Use Authorization

In presenting this thesis in partial fulfillment of the requirements for an advanced degree at Idaho State University, I agree that the Library shall make it freely available for inspection. I further state that permission to download and/or print my thesis for scholarly purposes may be granted by the Dean of the Graduate School, Dean of my academic division, or by the University Librarian. It is understood that any copying or publication of this thesis for financial gain shall not be allowed without my written permission.

Signature ____________________________________

Date ____

QUANTIFYING THORACIC SKELETAL TRAUMA

By

Cortney Hulse

A thesis

submitted in partial fulfillment

of the requirements for the degree of

Master of Arts in the Department of Anthropology

Idaho State University

Spring 2016

Copyright 2016 Cortney Hulse

To the Graduate Faculty:

The members of the committee appointed to examine the thesis of CORTNEY HULSE find it satisfactory and recommend that it be accepted.

____

Dr. Kyra Stull,

Major Advisor

____

Dr. Kate Reedy,

Committee Member

____

Dr. Karen Hartman,

Graduate Faculty Representative

Dedication

To Dr. Kyra Stull:

For finding me when I was lost, and helping me find a path to my dreams.

Acknowledgements

I would like to thank the Wake Forest CIREN center, in particular Ashley Weaver and Mark Scarboro, for making this research possible. Thank you also, to the Idaho Virtualization Laboratories for workspace you granted me, and helping volume render my data set. Thank you to Tell Holenbeck for your help with data collection. I would of course like to thank my advisor Dr. Kyra Stull for going above and beyond supporting me and my research; you are a constant inspiration. A special thank you to the faculty in the Idaho State University Anthropology and your support of me, particularly Christian Peterson and the kindness and belief in me you have shown me over the years. To Ely Taysom for being my constant support system, and for always being by my side and helping with everything through this process; thank you for being the Sam to my Frodo. And finally, to my Dad who taught me hard work accomplishes anything, my Mom who shows so much pride in my work, and to the rest of my family whose constant love made it all possible.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Within forensic anthropology, trauma analysis is rarely straightforward. Specifically, due to multiple variables that influence the pattern of fracture, analysis of the thoracic skeleton is rarely attempted. This study aims to identify variables useful to aid in interpretation of thoracic skeletal trauma.

The current research evaluated computed tomography (CT) images of 180 individuals with recorded injuries to the thoracic region and associated point of impact. Age, sex, presence/absence of fractures, belted, and side of impact were recorded for each individual. Chi-square tests and logistic regression were used to explore the relationship among the variables.

Age was the most important variable in the presence of fractures. Counterintuitively, speed was found to be not significant. The current research shows that in trauma interpretation of the thoracic region, age should be considered prior to interpretation of fractures. Continued research accounting for more extrinsic variables might help shed light on the trends observed in this data.

CHAPTER I: INTRODUCTION

Anthropology, put simply, is the study of humans. Biological anthropology is a sub field of anthropology that studies the biological, evolutionary, and anatomical aspects of humans and our closest relatives, the primates. Skeletal biology is included as a specific area of study within biological anthropology and involves the study of human osteology in multiple contexts and will often specialize in particular areas, such as bioarchaeology or forensic anthropology. Forensic anthropology is an applied field of anthropology that deals directly with medico-legal situations, particularly in which recovery and analysis of skeletal material is involved. Forensic anthropologists are directly involved with estimating the biological profile from skeletal material and assessment of any contributing factors to manner of death, such as trauma analysis (Christensen, et al. 2014). Trauma analysis is an objective of forensic anthropology that deals directly with the interpretation of bone injuries. The field remains largely untapped and under-developed compared to many other niches within forensic anthropology such as parameters associated with the estimation of the biological profile. Recognition, examination, and interpretation of skeletal trauma in modern human skeletal remains is the foundation to a successful death investigation (Symes, et al. 2012). The lack of research of skeletal trauma has resulted in gaps in knowledge that can impact numerous fields, including bioarchaeology and forensic pathology.

Trauma analysis is an atypical area of research that requires a multidisciplinary approach. Forensic pathologists use soft tissue to extrapolate information regarding the point of impact and its relationship to underlying injuries. However, when the soft tissue is compromised or nonexistent, as is frequently the case with forensic anthropological analyses, information is gleaned from the skeletal remains. Traumatic injury on the bone is the only evidence available to understand causation and there is limited anthropological literature regarding the frequency of fractures. Thus, when the anthropologist is faced with skeletal remains exhibiting traumatic injuries, the interpretation is largely descriptive and can rarely be substantiated (Charpail, et al. 2006).

Skeletal injuries within the thoracic region are particularly difficult to interpret. While there is little information about what factors could contribute to fractures in the thoracic region, much of this information is commonly studied in other parts of the skeleton, such as long bones or the crania. Currently, blunt force trauma to the ribs has no methodology to allow for proper interpretation. Literature exists for rib fractures in child abuse cases (Campbell Jr. and Schrader 2006; Worn and Jones 2007), yet little exists on rib trauma in adults. Most of the research done on rib trauma is focused on individual ribs. Often times these ribs are removed from the body, and in some cases will be dry before the fracture is inflicted for study. Examining biomechanical patterns in dry bones does not account for the viscoelastic properties of bone, which is a property that impedes fracture. While this allows for some general interpretation, it cannot be extrapolated to apply to the entire thoracic region. Fractures will occur differently *in situ* due to the complexities of the thoracic cavity. An intricate webbing of muscles and the buttressing structures of the bones are meant to displace force and protect the internal organs (Carpenter, et al. 2016). The complex structure of ribs makes interpretation difficult. Additionally, accounting for all possible extrinsic variables makes interpretation a nearly impossible task. Within real-life situations every co-variate cannot be accounted for. Often times there can be multiple points of impact and directional forces. Multiple points of impact will cause differences in frequency and location of fractures in each case. Existing skeletal collections that are used in forensic anthropological research will not have all recorded variables for skeletal injuries present. Collections like this can be useful in other areas of study within biological anthropology, but because the extrinsic variables to any observable trauma are unknown trauma research would be difficult. Due to the number of possible extrinsic variables required for interpretation, little research on thoracic skeletal trauma is done in real-world situations.

In an effort to use a sample with known variables, this study utilizes Computed Topography (CT) images from the Crash Injury Research and Engineering Network (CIREN) database, which is part of the National Highway Traffic Safety Administration (NHTSA). The CIREN database is unique in the detailed amount of information collected for each case, and each occupant involved in a car accident. Trained experts record data with methodologies set in place for approaching the scene, designating particular CIREN classifications, and any other important information recorded (Lee, et al. 2015). The detailed amount of information allows for the ability to be conscious of the possible bias or variables that might influence the research. The large amount of crash information, along with medical data and CT images, allows for significant opportunities within injury biomechanics research (Ritchie, et al. 2006). This being said, the CIREN database information is inherently skewed in that it only includes motor vehicle crash victims (Sochor, et al. 2003) and not other real-world situations.

The need for research of trauma to the thoracic region is evident with so little literature existing on the topic. The current study will provide insight into interpreting blunt force trauma injuries in the thoracic region, which will ultimately provide quantification to support interpretations and a foundation for future research projects. The study aims to explore the relationship between the frequencies of rib fractures based on known variables. While trauma analysis is somewhat immature compared to other aspects of biological anthropology, the interpretations have the greatest impact in the court of law. Quantification of traumatic injuries provides a novel approach to a longstanding problem and while the immediate scope of the project is narrow, the contributions to bioarchaeology, forensic anthropology, paleontology, and other sister disciplines, are significant.

CHAPTER II: LITERATURE REVIEW

Bone biomechanics and fractures

Bone is a heterogeneous material comprised of two basic compounds: collagen (34%) and hydroxyapatite (66%). Collagen is the primary organic matrix and provides elasticity to the bone. Collagen fibers bundle and run longitudinally along the bone. The viscoelastic properties of these collagen bundles allows for the bone to maintain a certain degree of flexibility while the bone is fresh (Shen, et al. 2011). Forensic anthropologists will interchange the terms fresh and 'wet' because the liquid in the collagen fibers is still present at this time. When the bone becomes dry, or is removed from the environment within the body, it slowly loses its viscoelastic properties and becomes brittle and less flexible (Galloway and Wedel 2014). Hydroxyapatite is the inorganic matrix that comprises the majority of bone. The structure of hydroxyapatite is primarily small crystals that embed themselves in the collagen fibers, which ultimately provide rigidity to the bone. When put under force, the hydroxyapatite crystalline structures allow for the bone to maintain strength. It is the combination of hydroxyapatite and collagen that allows the bone to maintain strength and flexibility, both of which are necessary for a bone to compensate for the many extrinsic and intrinsic factors that constantly impact the bone (Symes, et al. 2012).

Bone is also anisotropic, meaning that the strength and flexibility of each specific bone will depend upon the direction of loading and the force applied. Under normal conditions bones are well adapted to handle normal stress and strain levels. Stress is defined as force per unit of area, and strain is defined as the relative deformation (i.e., change in length, volume, or angle)(Symes, et al. 2012). In biomechanical studies, the use of Young's Stress-Strain curve is commonly used to visualize and understand the relationship between force, stress, and strain in bones (Figure 2.1). While each bone will have a different failure point associated with its anisotropic nature, certain patterns can be discerned because of its morphology. Cortical bone, which comprises the outer layer of thick dense bone, is strong on the long axis and is overall less porous (Galloway and Wedel 2014). Trabecular bone is most commonly found within the articular ends of a bone, such as long bones, and is extremely porous and highly vascularized, which allows for a greater absorption of applied force. Because of these differences, a bone that is comprised of mostly trabecular bone will react differently to stress and strain levels than a bone that is comprised of mostly cortical bone. Specifically, trabecular bone can better dissipate force, and cortical bone will resist deformation longer.

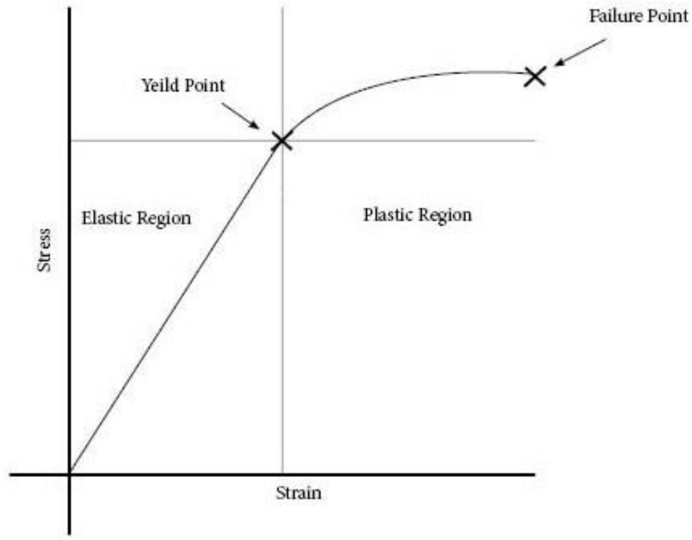


Figure 2.1 General representation of a Stress/Stress curve that depicts the general elastic and plastic thresholds and the associated yield and failure points.

Bone will experience deformation, or a permanent change in shape, prior to failure when subjected to increased levels of stress and strain. The generalized version of Young's Stress-Strain curve shown in Figure 2.1 shows the associated amount of stress and strain a bone can sustain before being altered, or deformed. Once stress and strain are applied outside of the normal level, bone will experience deformation; when maximum strain and stress are achieved the bone will fail (Berryman, et al. 2015; Galloway and Wedel 2014). There are two types of deformation. The first is elastic deformation and denotes the bone's ability to undergo a certain amount of stress and strain along with slight change in appearance as far as bending or compression of the bone. The bone is able to return to its original appearance and position once the force is removed. If the force is not removed, the bone experiences the second type of deformation, which is referred to as plastic deformation. Plastic deformation denotes the instance in which certain amounts of stress and strain are reached and micro fractures begin to appear within the bone. Progression from elastic deformation into plastic deformation permanently alters the appearance of bone and thus, the bone will not be able to return to its original state after the force is removed (Berryman, et al. 2015; Özkaya and Nordin 2012).

Load, or force associated with biomechanical studies of fractures, has several categories based on how the load or force is being applied to the bone (Figure 2.2). Compression is a force applied on opposite ends towards one another, where when tension is applied the bone is being pulled apart. Shear force is when oppositional forces are being applied at different sides of the bone, which results in fractures between the forces. Torsion is defined as the application of a spiraling force. In real life situations, fractures usually happen under the influence of more than one type of force and could be any combination of tension, compression, torsion, etc. (Galloway and Wedel 2014), as well as any combination of magnitude, direction, and duration (Symes, et al. 2012). Bone reacts differently to different types of forces, but due to the increased strength of hydroxyapatite, bone is stronger in compression than it is in tension. Therefore, the bone usually fails first in tension.

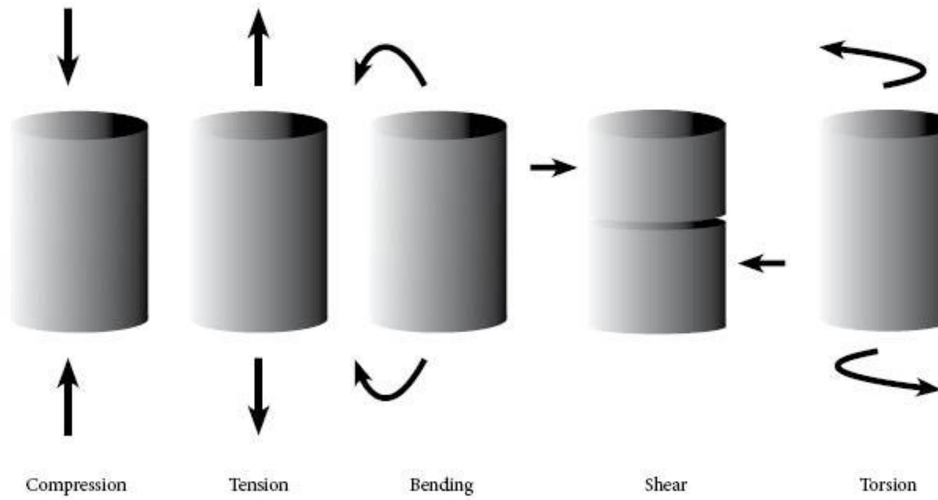


Figure 2.2 Depictions of directional forces applied to bone.

Forensic anthropologists use properties of biomechanics to interpret fracture patterns in skeletal material when trauma has been sustained. Statistical analysis of force, stress, strain, and other factors are also applied in order to determine contributing factors to the fracture pattern (Özkaya and Nordin 2012). Using biomechanical principles, forensic anthropologists will usually be able to determine direction and whether the force is slow load or rapid load.

The failure of the bone is dependent on how long a directional force is applied to the bone or at what rate it is applied. An important characteristic of fractures, is that they will follow the path of least resistance and fracture where there is less opposing strength (Christensen, et al. 2014). Bone will always fail in tension, except for rare circumstances, because there is more opposition in compression due to the hydroxyapatite. The same can be said for length of fractures. The failure will continue, or propagate, as long as there is not enough oppositional forces to stop it and it has enough kinetic energy to continue. The speed and length at which a fracture propagates decreases rapidly as it extends along the bone due to the oppositional forces working against it (Doblaré, et al. 2004). A fracture will occur and extend only as far as the biomechanics of the bone allows. Theoretically, more kinetic energy introduced to the bone will result in a longer fracture.

Trauma Classification in Forensic Anthropology

There are four types of trauma, and a fifth category is reserved for interpretation of healed trauma. Types of trauma include thermal, ballistic, sharp force, and blunt force. Each type of trauma have specific criteria associated with them, including intrinsic and extrinsic factors involved in the occurrence of the fracture, as well as diagnostic characteristics of the actual fracture itself (Table 2.1). A short differentiation of each type of trauma will be provided, but the majority of the literature review will focus on qualities of blunt trauma, as that will be the focus of the current research.

Table 2.1 Characteristics of Trauma Types
(Table adapted from Symes et. al. 2012)

Trauma Type	Sharp	Blunt	Ballistic	Burned
Characterics	Slow (mph)	Slow (mph)	Rapid (ft/sec)	Expand/Shrinking (spreading)
Fracture Types	1. Impact (incised) 2. Radiating 3. Concentric (in)	1. Impact 2. Radiating 3. Concentric (in)	1. Plug and Spall 2. Radiating 3. Concentric Heave (out)	1. Longitudinal 2. Transverse 3. Patina 4. Curved Transverse (heat shrink tension fractures)
Indications	*Simply beating with a sharp object* 1. Straight Lines 2. Incised	*Bone acts like Bone* 1. Delamination 2. Plastic Deformation	*Its all in the Speed* 1. Fractures as a Uniform Material 2. Bevel 3. Pre-exsisting Fractures	*Differential head shrink* 1. Delamination 2. Heat Related Change

The most distinct type of trauma is thermal. Instead of an external force being applied, a chemical process takes place due to heat activity in close proximity to the bone. The internal chemical structures of the bone are compromised due to chemical reactions and the bones will lose their elastic properties and fracture (Symes, et al. 2015). Chemical structure changes and unique fracture patterns allow for thermal trauma to be easily distinguishable from other types of trauma.

Speed is a common discriminating variable among sharp, blunt, and ballistic trauma. Sharp and blunt are both referred to as slow load trauma, while ballistic is rapid load. In ballistic trauma, tensile strength of the bone is compromised due to the intensity of speed inflicted on the bone. Because of the magnitude of force (i.e., rapid load) associated with ballistic trauma, bone does not progress through elastic and plastic deformation, and instead shatters like glass under the focused, rapid amount of force. Therefore, the bone reacts differently to rapid load forces than it does to slow load forces. Slow load forces will put the bone under stress and strain over a longer period of time, and the bone's strength becomes exhausted and it deforms and fails. Rapid load doesn't allow for the same amount of resistance to stress and strain and instead the bone shatters (Symes, et al. 2012).

Whereas speed is the major variable separating ballistic from blunt and sharp, the amount of surface area associated with the impacting force is the major discriminating variable between sharp force trauma and blunt force trauma. In sharp force trauma the area impacted is an incised edge, and therefore results in different reaction of the soft tissue and bone, creating incised markings confined to small areas (Rainwater and Crowder 2013). Blunt force trauma is observed as having a larger surface area at point of impact. A larger surface area usually results in multiple areas of bone to be affected by the inflicted force (Berryman, et al. 2015). In blunt and sharp force trauma, as they are both considered slow load, the bone experiences all phases of elastic and plastic deformation before final failure. Deformation combined with interaction of multiple directions of force and large impact areas creates a unique scenario were multiple fracture types can be evaluated in blunt trauma.

Speed and Injury Severity

Many extrinsic factors must be considered in understanding the severity behind injuries in any traumatic incident. The literature currently available on speed as a factor in injury severity is limited. The majority of literature insists there is some degree of positive correlation between increase in speed and increase in injury severity (Neyens and Boyle 2008; Otte 1999; Zambon and Hasselberg 2006). However, there is a plateau seen in the severity of injuries once a certain speed has been attained (Otte 1999; Renski, et al. 2014). Viano, et al. (1989) observed that severity of injury in individuals in car accidents tend to occur in the soft tissue due to the viscous reaction of the internal organs. Essentially, the internal organs, due to their liquid characteristics, will become lacerated from movement causing critical injuries in individuals when a certain impact speed is reached. Fractures, however, do not follow this same pattern; ribs fractures were observed at each impact speed, and no positive correlation was observed with an increase in speed (citation).

Rib Morphology

Ribs fall into a classification of bone called flat bone, which are largely flat in shape and act like shields to protect important internal organs. Flat bones are also different from other types of bones, like long bones, in the fact that they don't possess a medullary cavity. Instead ribs are largely comprised of a thin cortical layer of bone surrounding an interior entirely comprised of trabecular bone. Ribs are easily distinguishable within the skeleton due to their thin long body and curved shape. Posteriorly on the body, the rib articulates with the vertebral column. Near this junction there are several notable anatomical features. The head of the rib is a slightly more dense area of cortical and trabecular bone that articulates directly with the body of a corresponding vertebra. Immediately lateral to the head is the neck of the rib. At this point the bone narrows to create a thin bridge of bone between the head and tubercle. The tubercle of the rib articulates with a transverse process on a corresponding vertebra and is rougher and larger than the head and neck. Just laterally to the tubercle is the rib angle, which is where the bone begins to angle anteriorly. The rib angle is the widest portion on the bone (superiorly-inferiorly), and is the site of deep muscle attachments along the posterior of the entire rib cage structure. The complex anatomical structure of the posterior portion of the ribs, as well as the higher percentage of cortical to trabecular bone, results in large amounts of buttressing and force distribution when put under stress and strain (Carpenter, et al. 2016). The body of the rib is a long flat area that curves around anteriorly to meet the sternum, cartilaginous bridges, or in the case of ribs 11 and 12, termination without articulation. The body of the rib is unique in the greater amount of trabecular bone contained within it, in comparison to the posterior area of the rib. The most anterior section of the rib in ribs 1 - 10 is the articulation area. Ribs 1 – 7 articulate directly to the sternum, while ribs 8-10 articulate to costal cartilage. Ribs 11 and 12 are unique in that they do not articulate to anything and are typically referred to as floating ribs. The anatomy of the anterior portion of the rib is variable based on the type of articulation it possesses. Additionally, the first and second rib are unique in that they are considered atypical in their anatomy; they are shorter and wider than the other ribs. The first rib, specifically, possesses an overall larger articulation area with the manubrium anteriorly.

Differences of rib morphology will also occur due to the age and sex of the individual. There are slight geometric differences in rib anatomy between the sexes.

Female bone anatomy is generally considered more gracile throughout the body. The ribs specifically are affected by the overall average body mass index (BMI) difference between males and females. The average BMI is less in women, which means the ribs will be slightly more angled in females and overall more gracile. While as an individual ages, small scale changes occur in composition of the bone, as well as changes in overall geometry of the ribs. These changes will affect stiffness and distribution of strain within the rib cage. Costal cartilage also ossifies within older individuals, which affects the anterior fracture patterns (Kent, et al. 2005).

Trauma in the Thoracic Region

The literature available on blunt force rib trauma is still in its infancy. The thoracic region is extremely complex due to the overall morphology of the bones themselves, as well as the intricacy of the associated soft tissue. This makes trauma interpretation and creating reproducible methods very difficult (Holcombe, et al. 2009). The curved shape of the rib, as well as the differences in amounts of trabecular and cortical bone over the length of the rib will influence where fractures occur and under which conditions (Berryman, et al. 2015; Schmidt 1979). Due to the fact that the size and shape of the rib cage changes over an individual's lifetime (Weaver, et al. 2014), the most common findings suggest that age is a major contributing factor to fractures in the ribs. Sex and weight are also believed to contribute to the commonality and location of rib fractures (Gayzik, et al. 2008; Holcombe, et al. 2009; Kent, et al. 2005; Lee, et al. 2015; Schmidt 1979; Weaver, et al. 2014). This lack of research indicates a need within the field of anthropology for a more basic way to understand and interpret fractures to glean any information that might be helpful in trauma interpretation.

Technological Advancements

Trauma analysis has historically been a descriptive science. However, there has been a movement in the field to introduce technological advancements to substantiate and aid in trauma interpretations. Recently, the use of microscopes to determine tension and compression characteristics in bone fractures has been advocated (Rainwater and Crowder 2013; Symes, et al. 2012). Computed Tomography (CT) imaging has also been advocated for as a beneficial tool in trauma analysis (Gayzik, et al. 2008; Lee, et al. 2015; Ritchie, et al. 2006; Sochor, et al. 2003). When observing trauma in individuals through imaging techniques, radiograph images were found to be less accurate when compared to CT imaging in observing location and diagnosis of fractures (Sochor, et al. 2003). Another common method of rib fracture study is through three point bending, where a single rib is placed in a fixed position within a machine and a mechanical arm places the rib under controlled stress and strain levels until the rib fails. This method is supported in the literature, and allows for control of many extrinsic variables of the fracture. However, the rib is removed from the body as preparation for the test, and is not tested within the closed system of the rib age. The articulations anteriorly and posteriorly of the ribs allow for the ability of that rib to displace some of the stress and strain to avoid fracture. Therefore, removing a single rib element from the rib cage does not allow for the same observation of fracture locations within the rib cage. Using CT imaging in rib fracture analysis allows for the ability to observe the rib cage as a complete integrated system. Fracture locations are observed *in situ* without hindering autopsy or removing the skeletal element. Location and frequency of fractures can be correlated with one another and the overall anatomy of the rib cage.

CHAPTER III: MATERIALS AND METHODS

The current study utilizes advanced imaging techniques, specifically computed tomography (CT), to visualize the entire thoracic region and quantify fracture patterns and overall trends *in situ*. Images were acquired from the Crash Injury Research and Engineering Network (CIREN) database, which is part of the National Highway Traffic Safety Administration (NHTSA) and is dedicated to recording information from severe motor vehicle crashes and the associated medical injury profiles. The CIREN database only includes individuals with a single injury and a Major Abbreviated Injury Score (MAIS) from 3 or two injuries with a MAIS score of 2, and above. MAIS scores exist on a scale from 1 to 6, with 1 being minor injuries and 6 being maximum injury. An injury score of 1 indicates minor injuries, while a score of 6 indicates a fatal, untreatable injury. The MAIS score of 2 constitutes moderate injuries, such as major broken bones and a MAIS score of 3 indicates a severe injury, such as an open fracture (Gennarelli and Wodzin 2008). The CIREN Center at Wake Forest University in North Carolina was the collaborating establishment for this project and provided all of the data. The data was previously recorded, and therefore the project was retrospective in nature. Idaho State University Institutional Review Board did not find this study to meet their definition of research under the Code of Federal Regulations Title 45 Part 46. 102(d), and therefore it did not need IRB approval (IRB # FY2016-30).

CT images were analyzed from any individual that was involved in a motor vehicle crash with a front, near, or far side impact and was 18 years or older. Individuals fitting the specific inclusion criteria were queried through the CIREN database and resulted in 214 individuals for the current study. The variables collected from CT images included location of fractures and frequency of fractures per side of rib cage. Additional variables, such as velocity, side of impact, and belted versus unbelted were also recorded from the CIREN database as covariates as they would hypothetically influence fracture patterns and help elucidate any trends in the fracture patterns. Any active osteoblastic responses in the thoracic region (i.e., rib fractures in an active state of healing) or with any documented bone pathologies were recorded for each individual as well.

The data was analyzed using R 3.2.2 software (R Core Team 2015). Due to the continuous nature of the variables, some variables were categorized to better understand and visualize the data. Age was kept as a continuous variable, but a variable called “Age Category” was also created that classified each individual into young (less than 43 years of age), middle aged (between 44 and 68), or old (from 68 to 94). The age categories were created based on the process of natural skeletal deterioration. Individuals under the age of 45 exhibit little skeletal deterioration. In contrast, skeletal changes appear in the deterioration, ossification of cartilage, and change in mineral content of the bone in individuals greater than 45 years of age (Christensen, et al. 2014; Ritchie, et al. 2006). Equal numbers of individuals per age category were preserved. Similarly, a “Speed Category” was created that separated the speed into three categories: slow speed (less than 25 km/hr), medium speed (between 26 and 50 km/hr), and fast speed (greater than 50 km/hr). Additional to the number of fractures recorded on each individual, a binomial category was created to indicate the absence (0) or presence (1) of fractures for each individual.

Chi-squared tests were performed to explore the effects of sex, side of impact, belted or unbelted, age category, and speed category on the number and overall presence or absence of fractures. Specifically, chi-squared tests are used in order to determine the significance of an experimental outcome. The null hypothesis is that all variables are independent of one another and no variable has an influence on the presence of fractures. In each chi-squared test the returned p-value will indicate the likelihood percentage that the null hypothesis is correct. If the p-value is > 0.05 there is a higher than 5% chance that the variables are independent, and therefore not significant. However, if the p-value is < 0.05 then the null hypothesis of independence is rejected, and indicate the variables influence each other (Field, et al. 2012; Kabacoff 2011).

Logistic regression was employed to see what variables were significant in occurrence of fractures (i.e., presence or absence). Within logistic regression each variable is measured for any relationship it has to the presence or absence of a fracture for each individual. The output will suggest which variables have the strongest relationship (Sperandei 2014). All of the recorded variables were used as predictor variables. Logistic regression is a robust statistic that will predict the probability of an event given known variables. The outcome will be based off of certain criteria and will determine if the event did occur (1) or did not occur (0). Odds ratios were created from the exponentiated coefficients of the logistic regression results to better interpret the results. An odds ratio compares the odds of an event happening to the odds of that event not happening in order to be able to determine if a certain outcome is more likely given certain circumstances. Variables that reported $OR < 1$ are associated with lower odds of outcome, $OR=1$ does not affect outcome, and $OR > 1$ is associated with higher odds of outcome (Szumilas 2010).

CHAPTER IV: RESULTS

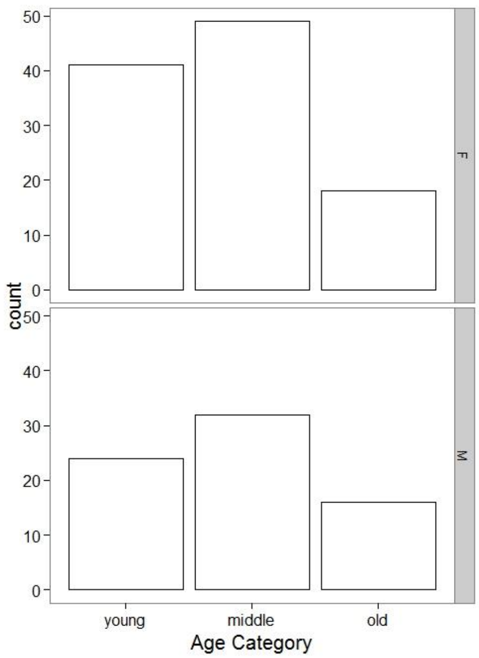
Descriptive statistics

Previous to any analysis individuals were removed from the sample that classified as outliers, had missing variables, and/or that had poor quality CT scans that obscured fracture identification. The final sample consisted of 180 individuals. The frequency of fractures ranged from 0 to 19 fractures per individual, with a median of 1 fracture per individual. Unlike most samples associated with modern skeletal collections, the sex bias in the sample resulted in more females (*f* = 108) than males (*m* = 72). The minimum age was 18 years, the maximum age was 92 years, and the mean age of the entire sample was 49 years. The ages were separated into categories of young (18 to 43 years, *n* = *65*), middle (44 to 68 years, *n*=*81*), and old (69 to 92 years, *n*=*34*); each category was a 25 year interval (Table 4.2, Figure 4.1). Speed was recorded in kilometers per hour with the minimum speed of 11 km/hr, the highest speed of 92 km/hr, and a mean speed of 41 km/hr (Table 4.1). Speed was also categorized into three categories of slow speed (below 26 km/hr, *n* = 36), medium speed (26- 50 km/hr, *n*=94), and fast speed (50 km/hr and over, *n*=50) (Table 4.3, Figure 4.2). Wearing a seat belt was also added into the data set as a possible influential variable. The sample consisted of belted (*n* = 42) and unbelted (*n* = 138) individuals (Figure 4.3). Side of impact was also included and grouped into front (*n* = 126) and side (*n* = 54) impacts (Figure 4.4); side impacts included both near-sided and far-sided impacts.

Table 4.1 Descriptive statistics – Continuous Variables Total study sample (n=180)			
	Min	Max	Mean
Speed	11 km/hr	92 km/hr	41 km/hr
Age	18 years	92 years	49 years

Table 4.2 Descriptive statistics – Age Category Total study sample (n=180)	
	(n =)
Young	65
Middle	81
Old	34

Table 4.3 Descriptive statistics – Speed Category Total study sample (n=180)	
	(n =)
Slow	36
Medium	94
Fast	50



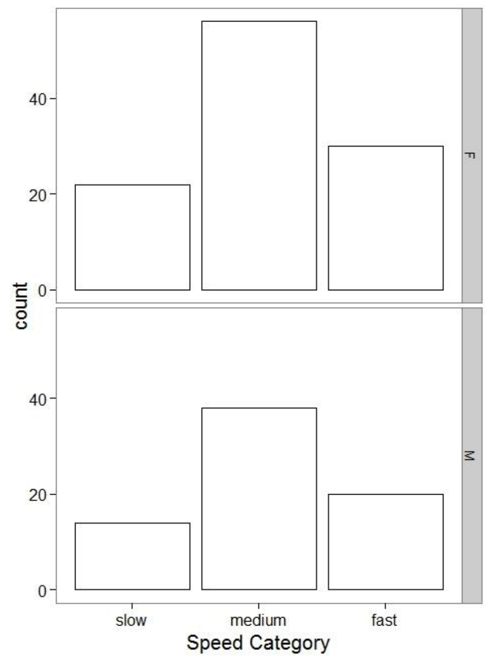
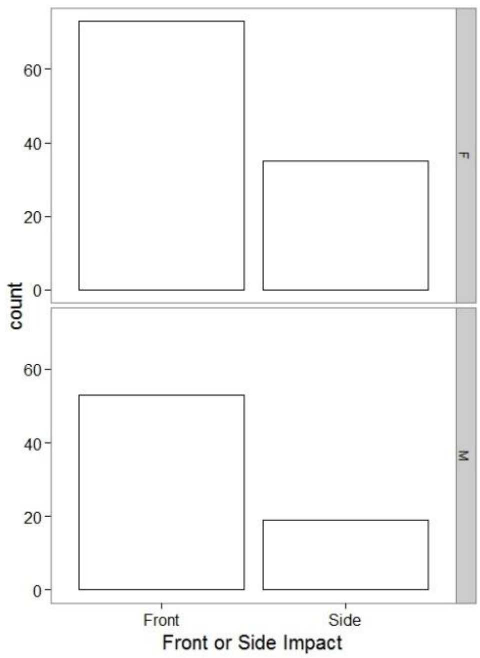


Figure 4.1 Histogram indicating number of individuals in the Age Category separated by sex

Figure 4.2 Histogram indicating number of individuals in the Speed Category separated by sex



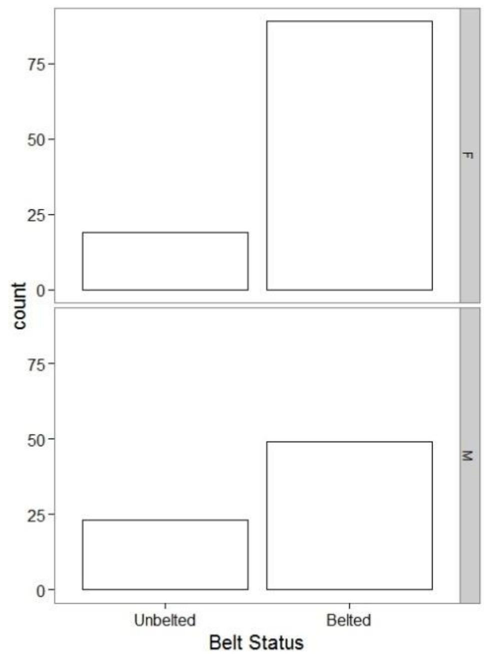
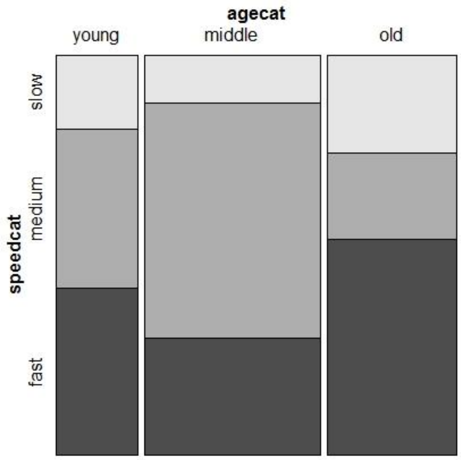


Figure 4.3 Histogram indicating number of individuals in front or side impacts separated by sex

Figure 4.4 Histogram indicating number of individuals that were unbelted or belted separated by sex



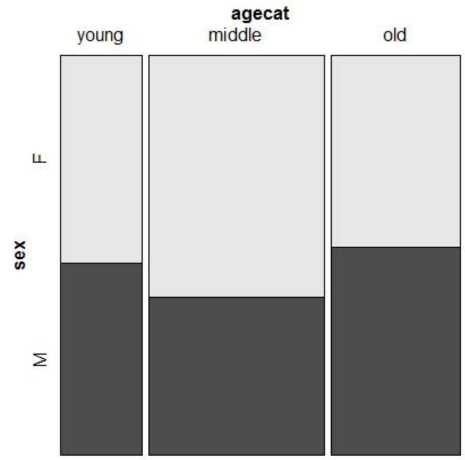
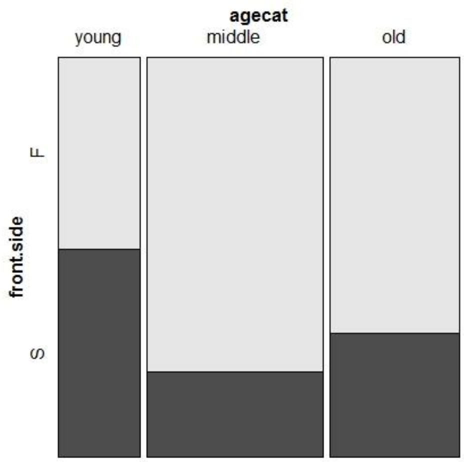


Figure 4.5 Mosaic Plot depicting number of fractures per within age and speed categories. The shaded region is proportional to the amount of fractures found in that region.

Figure 4.6 Mosaic Plot depicting number of fractures per within age and sex categories. The shaded region is proportional to the amount of fractures found in that region.



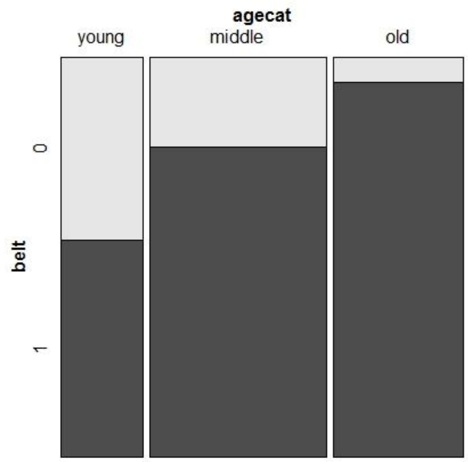


Figure 4.7 Mosaic Plot depicting number of fractures per within age and front or side impact categories. The shaded region is proportional to the amount of fractures found in that region.

Figure 4.8 Mosaic Plot depicting number of fractures per within age and belt categories where (1) = belted, (0) = unbelted. The shaded region is proportional to the amount of fractures found in that region.

Chi-squared

Chi-squared tests were used to observe the relationships among categorical variables. Within this study, each covariate was tested against the presence of fractures to see if they were independent of one another. Only one variable, which was age, showed a statistically significant relationship with the presence of fractures. Particularly with the age category variable when tested against the presence of fractures, the two variables appeared to be dependent on each other at a substantial level ($\chi^2(2) = 15.902$, $p > 0.05$). The null hypothesis was accepted for all other variables, in other words there was not a significant difference ($p > 0.05$) (Table 4.4).

Table 4.4 Chi-Square values

	χ^2	Degrees of Freedom	P-Value
Fractures(P/A) –Sex	0.075758	1	0.7831
Fractures(P/A) –Side (F/S)	0.068409	1	0.7937
Fractures(P/A) –Age Category	15.902	2	0.0003522
Fractures(P/A) –Speed Category	0.30604	2	0.8581

Logistic Regression

Logistic regression is used to explore relationships between variables, single or multiple, to one dichotomous dependent variable, which, in this case, is the presence or absence of fractures. The first logistic regression was performed with presence or absence of fractures as the response variable, and the original recorded variables as the predictor variables, which included speed, age, sex, belted/unbelted, and front/side impact. The results indicated that age was the only variable that was significant (p <

0.001). An odds ratio was created for the significant variable, age, with the result of 1.039. An odds ratio > 1 suggests that it increases the likelihood of a fracture happening.

Since age was the significant variable, the second logistic regression evaluated the relationship between presence or absence of fractures with only the age category variable. Middle and old categories were both found to be significant ($p < 0.001$). The Middle Age category returned an odds ratio of 2.61, indicating an individual placed in the Middle Age category is 2.61 times more likely to have fracture reported than an individual in the Young Age category. Similarly, the odds ratio for the Old Age category was 5.55, which indicates an individual placed in the Old Age category is 5.55 times more likely to have fractures present than an individual in the Middle Age category.

The next logistic regression model was created with presence or absence of fractures as the response, and the speed category variable as the predictor. No category was specified as statistically significant over the others. Logistic regression was also performed to explore the relationship between side of impact and sex on the probability of fracture. Neither model observed significant relationships between the predictor and response variables.

Because age was consistently recognized as an important variable predicting probability of fracture, additional explorations of the relationship between fracture frequency, age, and speed were explored. Figure 4.1 is a scatter plot showing the bivariate relationship between frequency of fractures and age based on sex. Loess lines were used to visualize any trends present. Loess is a smoothing statistic that uses a local fitting method to better visualize the any correlations determined by numerical predictors found nearest to a point (R Core Team 2015).The figure visually demonstrates that there is a moderate positive correlation between age and number of fractures. The Pearson's correlation returned a value of r = 0.28, indicating a slight, but noticeable correlation between the variables.

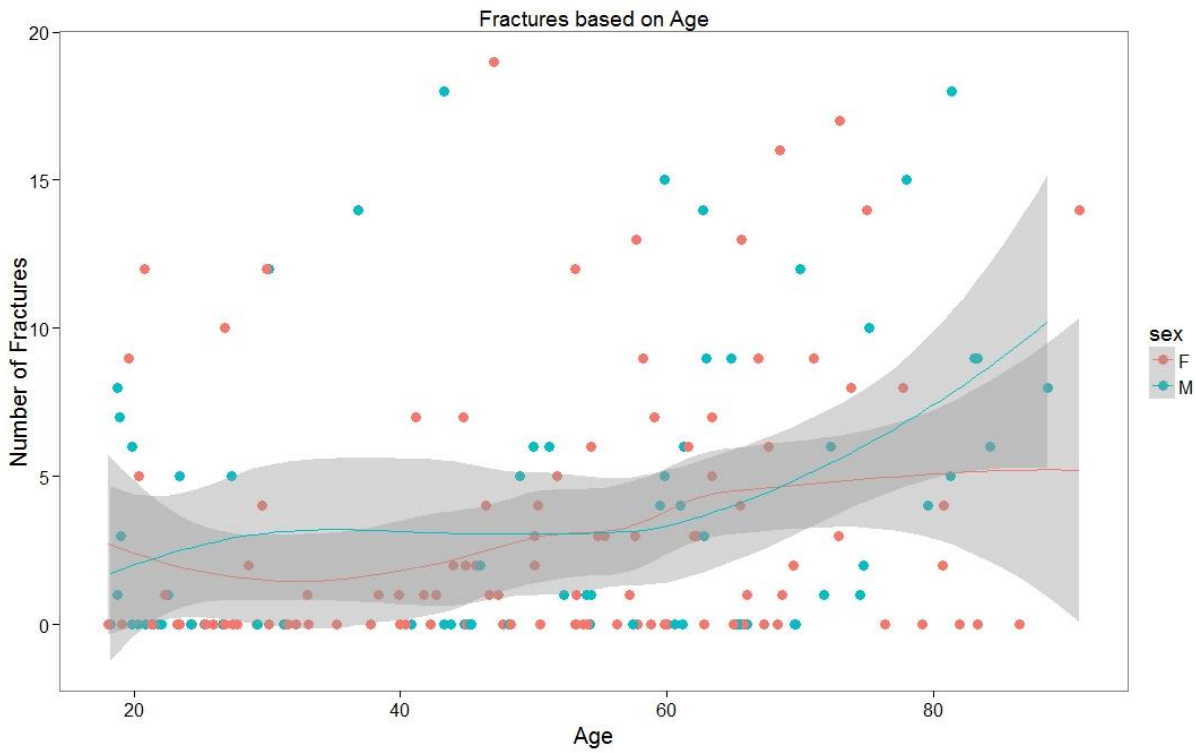


Figure 4.9 Visual representation of age in years as an influencing variable on number of factures present separated by sex.

When exploring the age categories and speed, there are overall higher frequencies of fractures present in the Old Age Category at all speeds (Figure 4.2). Individuals in the Middle Age Category have higher frequencies of fractures than those in the Young Age Category. As speed increases along the *x*-axis it does not largely influence the number of fractures in the Young Age Category because the bone is in the best condition. As the individual ages more fractures are present at all speeds.

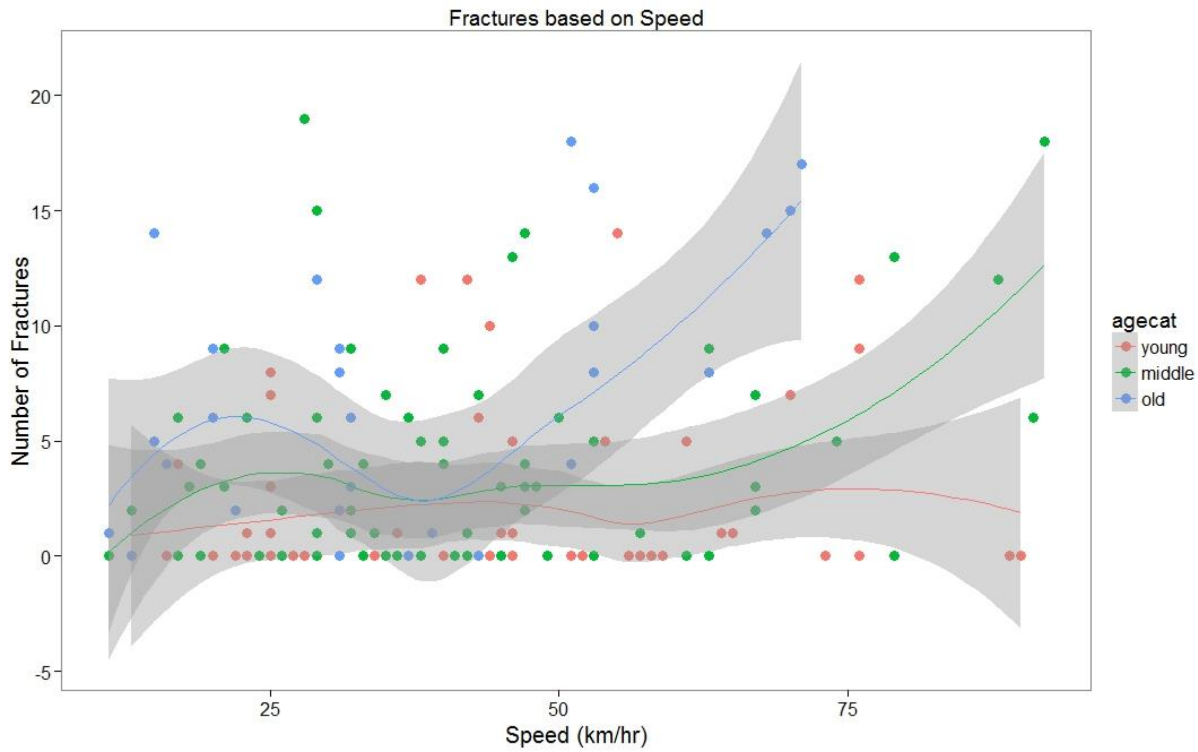


Figure 4.10 Visual representation of number of fractures based on speed separated by age category

The final scatterplot (Figure 4.3) shows number of fracture as the *y*-axis with speed in kilometers per hour as the *x*-axis, however, individuals have been separated by sex rather than Age Category. When the age categories are not considered, there appears to be no visual correlation between number of fractures and speed. A Pearson's correlation (r = 0.19) confirms that there is little to no correlation is found between the two variables.

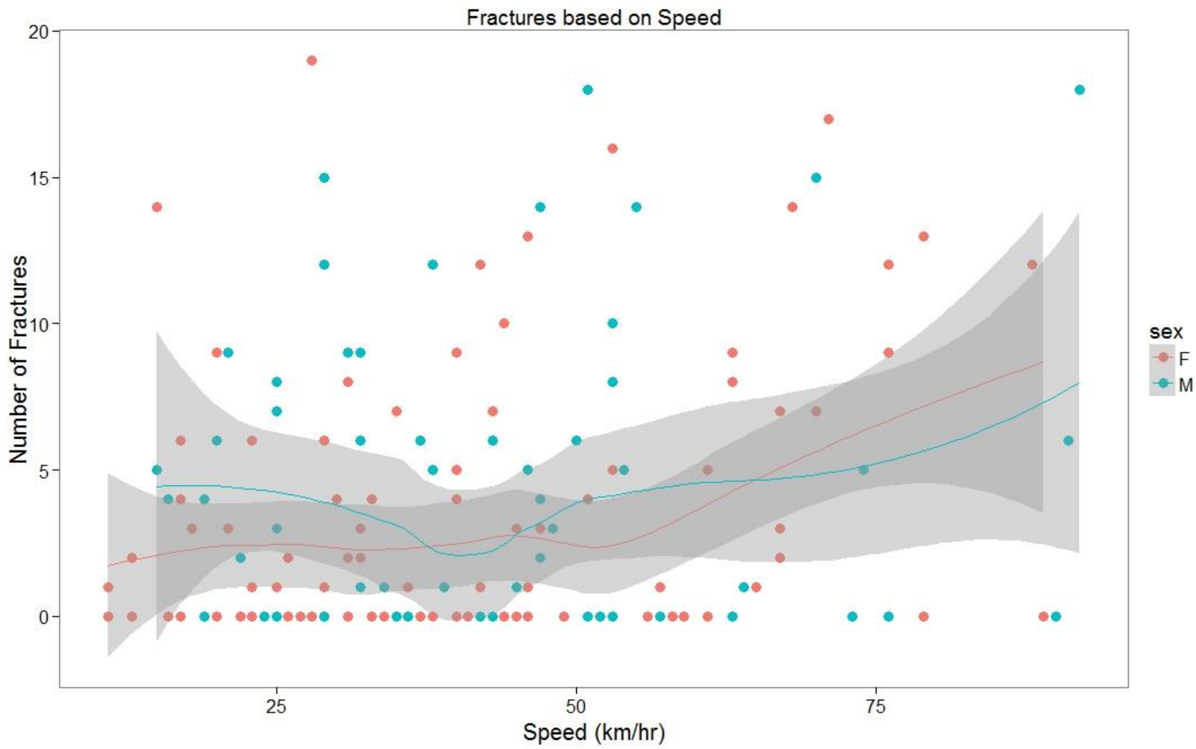


Figure 4.11 Visual representation of speed in kilometers an hour as an influencing variable on number of factures present separated by sex.

While Figures 4.9 and 4.11 both show individuals grouped by sex, there does not appear to be a significant difference in number of fracture between groups. The spike in number of fractures for males with age can be considered a trend, but was not statistically significant. The rise in number of fractures could also be a result of the lower number of males that existed within the sample.

CHAPTER V: DISCUSSION

Among all variables tested, age was the only significant variable, and suggests that as age increased the chances of a fracture occurring also increased. When individuals were classified into separate age categories the correlation became more apparent. Odds ratios suggest the Middle Age category had over two times the chance of a fracture to occur than the Young Age category while the Old Age category had 5.5 times the chance of a fracture to occur than the Middle Age category. Age being the only significant variable is notable because the presence of fractures would be thought to be associated with greater velocity and force (Doblaré, et al. 2004). However, this is obviously not the case here as velocity was found to be not significant in the probability of fracture.

The documented degenerative changes that occur within the bone as an individual ages are the most likely the reason as to why age is significant. The flexible, viscoelastic properties collagen produces declines steadily into old age (Kent, et al. 2005). Therefore, the more mineralized a bone, the more brittle they become, and thus more likely to fracture. Additionally, the rib angle becomes less severe as an individual ages (Kent, et al. 2005). The angle expands and the rib runs anterior-posterior rather than curving medially to articulate with the sternum. The shape changes with increased age occur because the ossification of the costal cartilage. The changes in morphology are more apparent in males than they are in females (Weaver, et al. 2014). The differential ossification trends *may* account for some of the differences in fracture frequencies between the sexes regardless of the slight sex bias of this sample.

Osteoporosis can be acknowledged as a possible reason for the high amount of fractures in the old age category. Individuals under the age of 50 rarely show evidence of osteoporosis within their skeleton. The average percentage of individuals within the United

States that show osteoporosis in specific areas over the age of 50 is 5.8% for males and 22.5% for females according to a study done by Kanis et al. in 1994. More specifically, the average percentage of individuals that show evidence of osteoporosis between the ages of 50 and 68 are 3.4% for males and 15.3% for females (Kanis, et al. 1994). While individuals over the age of 69 usually have progressively larger percentage chance of osteoporosis with each decade. Once an individual passes the age of 85, the average percentage for males affected reached almost 30% and for females was over 60% (Kanis, et al. 1994). The old age category within this study includes individuals over the age of 69 years, which is when substantial percentages of the population show indications of osteoporosis. Interestingly, however, osteoporosis is more common in women than in men, which is not reflected in presence or absence of fractures within this study.

Within the data set there was a slight trend in association with sex and presence or absence of fractures. The differences between the number of male and female fractures is most likely due to the fact that males on average have a larger BMI, and thus male ribs have a slightly more obtuse angle than females (Kent, et al. 2005). These findings are substantiated by some of the current research in the field, which should indicate morphological skeletal differences between males and females, and therefore should be a contributory variable to fracture patterns (Weaver, et al. 2014). Within this study, values for frequency of fractures with sex were consistently different between the sexes. Males tended to have more fractures on average than females. However, unlike the current literature, sex was not found to be significant in any form of the statistical analysis conducted. Within this study, sex was only found to be a possible trend, with no statistical evidence that it was significant in presence or absence of fractures.

Velocity, which was hypothesized to be an important contributory variable to presence of fractures, was found to be not significant. Speed had little to no effect. Though speed and its relationship to fracture is a contentious topic in the literature, usually a higher velocity results in greater severity of fractures. However, the current study did not demonstrate the expected pattern. The results of this study showed that when an individual is within a car there is a plateau associated with the amount of damage caused by increased velocity. The results of the current study show that after the speed exceeds 50 km/hr, the number of fractures levels off. The pattern could be due to the kinetic energy associated with the individual being inside the vehicle. When an individual is in a car, they are traveling at the same velocity as the vehicle. The speed of the individual interacting with the speed of the car may influence the occurrence of fractures and injury patterns. In other words, fracture patterns may be different when a car, or some other moving object, makes contact with an individual. While situations surrounding death may not always be known, this research should be further evaluated, as it would affect fracture interpretation of unknown cases.

Correlations with side of impact returned complicated results. Overall, the frequency of fractures was greater when the individual was in a front impact. However, due to the nature of the data set, there was a bias in the number of front and side impacts, with front impacts being the majority of impacts recorded. Once fracture location associated with left or right side of the individual was incorporated into the data set more trends began to appear. Right fractures are more common in front impact, but it was not statistically significant. Fractures occurring on the left side of the rib cage are more common in side impact crashes, but again these results are a trend and not statistically significant. Further exploration into the data set showed that there is only a very slight correlation between fractures and the side that was nearer the point of impact (e.g. left fractures correlated with left side of impact). The information is being reported as trends, however with a better sample size and more recorded information, these trends could indicate a statistically significant relationship that bears the need for further research.

Current literature on car accidents suggest wearing a seat belt was a contributing variable to frequency of fractures due to their close proximity to the anterior ribs and association with broken sternums (Lee, et al. 2015). In the current study, wearing a seat belt did not contribute to the overall presence or absence of fractures and was found not significant in each analysis. However, even though wearing a seat belt is not significant in contribution to fractures, that does not mean belted or unbelted status does not correlate with mortality rates, which is beyond the scope of this paper.

Forensic anthropology is utilized within medico-legal situations. Often times forensic anthropologists are called to court in order to testify on identification of trauma on the skeleton. For this reason having statistically substantiated research on which to base identification and interpretation of skeletal trauma within the field of forensic anthropology is extremely important. The lack of information on blunt skeletal trauma to the ribs has not allowed for forensic anthropologists to reliably interpret information on rib fractures. However, with the current study some conclusions can be made concerning age of the individual and association with presence of fractures.

In the study of blunt force trauma, knowing all contributing variables is extremely important. In real world cases of blunt force trauma multiple directional forces could be applied, as well as multiple sides of impact. If a car hits an individual there will be any number of tension, compression, torsion and shear forces enacting on the bone. The primary impact will be the car, but the individual will then be thrown to the ground creating multiple other points of impact and directional forces associated with those impact points. Recording the speed, location, and duration of each extrinsic variable in this instance is nearly impossible. Therefore, most individuals inflicted with this blunt force trauma lack all variables associated with the fractures. Medical examiner's offices and skeletal collections, where the majority of forensic anthropological research takes place, lack this information within their trauma collections. This study is unique in that it can account for the majority of extrinsic variables that influenced fracture in the sample. While the sample is large and includes important information about extrinsic variables, having attained the sample from the CIREN database could influence the results, due to the fact they only include MAIS levels over 2 indicating a moderate injury severity. Some individuals may have rib fractures though a MAIS level was not greater than 1 to elicit the CIREN response. The data set consists of data is taken from car accidents which excludes any other modes of trauma. However, due to the large number of individuals included and the amount of variables recorded within the dataset, the results can be considered significant.

Further research needs to be done in correlating frequency of fractures with extrinsic variables in order to understand what factors contribute to failure of the ribs. This study accounted for a limited amount of variables that are found in car accidents. A similar study expanding the parameters to include more variables might show other extrinsic variables that influence number of fractures. A similar study could also be conducted with individuals with blunt thoracic trauma that were not involved in a car accident. However, this kind of study would have be conducted on a very controlled sample. For example, when examining individuals outside of a controlled environment like the inside of a car would need to account from multiple directions of impact and force. The results found within this research could also be compared to a similar sample done within a lab setting. Blunt force inflicted on a rib cage from a controlled mechanism with associated speed and single point of impact could allow for less nebulous results.

CHAPTER VI: CONCLUSION

Trauma analysis is indispensable in interpretation of medico-legal scenarios. Within a court of law, trauma interpretation is the majority of a forensic anthropologist's testimony. However, trauma analysis is lacking information in comparison to other areas within forensic anthropology. The practice of trauma analysis is purely heuristic with no standard to measure the accuracy of interpretation. Thoracic trauma in particular is avoided because of the complexity of bone morphology and muscle attachment sites. However, with the patterns uncovered in this study, some new conclusions can be made. Primarily, age is an important indicator of presence of fractures in the thoracic cavity. Multiple fractures found on the rib cage are not an indication of velocity or side of impact, but rather the age should be considered first as an interpretive variable in understanding thoracic trauma. Continuing research needs to be done to expound on trends found in this research and allow for examination of other extrinsic variables that might influence number of fractures.

REFERENCES

Berryman, Hugh E. , Natalie R. Shirley, and Alicia K. Lanfear

2015 Skeletal Trauma Analsis: Case Studies in Context

Chapter 14: Low-Velocity Trauma: Wiley.

Campbell Jr., Robert M. , and Timothy Schrader

2006 Chapter 7 Child Abuse.

Carpenter, Kelsey A. , Kena A. Ihle, and Steven A. Symes

2016 Reassessing Blunt Force Trauma to True Rib Heads Utilizinf Tension-Compresstion Theory. American Academy of Forensic Sciences, Las Vegas, Nevada, 2016.

Charpail, E., et al.

2006 Material and structure characterization of human ribs. Journal of Biomechanics 39:S155-S156.

Christensen, Angi M., Nicholas V. Passalaqua, and Eric J. Bartelink

2014 Forensic Anthropology: Current Methods and Practice: Elsevier.

Daegling, D. J., et al.

2008 Structural analysis of human rib fracture and implications for forensic interpretation. J Forensic Sci 53(6):1301-7.

Doblaré, M., J. M. García, and M. J. Gómez

2004 Modelling bone tissue fracture and healing: a review. Engineering Fracture Mechanics 71(13-14):1809-1840.

Field, Andy, Jeremy Miles, and Zoe Field

2012 Discovering Statistics Using R. Thousand Oaks, California 91320: SAGE Publications Ltd.

Galloway, Alison, and Vicki L. Wedel

2014 BROKEN BONES: Antrhopological Analysis of Blunt Force Trauma. Springfield, Illinois USA: Charles C Thomas.

Gayzik, F. S., et al.

2008 Quantification of age-related shape change of the human rib cage through geometric morphometrics. J Biomech 41(7):1545-54.

Gennarelli, Thomas A. , and Elaine Wodzin

2008 The Abbreviated Injury Scale Des Plaines, IL.

Gonza, Eric R.

1982 Chapter 1: Biomechanics of Long Bone Injuries.

Holcombe, Sven , et al.

2009 Patterns of local and regional variation in ribcage anatomy. *In* JSAE Annual Congress. Pacifico Yokohama.

Kabacoff, Rob

2011 R in Action. Shelter Island, NY 11964: Manning Publications.

Kanis, J. A., et al.

1994 The diagnosis of osteoporosis. J Bone Miner Res 9(8):1137-41.

Karadayi, Sule, et al.

2011 An analysis of 214 cases of rib fractures. Clinics 66(3):449-451.

Kent, Richard , et al.

2005 Structural and Material Changes in the Aging Thorax and Thier Role in Crash Protection for Older Occupants. Strapp Car Crash Journal 49.

Lee, E. L., M. Craig, and M. Scarboro

2015 Real-World Rib Fracture Patterns in Frontal Crashes in Different Restraint Conditions. Traffic Inj Prev 16 Suppl 2:S115-23.

Love, Jennifer C., and Steven A. Symes

2003 Understanding Rib Fracture Patterns. Journal of Forensic Sciences 49(6).

Neyens, David M., and Linda Ng Boyle

2008 The influence of driver distraction on the severity of injries sustained by teenage drivers

and thier passengers. Accident Analysis & Prevention 40(1):254-259.
O'Connor, John F., and Jonathan Cohen
Chapter 7: Dating Fractures.
Otte, D.
1999 Severity and mechanism of head impacts in car to pedestrian accidents. International Research Council on Biomechanics of Injury Conference, Zurich, Switzerland, 1999. Vol. 27, pp. 329-341. International Research Council on Biomechanics of Injury.
Özkaya, Nihat , and Margareta Nordin
2012 Fundamentals of Biomechanics: Equilibrium, Motion, and Deformation: Springer.
R Core Team
2015 R: A Language and Environment for Statistical Computing. R.F.f.S. Computing, ed. Vienna, Austria.
Rainwater, Christopher W., and Christian Crowder
2013 Microscopic Analysis of Sharp Force Trauma From KnivesL A Validation Study. Journal of Forensic Sciences 58(5):1119-1126.
Renski, Henry, Asad Khattak, and Forrest Counsil
2014 Effect of Speed Limit Increases on Crash Injury Severity: Analysis of Single-Vehicle Crashes on North Carolina Interstate Highways. Journal of the Transportation Research Board 1665(14).
Ritchie, Nichole L. , et al.
2006 A Method for Documenting Locations of Rib Fractures for Occupants in Real-World Crashes Using Medical Computed Tomography (CT) Scans. SAE Technical Paper Series.
Schmidt, Georg
1979 Rib-cage injuries indicating the direction and strength of impact. Forensic Science International 13:103-110.
Schneider, Lawrence W. , et al.
2011 BioTab - A new method for analyzing and documenting injury causation in motor vehicle crashes. Traffic Injury Prevention 12(3):256-265.
Shen, Z. L., et al.
2011 Viscoelastic properties of isolated collagen fibrils. Biophys J 100(12):3008-15.
Smith, O.C., Elayne J. Pope, and Steven A. Symes
Chapter 10: Look Until You See, Identification of Trauma in Skeletal Material.
Sochor, Mark R. , et al.
2003 3D CT imaging versus plain x-ray in diagnosis of rib fractures in lateral impact crashes. Association for the Advancement of Automotive Medicine 47.
Sperandei, S.
2014 Understanding logistic regression analysis. Biochem Med (Zagreb) 24(1):12-8.
Subit, Damien , et al.
2010 Respnse of the Human Torso to Lateral and Oblique Constant-Velocity Impacts. Association for the Advancement of Automotive Medicine 54:27-40.
Symes, Steven A. , et al.
2012 Chapter 17: Interpreting Traumatic Injury to Bone in Mediolegal Investigations.
Symes, Steven A. , et al.
2015 Chapter 2: Patterned Thermal Destruction of Human Remains in a Forensic Setting.
Szumilas, Magdalena
2010 Explaining Odds Ratios. Journal of the Canadian Academy of Child and Adolescent Phychiatry 19(3):227-229.
Tencer, Allan F.
Chapter 1: Biomechanics of fixation and fractures.
Tomezak, Paula D. , and Jane E. Buikstra
1999 Analysis of Blunt Trauma Injuries: Vertical Deceleration Versus Horizontal Deceleration Injuries. Journal of Forensic Sciences 44(2):253-262.
Viano, David C., Ivan V. Lau, and Corbin Asbury
1989 Biomechanics of the human chest, absomen, and pelvis in lateral impact. Accident

Analysis & Prevention 21(6):553-574.
Wasserstein, Ronald L., and Nicole A. Lazar
2016 The ASA's statement on p-values: context, process, and purpose. The American Statistician:00-00.
Weaver, A. A., S. L. Schoell, and J. D. Stitzel
2014 Morphometric analysis of variation in the ribs with age and sex. J Anat 225(2):246-61.
Worn, M.J. , and M.D. Jones
2007 Rib fractures in infancy: establishing the mechanisms of cause from the injuried -a literature review. Med. Sci. Law 47(3).
Zambon, Francesco , and Marie Hasselberg
2006 Factors Affecting the Severity of Injuries Amoung Young Motorcyclists -A Swedish Nationwide Cohort Study. Traffic Inj Prev 7(2):143-149.
Zhu, Qingan, et al.
1999 Traumatic Instabilities of the cervical Spine Caused by High-Speed Axial Compression in a Human Model: An in Vitro Biomechanical Study. Spine 24(5):440-444.