system. Speed ($||\underline{v}||$), which is scalar, is the magnitude of an object's velocity.

Acceleration is the change of an object's velocity over time. Acceleration changes when either the direction or the magnitude of an object's velocity changes. An object that has a velocity, acceleration, and net force of zero is considered to be in static equilibrium (e.g. a building is in static equilibrium). Acceleration is an important variable in trauma analysis, as the speed of the force alone is inadequate to properly understand how injuries occur, as an impact that occurs at a higher speed with a more gradual deceleration may not cause injury while an impact at a lower speed but with a rapid acceleration or deceleration may inflict trauma upon the affected object (Kroman 2007).

The term load is used to describe the force(s) that are applied to an object (Frost 1967; Kroman 2007; Low and Reed 1996), causing stress. Stress ($\underline{\underline{\sigma}}$) is used to describe “the magnitude of the load applied to the affected bone surface” (Ubelaker and Montaperto 2011: 34) and is expressed with a double underbar as it is a tensor quantity. Formulaically, stress is the force applied over a given area (Kroman 2007; Martin and Burr 1998; Zephro and Galloway 2014; see also Currey 2002; Nordin and Frankel 2001; Turner 2006; Turner and Burr 1993) as expressed below:

$$\underline{\underline{\sigma}} \cdot \underline{\underline{n}} = \frac{F}{A}$$

Stress is an exceedingly important variable in trauma analysis, as an object may react differently to various impacts with the same amount of force due to varying distributions of the force across the area of an object (Kroman 2007). Anne Kroman illustrates this well by providing the example of a 12-pound bowling ball in the palm of a human hand versus the impact of a 12-pound knife on the same hand (2007). Stress is increased due to the small surface area of the knife point, causing an injury (Kroman 2007).

Stress is generally divided into several categories based on the ways in which the application of the load causes bone deformation (Kroman 2007; Ubelaker and Montaperto 2011). Compressive stress occurs when two forces simultaneously act on an object in opposite directions, causing the object to become more compact (Kroman 2007; Zephro and Galloway 2014). Tensile stress can be considered as opposite to compressive stress, as it occurs when two forces act upon an object to pull it in opposite directions, lengthening the material (Kroman 2007; Martin and Burr 1998; Zephro and Galloway 2014). Shearing occurs when two loads are applied in parallel to the object (Kroman 2007; Zephro and Galloway 2014). Torsion occurs when a load causes the affected object to twist on an axis (Zephro and Galloway 2014). Zephro and Galloway (2014) also discuss bending stress, which occurs when compression, tension, and shear forces work in concert on an object, generally producing a butterfly, or triangular fracture.

Strain (ϵ) is the relative deformation of an object expressed in ratio form as equal to the change due to deformation over the dimensions of the object prior to the infliction of a load (Carter et al. 1976; Cowin 1989; Currey 1970; Harkness et al. 1991; Kroman 2007; Turner and Burr 1993; Zephro and Galloway).

Poisson's ratio is a crucial aspect of examining strain (Ubelaker and Montaperto 2011), and is characterized as the ratio of longitudinal and lateral strain, or the ratio of differences of strain in the length and the width of the affected object (Kroman 2007; Turner and Burr 1993; Ubelaker and Montaperto 2011). Poisson's ratio is vital to fracture interpretation as a bone may be multiply altered from a single applied load (Ubelaker and Montaperto 2011). Also of importance is Young's modulus (the modulus of elasticity). Young's modulus is a ratio that examines the relationship of stress to strain and measures how stiff an object is (Kroman 2007; Turner and Burr 1993). Stiffness should not be mistaken for how brittle an object is, as Kroman's

2007 dissertation used the term interchangeably when defining Young's modulus. Brittle objects fail under low values of strain (e.g. glass) (Gere 2004). Stiffness; however, is the ability of an object to withstand deformation (Gere 2004). The ratio is the slope of the stress-strain curve, which describes the magnitude of a load an object can bear before failure occurs, causing plastic deformation and eventually breakage (Gere 2004; Turner and Burr 1993; Zephro and Galloway 2014). Distortion stress, or von Mises stress, is also important here, as it can assist in predicting when an object will fail (Barsanescu and Comanici 2016).

Plastic deformation occurs when an object is damaged and cannot return to its original shape (Turner and Burr 1993; Zephro and Galloway 2014). A fracture; however, is "...a disruption in the continuity of a bone..." (Zephro and Galloway 2014: 35) and occurs when the bone has reached the point of failure, causing the propagation of a crack (Kroman 2007; Zephro and Galloway 2014). Fractures in bone propagate variably depending on location, direction of force, duration and rate of the inflicted load, and the mechanical properties of bone itself (Hall 2006; Ubelaker and Montaperto 2011; Zephro and Galloway 2014). To properly conduct experimental trauma analysis, anthropologists must understand the mechanical properties of the bones they are working with and have a very basic understanding of solid mechanics.

Introduction to Solid Mechanics

Simplistically, solid mechanics is a field that examines how materials deform under various conditions. The example of a spring will be used to demonstrate how this work is done because in a basic sense, every material acts as a spring when applied with a small enough load.

When a spring is pulled, more force is required to pull it further. In other words, the force required to pull the spring is related to how much tensile stress there is acting upon that spring. This concept is represented by the formula below in which Δx stands for the object's change in position and k is a measure of the stiffness or rigidity of the object.

$$\underline{F} = k \Delta \underline{x}$$

Even very solid objects such as bricks or planks of wood still act as springs when a small enough deformation is applied. A larger required force is simply necessary to change the object's position dramatically, as the value of k will be higher in stiffer objects. This applies to osseous tissue as well, although organic matter is more complex due to the mechanical properties of various biological materials, which will be discussed later in this chapter.

When creating experimental models, it is important to understand how force (an extrinsic quantity) and stress (an intrinsic representation of force) can be related to displacement (an extrinsic quantity describing an object's relative change in position) and strain (an intrinsic representation of displacement) through constitutive models. Extrinsic quantities depend on how much of something you have (e.g. mass), while intrinsic quantities depend on what type of properties from which the material is made (e.g. carbon or silicon). The relationships between these quantities can be difficult to fully understand, prompting Dr. Daniel Simkins to create a graphic representation of how researchers can better think of the variables they are using in their experiments and how they interact with each other (see Figure 2.1).

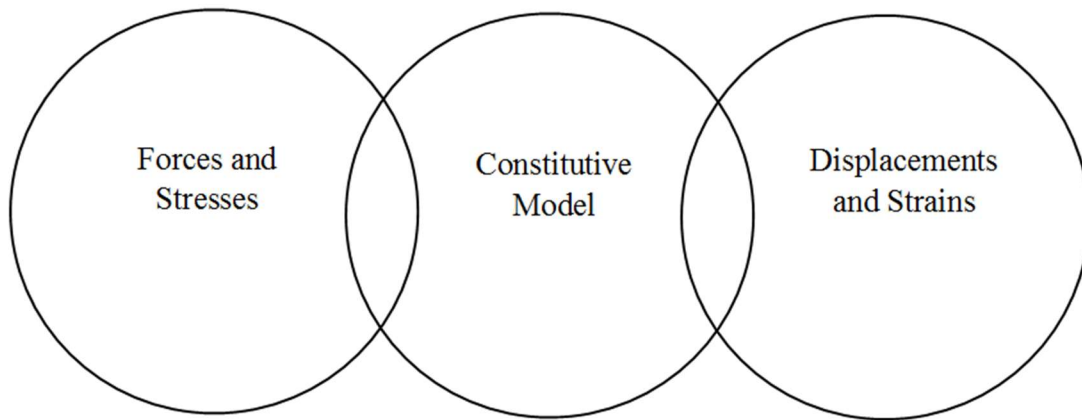


Figure 2.1. The three circles of solid mechanics created by Daniel Simkins.

Simkins states that by understanding which variables belong in which of the three circles and how forces and stresses can be related to displacements and strains through constitutive modeling, researchers can better formulate their experiments. For example, an anthropologist conducting an experiment using a porcine model may consider how strain may be affected by their choice of a model, as the bone histology and cranial morphology of pigs are dissimilar from those of humans (see Zephro et al. 2014).

This elementary understanding of solid mechanics is crucial to creating better experimental models and refining best practices in anthropological biomechanics. Additionally, it is critical that forensic anthropologists engaged in trauma research have a solid understanding of the mechanical properties of bone, especially in the context of the stage of growth and development under study (e.g. juveniles versus adults) and the type of bone under study, as different bone types have different mechanical properties.

This literature review provided a comprehensive overview of experimental trauma analysis. In the following chapter, the methodology utilized to examine child fatalities will be discussed, and the process of validating FE methods for trauma research using a simple representation of a cranial vault will be described.

CHAPTER THREE:

METHODS

Chapter three details the methods utilized to select, code, and organize cases in the child fatality component of this thesis. Secondly, statistical tests used to analyze the case data will be provided. Finally, the design of the skull models will be provided, and the process of validating the efficacy of FEM using differing boundary conditions will be discussed.

Child Fatality Study

All child fatalities (n=84) that occurred in Pasco County, Florida between the years 2009 - 2015 were reviewed. Victims whose ages-at-death range from newborn infants to 17 years were included in the study. Law enforcement records, medical records, autopsy reports, and other available documents such as autopsy diagrams and field reports were reviewed. All information was taken from deceased individuals, and any identifying information about the case was removed. Refer to Appendices A and B for copies of the data protocol forms.

The data collected from the reviewed reports were recorded using a numeric coding system that accounts for multiple aspects of each case. If it is probable or confirmed that the death of the child was a homicide, the classification of the homicide (e.g. 1st degree, 2nd degree,

negligent manslaughter etc.) was scored. These diagnoses were usually provided by the medical examiner or field reports, though in cases of equivocal deaths that appeared to be a potential homicide, this designation was made by the researcher. The context of the death was coded in order to note motive or other associated crimes such as robbery or sexual assault. The offender-victim relationship, victim profile, offender profile, and cause of death were similarly coded. The type of weapon utilized in the homicide was logged. Types of evidence (e.g. trace evidence or DNA) recovered at the scene were also coded.

Spatial data were recorded for where the incidence occurred such as the abduction site (if applicable), scene of the homicide, and site of discovery (for bodies that were moved postmortem) were mapped to determine if spatial patterns exist. Disposal methods were also coded if the child was not admitted to a hospital prior to or immediately around the time of death. Information relating to the state of decomposition of the victim in cases of delayed discovery were also noted.

Both trauma that was related to the cause of death and other injuries from systemic abuse were identified and coded. Injuries were described in terms of their physical location on the body and were classified as caused by blunt force trauma, sharp force trauma, gunshot wounds, suffocation, or strangulation. Through examination of the autopsy reports, the location of both fatal and nonfatal injuries were coded, and data on skeletal fracture patterns as well as other contributing factors relating to cause of death were extensively collected when available. Injuries that manifest on soft tissue were coded in terms of type (e.g. hemorrhage, ecchymosis, etc.), broad location (e.g. brain, heart, etc.), and specific location when regarding brain injuries (e.g. temporal lobe, cerebral fossa, basal ganglia, etc.). Blood loss as determined by the medical examiner during the autopsy was recorded if it was noted in the autopsy report. The presence of

drugs or alcohol in the body of the victim was noted. When possible, the amount of activity exerted by the victim immediately prior to death was recorded.

After each case was thoroughly reviewed, and all data were coded, the case was given a designation of probable homicide, possible homicide, unlikely homicide, death due to neglect, or not a homicide, loosely based off of the Missouri Child Fatality Study classifications of definite, probable, possible, and non-maltreatment, or inadequate information to determine (Ewigman et al. 1993). Cases in which there was inadequate information to determine whether manner of death was misdiagnosed were coded as such. The context surrounding the death, manner of body disposal, patterns of injuries, and statements made by witnesses were most heavily considered in this final designation.

Descriptive statistics were developed to examine frequencies of varying types of case resolutions (e.g. administrative clearance, arrest, death of offender), overall case impressions (e.g. likely homicide, unlikely homicide), diagnosed MOD, and homicide type. When calculating frequencies of homicide types, all diagnostic categories were included except “unlikely homicide” (n=41). Frequencies were also generated to examine perpetrator and victim characteristics such as age, sex, and race/ethnicity.

The ages of both victims and the known or presumed perpetrators were collapsed into culturally meaningful categories for analysis. Infants are considered to be children under one year of age, toddlers are classified as one to three years old, children are between four and 11 years old, and adolescents are between 12 and 17 years. Perpetrators were categorized as under 18 years old, between 18 and 24, which is a time known as “emerging adulthood” that is characterized by risky behavior and an increased likelihood of perpetrating and becoming a

victim of violence (see Arnett 2000; Arnett 2010; Arnett 2015; Garbarino 2015), between 25 and 35 years, and over 35 years old.

Chi-square tests are conducted to examine associations between various categories. The first chi-square test examines the association between mechanism of injury and victim age. The second test looks at the association of perpetrator to victim relationship and the age of the victim. The third test aims to reveal associations between the race/ethnicity of the offender and the race/ethnicity of the perpetrator. Alpha (α) is set to 0.05 for all chi-square tests to provide a high (95 percent) chance that the null hypotheses are rejected or not rejected appropriately.

Trauma Modeling

Several simple three-dimensional FE models roughly approximating the material properties of an infant neurocranium were created by Daniel Simkins in the USF Department of Civil and Environmental Engineering in collaboration with the author. The code was shared and tested by the author prior to interpreting final results. All models were processed using MATLAB 2019 and visualized using ParaView 5.1. First, two models (Skull32 and Skull21) constructed using different meshes were processed using fixed boundary conditions to examine the impact of mesh construction on the essential boundary condition (see Table 3.2 for summaries of the model characteristics). Second, the highest resolution model (Skull32) was run twice, first with fixed boundaries and then with sliding fixities to evaluate any differences in the results. Finally, Skull32 was rerun (both with fixed and sliding fixities) with the addition of force to the horizontal plane to compare those results. The nodes in the fixed boundary condition are

restricted, while the sliding fixities are mostly unrestricted, though some nodes remained fixed to remove rigid body motion. Rigid bodies do not deform, and therefore are not suitable to even the coarsest model of osseous tissue. In all models, no cracking algorithm was applied; however, varying results to the models still have implications that are important to the integrity of trauma analyses made based on FE modeling.

Originally, an additional component of this project aimed to evaluate the efficacy of FE models in trauma analysis and demonstrate its potential utility in real-world casework by comparing fracture propagation in a meshfree model and FE model with loads applied to mirror a case with known fracture propagation and mechanism of injury from the Pasco dataset. The time required to do this correctly in collaboration with the engineering team, test the code, and experiment with the loads was not possible prior to the completion of this thesis, but is planned as a subsequent phase of this project. This necessary change in direction demonstrates the complex nature of this work, and the importance of taking the time to understand the concepts behind the models before jumping into comparative work with real-world case implications.

Table 3.1. Summary of model characteristics.

Characteristic	Skull 21	Skull 32
Diameter	94.46	92.70
Thickness	6.02	6.26
Number of Nodes	759	3044
Number of Elements	458	2160

CHAPTER FOUR: RESULTS

Chapter four discusses the results of the two components of this thesis. First, the results of the statistical analyses on equivocal deaths are presented. Second, the results of the trauma modeling analysis are provided.

Child Fatality Study

Frequency tables were generated to examine which variables in the dataset most commonly occurred. Frequencies for case status are available in Figure 4.1. Frequencies of researcher diagnoses were also examined (Figure 4.2). Victim characteristics were reviewed, and the age, sex, and race/ethnicity frequencies are available in Figures 4.3, 4.4, and 4.5, respectively.

The demographic characteristics of perpetrators or responsible parties for the victim's death were also generated. The age breakdown of offenders can be found in Figure 4.6. Figures 4.7 and 4.8 display frequencies for perpetrator sex and race/ethnicity. There is also a significant association between perpetrator and victim race/ethnicity ($\chi^2 = 20.4$, $df = 4$, $p \leq 0.001$).

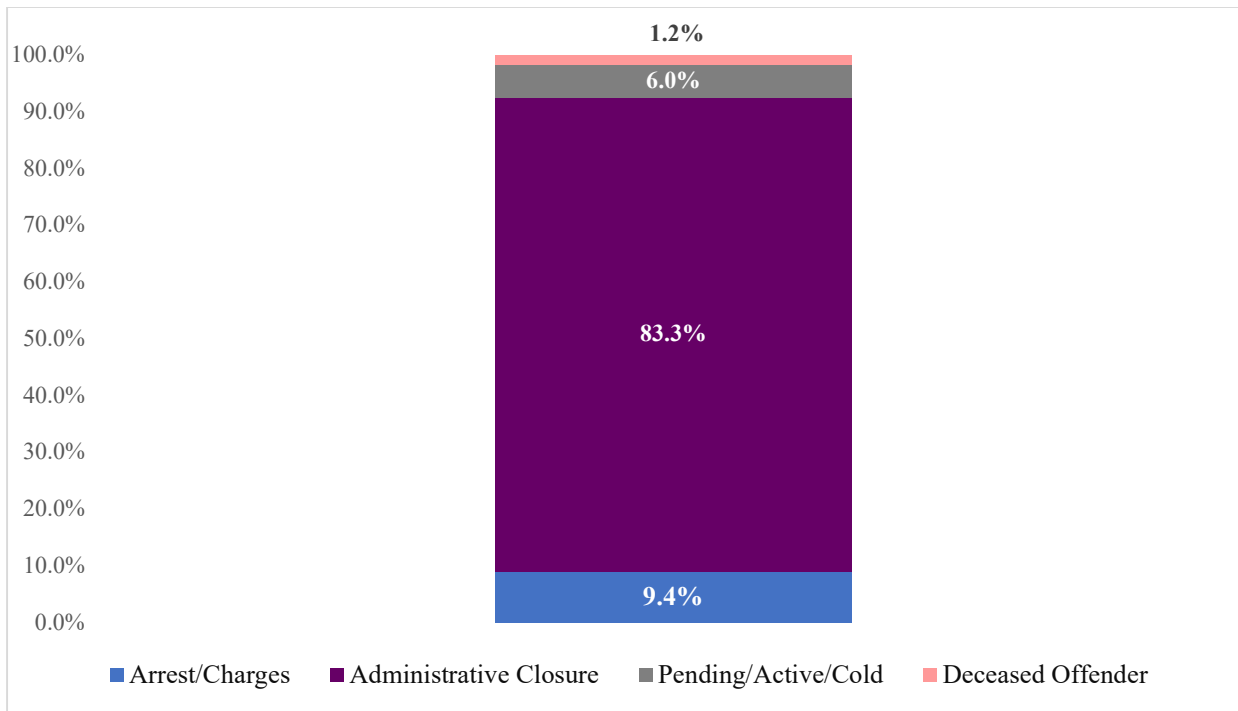


Figure 4.1. Chart displaying relative frequencies of official case status designations (n=84).

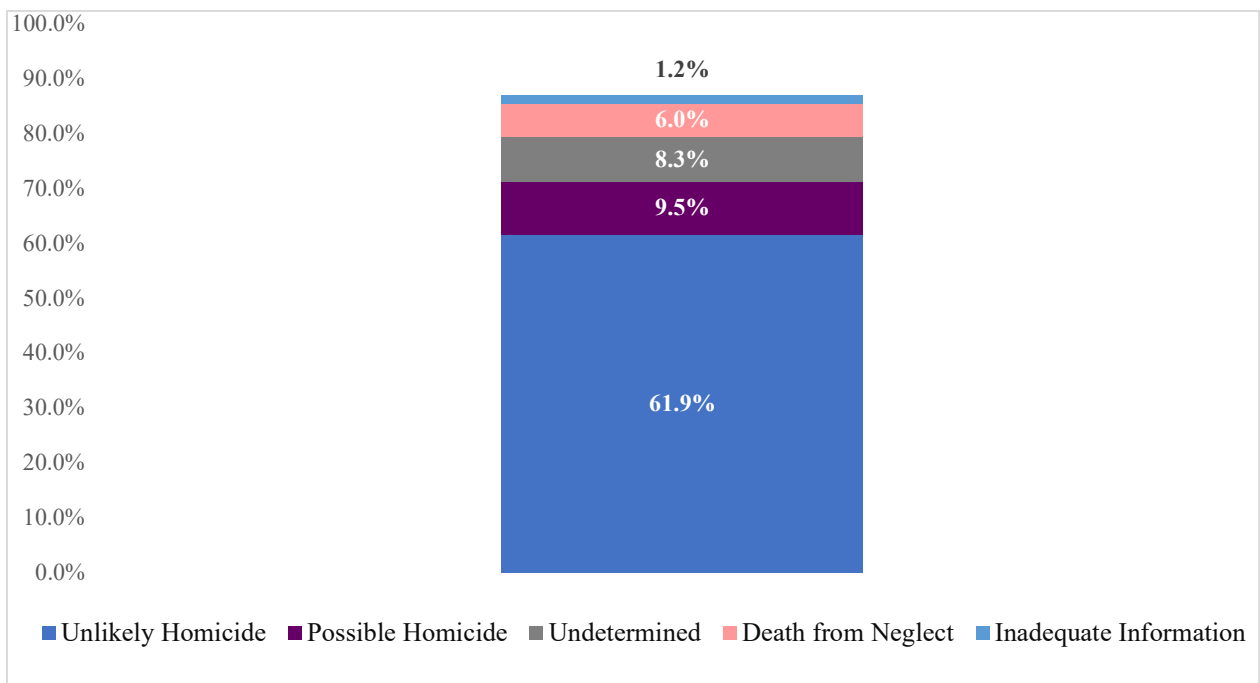


Figure 4.2. Relative frequencies of researcher diagnoses defined by current study (n=84).

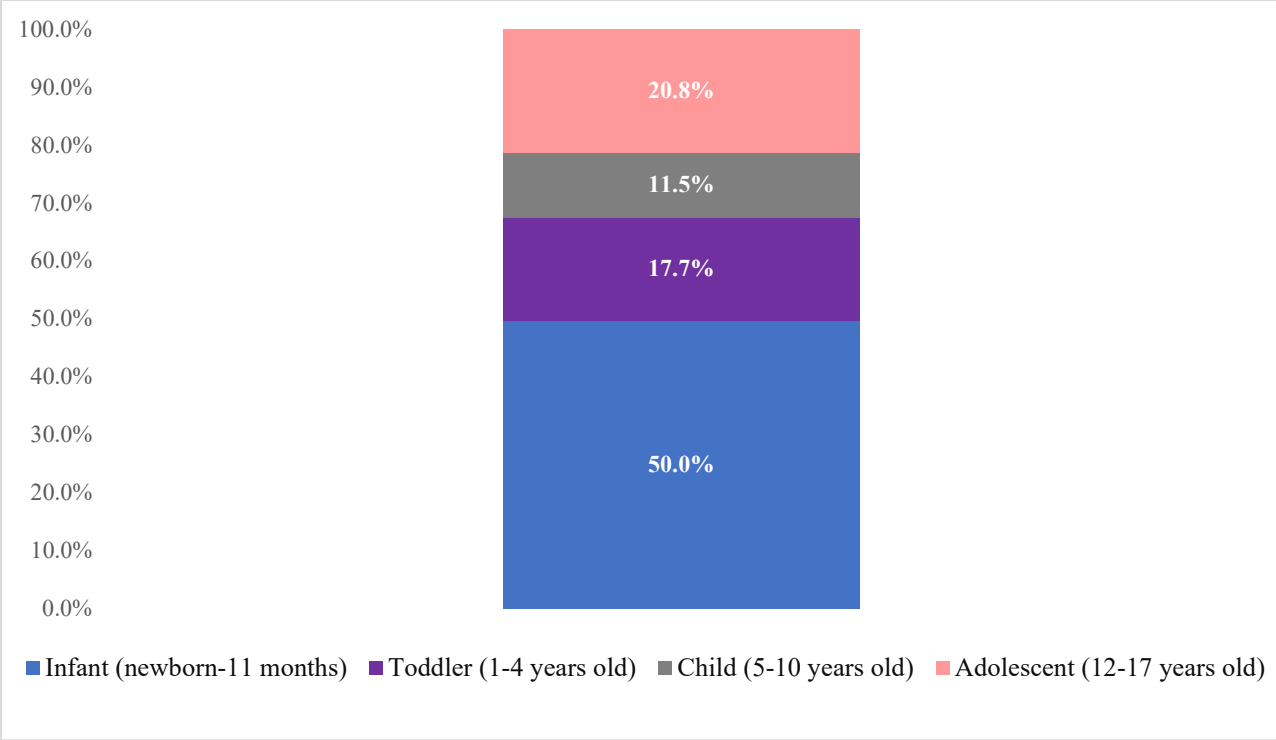


Figure 4.3. Chart displaying relative frequencies of victim ages (n=95).

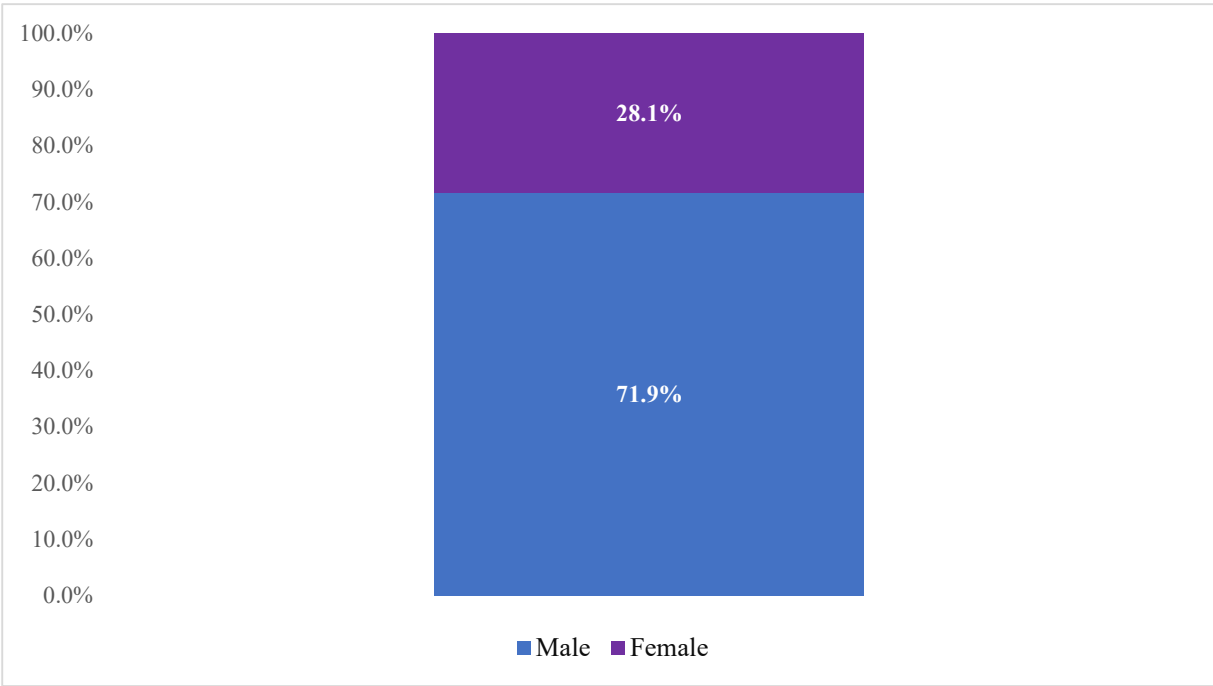


Figure 4.4. Chart displaying relative frequencies of victim sex designations (n=95).

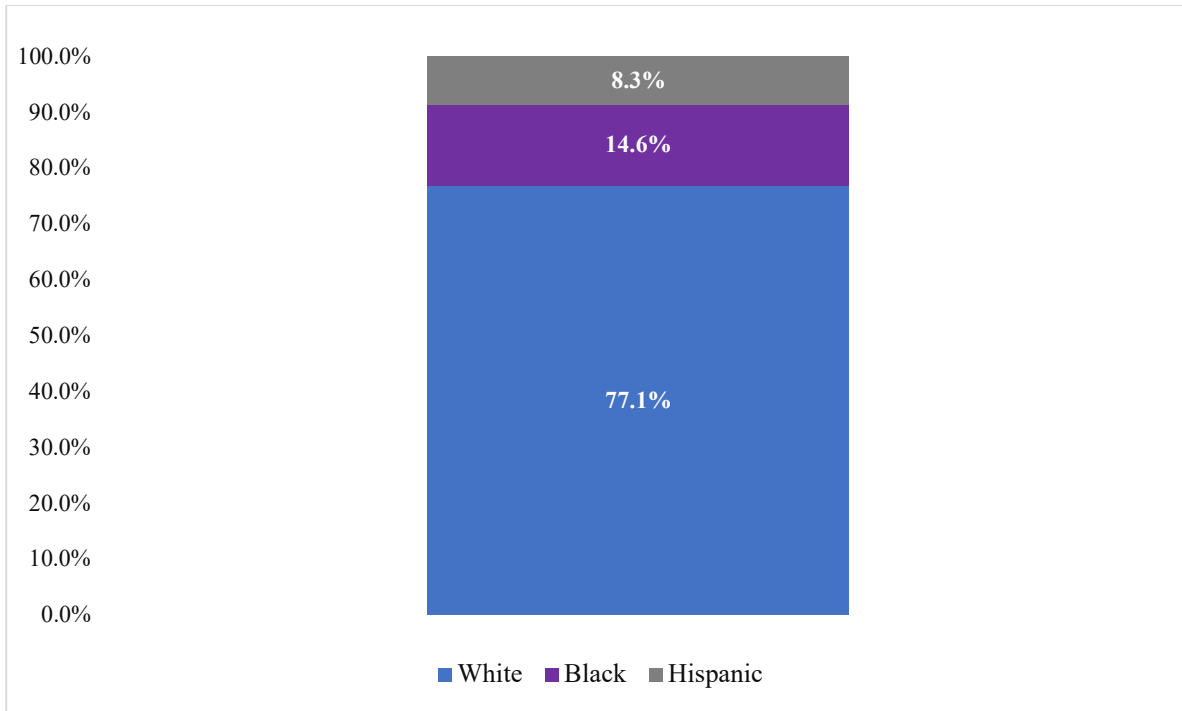


Figure 4.5. Chart displaying relative frequencies of victims' racial/ethnic backgrounds (n=95).

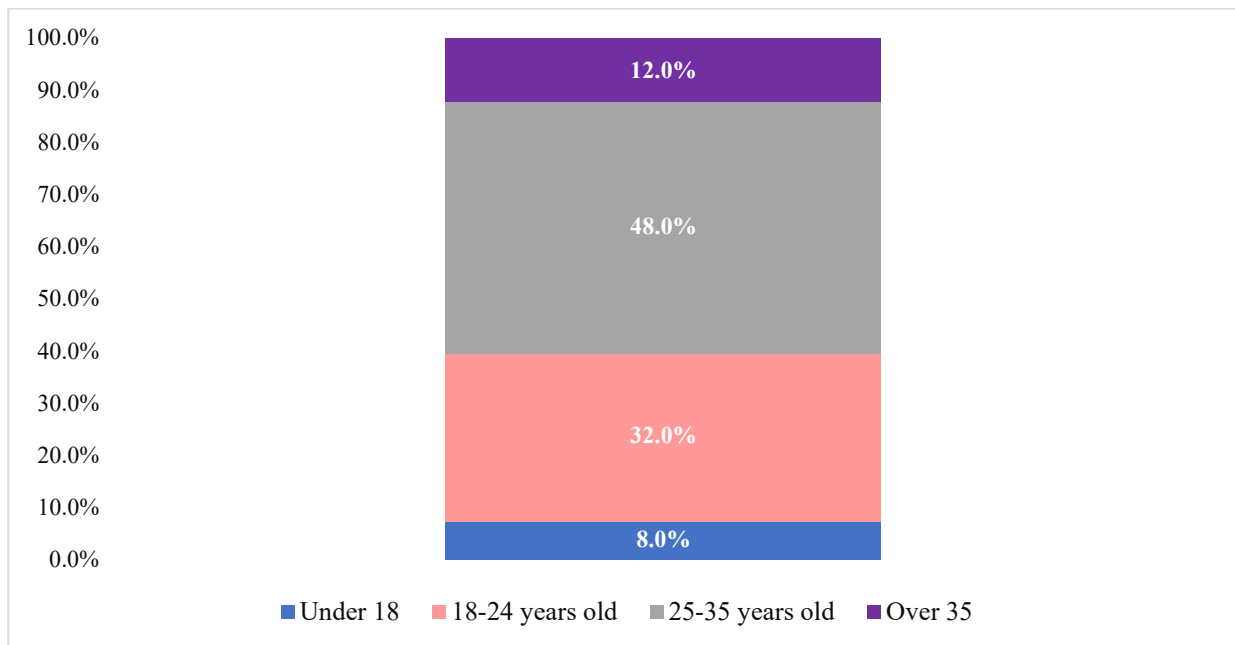


Figure 4.6. Chart displaying relative frequencies of perpetrator ages (n=23).

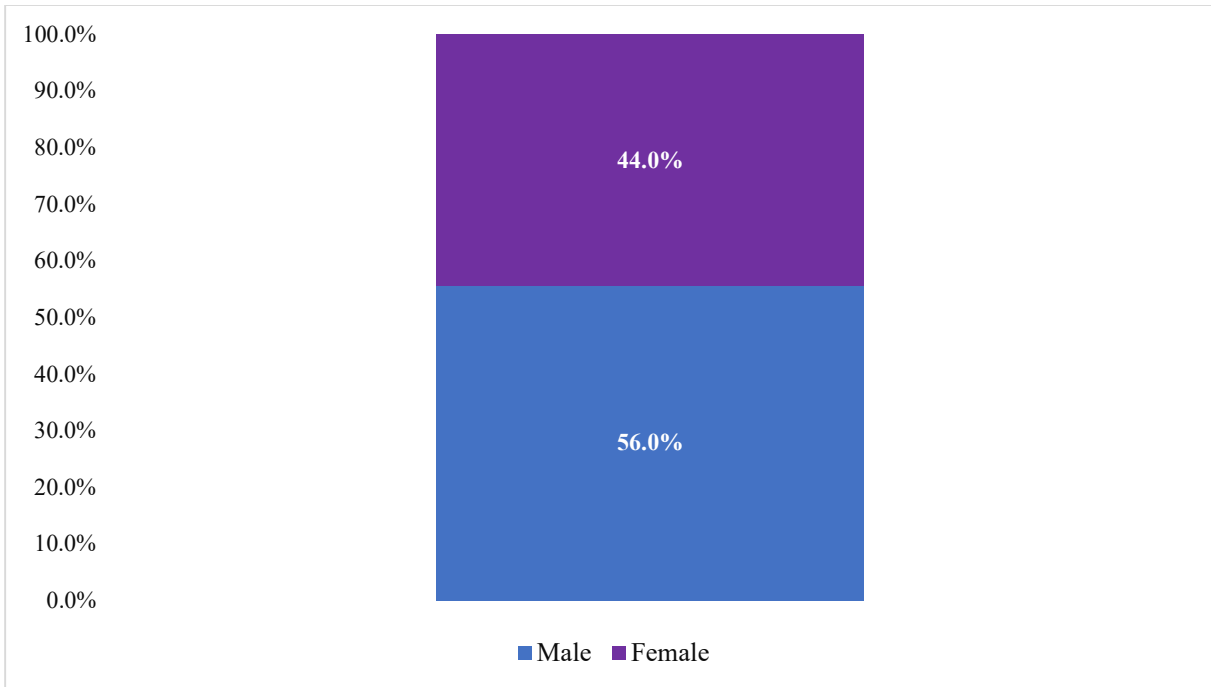


Figure 4.7. Chart displaying relative frequencies of perpetrator sex designations (n=23).

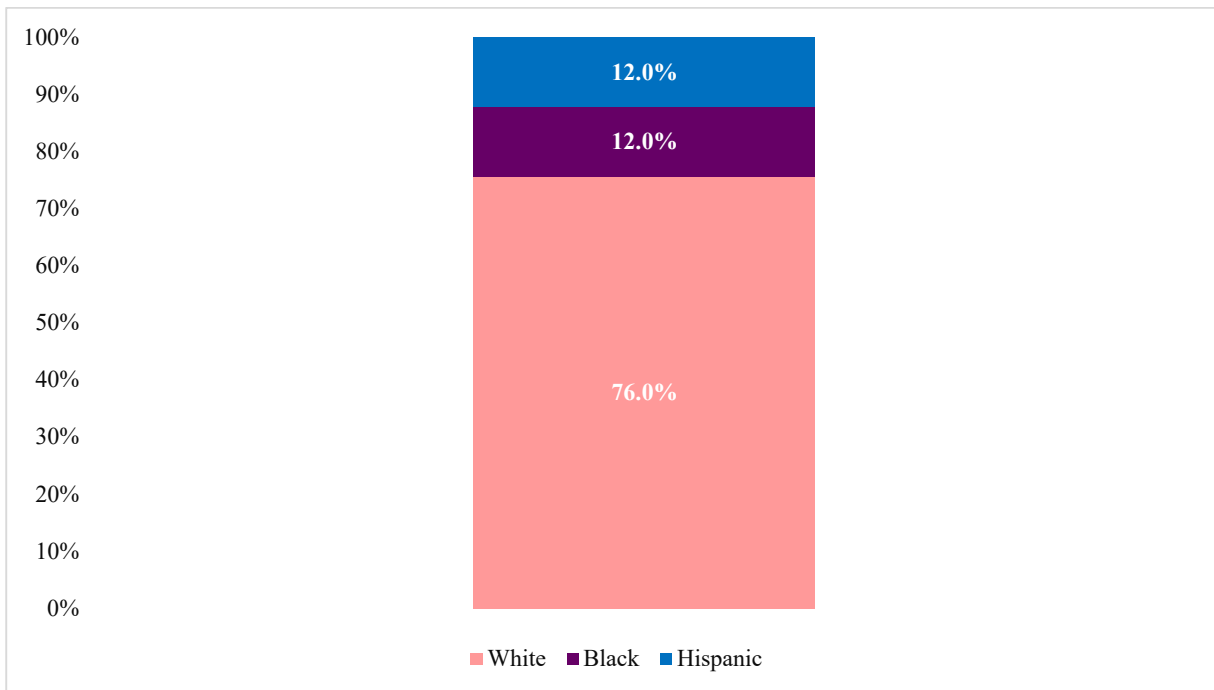


Figure 4.8. Chart displaying relative frequencies of offender racial/ethnic categories (n=23).

Frequency data for manner of death is displayed in Figure 4.9. There is a significant association between mechanism of injury and victim age group ($\chi^2= 79.5, df= 27, p \leq 0.001$). Bar charts displaying the results of this analysis are in Figure 4.10.

Figure 4.11 displays the frequency data for homicide types. Figure 4.12 provides frequencies of perpetrator relationship to the victim for cases where an offender was identified. There is a significant association between the age of the victim, and the relationship between the victim and offender, as seen in Figure 4.13 ($\chi^2= 52.2, df= 27, p= 0.002$).

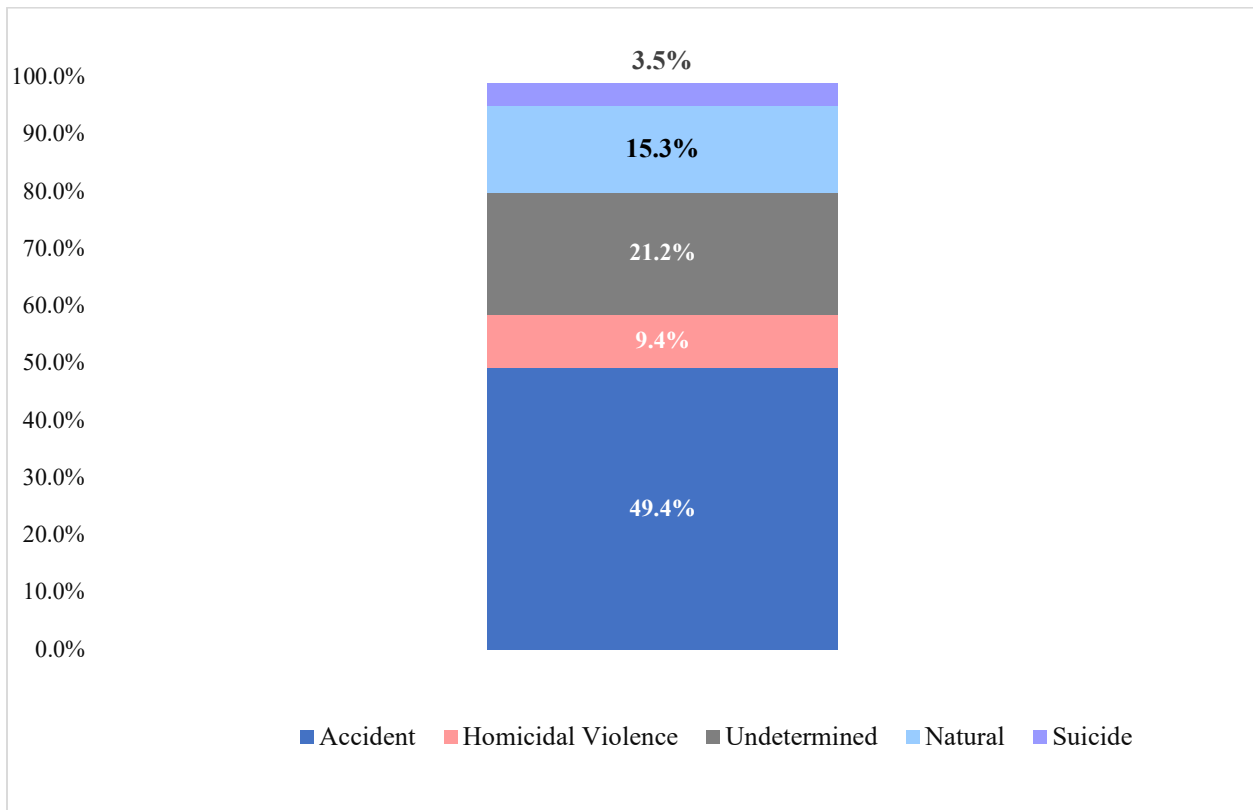


Figure 4.9. Chart displaying relative frequencies of manner of death designations (n=84).

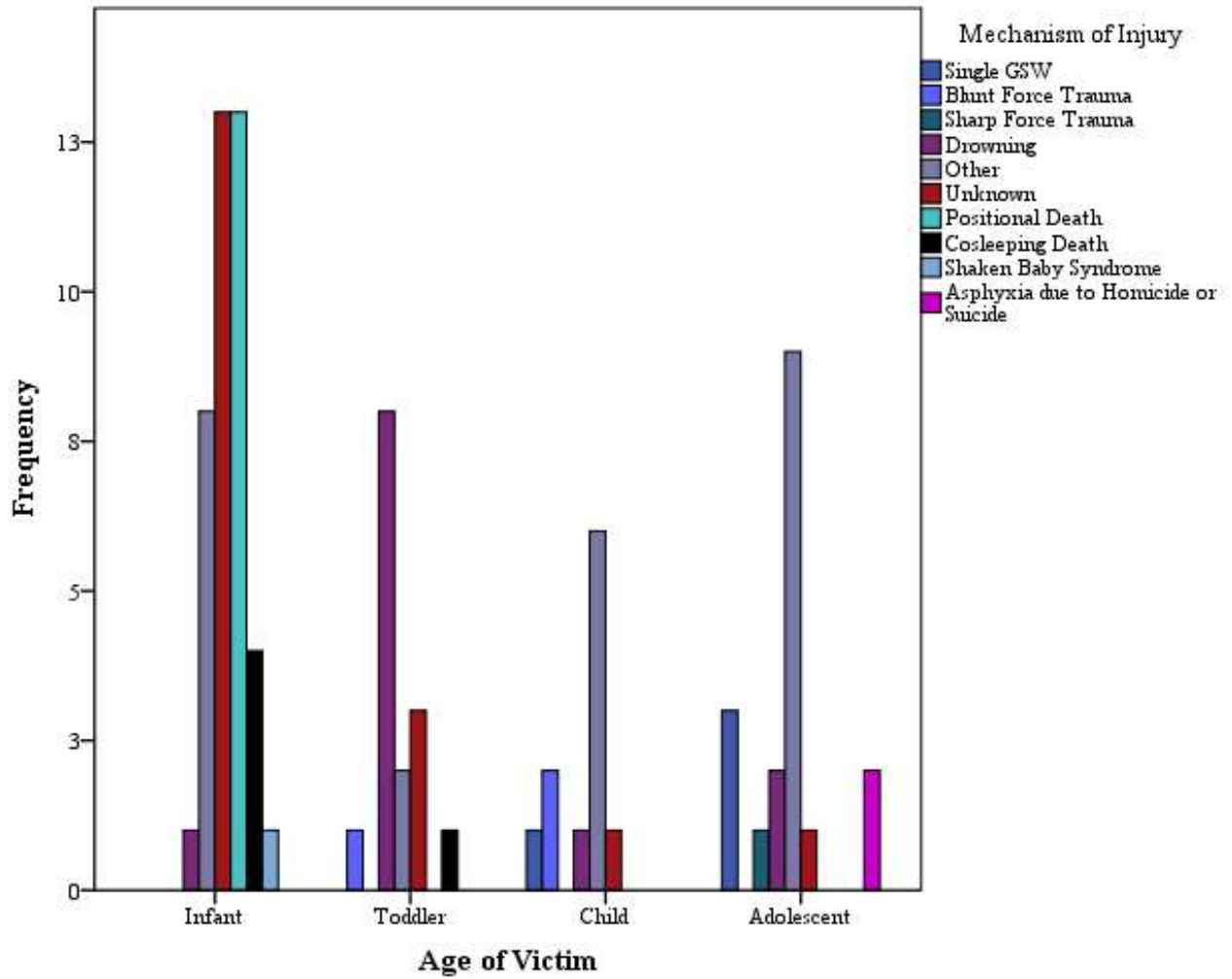


Figure 4.10. Clustered bar chart showing mechanism of injury and age of victim (n=95).

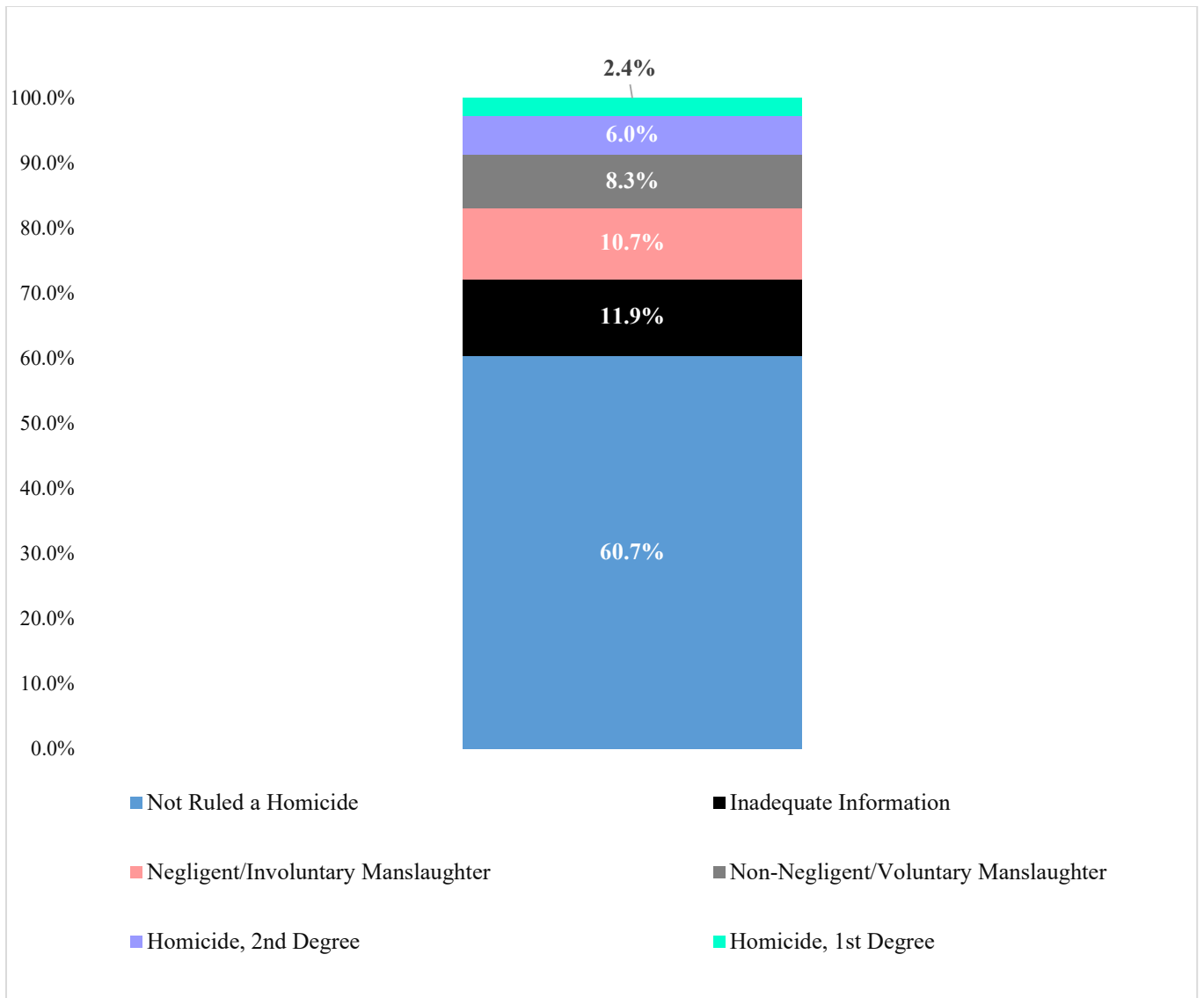


Figure 4.11. Chart displaying relative frequencies of homicide type (n=84).

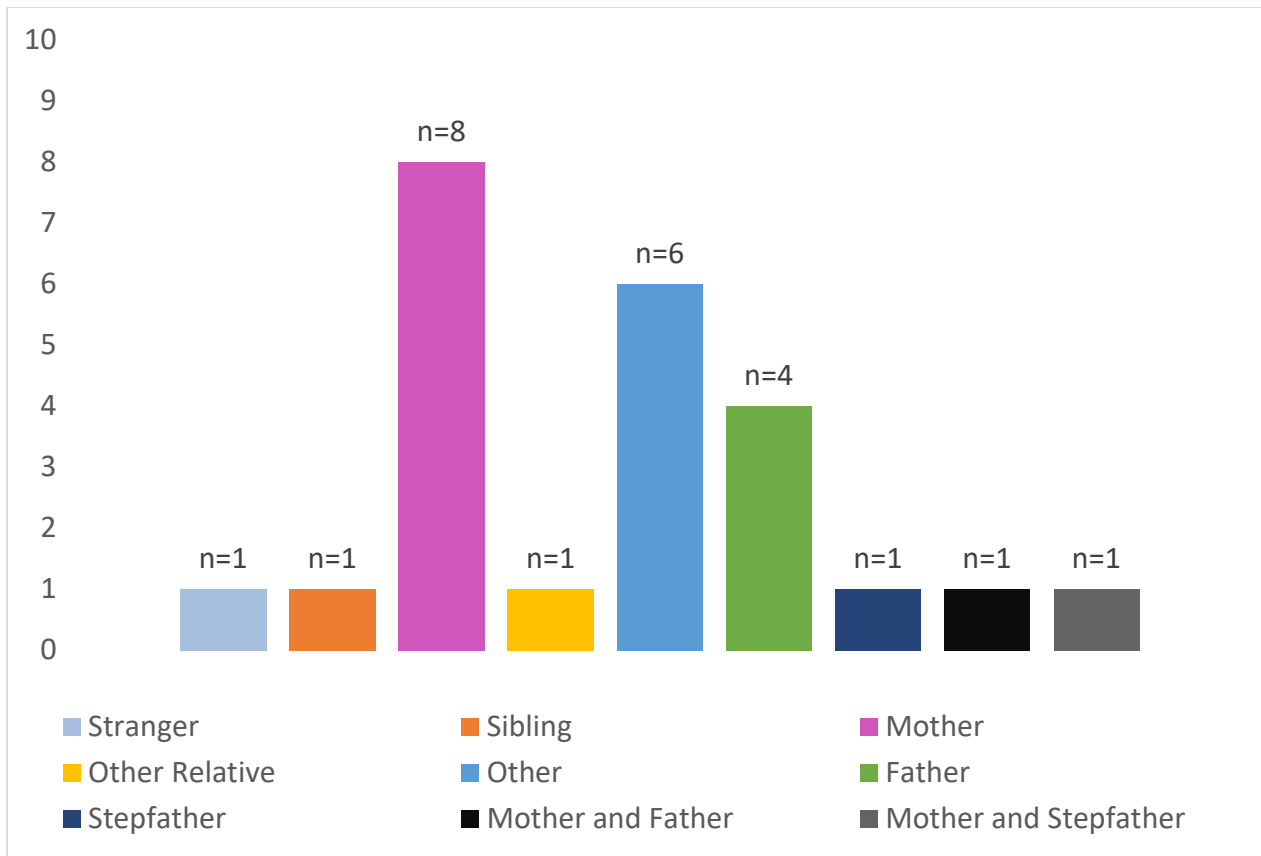


Figure 4.12. Chart displaying relative frequencies of offender relationships to victim excluding unknown and non-applicable cases (n=23).

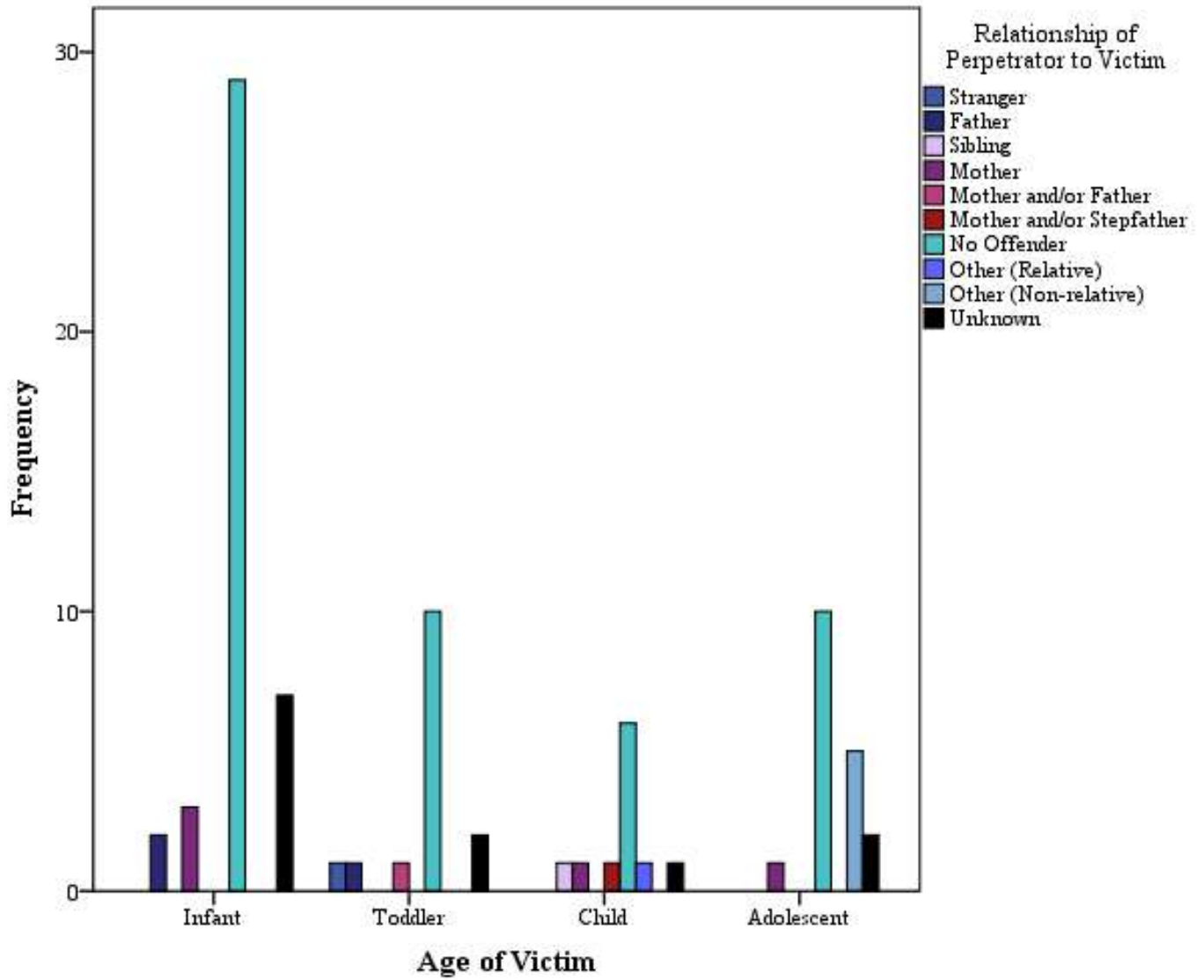


Figure 4.13. Clustered bar chart showing relationship and victim age group (n=23).

Trauma Modeling

The first test examined the differences in the essential boundary conditions for two models constructed with different meshes (see Figure 4.14). Skull21 is a coarser model that was built with fewer, larger elements than Skull32. This restricts the ability of the Skull21 model to provide a realistic picture of deformation or failure compared to Skull32. Skull32 is more refined, with smaller elements that better approximate the geometry of a hemisphere than Skull21. The essential boundary conditions of both models are highlighted in Figure 4.14 in the pale blue and red colors towards the bottom of the figures, and are visually very different due to the differences in mesh construction.

The second test compared two versions of the Skull32 model: one upon which a nearly symmetric vertical load was applied to the model with fixed boundary conditions, and one with sliding fixities. The results of this test are displayed in Figure 4.15 and Figure 4.16. Figure 4.15 shows the interior of the model with deviatoric stress highlighted, and Figure 4.16 shows the same models in a cross-section view. There are some visual differences between the models, such as the dark band at the base of Skull21, though the variation is relatively subtle without examining the values of the model variables.

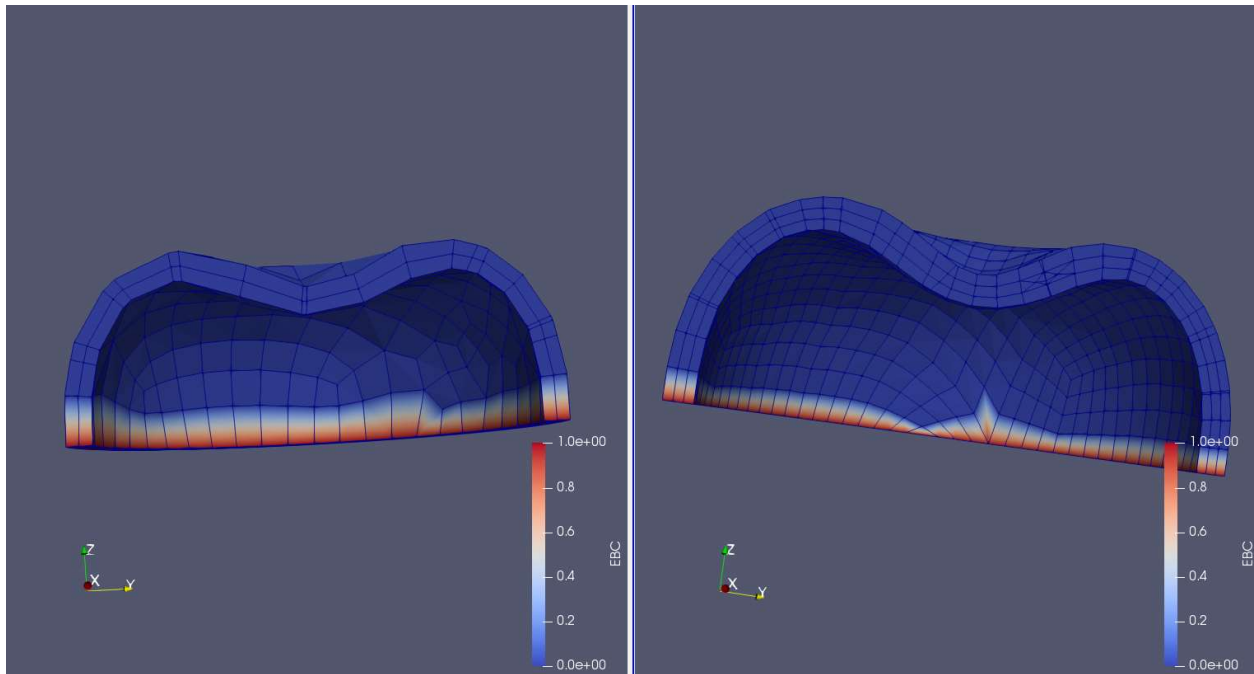


Figure 4.14. Skull21 (left) and Skull32 (right) with highlighted essential boundary conditions.

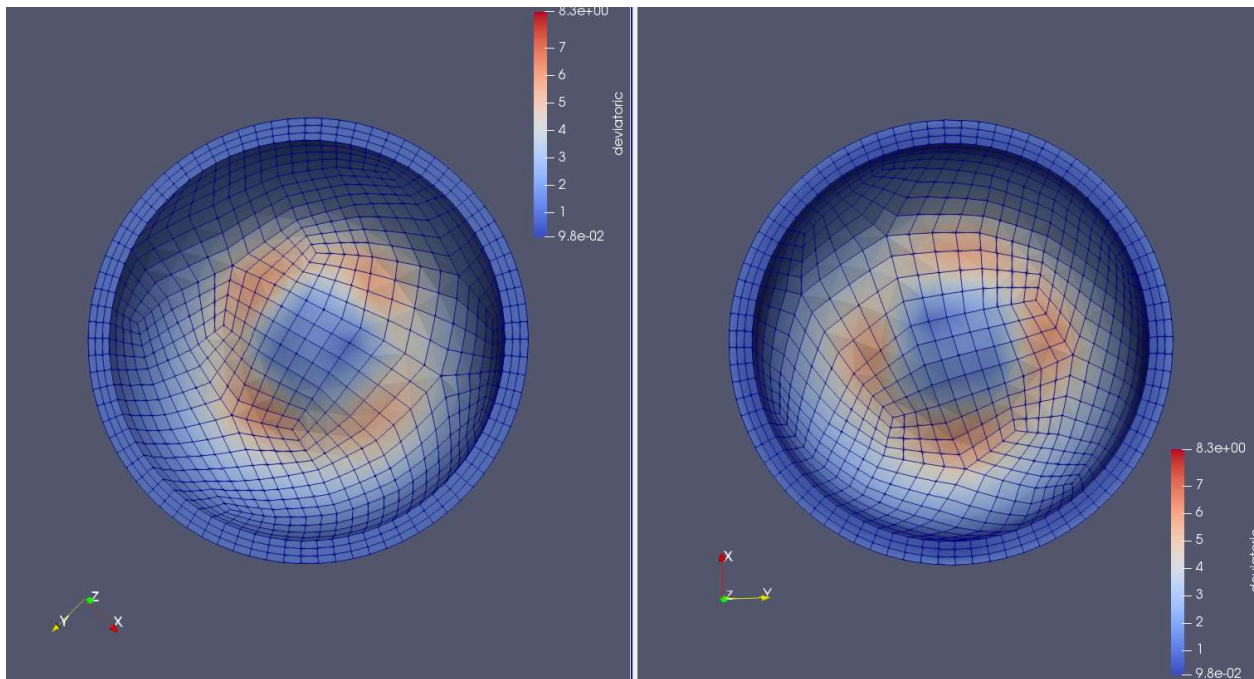


Figure 4.15. Skull 32 processed with sliding fixities (left) and fixed boundary conditions (right).

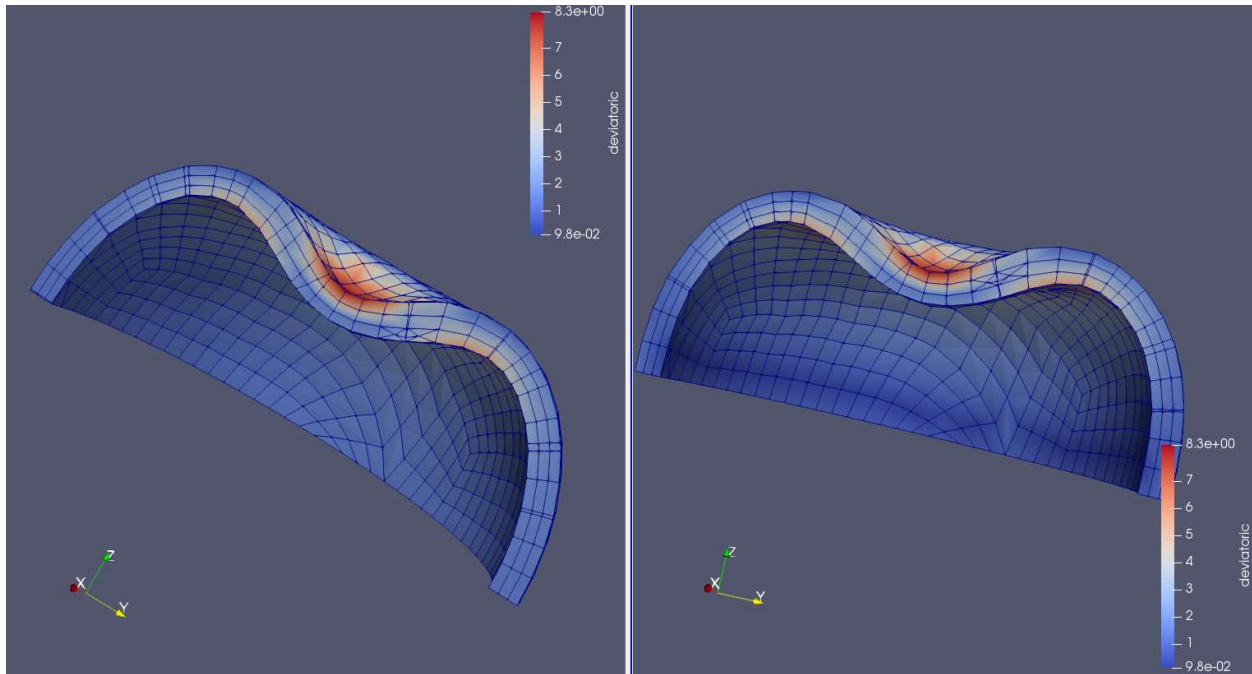


Figure 4.16. Cross-section of Skull 32 processed with sliding fixities (left) and fixed boundary conditions (right).

To expand upon the second test, Skull32 was run twice more with both fixed and sliding boundaries after an additional horizontal component of force was applied to the horizontal plane of the skulls to simulate glancing blows. Figure 4.17 shows there are considerable visual differences to the results upon this change. The version of the model with sliding fixities displays deformation to the base of the hemisphere while the version with fixed boundaries did not due to the restriction of the nodes in the second essential boundary condition. The importance of these contrasting results, and the results of the child fatality study, are discussed in detail in the next chapter.

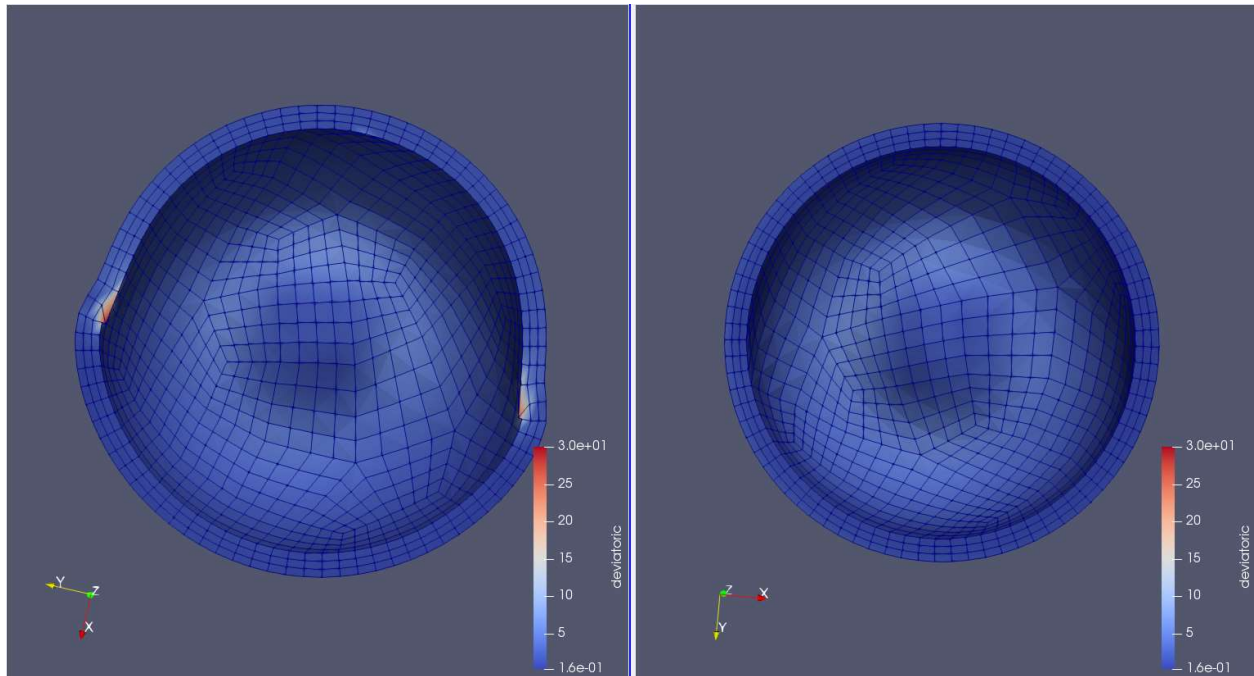


Figure 4.17. Skull32 reprocessed with sliding fixities (left) and fixed boundary conditions (right).

CHAPTER FIVE:

DISCUSSION AND CONCLUSIONS

Chapter five discusses the results of this study in the context of the published literature, medico-legal practice, and theoretical background in biological anthropology, civil engineering, and criminology. First, the results of the child fatality study will be discussed, followed by the implications of the trauma modeling component of the study. Finally, the conclusions of the study are described, and opportunities to continue this line of inquiry are presented.

Incidence of Child Fatalities

The results of this study support many of the patterns published in the criminological and anthropological literature on child fatality. The frequencies of administrative clearance compared to the frequency of researcher diagnosis suggest that there is a possibility that child homicides could have been underreported in the Pasco County dataset, which is consistent with the results of previous studies (Ewigman et al. 1993; McClain et al. 1993).

Similarly, victim ages are roughly consistent with criminological research which suggests that infants and toddlers are most at risk for morbidity, and children generally see a decrease in risk over time, until adolescence where the risk again increases (Boudreaux et al.

2001). The sex frequencies of the victims are also consistent with the literature, which suggests that males are more at risk of childhood mortality and maltreatment than females in the United States (Abel 2011; Boudreaux et al. 2001; Korbin 1987; Ross et al. 2009).

The association found between victim and perpetrator racial/ethnic group is also consistent with the literature, which suggests that perpetrators of child homicide often prey within their own groups (Boudreaux et al. 2001; Hanfland et al. 1997). This does not mean; however, that victims were selected due to their ethnicity, rather they were more accessible to the assailant due to their group affiliation.

Frequencies of manner of death show that accidental deaths were most commonly ruled in the sample. These deaths primarily included drownings, drug overdoses, and positional or co-sleeping deaths. When considering mechanism of injury, older children were also seen to die more violently, with higher frequencies of gunshot wounds and sharp force trauma, which is consistent with previous studies (Boudreaux et al. 2001). Adolescents were also the only age group in which individuals died by suicide in the sample.

Adolescents were more commonly killed by non-related individuals such as school acquaintances. This is also in agreement with previous studies that have reported older children are more likely to experience violence outside of the family unit than young children (Boudreaux et al. 2001).

When considering the frequencies of perpetrator relationship to the victim when an offender could be identified, mothers were the most common offender in the dataset, supporting the evolutionary perspective provided by Sandra Hrdy (2016). Hrdy (2016) demonstrated that humans may be hardwired for alloparenting, a form of communal or cooperative parenting. This is significant, as infanticide is more common when a mother has lowered postpartum

responsiveness due to this adaptation and little help from others in raising the infant (2016). Coupling this perspective with the literature provided by cultural anthropologists, it seems as if infanticide risk mostly depends on whether families have access to a whole suite of resources, not just solely financial capital. This may help explain why some mothers with very low socioeconomic status thrive when they have access to family or other community members to help them raise their children. Similarly, it may also explain why abuse still occurs in (and is more frequently underreported) in higher-income families (see Hampton and Newberger 1985), as mothers may be isolated if they do not have hired or familial help, causing frustration and potentially contributing to low postpartum responsiveness, which may lead to neglectful or abusive behavior. This study is limited because data on socioeconomic status could not be collected. However, the perspectives provided by anthropologists help to chip away at the complicated reasons humans engage in infanticide.

From these results and the experience of intensive case review, other issues were identified with regard to child fatality in Pasco County. For example, there were several cases in which law enforcement had reason to believe that children died due to neglect, not only because of how the fatal incident occurred, but because the parents were found to have chronically neglected the children prior to death. In most of these cases, the State Attorney's Office declined to prosecute. While it is not always clear from reports alone how decisions are made in the field or by the attorney, it is clear that definitions of neglect and expectations of law enforcement need to be clarified. A clear line of communication should be established between law enforcement and their respective state attorneys in regards to child neglect.

Another area of concern is the lack of skeletal surveys implemented by anthropologists at autopsy. While it is perhaps not standard for forensic anthropologists to be consulted for every

child fatality case, for some situations it is vital to assist in discerning whether or not a child was abused ante or perimortem. Two infant fatality cases that were administratively cleared and ruled undetermined for both cause and manner of death by the medical examiner illustrate the need for more anthropological involvement in cases in which abuse is a possibility, as both children sustained bilateral rib fractures antemortem. This is generally noted by anthropologists as a sign of child abuse prior to death, possibly caused from shaking or squeezing the infant (Abel 2011). It is important to note that bilateral rib fractures generally do not occur from daily activities, as the infant skeleton is very elastic and can sustain greater strain values before failure than adult ribs (Abel 2011). Anthropological knowledge regarding how injuries may occur is invaluable to child homicide investigations, as there are rarely witnesses outside of the family who are able to speak about the fatal incident.

While the existence of bilateral healing rib fractures does not provide an exact cause or manner of death, a better understanding of potentially abusive skeletal trauma could assist medical examiners and law enforcement in making their investigative decisions. Had a forensic anthropologist been consulted to conduct a skeletal survey, an invasive technique that consists of exposing all bones during autopsy *in situ* and thoroughly examining any bones that present as potentially fractured or atypical (Love and Sanchez 2009; Love et al. 2011), it is possible that more evidence of injury could have been uncovered. This is particularly important, as radiographs do not always show fractures, and CT scans or skeletal surveys at autopsy are necessary to ensure no fractures are missed (Flaherty et al. 2014).

Finite Element Modeling

The modeling component of this thesis provides important discussion items for trauma analysts and anthropologists interested in employing finite element modeling or other computational methods to examine crack propagation. The way in which a mesh is constructed and refined is of integral importance to the results. The observed differences in the essential boundary conditions between Skull21 and Skull32 were marked, with the essential boundary condition of the coarser Skull21 model sitting further from the base of the hemisphere.

Similarly, the more refined Skull32 model showed minor differences in visual results when a symmetric vertical load was applied to two versions of the model with fixed and sliding boundaries. However, when horizontal force and magnitude were incorporated to simulate a glancing blow to the hemisphere, the version with sliding fixities showed drastically different results. This demonstrates the importance of carefully constructing the parameters of the FE model, as small changes in boundary conditions or other variables display very different results. It is also important to note that some of the nodes in the version with sliding fixities remained fixed to remove rigid body motion from the model, so even if only some nodes have freedom of motion in the essential boundary condition, results can be very different from a model that uses all fixed nodes.

These demonstrations illustrate the need for consideration of whether FE modeling is has a place in computational trauma modeling in forensic science. Considering the restrictiveness of meshed modeling methods and the many ways results can be influenced by the generation of the mesh itself, anthropologists should explore opportunities to work with engineers utilizing meshfree methods. Meshfree modeling techniques such as the Reproducing Kernel Particle

Method could lead to better results for trauma analysis, as meshfree methods allow deformation and cracking more freely than meshed methods.

Additionally, there are opportunities to create patient-specific models with CT scanning technology that could yield promising results when coupled with meshfree modeling methods. Using patient-specific data to create a model reduces error in the geometry, while the lack of a mesh provides more freedom for the cracks to more closely approximate a real-world scenario.

The use of patient-specific models is not only of interest in forensic science, but also in medical fields such as orthopedics, which require modeling tools to design implants and assess fracture risk in patients (Poelert et al. 2013). While a great deal more research is required to determine best practices for creating patient-specific meshfree models for use in either clinical contexts or trauma analysis, the potential results from such a line of inquiry could allow forensic anthropologists better opportunities to study trends in fracture propagation and make more informed decisions on fracture etiology in cases where injury is of a disputed origin.

Conclusions

The first chapter of this thesis provided several research questions and hypotheses, listed along with the subsequent results in Table 5.1. The results of this thesis showed that Pasco County child fatalities had many similar characteristics to those described in the literature, and that there were several cases in the data set that may have been misclassified based on intensive review. These conclusions demonstrate the need for clear expectations between all parties and fields involved in criminal justice and medicolegal investigations, and the need for forensic

anthropologists to be involved at autopsy in cases where surface-level trauma may not provide sufficient information to determine manner or cause of death.

Further research should be explored on this topic in different localities to examine the prevalence of misdiagnosed manner of death, though it is important to note that social scientists undertaking these case reviews have ethical considerations. It is important to acknowledge the real-life impact case reviews can have on people and families, and should take great precautions to not make stronger conclusions than are possible with retrospective examination of case reports and images. That being said, it is possible for anthropologists to collect more reliable data on ambiguous fatalities in order to assist agencies develop protocols and training for identifying signs of inflicted trauma. Similarly, these data could provide anthropologists with the opportunity to educate medical professionals on the importance of thorough review of child injuries, as many victims of fatal abuse have seen a medical provider for treatment prior to their deaths (King et al. 2006).

This thesis also explored simple FE models to explore some issues with FE models and how they relate to the context of skeletal trauma research. This study found that without careful, expert mesh construction and determination of boundary conditions, FE models may not be the most reliable method for computational models of skulls for trauma investigations.

Unfortunately, this research was unable to support the creation of a meshfree model to compare with the FE models, and no cracking algorithms were applied to either of the FE models utilized in this study so some of the conclusions on this component are limited. This research did demonstrate; however, the many ways in which FE models can provide varied and incorrect results. While this research does not suggest that FE modeling cannot be successfully

implemented for trauma purposes, it warns that FE models require a great deal of knowledge and care to produce accurate results.

Table 5.1. Research Questions, Hypotheses, and Results.

RQ	Hypothesis	Results
How does child fatality data compare to child fatality from previous studies and other parts of the United States?	Research cases will have similar patterns in child homicides from previous studies.	Research sample has similar patterns in child homicides as hypothesized.
Is there potential under or overreporting of child homicides in this area?	There may be some potentially misclassified cases in the dataset.	There were potentially misclassified cases in the dataset.
In what ways is computational modeling useful to trauma analysis researchers who are interested in elucidating the differences between accidental and inflicted injury?	FE models are not the best method for studying fracture propagation	While cracking algorithms were not explored at this time; however, the following two results suggest that FE models are not best suited to studying fracture propagation.
Are there issues with using FE models for trauma modeling?	Yes, due to the restrictiveness of the mesh and because slight adjustments to boundary conditions could drastically influence results.	Adjustments to boundary conditions did influence the results of the models.
Are there alternative methods for modeling crack propagation for trauma research?	Yes, though this thesis is unable to test meshfree models directly.	This thesis could not fully test this RQ; however, the results in this thesis support future research on meshfree modeling methods for fracture propagation.

Even when precautions are taken, the existence of a mesh in the FE models can confound the propagation of a fracture in a model versus actuality. Other methods such as Reproducing Kernel Particle Method should be researched and tested by anthropologists and engineers interested in circumventing the issues created by meshes in FE modeling. Further, anthropologists should explore patient-specific trauma modeling through the use of CT scans or other medical imaging systems, as the use of meshfree modeling that approximates not only the general shape of a cranium or other part of the body, but the patient themselves could further provide forensic scientists with insight into mechanism of injury in trauma cases of unknown origin.

In the context of the broader field, this thesis demonstrates the importance of leveraging tools and concepts from various disciplines to create powerful methods for researching and diagnosing manner of death. Criminological research and case review techniques provide anthropologists with categorical and descriptive data that can provide context to the issue of misdiagnosed manner of death and suggestions for improvement in collaboration with local agencies. Engineering methods and expertise also provides forensic scientists with future opportunities for researching trauma, as well as the potential to develop powerful tools for use in casework that would not be possible without interdisciplinary collaboration.

For forensic science, improved methods in computational modeling and partnerships with engineers would not only inform child fatality cases or domestic casework, but could also assist in international contexts. For cases that involve victims of armed conflict who sustained skeletal

trauma, improved modeling could potentially shed light on how their injuries were inflicted, informing forensic analysis in major cases of human rights abuses.

The medical field would also benefit from these partnerships, as improved research in forensic trauma analysis could inform protocols for evaluating juvenile patients presenting with injuries of unknown or disputed etiology. Additionally, computational modeling could be used not only for research on skeletal trauma, but could also shed light on traumatic brain injuries in automobile collisions, athletes, and victims of armed conflict or interpersonal violence.

Anthropologists similarly have much to provide the fields of criminology and civil engineering. Biocultural research provides avenues of exploration for those who study criminality, particularly in the context of intrafamily violence and infanticide. Similarly, forensic anthropologists can help engineers create more context-sensitive models with utilize population-specific data that may otherwise be lost in model creation. The rich possibilities that this collaboration opens up could transform the ways in which medical and forensic professionals work diagnose injuries of many types on both living and deceased individuals.

In conclusion, the problem of child fatality is extraordinarily complex and this thesis has attempted to demonstrate this complexity through experimentation, case review, and intensive literature review while also providing directions for future research. The contributions of multiple fields in social sciences and STEM are needed to holistically tackle child fatality as a social and forensic issue, and anthropologists should consider opportunities to collaborate with their colleagues in other professions to enrich their research efforts on child fatality.

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APPENDICES

Appendix A: Child Fatality Study Protocol

Traumatic Child Deaths: Patterns of Homicide
Data Collection Protocol
Last Mod. 11/17/2015
Jaime D. Sykes, Erin H. Kimmerle,

Introduction:

The issue of misdiagnosed manner of death in child homicides has been discussed in the literature of multiple disciplines. This study aims to identify cases of misdiagnosed manner of death as well as child homicide patterns in traumatic child fatalities in Pasco County, Florida over the last 45 years. Children whose ages range from newborn infant to 17 years old at time of death will be included in this study. This will assist law enforcement improve current investigative methods, and add to the body of knowledge that exists on homicide patterns and the prevalence of misdiagnosed manner of death in child abuse cases.

Definitions:

- First-degree murder consists of both premeditation and malice aforethought.
- Second-degree murder means there is malice aforethought without premeditation. In other words, the offender intends to kill the victim but does not plan the lethal act.
- An act of voluntary or non-negligent manslaughter is committed when a person attempts to hurt, but not kill, another human being—but the victim dies in the process. Negligent or involuntary manslaughter is characterized by accidental death. Some states distinguish between vehicular and non-vehicular accidental death and others do not.
- Victim precipitated homicide refers to those instances in which the victims' actions resulted in their demise. In this form of murder, the deceased may have made a menacing gesture, was first to pull a weapon, or merely used words to elicit a deadly response from the killer.
- Hate homicide is a form of killing involving taking the life of "victims who are targeted because they differ from the perpetrator with respect to such characteristics as race, religion, ethnic origin, sexual orientation, gender, or disability status" (Fox and Levin 2001, p. 128).
- Probable misdiagnosis will be designated when the case has been thoroughly reviewed and there is probable cause of misdiagnosed manner of death (e.g. trauma patterns indicate that the explanation given by the abuser obviously do not match the injury).
- Possible misdiagnosis will be designated when the case has been thoroughly reviewed and there is reason to suspect a misdiagnosis in manner of death could have occurred, but there are no obvious indicators of homicide (e.g. a child that exhibited symptoms of shaking injury, but CT scans were never performed to evaluate intracranial damage).

DATE AND RECORDER:
POLICE REPORT NO.:
DATE OF INCIDENT:

POLICE AGENCY:
AUTOPSY NO.:
DATE/YEAR OF POLICE REPORT:

Overall Impression of Case – Misdiagnosis of Manner of Death

- 1 = probable misdiagnosis
- 2 = possible misdiagnosis
- 3 = no misdiagnosis
- 4 = inadequate information

OBS. 01: DIAGNOSED MANNER OF DEATH:

- 1= Accident
- 2=Homicide/homicidal violence
- 3=Unknown

OBS. 02: TYPE OF HOMICIDE:

- 1=criminal homicide, first degree
- 2=criminal homicide, second degree
- 3=manslaughter, negligent/involuntary
- 4=manslaughter, non-negligent/voluntary
- 5=not a homicide
- 6=inadequate information

CONTEXT:

- | | | |
|---------|--|----------------------|
| OBS. 03 | Was this is a "victim precipitated" homicide? | 1=Yes 2=No 3=Unknown |
| OBS. 04 | Was this is a "hate murder"? | 1=Yes 2=No 3=Unknown |
| OBS. 05 | Was this a domestic dispute or familial killing? | 1=Yes 2=No 3=Unknown |
| OBS. 06 | Was there an associated robbery? | 1=Yes 2=No 3=Unknown |
| OBS. 07 | Was there an associated rape? | 1=Yes 2=No 3=Unknown |
| OBS. 08 | Was this a sexual homicide? | 1=Yes 2=No 3=Unknown |
| OBS. 09 | Was there extortion? | 1=Yes 2=No 3=Unknown |
| OBS. 10 | Was there an associated kidnapping? | 1=Yes 2=No 3=Unknown |
| OBS. 11 | Was the assailant known by the victim? | 1=Yes 2=No 3=Unknown |

OBS. 12: What was the nature of the assailant's relationship to the victim?

- | | | |
|------------|---|------------|
| 1=Stranger | 2=Spouse (married, separated, divorced) | 3=Parent |
| 4=Child | 5=Boyfriend/Girlfriend | 6=Coworker |
| 7=Neighbor | 8=Other: (list) | 9=Unknown |
- Friend, roommate, acquaintance, relative (not spouse)

Obs. 13: Was there a history of domestic violence against the victim by the assailant in the past?

- 1= Yes 2= No 3= Unknown

Obs. 14: If there was a record of domestic violence, state source:

- | | | |
|-------------------|-------------------------|-------------------------|
| 1=DFS report | 2=Witness statement | 3=Perpetrator admission |
| 4=Hospital record | 5=Other (list in notes) | 6=Not applicable |

OBS. 15: Was the victim a prostitute? 1=Yes 2=No 3=Unknown

OBS. 16: If yes, was assailant any of the following? 1=prostitute 2=pimp 3=client

Demographic Information of Decedent (repeat if multiple victims):

- OBS. 17: Sex 1=Male 2=Female
OBS. 18: Age (years)
OBS. 19: Ancestry:
1=Caucasian 4=Hispanic 6=Other (list)
2=African-American 5=American-Indian 7=Unknown
3=Asian

Demographic Information of Offender (repeat if multiple assailants):

- OBS. 20: Sex 1=Male 2=Female
OBS. 21: Age (years)
OBS. 22: Ancestry:
1=Caucasian 4=Hispanic 6=Other (list)
2=African-American 5=American-Indian 7=Unknown
3=Asian

OBS. 23: Nature of Injury – Mechanism of Death:

- 1=Single GSW 4=SFT 6=Other (list and describe)
2=Multiple GSW 5=Strangulation 7=Unknown
3=BFT

OBS. 24: Nature of other injury associated with attack:

- 1=Single GSW 4=SFT 7=Unknown
2=Multiple GSW 5=Strangulation
3=BFT 6=Other (list and describe)

OBS. 25: Weapon:

- 1=Handgun 5=Blunt (list specific) 9=Unknown
2=Shotgun 6=Ligature (list specific)
3=Rifle 7=Manual strangulation
4=Sharp (list specific) 8=Other (list)

OBS. 26: Location of Fatal Injuries (on body):

- 1=Head 4=Abdomen 7=Back
2=Neck 5=Upper Extremity 8=Combination (list)
3=Thorax 6=Lower Extremity 9=Other

OBS. 27: Location of other non-fatal injuries (list all that apply):

- 1=Head 4=Abdomen 7=Back
2=Neck 5=Upper Extremity 8=Combination (list)
3=Thorax 6=Lower Extremity 9=Other

Obs. 28: Was a radiological skeletal survey of the victim conducted?

- 1= Yes

2= No
3=Unknown

Obs. 29: If the victim had cranial fractures, were there also intracranial injuries present?

1=Yes
2= No
4=Not applicable
3=Unknown

Skeletal Fracture Patterns (refer to survival time protocol)

LOCATION OF CRIME SCENES:

OBS. 30: Was the body moved following the murder? 1=Yes 2=No 3=Unknown

OBS. 31: Provide complete street addresses for the following:

Victim's Residence, Assailants Residence, 1st Encounter, 1st attack, 2nd attack, Murder Location

Body deposition – primary location, Secondary body deposition

Obs. 32: Was the victim admitted to a hospital?

1=Yes, antemortem 2=Yes, DOA 3=No
4=Unknown

Obs. 33: What time of day was the victim admitted?

1=9:00 am – 11:59 am 2=12:00 pm – 2:59pm 3=3:00 pm – 5:59 pm
4= 6:00pm – 8:59 pm 5=9:00 pm – 11:59 pm 6=12:00 am – 2:59 am
7= 3:00 am – 5:59 am 8= 6:00 am – 8:59 am 9= Not applicable

Obs. 34: Was the victim clothed on arrival?

1= Yes 2= No 3=Unknown
4=Not applicable

BURIAL FACTORS

OBS. 35: Context of burial location:

1= Surface deposition
2= Sub-surface Burial
3= Dismemberment
4= Water (list type of body of water, i.e. river, bay)
5= Burning/fire or cremation
6=Not applicable – Will not code OBS 31-39.

OBS. 35: Environment where body was recovered:

1= Public space 2= Private residence 3= Along roadside
4= Wooded area/field 5= Abandoned structure 6 =Railroad tracks
7= Other (please list):

OBS. 36: Container:

OBS. 49: Was this case closed by arrest?

1=Yes 2=No 3=Unknown

If not, list other means of closing case (List):

Appendix B: Survival Time Data Protocol

Data Key for Survival Time/Fx Pattern Data

Revised: May 2008

Victim Information:

Sex: 1 = Male
2 = Female

Age (years)

Ancestry

1 = Caucasian 2 = African-American 7 = Unknown
3 = Hispanic 4 = Asian
5 = American-Indian 6 = Other

Manner (Manner of death)

1 = Homicide 2 = Suicide 5 = Indeterminate
3 = Accident 4 = Natural

Cause (Cause ~ mechanism of death, also list primary and secondary causes)

1 = Multiple GSW 2 = Single GSW 5 = Other (List/Describe numbered
3 = Exsanguation/GSW 4 = Blunt Force Trauma factors)

obs. 1 Contributing factor (Contributing factors / List as many as apply)

1 = Multiple GSW
2 = Single GSW
3 = Exsanguination
4 = Blunt Force Trauma
5 = Sharp Force Trauma
6 = hemopericardium
7 = cardiac tamponade
8 = Hemorrhage
9 = Ecchymoses
10 = Cranial Cerebral Injuries
11 = Sub-arachnoid Hemorrhage
12 = Subdural Hematoma
13 = Subgaleal Hemorrhages
14 = Multiple Skeletal Fractures
15 = Subdural Hemorrhages
16 = Avulsion both cerebral hemispheres
17 = Pneumothorax
18 = Hemoperitoneum

- 19 = Cerebral Edema
- 20 = Subendocardial Hemorrhage
- 21 = Pulmonary Edema
- 22 = Infarct Lf. Cerebral Hemisphere
- 23 = Respiratory Failure
- 24 = Hemothorax
- 25 = Other (List Describe)

- obs.2 Location (Location of fatal injury)
- 1 = Inside Residence
 - 2 = Vehicle
 - 3 = Outside Residence
 - 4 = Public/Commercial (inside or outside)
 - 5 = Unknown
 - 6 = Home, other than Victim's residence
 - 7 = Other (List)

- obs.3 Type (Type of fatal injury)
- 1 = Single
 - 2 = Multiple

- obs.4 Weapon (Type of weapon)
- 1 = Handgun
 - 2 = Rifle
 - 3 = Shotgun
 - 4 = Kitchen Knife
 - 5 = Knife/Unknown
 - 6 = Butcher Knife
 - 7 = Blunt force object (list weapon, ie hammer or fist)

* If 1, 2, or 3: also list caliber of shot

- obs.5 Distance (Distance of Gunshot)
- 1 = Contact
 - 2 = Not Contact
 - 3 = Contact and Non-contact

- obs.6 Number of Wounds
- ** Count enter/exit wounds separate or each # of blunt force impact site

- obs.7 Wound size (Size of Wound, give dimensions in cm)

- obs.8 Areawond (Anatomical area of primary wound)
- 1 = Head
 - 2 = Neck
 - 3 = Chest
 - 4 = Abdomen
 - 5 = Back of Thorax
 - 6 = Upper Extremity Left
 - 7 = Upper Extremity Right
 - 8 = Lower Extremity Left
 - 9 = Lower Extremity Right
 - 10 = Combination (list numerous locations)
 - 11 = Left Groin
 - 12 = Other (list)

- obs.9 Areawond2 (Anatomical area of second wound)
- 1 = Head
 - 2 = Neck
 - 3 = Chest
 - 4 = Abdomen
 - 5 = Back of Thorax
 - 6 = Upper Extremity Left

- 7 = Upper Extremity Right 8 = Lower Extremity Left
- 9 = Lower Extremity Right 10 = Combination (list numerous locations)
- 11 = Left Groin 12 = Other (list)

* If more than two wounds, list them separately same as above

obs.10 Organ (Organs injured / List as many as apply)

- 1 = Brain 2 = Heart
- 3 = Lung 4 = Liver
- 5 = GI Tract 6 = Spleen
- 7 = Kidney 8 = Other (list describe)

obs.11 Brain Injury (List as many as apply)

- 1 = Rt Parietal Lobe
- 2 = Lf Parietal Lobe
- 3 = Frontal Lobe
- 4 = Lf Occipital Lobe
- 5 = Rt Occipital Lobe
- 6 = Lf Temporal Lobe
- 7 = Rt Temporal Lobe
- 8 = Rt Basal Ganglia
- 9 = Rt Lateral Ventricle
- 10 = Septum pellucidum
- 11 = Corpus callosum
- 12 = 4th ventricle
- 13 =C omp. destruct. Cerebral hem.
- 14 = Rt temporalis muscle
- 15 = Cerebral Fossa
- 16 = Lac. falx cerebellum/sagittal sinus
- 17 = Pons, Cerebellum
- 18 = skeletal fractures (list which bones are fractured)
- 19 = Other (List/describe)

obs.12 Organ Injury - other than Brain (List as many as apply)

- 1 = Skeletal fractures (list which bones are fractured)
- 2 = Mediastinum
- 3 = Great vessels (List specifically)

(carotid, coronary, ventricular aorta, septum, endocardial, pulmonary vein/artery, inf. Vena cava, brachial artery/vein, femoral vein, abdominal aorta, lt. Vertebral artery, Iliac arteries/veins, subclavian vein, Thoracic aorta)

- 4 = viscera of chest (pericardial sac)
- 5 = diaphragm
- 6 = spinal cord
- 7 = eye
- 8 = thyroid, phalanx, jugular vein, trachea, esophagus
- 9 = Gall Bladder

- 10 = pancreas
- 11 = scrotum
- 12 = Other (list/Describe)

obs.13 Blood loss (Internal blood loss measured at autopsy, ml or cc)

obs.14 Time of injury*

** NOTE IF THIS IS THE TIME OF BIOLOGICAL DEATH OR THE TIME DEATH WAS PRONOUNCED. LIST BOTH IF POSSIBLE. BE SURE TO INCLUDE DATES AND TIME TO THE MINUTE.

Obs.15 Time of death*

(i.e. injury: 6/1/00 10:32am, death: 6/2/00 4:43pm, pronounced 6/2/00 4:45pm)

obs.16 Drugs (Drugs/alcohol present)
0 = Absent 1 = Yes 2 = Unknown

obs.17 Type of drug (Type of Drug)
0 = None 1 = Alcohol 2 = Other 3 = Alcohol and other 4 = Unknown
*If other, list specifically

obs.18 activity* (Amount of activity between the time of injury and the time of death.)
1 = No Activity / Immediate death
2 = Immediate Collapse / life but no movement
3 = Minimal Movement/ agitated, verbal response, slight involuntary movements
4 = Moderate Movement/ Fully Alert, ask for help, walk, fight back, etc.
5 = Maximum Activity/Drive a car, run a short distance, etc.

* This is rather subjective, therefore, list and describe specific activities and events of incident in comments section.

obs.19 Medical Intervention
0 = None 1 = Present

obs.20 Type of Crime (Circumstances surrounding death)
1 = Domestic Dispute
2 = Gang Related
3 = Drug Related
4 = Robbery
5 = Shot by Police
6 = Standoff w/police (suicide)/in-custody deaths
7 = Rape/Self-defense
8 = Motor Vehicle Accident (indicate if passenger, driver, pedestrian, or biker)
9 = Other (list/describe)

SKELETAL FRACTURES

Obs. 21 List each bone that is fractured, separately, then for each answer these questions:

For each bone, list bone code. Also, list specific side, section, and aspect codes (see pathology protocol)

In addition to the standard bone code, these may be added:

230: ethmoid

240: nonspecific orbital fracture.

250: nonspecific basilar skull fracture.

260: teeth

Obs. 22 Fracture codes: for each bone list the type of fracture (provide measurements in mm when appropriate)

1: fracture/dislocation. In a few instances, also refers to fx/subluxation or fx/separation, in which case it is specified in the fracture comments section.

2: amputation

3: compound/open

4: comminuted

5: compound-comminuted. This has its own code because this combination occurs frequently.

6: transverse. This needs to be taken with caution regarding vertebral fractures; the term was commonly used, but did not indicate if it referred to a fracture type or if it referred to the transverse processes.

7: crush

8: hinge

9: depressed

10: eggshell

11: diastatic

12: radiating

13: linear

14: displaced

15: incomplete

16: complete. Complete/incomplete occur only rarely in the Nebraska data.

Obs. 23 Bone healing:

41 = no healing.

42 = any degree of active healing at time of death

43 = indicates a completely healed fracture.

Obs. 24 Soft tissue injury codes (list specific location and size)

1: contusion/bruise/hematoma

2: abrasion

3: laceration

4: combination of two or more including 1, 2, and/or 3

5: Other soft tissue injury (i.e. bitemark, thermal): list

COMMENTS:

Describe circumstances surrounding death/incident, and deceased's activities.
Also, describe all other relevant information.