ANALYZING LOWER EXTREMITY INJURY PROFILES OF PEDESTRIAN TRAFFIC FATALITIES ACCORDING TO VEHICLE TYPE

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ABSTRACT

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Skeletal trauma analysis of motor vehicle collisions has the potential to support or contradict reported collision circumstances. This project analyzed the skeletal injuries that pedestrians sustain in fatal collisions according to vehicle types (car, truck, SUV, van, bus, semi, etc.). Data were collected from reports and databases related to cases that occurred in King County, Washington. The pelvis and lower extremities of the body were analyzed for the frequency of skeletal fractures, grouped by pelvis, femora, patellae, tibiae, and fibulae skeletal groups. A Kruskal-Wallis test showed an overall no significant difference ($P<0.05$) in fracture quantity in skeletal regions between different vehicle groups. A multiple pairwise comparison using Dunn's procedure also found no significant differences between vehicle type groups. A Partial Least Squares Discriminant Analysis showed an overall success rate of 37.29% when classifying injury profiles to vehicle type. The findings of this project can be applied to further research into the skeletal analysis of automobile versus pedestrian collisions. Low classification rates suggest that fracture frequency alone should not be used to assist in associating injuries with potential vehicle types in medicolegal investigations. Rather, the findings of this project lead the researcher to recommend that investigators and forensic practitioners

move towards standardization in the quality and type of collected data—specific recommendations being the collection of actual speed and inclusion of full-body imaging in postmortem examinations to enable more detailed analyses.

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INTRODUCTION

Overview of Traffic Collisions and Trauma Analysis

According to the National Highway and Traffic Safety Administration, 5,977 pedestrians were fatally struck by automobiles in 2017 in the United States; this number is 19% of all the fatal motor vehicle collisions (U.S. DOT and NHTSA, 2018). In Washington State, 85 pedestrians died from injuries after being struck by an automobile in 2017 (WSP Collision Tool, Accessed 2.2018). Pedestrian deaths are considered preventable because of the safety rules and regulations in place to protect them (e.g., crosswalks or sidewalks). Analysis of the skeletal trauma by a forensic anthropologist can assist in determinations about issues related to fatal hit and run collisions, risk factors for pedestrians, vehicle design, and vehicle safety features from the information included in injury profiles. In the case of a fatal hit and run collision, the pedestrian may not be immediately discovered, raising potential issues related to the identification and determination of cause or manner of death.

The pattern of injuries an individual sustains from a traumatic event (e.g., hit by an automobile) is commonly referred to as the 'injury profile' (Aharonson-Daniel, Boyko, Ziv, Avitzour, & Peleg, 2003; Baker, O'Neill, Haddon, & Long, 1974). Injury profiles can be used not only to understand the mechanism in which an injury was sustained but also to understand and predict what type and pattern of fractures are associated with various injury mechanisms. Injury profiles of decedents in automobile collisions are well researched, and it is possible to determine if the decedent is either a driver, front row passenger, back row passenger, two-wheel operator, or pedestrian (Benson et al., 2007; Calosevic & Lovric, 2015; Conroy et al., 2007; Curtin & Langlois, 2007; Santamariña-Rubio et al., 2007). The risk for lethal injury is elevated in pedestrians because they are the most vulnerable and, therefore, have been found to have a higher frequency of fractures of the extremities (arms and legs) and head and neck region (Calosevic & Lovric, 2015; Rubin, Peleg, Givon, & Rozen, 2015; Santamariña-Rubio et al., 2007). The injury profiles of pedestrians have been associated with the bumper height of a vehicle. For example, if the bumper is below a pedestrian's center of gravity, the body would be pushed upwards; and if the bumper is above the center of gravity, the body would be pushed downward (Galloway, 2014). Less examined is how much variation exists within an injury profile according to a specific vehicle type.

In a hit and run collision, the vehicle make and model may be misremembered or unknown by witnesses or investigative agencies. Identifying vehicle type from injury profiles may assist investigators in identifying possible suspects. This matching of injury profiles to vehicle type is not to identify the specific vehicle make and model per se, but instead, provide information to focus an investigation towards a type of vehicle (car, small/lightweight truck/SUV, large/heavyweight truck/SUV, etc.). This project analyzed and characterized the injury profiles of pedestrians who were fatally struck by an automobile from 2007-2014 in King County, Washington. In this project, based on the available data, the term 'injury profile' refers only to the patterning of skeletal fractures in the pelvis and lower extremities that pedestrians have sustained from being fatally struck by an automobile.

This project utilized reconstruction theory to identify and create injury profiles by analyzing fracture quantities against vehicle type. Reconstruction theory is defined as the ability to infer the behavioral phenomena of the past (Schiffer, 1988). This theory has roots in geology, biology, and chemistry and is heavily applied in both archaeology and forensic settings. Reconstruction theory can be applied on both a small scale (snapshots) or large-scale (circumstances). For example, small scale applications would be using the evidence available to reconstruct a specific tool, structure, or single injury. An example of a large-scale application would be using the snapshot reconstructions to piece together (reconstruct) the order of events, mechanism of injury, or both.

In forensic anthropology, this theory has been modified and applied during the process of crime scene reconstruction for investigators to collect relevant evidence (Dirkmaat, Cabo, Ousley, & Symes, 2008). Accurately interpreting the data is critical to differentiation among sources of impact in a collision (e.g., vehicle, ground, tree, pole, building, etc.). Successful attempts at reconstructing the events of a collision through osteology require a thorough skeletal analysis of imaging materials, bones, or a combination. Principles of skeletal biomechanics and bone tissue biology allow osteologists to differentiate between the type of trauma (e.g., blunt, sharp, or projectile), the context in which it occurred (e.g., antemortem, perimortem, or postmortem), the fracture types and quantities (Cohen et al., 2016; Dirkmaat, 2015; Galloway, 2014;

Sharkey, Cassidy, Brady, Gilchrist, & NicDaeid, 2012; Symes, L'Abbe, Chapman, Wolff, & Dirkmaat, 2012). All of this together can create a comprehensive injury profile of a traumatic event. Focusing on the fracture quantities according to vehicle type, as is done in this project, was to provide a snapshot of what may be accomplished with a comprehensive skeletal analysis.

Research Question and Hypotheses

Research questions

The research questions identified for this project and the corresponding hypothesis are outlined below.

Main Research Question: How and to what extent do injury profiles differ between vehicle types in the pelvis and lower extremities?

Tested hypotheses

The specific questions and hypotheses tested in this project are as follows:

Q: Are there differences in the injury profile according to vehicle type for skeletal regions separately?

H_0 – There is no difference between vehicle type groups.

H_1 – There is a difference between vehicle type groups.

Q: Can the frequencies of fractures in the lower extremities and pelvis be used to assign an individual to the correct vehicle type?

H_0 – Lower extremity fractures do not provide enough variation between vehicle type groups to assign an unknown individual correctly.

H_1 – Lower extremity fractures do provide enough variation between vehicle type groups to assign an unknown individual correctly.

Variables and expectations

Traffic collisions have a long list of related variables that can either be attributed to the cause or the outcome of a collision. Variables such as a pedestrians age, direction of impact, vehicle mass, vehicle shape, and vehicle speed have been identified as variables that may influence the observed injury profiles of a pedestrian that has been struck by an automobile (Ehrlich, Tischer, & Maxeiner, 2009; Galloway, 2014; Nagata, Uno, & Perry, 2010; Roudsari et al., 2004; Santamariña-Rubio et al., 2007; Spitz & Fisher, 1993). It was expected that there is a difference in the injury profiles between each vehicle type group. It was also expected that those differences had enough variation between the vehicle type groups to correctly assign an unknown individual to a vehicle type group when only the pelvis and lower extremity fractures are known.

Rationale and Significance

A better understanding of injury profiles through radiographic analysis can add to the overall understanding of automobile versus pedestrian fatalities (AVP). The findings from this project can be applied to a variety of fields such as forensic anthropology, medicolegal and law enforcement investigations, and the medical field. Through documentation and cataloging of injury profiles, this research can provide a reference for individual investigations. For example, the analysis of postmortem radiographs in an anthropological or medicolegal setting can provide information to law enforcement agencies in an attempt to narrow the search of a suspected vehicle. In a medical environment, such as hospitals or emergency medicine, the identified injury profiles can help medical professionals understand the associated injuries to pedestrian cases where the outcome is not fatal. In the case of forensic anthropology, remains are often discovered well after the initial incident occurred, and remains can be in late stages of decomposition resulting in limited information. This lack of information can typically mean the circumstances surrounding a death are unknown, and the findings from this project can aid in identifying (or ruling out) injuries consistent with AVP collisions.

RESEARCH BACKGROUND AND THEORETICAL PERSPECTIVES

Forensic Anthropology and Trauma

A forensic anthropologist has historically been called upon to assist in the identification of deceased individuals by estimating age, sex, stature, and ancestry (Dirkmaat et al., 2008; Johnson, 1985). The pursuit of identification through skeletal remains has been in practice before the emergence of forensic anthropology in the 1970s (Işcan, 1988; Symes et al., 2012). The duties of a forensic anthropologist have grown since then and have slowly integrated skeletal trauma analysis over the past 30+ years (Dirkmaat et al., 2008; Kranioti & Paine, 2011; Symes et al., 2012). Before this integration, a skeletal analysis was conducted by other scientists or physicians in medicolegal investigations (Kranioti & Paine, 2011). The involvement of a forensic anthropologist in the field or autopsy setting has now become routine so that anthropologists can collect contextual information about a set of remains (O Smith, Berryman, & Symes, 1990; Symes et al., 2012). The contextual information allows a forensic anthropologist to identify injuries according to when the trauma occurred and the type of trauma (Dirkmaat, 2015; Galloway, 2014).

Confident analytic methods of skeletal trauma have stemmed from both experimental and case study research (DiGangi & Moore, 2012). Experimental research can be repeated and replicated and then used to validate the examples found in case studies. Fracture behavior and the influences on that behavior are what drive forensic applications of trauma analysis and potentially provide insight as to the source of trauma (D. C. Boyd, 2018). For example, butterfly fractures are caused by a compression force to the side of a long bone while the bone is supporting weight, such as when a standing individual is impacted by a vehicle (Galloway, 2014). Knowing how butterfly fractures are created allows the inference of point of impact, the base of the triangular fragment, and direction of impact/force, the direction in which the apex of the triangle points (Spitz & Fisher, 1993). For this project, the source of trauma is automobiles, and being able to suggest a vehicle type from the injury profiles of pedestrians can help assist in an investigation by providing information that was not previously available.

Timing of trauma

Within forensic anthropology, trauma is classified into three different categories for reference to when the trauma occurred: antemortem, perimortem, and postmortem. Antemortem describes trauma that occurred before death, perimortem describes trauma that occurred around the time of death, and postmortem describes the damage that occurred after death (Dirkmaat, 2015; Galloway, 2014; White, Black, & Folkens, 2012). Specifically, trauma to bone is defined as the physical disruption of living tissues, and therefore postmortem ‘trauma’ to bone is more commonly referred to as postmortem damage or postmortem alterations (Christensen, Passalacqua, & Bartelink, 2019; Wescott, 2019). A variety of fracture characteristics such as color, fracture outline, fracture surface, and fracture angle are observed to aid in categorization. It is important to note that there is some overlap of characteristics in the postmortem interval phase when the bone tissue is drying out and losing its wet characteristics, research on this phase is sparse in the literature (Galloway, 2014; Wescott, 2019; Wieberg & Wescott, 2008). Wet bone characteristics have been observed in fractures sustained to deer femora up to one year after death (Wheatley, 2008). Since the context in which trauma occurs is important when distinguishing which traumas can be attributed to the cause or manner of death, some traumas are only classified as occurring in the wet or dry bone. This dichotomous classification is to avoid making incorrect conclusions or overstating the evidence that is present.

Antemortem trauma. Injuries to bone sustained during life immediately begin to heal, and this process leaves visual evidence of healing, which helps identify antemortem injuries (Galloway, 2014). Healing is often referred to as remodeling; however, remodeling can occur in times of both homeostasis and repair. Repair begins through the formation of a fracture hematoma, blood vessel rupture and clotting around the fracture site, and removal of dead tissues; this first step of repair begins as quickly as 6 hours after injury and lasting upwards of several weeks (Tortora & Nielsen, 2010). Next, a fibrocartilaginous (soft) callus is formed, bridging the broken ends of a bone (formation takes about 3-4 weeks) (Tortora & Nielsen, 2010). A study of fracture healing in children showed that the earliest signs of healing in a radiograph occur around two weeks by the presence of periosteal separation from the bone (Islam et al., 2000). However, as an individual ages, especially post-menopausal women, the mineral bone density and overall balance in remodeling decreases (Brockstedt, Kassem, Eriksen, Mosekilde, & Melsen, 1993; Galloway, 2014; Grynpas, 2003; Turner, 2006). In adulthood, however, the rate of change becomes relatively constant, allowing for predictable patterns of fracture healing (Symes et al., 2012).

Since the first processes of healing are lost to decomposition, as they include soft tissue, other indicators are used to identify healing on skeletal material. These additional signs of healing include the formation of a bony (hard) callus at the site of the fracture, the rounding of fracture margins (edges), or both at around 3-4 weeks post-injury (Barbian & Sledzik, 2008; Galloway, 2014; Tortora & Nielsen, 2010). These hard calluses can be seen radiographically anywhere from 3 months to 2 years after injury (Islam et al., 2000). Additionally, if an antemortem fracture received medical attention, there is an increased chance that a fracture is set or secured using hardware (e.g., plates or screws) of artificial material (Claes, Recknagel, & Ignatius, 2012). Setting a fracture can speed up the repair process and change expected timelines; however, the placement of artificial materials can increase the risk for infection and alter the repair process (Thomas & Puleo, 2011). A bony callus can be present anywhere from one week to several months after when the initial fracture occurred (Claes et al., 2012; Galloway, 2014). Radiographically, antemortem injuries that have partially undergone the remodeling process show smooth fracture margins, bony callus, bridging, and increased density at the fracture site (Islam et al., 2000). Smooth fracture margins and bony calluses are also visible on the bone itself when analyzing skeletal materials (Dirkmaat, 2015).

<u>Perimortem trauma.</u> Perimortem injuries are typically the injuries that were sustained at or around the time of death and may be associated with cause and manner of

death. Injuries sustained within two weeks before or after death may be classified as perimortem due to a lack of healing characteristics and maintained wet bone characteristics (Galloway, 2014). These fractures demonstrate the plasticity of wet bone when compared to dry bone. Plasticity is when a force is applied, and the shape of a bone is deformed to a point where it does not fracture, and it does not return to its original shape once the force is removed (Galloway, 2014; Johnson, 1985; Symes et al., 2012). Fractures sustained around the time of death show no signs of healing, meaning fracture edges are abrupt (sharp/blunt) with no roundness or smoothing of irregular areas on the fracture edges (Johnson, 1985; Wieberg & Wescott, 2008). Fracture margins are similar in color to the rest of the bone and may show evidence of blood staining (DiMaio & DiMaio, 1989). Since wet bone characteristics are retained well after death, injuries that cannot be confidently distinguished as perimortem or postmortem are typically said to have occurred in wet bone (Wieberg & Wescott, 2008).

<u>Postmortem/taphonomic damage.</u> After death, the process of remodeling ceases, organic compounds of bone (collagen) begin to break down during processes of decomposition, and the inorganic components of bone (hydroxyapatite) are leftover (Symes et al., 2012). Specifically, the water content found in the inorganic, organic, and void spaces begins to decrease, resulting in skeletal material that becomes more brittle, dry, and susceptible to damage (Wescott, 2019). Wet bone characteristics can be observed up to one year after the death in deer femora and heavily depend on the taphonomic conditions (Wescott, 2019; Wheatley, 2008). Damage can occur due to

natural processes (e.g., weathering) or accidental/intentional damage (Dirkmaat, 2015; Symes et al., 2012; White et al., 2012). Examples of natural processes include freeze-thaw cycles, rodent gnawing, carnivore scavenging, displacement of bones due to scavengers, presence of soil, rainfall, sun bleaching, or vegetation staining (Calce & Rogers, 2007). Natural processes during the postmortem period, such as abrasion and sun bleaching, may hide perimortem characteristics by smoothing or hiding color differences on fracture margins (K Moraitis, Eliopoulos, & Spiliopoulou, 2008). These changes decrease the chance of correctly identifying the number of fractures, direction, or force of impacts, patterns, timing, and location of blunt force trauma (Calce & Rogers, 2007).

Naturally occurring cracks/damage/breakage during the postmortem interval in dry bone typically follow the length (long axis) of the bone, have sharp margins, or have a mosaic/patterned appearance (Symes et al., 2012). Specifically, fracture margins that are transverse and perpendicular to the bone's long axis, rough and jagged in texture, and at right angles are typical of dry bone damage characteristics (Wescott, 2019). Radiating and concentric fracture lines are rare in postmortem, dry bone, circumstances because the bone is brittle, and fragments are smaller and less likely to hold together (Galloway, 2014). Since decomposition processes and the environment can cause staining on the outside of the bone, if a bone is damaged after skeletonization is complete, then the fracture margin is often a different color in comparison to the bone surface (Dirkmaat, 2015; Ubelaker, 1994). Therefore, dry bone postmortem damage is characterized by sharp, dry margins that are often a different color than the rest of the bone.

Type/mechanism of trauma

Skeletal trauma is further defined by how bone changes depending on the velocity of the impact (Symes et al., 2012). Analysis of injury morphology (how the injury appears) allows a forensic anthropologist to assign traumatic injuries to the following categories: sharp force, ballistic, blunt force, or a combination of multiple types. Each type has specific characteristics, as discussed below, that may present differently as the composition of bone changes after death (Konstantinos Moraitis & Spiliopoulou, 2006; Passalacqua & Fenton, 2012). Together the timing and mechanism of injury can assist in the reconstruction of the circumstances of death. Injuries may not need to present in a specific pattern, but instead, the pattern can create a predictable distribution that suggests a particular mechanism of injury (Spitz & Fisher, 1993).

Sharp force. Sharp force trauma (SFT) is the result of injury via a slow-moving (kilometers per second) blade (Dirkmaat, 2015; Symes et al., 2012). Analysis of sharp force injuries to bone includes determining the impacting action and the class of the blade. The impacting action can be classified as stabbing, cutting/chopping, or sawing; class of the blade includes identifying characteristics such as the angle of bevel and serration (or lack thereof) of a blade (Crowder, Rainwater, & Fridie, 2013; Symes et al., 2012). Incised marks (kerf marks) are an identifying characteristic of SFT. It is the shape and size of these kerf marks (V or W shaped), in addition to serration marks on the kerf wall, that may describe what type of blade may have caused a particular sharp force injury (Humphrey & Hutchinson, 2001; Symes et al., 2012).

Ballistic/projectile. Ballistic (or projectile) trauma is the result of a fast-moving (meters per second) projectile (e.g., bullet, shrapnel, or arrows) (Dirkmaat, 2015; Symes et al., 2012). Analysis of ballistic/projectile trauma includes determining the impacting action, the extent of damage, and the direction of impact. For example, the impacting action could be classified as a gunshot wound or explosive (Symes et al., 2012). The extent of damage due to ballistic/projectile trauma is documented based on the number of fractures, the path of fractures, fracture edges, and bone deformation (Symes et al., 2012). Identifying fracture characteristics of ballistic/projectile trauma to the skull include plug-and-spall fragments, radiating fractures, and concentric heaving fractures (O'bc Smith, Berryman, & Lahren, 1987). A "keyhole" defect is indicative of an oblique trajectory of a bullet in the cranial vault, and similar characteristics have been noted in long bones (Berryman & Gunther, 2000; O'bc Smith et al., 1987). Other postcranial characteristics of ballistic/projectile trauma include "drill hole" injuries at low-velocity impacts and irregular and radially displaced fractures at high-velocity impacts (Huelke, Buege, & Harger, 1967; Symes et al., 2012). Blast/explosive trauma characteristics in bone include "blowout" fractures in the sinus cavities, transverse mandibular fractures, and rib fractures on the visceral (i.e., internal, organ) surface (Dussault, Smith, & Osselton, 2014).

Blunt force. Blunt force trauma (BFT) is the result of impact with a slow-moving (kilometers/miles per hour) object or a fall from height (Symes et al., 2012). Due to the variety of surfaces and objects that can cause BFT, this category is highly variable in the way that bone reacts to BFT. Some key characteristics of BFT include delamination, plastic deformation, and internal beveling of bone (Symes et al., 2012). Delamination is when the outer layer of the bone separates from the skull, plastic deformation is a permanent deformation in a bone due to a force, and beveling of bone is when the fracture margin has an angle that is not 90 degrees (Christensen et al., 2019).

Analysis of BFT includes assessing the impacting action, point of impact, minimum number/sequence of impacts, and occasionally the class of tool/implement used (Galloway, 2014; Symes et al., 2012). Impacting action can refer to impact with a blunt object, fall from a height, or in the case of this project, automobiles. Steps of analysis to identify points of impact may include fitting together fragments, macroscopic, and microscopic analysis of points of compression (impact points) (Symes et al., 2012). Puppe's law of sequence is applied when analyzing skeletal material for the minimum number or sequence of impacts. Puppe's law is defined as a fracture that will follow the path of least resistance (Madea & Staak, 1988). This law means that later impacts in the same area of initial impact(s) will typically have fracture lines that terminate into the fracture lines of those initial impact(s) (Symes et al., 2012). Of the three types of trauma, BFT is the most common type of trauma that results from being struck by an automobile (Galloway, 2014).

Biomechanics of blunt force trauma

Fractures are dependent on extrinsic factors such as rate, duration, magnitude, and direction of force, and these variables assist in the interpretation of the cause of the fracture (e.g., automobile collision) (Galloway, 2014; Symes et al., 2012). Injury and fractures are also dependent on intrinsic factors such as the bone tissue itself and surrounding tissues in how the body responds to fractures (DiGangi & Moore, 2012). Tissue properties and geometric form influence the structural properties of bone, and fractures are dependent on size, shape, density, mineralization of tissue, and microdamage (Wescott, 2019).

Loading. Loading is defined as a mechanical/physical disturbance that causes an object to deform; in the case of this project, the object is bone (Symes et al., 2012). The skeleton undergoes loading every day; when an individual is walking, running, or even sitting, bodyweight (i.e., gravitational force) is applied as a force to bone. These everyday forces are constantly absorbed, and energy is transmitted throughout the surrounding hard and soft tissues; when loading instances occur that exceed everyday limits, bone failure occurs (Galloway, 2014; Wescott, 2019). The rate of loading can further be divided into two types of loading; static and dynamic. Static loading is defined as constant loading; dynamic loading is defined as rapid loading with high kinetic energy (Martin, Burr, Sharkey, & Fyhrie, 2015). In BFT, fracture of a bone is caused by a slow-loading (kilometers/miles per hour) impact at a single point of bone (Symes et al., 2012). The point of impact can either be a small, focused area or a broad area. For example, a small, focused area could be one inch of the femoral shaft, whereas a broad area would be the entire shaft of the femur. It is important to note that in BFT, the amount of energy that is transferred from an object to the bone is more important than the object itself. This characteristic is because the amount of damage is dependent on the amount of energy transferred (Symes et al., 2012).

Plastic deformation. When a force is applied to bone tissue, it goes through three phases of deformation, elastic deformation, plastic deformation, and failure. Elastic deformation is the phase where a force applied to a bone causes deformation, but when that force is removed, the bone returns to its original shape (Symes et al., 2012). Plastic deformation is defined as the point at which bone deforms without failure and cannot return to its original state when a force is removed (Galloway, 2014). Bone cannot return to its original shape once it has reached plastic deformation due to the presence of microcracking (Johnson, 1985). The slow-loading impact nature (kilometers/miles per hour) of BFT mechanisms is what allows the bone to pass through elastic and plastic deformation prior to failure. It is important to note that while SFT also occurs through slow-loading mechanisms, BFT is the loading of the slow-moving force at a point of impact. This is not to say that SFT cannot exhibit plastic deformation because that can be true in instances of SFT with a higher amount of mass or where the hilt of a blade has enough force on bone to exhibit deformation characteristics (Galloway, 2014; Symes et al., 2012). The act of passing through these phases of deformation prior to failure is a key characteristic of blunt force trauma (Johnson, 1985; Wieberg & Wescott, 2008). Additionally, plastic deformation characteristics are only present when moisture is, thus the presence of plastic deformation assists in assessing the timing of injury (i.e., perimortem or postmortem).

Bone biology

Bone is made up of both organic and inorganic materials that provide both strength and flexibility. During life, bone is also in a constant state of remodeling, the replacement of old bone material with new bone material. Removal of bone is called resorption and carried out by osteoclasts, and the formation of bone is called deposition and carried out by osteoblasts (Sherwood, 2013; Tortora & Nielsen, 2010). Bone tissue can also be separated into either cortical (dense) and trabecular (spongy/cancellous) bone based on how cells are organized (White et al., 2012). The differences between these two types of bone result in different fracture characteristics and assist in classifying the type of trauma, identifying the minimum number of impacts, estimating the velocity of an impact, and differentiating between falls and blows (Cohen et al., 2016; Sharkey et al., 2012; Symes et al., 2012).

Composition and strength. Bone tissue is made up of both organic and inorganic materials. The organic content is estimated to be 90% collagen and 10% non-collagenous proteins; the inorganic content is a combination of mineral salts, the most abundant of which is hydroxyapatite (Christensen et al., 2019; Sherwood, 2013; Tortora & Nielsen, 2010; White et al., 2012). By volume, bone is made up of 40% inorganic minerals, 25% water, and 35% collagen (Nordin & Frankel, 2012). Collagen gives the bones flexibility while the hydroxyapatite provides strength and structure. The content of bone allows it to better withstand compressive forces than tensive forces as a whole (Galloway, 2014). This makeup means that bone is more likely to fail under tensile, pulling, forces than compression, pushing, forces. When the bone tissue is struck, stressing forces such as compressive forces are applied at the point of contact while tension forces are applied to the surrounding bone (Galloway, 2014; Symes et al., 2012). Compression and tension forces are always applied opposite each other, and failure of the bone tissue typically occurs under tension before compression (Nordin & Frankel, 2012). For example, in butterfly fractures, bone is undergoing tensile and compression forces at impact, and the point of the first failure is on the opposite side of the bone from the impact, where the pulling forces are felt by bone tissue.

Cortical bone. Cortical bone is also known as compact or dense bone because of its cellular organization. This type of bone is found in all bones but is thickest in flat and long bones; cortical bone also acts as a protective outer surface for trabecular bone and yellow marrow in long bones. Bone is formed through a process called deposition and carried out by cells called osteoblasts (Sherwood, 2013; Tortora & Nielsen, 2010; White et al., 2012). Osteoblasts deposit an osteoid matrix around themselves, some of which eventually become trapped in cavities called lacunae; once trapped, these cells no longer deposit an osteoid matrix and instead take on a maintenance role and are then called osteocytes (Currey, 2006). In cortical bone, osteocytes are organized densely with multiple layers called lamellae and take on an appearance like that of "an end view of a pile of sawed-off tree trunks" (White et al., 2012, p. 35). Each tree trunk in the pile is called a Haversian system and typically measures 0.3mm in diameter and 3-5 mm in length, running parallel with the overall direction of the bone they are in (i.e., long bone) (White et al., 2012). The maintenance role of osteocytes requires constant communication with other osteocytes and bone lining cells. Communication is accomplished by the presence of channels called canaliculi, little tunneled gap junctions that allow information to pass through (White et al., 2012). Haversian systems are also tightly organized with each other, and this organization gives cortical bone its strength and stiffness, allowing for the ability to withstand more axial compression (i.e., crushing) than tension (i.e., stretching) (Nordin & Frankel, 2012).

Blunt force trauma in cortical bone. In cortical bone, the most common trait in perimortem trauma is layered breakage, which is when the cortical bone breaks, leaving 'steps' in the surface (Scheirs et al., 2017). Other traits include wave lines in fracture margins, bone scales that look like fish scales, flakes when one of the scales breaks off, and crushed margins, all of which are associated with perimortem trauma. Fracture angles in cortical bone are also described as either being obtuse or acute as right angles are typically observed in postmortem/dry bone alterations (Wieberg & Wescott, 2008).

Trabecular bone. Trabecular bone is also known as cancellous or spongy bone because of the way it is organized. This type of bone is found within the metaphyses of long bones (i.e., femora) and all irregular bones (i.e., vertebrae). The formation of bone is the same as described under cortical bone; however, instead of being tightly organized into Haversian systems, lamellae are organized into irregular columns reminiscent of a sponge (Tortora & Nielsen, 2010). The irregular organization of columns is purposeful in that the columns are organized according to the direction of tensile stressors (Tortora & Nielsen, 2010). This organization allows the bone to be less stiff than cortical bone and allows for a greater ability to withstand axial tension than compression (Nordin & Frankel, 2012). It also allows for blood vessels to easily access the bone marrow for nourishment.

Blunt force trauma in trabecular bone. Assessing blunt force trauma in trabecular bone is shown to be more difficult than in cortical bone, especially over time, about 80% of error for correctly identifying BFT occurs in trabecular bone (Cappella et al., 2014). Trauma in trabecular bone is typically due to compressive forces with crush type fractures being commonly found in areas with a high trabecular to cortical bone ratio (Galloway, 2014). Trabecular bone is also able to sustain more microdamage prior to failure than cortical bone due to the higher number of lamellar interfaces in trabecular bone (Szabó, Zekonyte, Katsamenis, Taylor, & Thurner, 2011). When differentiating between perimortem and postmortem trauma, the sponginess of the trabecular bone and thin layer of surrounding cortical bone create different characteristics than the thick cortical bone alone. The thin cortical layer surrounding trabecular bone doesn't provide enough 'elastic' characteristics and may also be more easily altered by taphonomic factors than thicker cortical bone (Cappella et al., 2014).

Types of fractures in blunt force trauma

Fractures of the cranial vault include linear, diastatic, depressed, comminuted, or stellate. Linear fractures are defined as fractures that pass quickly and follow the path of least resistance, which may or may not cause distinct fragments of bone (Galloway, 2014). Diastatic fractures are like linear fractures but instead divert to a nearby suture, typically the coronal or lambdoidal sutures (Gurdjian, 1975). Depressed fractures cause the space between the inner and outer layers of bone in the cranial vault to collapse and may or may not include both the outer and inner layers of bone (Galloway, 2014). Comminuted fractures are when the bone is fragmented into multiple pieces, often making recovery of all fragments difficult (Galloway, 2014). Stellate fractures are fractures that consist of multiple linear fractures that radiate out in a star shape (Gurdjian, 1975).

Fractures of the vault typically follow a path of least resistance, such as suture lines, and can either completely separate bone into two or more fragments; or partially separate bone with fracture lines terminating in the bone. (Galloway, 2014; Symes et al., 2012). These fracture lines can either follow radiating patterns or concentric patterns, or even both. Radiating fracture lines extend away from the point of impact, and concentric fracture lines are observed as “connecting” the radiating fracture lines in a circular pattern (Symes et al., 2012). Due to the spherical nature of the cranium and fragility of the facial bones, high fragmentation of the skull is common (Galloway, 2014).

Basilar fractures are fractures that occur anywhere along the base of the cranial vault. Basilar fractures typically run along the entire width of the skull and may include more than one skeletal element such as the ethmoid bone, orbital plate of the frontal bone, temporal bone, sphenoid bone, and the occipital bone (Cooper & Golfinos, 2000). Hinge and Ring fractures are specific combinations of fracturing to the base of the cranial vault. Hinge fractures, also known as transverse fractures, separate the cranial vault into anterior and posterior sections and typically run through the sella turcica of the sphenoid bone (Galloway, 2014). These fractures are typically the result of compressive forces to the front, side, or base of the skull (Oehmichen, Auer, & König, 2006; Živković et al., 2012). Ring fractures occur when the base of the skull is separated from the rim of the foramen magnum of the occipital bone (Spitz & Fisher, 1993). These ring fractures can occur when the skull is compressed into the vertebral column, such as in falls from heights (Galloway, 2014; McElhaney, Hopper, Nightingale, & Myers, 1995)

Fractures to the long bones are characterized as either incomplete fractures or complete fractures. Incomplete fractures are a fracture of bone where some continuity between the fracture portions is retained (Galloway, 2014). Examples of incomplete fractures include a bow fracture, torus fracture, greenstick fracture, toddler’s fracture, vertical fracture, and depressed fracture. A bow fracture is a classic example of plastic deformation as the fracture appears as an obvious curve of the bone without complete separation of the bone tissue (Galloway, 2014). A torus fracture is when the bone collapses under compressive forces displacing cortical bone in an outward direction around the entire circumference of the element (Rogers, 2002). A greenstick fracture is defined as a split in the bone that does not separate into two or more fragments (Galloway, 2014; Rogers, 2002). A toddler’s fracture is defined as a non-displaced fracture that may not be visible radiographically or macroscopically and typically involves the tibia but has been applied to other lower limb injuries (Galloway, 2014). Vertical fractures run the length of the long axis in long bones. Like cranial depression fractures, those occurring in long bones typically occur in the metaphyses were there is the presence of trabecular bone. These fracture types are indicative of low impact forces and wide dissipation of that force (Galloway, 2014; Symes et al., 2012).

Complete fractures are defined as a failure of bone that results in complete separation of two or more bone fragments (Galloway, 2014). Examples of complete fractures include transverse fracture, oblique fracture, spiral fracture, comminuted fracture, butterfly fracture, and segmental fracture. Transverse fractures run perpendicular to the long axis of a long bone. These fractures occur under circumstances when a long bone undergoes bending while not under normal weight-bearing forces (Galloway, 2014). Oblique fractures run across the long axis of a long bone, not at a perpendicular angle. Oblique fractures occur under similar circumstances as those causing transverse fractures. However, a key difference is the forces that initiated the fracture quickly magnify resulting in uneven bending, and the fracture line deviates from perpendicular (Galloway, 2014; Rich, Dean, & Powers, 2007) Spiral fractures circle the diaphysis of a long bone at approximately 45 degrees (Galloway, 2014). A comminuted fracture in the long bones is similar to comminuted fractures in cranial bones as it results in multiple bone fragments that can make the recovery of all fragments difficult. Butterfly fractures are a specific type of comminuted fracture, also known as a wedge fracture, as they appear with a triangular wedge between two large fragments of a long bone (Reber & Simmons, 2015). Butterfly fractures occur under bending circumstances (similar to transverse and oblique fractures) while the bone is undergoing weight-bearing forces (Galloway, 2014; Reber & Simmons, 2015). Segmental fractures are another specific type of comminuted fracture and defined as two transverse fractures binding a segment. Segmental fractures can occur when a long bone is struck simultaneously at two points or by a large surface (Galloway, 2014). As there are multiple bone fragments involved in complete fractures, a high impact force over a small localized area of bone is the typical mechanism of injury (Galloway, 2014; Symes et al., 2012).

Blunt force trauma of motor vehicle collisions

In the case of motor vehicle collisions (MVC), as it the focus of this project, trauma can be caused by a moving object striking a stationary object or two moving objects colliding with each other. The MVC itself can be classified based on the type of impact, front/head-on, side/broadside, rear, rollover, or left the roadway. The type of impact aids investigators in the analysis of vehicle damage and bodily injury. Since the type of impact indicates the direction of force, the changes in acceleration by vehicle occupants or non-occupants can be estimated, and various injuries are anticipated based on specific trajectories (Spitz & Fisher, 1993). When a vehicle impacts an object/vehicle, either stationary or moving, the energy is transferred on impact and absorbed in the object/vehicle, resulting in deformation (Galloway, 2014). However, vehicle occupants or pedestrians are considered independent or semi-independent from the vehicle. This consideration is because, on impact, the vehicle has a sudden change of acceleration before the occupant, who remains traveling in the original direction and speed (Galloway, 2014). For example, in a head-on collision, an occupant would continue traveling forward as the vehicle suddenly comes to a stop; or in a side-impact collision, the vehicle's sudden change in direction causes the occupant to travel toward the side of impact (Spitz

& Fisher, 1993). Just as objects and vehicles absorb energy on impact, the occupant and any safety mechanisms/restraints in use will absorb the energy from the momentum of the occupant. Therefore, injuries sustained due to vehicle design, safety mechanisms, or both can be inventoried and grouped into "injury profiles."

Injury profiles

Initially, the term 'injury profile' was coined as a way to describe the skeletal and soft tissue injuries as they appear in each region of the body (Baker et al., 1974). A more recent definition of an injury profile refers to specifically the skeletal fractures and the patterning according to body region (Santamariña-Rubio et al., 2007). This project utilizes this more recent definition. Injury profiles are identified by and associated with a decedent's position/location during a collision. These locations refer to the decedent as being either a driver, front row passenger, back row passenger, two-wheel operator, or pedestrian (Benson et al., 2007; Calosevic & Lovric, 2015; Conroy et al., 2007; Curtin & Langlois, 2007; Santamariña-Rubio et al., 2007). Pedestrian injury profiles are constructed based on the frequency in which the fractures appear in a specific pattern throughout the body. The pattern itself creates a predictable distribution of injuries of a specific mechanism rather than the mechanism producing an exact pattern (Spitz & Fisher, 1993). As previously discussed, the biology of skeletal material changes as individuals age and is another factor that adds to the understanding of fracture patterns. For example, elderly individuals are more likely to sustain injuries to the chest as bone density decreases, and ribs become less resilient with age (Galloway, 2014; Nagata et al., 2010; White et al., 2012).

Typical vehicle occupant injury profiles. Typical skull fractures of the cranial bones in motor vehicle occupants include depression fractures, linear fractures, and hinge fractures (DiMaio & DiMaio, 1989; Galloway, 2014). Facial fractures of the nasals, maxillae, and mandible are also common in front impact collisions as individuals are typically thrown forward into the dash components, back of front row seats, or collide with airbags (Cormier & Duma, 2009; Hitosugi, Mizuno, Nagai, & Tokudome, 2011; Natu et al., 2012). Hyperextension or flexion of the neck in automobile collisions can result in fracturing of the atlas (C1) and axis (C2) (DiMaio & DiMaio, 1989; Galloway, 2014). Injuries to the chest are typical for drivers because of an impact with the steering wheel (Spitz & Fisher, 1993). Seatbelts have also been shown to cause fractures in the clavicles, ribs, and sternum (Hayes, Conway, Walsh, Coppage, & Gervin, 1991). Pelvic injuries are more common for vehicle occupants, where the seatbelt was not in use, and pelvic injuries are the most common injury in fatalities (Galloway, 2014). Shearing forces of seatbelts can cause compression fractures in the lumbar vertebrae (Greenbaum, Harris, & Halloran, 1970; Hayes et al., 1991). Fractures in the pelvis as a result of transferred force from the femora have been labeled “Instrument panel syndrome” (Kulowski, 1961). The mechanism in which this occurs is caused by a chain reaction of the knees colliding with the instrument panel, which then drives the femora into the pelvis with enough force to cause fractures.

Typical driver and passenger injuries. Drivers are more likely to sustain lower extremity injuries to the right side compared to front-row passengers; this may be due to occupants bracing or preparing for impact by stiffening the legs (Assal et al., 2002; Spitz & Fisher, 1993). In calcaneal injuries, the act of pressing down on the brake pedal prior to impact adds to the force applied to the right leg (Benson et al., 2007; Galloway, 2014). However, front-row passengers, regardless of position, are more likely to sustain calcaneal fractures than rear row passengers (Benson et al., 2007). In addition to calcaneal fractures, drivers are also more likely to have dislocation of the hip joint as the leg extends, pressing on the brake pedal (Stewart & Milford, 1954). Many of the injuries expected and sustained by vehicle occupants are based on vehicle structures (e.g., steering wheel location, pedals, seat location, etc.) and in the use of safety mechanisms (e.g., seatbelt, airbag, etc.). However, when occupants are unrestrained, they show more variability in patterns of injury as they are more independent of the vehicle (Galloway, 2014).

Typical motorcycle injury profiles. Motorcyclists, and other two-wheeled operators (e.g., moped), lack protective measures like those found within motor vehicles such as the vehicle itself or airbags, thus exposing operators to an increased risk for injury. Head and neck injuries are the most common and typically more severe than vehicle occupants (DiMaio & DiMaio, 1989). For example, hinge fractures are the most common head injury in motorcycle operators because individuals are thrown to the ground or into stationary objects at high speeds (Galloway, 2014). When helmets are worn correctly by riders, head, face, and neck injuries become less frequent (Ankarath et al., 2002; Murphy, Nyland, Lantry, & Roberts, 2009). Injuries sustained by two-wheel operators are typically more dispersed throughout the body than vehicle occupant injuries (Galloway, 2014). Pelvic ring fractures, lower thoracic, and upper lumbar vertebral injuries are more common in riders (Ankarath et al., 2002; Rothenberger, Velasco, Strate, Fischer, & Perry, 1978). The most common fractures to the limbs in two-wheel operators include fractures of the radius (coined "motorcycle radius") and the tibia and fibula (Varley et al., 1993). Frequency of lower limb fractures occur in the following order of highest to lowest frequency: tibia/fibula, ankle, femur, then foot (Lateef, 2002).

Typical pedestrian injury profiles. The risk for lethal injury is elevated in pedestrians even more than two-wheeled operators because there are no required safety mechanisms for pedestrians to use. Compared to vehicle occupants and two-wheeled operators, pedestrians have been found to have a higher frequency of fractures in the extremities (arms and legs) when compared to the frequency of torso injuries when struck by a vehicle (Santamariña-Rubio et al., 2007). Pedestrians are also twice as likely as vehicle occupants or two-wheeled operators to sustain pelvic fractures (Adams, Davis, Alexander, & Alonso, 2003). Specific fracture patterns labeled as 'fatal triad' or 'ipsilateral dyad' have been identified to have a high frequency of appearance in pedestrians struck by vehicles (Calosevic & Lovric, 2015). The fatal triad consists of fractures of the skull, pelvis, and lower extremities. The ipsilateral dyad can appear in two locations, always on the same side. Ipsilateral dyad 1 are fractures of the upper and lower extremity of the same side; Ipsilateral dyad 2 are associated fractures of the pelvis and femur (Calosevic & Lovric, 2015). Research demonstrates pedestrians are at the highest risk of not only sustaining fatal triad injuries but also sustaining ipsilateral dyad (1) fractures, with common upper extremity fractures of the forearm and humerus and lower extremity fractures of the femur (Calosevic & Lovric, 2015; Rubin et al., 2015).

Newer vehicle types with pop up hood design may reduce head injury in primary impact due to the change in front end shape because the head is more likely going to impact with the hood rather than the windshield (Gupta & Yang, 2013). However, this design does not prevent secondary impact injuries of the head and may even lead to more severe secondary impacts to the head by the head striking the ground surface before other body regions (Gupta & Yang, 2013). Older vehicles (1970's-1980's) result in a higher frequency of injuries to the head and lower leg than newer vehicles (the 1990s to mid-2000s) due to changes in the design of the front end (Ehrlich et al., 2009). These changes include a rounded frontal form and a better ability of the front end to deform at impact, meaning the energy is absorbed by the vehicle rather than by the pedestrian. Ehrlich et al. (2009) also found that while injuries to the head and lower leg injuries decreased, there was an increase in chest and pelvic injures in the newer vehicle designs likely due to the aforementioned changes to vehicle front ends. As vehicle size increases, the associated injuries in pedestrians are more likely to lead to death than smaller vehicle types (Roudsari et al., 2004). At slower speeds, an impact with a larger vehicle type results in fractures higher on the leg, indicating an association between an injury profile and vehicle type (Ballesteros, Dischinger, & Langenberg, 2004).

The position of the pedestrian at the time of impact is also essential when analyzing injuries sustained by an automobile. Unlike occupants of a vehicle who are seated, a pedestrian could be walking/running, bending down, sitting/laying in the road, or standing at the time of impact resulting in various locations at which a vehicle could strike them. One way to assess whether a pedestrian was erect at the time of impact is by the presence of fractures in the cervical or lumbar vertebrae (Karger, Teige, Fuchs, & Brinkmann, 2001). Additionally, the location of a pedestrian's center of mass to the vehicle's center of mass at the time of impact will determine whether the pedestrian is "run-under" or "run-over" (Galloway, 2014).

In run-over collisions, compression injuries are the most common type of injury with shearing and crushing injuries occurring from a moving wheel rather than a locked wheel (Spitz & Fisher, 1993). Run-over collisions typically occur at slower-moving speeds (<15mph) or when the pedestrian's center of gravity is lower than that of the vehicle (Knight, 1991). In run-under collisions at lower speeds (most common in adults), typical injuries include the bumper causing injury to the knees/tibia/fibula, the front end causing injury to the hips/thighs, the hood causing injury to the chest and abdomen, and the hood/windshield/roof causing injuries to the head if an individual is standing at the time of impact (Galloway, 2014).

Higher speeds result in the pedestrian being thrown higher, sometimes up and over the vehicle (DiMaio & DiMaio, 1989). It is these run-under circumstances that typically result in a pedestrian being airborne and thus sustaining fractures from secondary impacts (Gupta & Yang, 2013). Secondary impacts are usually opposite from the side of impact and are more severe, the faster the speed of the vehicle at impact (DiMaio & DiMaio, 1989; Knight, 1991).

Differentiation between run-over and run-under injuries based solely on fracture identification can be complicated if a pedestrian is run-over after being run-under. This complication occurs because the deceased will show injuries consistent with both mechanisms of injury in the same perimortem timeframe. It is also important to note that both run-over and run-under pedestrians will exhibit a similar frequency of head, chest, abdominal, upper extremity, and lower extremity injuries (Galloway, 2014). However, “butterfly” fractures in the lower limbs and traumatic amputations are highly associated with impact rather than run-over instances (Galloway, 2014). In addition to a pedestrian being run-under or run-over, being sideswiped is also a possibility. The frequency of head injuries surpasses the frequency of characteristic lower limb fractures in sideswiped pedestrians (Galloway, 2014).

Theoretical Background and Framework

Theory specific to forensic anthropology has historically been said not to exist (C. Boyd & Boyd, 2011; Schiffer, 1988). Not to say that forensic anthropology does not utilize theory, but instead, theory is borrowed from other fields and applied in a forensic context. Just as reconstruction theory is used in archaeology to reconstruct past events, this project utilizes a modified version to infer vehicle type from fracture patterns.

Reconstruction is accomplished by identifying fractures in postmortem radiographs in conjunction with the traffic-related information recorded in death and collision reports.

Reconstruction theory

Reconstruction theory is an example of a borrowed theory because its roots are in geology, biology, and chemistry (Schiffer, 1988). Schiffer (1988) defined reconstruction theory as the ability to infer the behavioral phenomena of the past, though the author notes that reconstruction cannot create a complete picture of events. Archaeology applies reconstruction theory to create a snapshot in time rather than a story. The field of forensic anthropology has modified and applied reconstruction theory to reconstruct crime scenes and tell a story of how the injuries may have occurred to the victim (Dirkmaat et al., 2008). This project utilized the forensic interpretations of reconstruction theory to explain and interpret the fractures observed in postmortem radiographs. Utilizing collision reports from law enforcement adds to the amount of information that can be collected from the radiographs. In a sense, the collision is reconstructed by “following the lines of evidence” and ideally match injury profiles to vehicle types (Schiffer, 1988). The application of reconstruction theory and accurate radiographic analysis will assist in identifying correlations that may exist between types of vehicles cause what types of injury profiles. This will, therefore, help forensic anthropologists and medical personnel predict the types of fractures that can be expected in AVP collisions.

METHODS

Research Design

The methods followed in this project were determined to be of Exempt status by the Institutional Review Board at Humboldt State University (no. 18-106) and the Research Administration and Review Committee of King County (Appendix A and B). Fracture data were collected from postmortem radiographs accessed from the King County Medical Examiner's (KCME) office in Seattle, Washington. Automobile and collision data were collected from the KCME office and the Washington Traffic Safety Commission (WTSC). Limiting the number of agencies where data were collected minimized the number of disparities between cases because traffic-related incidents are already highly variable (e.g., speed, weather, road conditions, etc.). While the data collected by the WTSC originated from all levels of law enforcement agencies around Washington State, the data is coded and therefore uniform for statistical testing.

King County was chosen for this research project based on the county's population size (2,188,649)(U.S. Census Bureau, n.d.) and the structure of the Medical Examiner's (ME) record keeping. King County Medical Examiner takes in-house radiographs and uses a digital case management system, making access to radiographs, demographic data, and collision data easily searchable and exportable. Washington State Law Chapter 46.52 RCW mandates that collision reports are forwarded to the Chief of the Washington State Patrol (WSP) (Washington State Legislature, Accessed 8.2018).

Through agreements between WSP and the WTSC, the reports are made available to the WTSC and are coded into a database to be made available for various statistical analyses. Therefore, only the cases investigated by KCME and available in the WTSC repository are included in this project.

Population Sample

A total of 86 cases were initially selected, starting with the most recent (2017) and working backward linking up cases between KCME and WTSC records based on the collision date and time and pedestrian age and sex. The primary criteria for inclusion required that quality radiographic information was present, the incident occurred in King County, the pedestrian died at the scene, and the vehicle type was known.

King County adopted digital radiographic methods in 2008; any radiographic material before 2008 was scanned into digital archives (K. Taylor, personal communication, October 3, 2018). The decline in the quality of digital radiographs when reviewing 2007 and 2006 cases resulted in 19 cases from this timeframe being excluded to avoid oversight of skeletal fractures due to poor quality. Cases from earlier years were also excluded due to the decline in image quality. Additionally, a total of eight more cases were excluded for reasons including date and time discrepancies or missing vehicle information. One case was removed due to a discrepancy in the date and time of the collision between KCME and WTSC records resulting in an inability to confirm it was the same case confidently. Seven cases were removed from the final sample as a specific vehicle type was listed as unknown in both KCME and WTSC records. Out of the 86 cases reviewed, only 6 cases had images for the head and neck, 4 cases had images for the chest, and 9 cases with upper extremity images. Only 1 of the 86 cases contained full-body imaging. Due to these findings, only the lower extremities were analyzed to create regional injury profiles and test against vehicle type.

For the cases that had lower extremity imaging, 45% of the time, the metatarsals, phalanges, or both were cut off the edge of the image, thus preventing a comprehensive analysis of the foot. The lack of full-body imaging was explained to the researcher by KCME staff as occurring because the pelvis and long bones of the lower extremities were considered the most important bones to document via radiographs. This was the procedure because the pelvis and long bones were likely to indicate a fatal injury, and injuries to the head, neck, and chest fractures were documented via autopsy. Due to the limited number of cases with upper body radiographs, the pelvis and lower extremities were the only radiographs included for analysis in this project. The final population sample for analysis consisted of 59 cases of adult pedestrians aged (19-95) years fatally involved in AVP collisions between 2007 and 2017 within King County.

Data Collection Methods

Data were collected from the King County Medical Examiner's Office and the Washington Traffic Safety Commission. Since the purpose of this project was to test for relationships among injury profiles and vehicle types, multiple variables were identified for collection (Table 1). Fracture data were collected from the KCME office, and traffic data were collected from the WTSC database.

Fracture data

Postmortem radiographs document the skeletal injuries sustained around the time of death. Fractures were identified via a macroscopic analysis of digital radiographic images. The fracture quantities of an individual were collected from radiographs by identifying how many fractures were present in a single skeletal element. Comminuted fractures with a small amount of fragmentation (i.e., butterfly or segmental fractures) were assigned one number less than the number of fragments. For example, a butterfly fracture has three fragments, the two portions of a long bone with a triangle wedge. This type of fracture required two fracture lines to create the number of fragments and assigned an integer of two. This same treatment was also used for comminuted fractures with more than three fragments where the individual fragments themselves were still countable (i.e., non-shattered appearance). When comminuted fractures with high levels of fragmentation (i.e., shattered appearance) were present in a skeletal element, it was assigned the highest integer for that skeletal region. The shattered appearance was assigned to a skeletal element as a whole when it appeared there might be missing fragments (likely due to open fractures) and, therefore, an accurate fragment count was not possible.

Paired left and right skeletal elements were then combined to create skeletal regions. The pelvis skeletal region includes the sacrum with the paired left and right innominates. Grouping fracture data this way resulted in five skeletal regions: pelvis, femora, patellae, tibiae, and fibulae. Paring elements into a group controlled for ‘sidedness’ or the side of the body that was struck by the vehicle as that specific variable was not available. Fracture quantities were totaled, creating a total fracture quantity for each skeletal region for each case.

As mentioned in the background section of this thesis, fracture types are different based on various mechanisms. These mechanisms, in turn, provide an increased amount of information and, therefore, enable more comprehensive interpretations of injury mechanisms. For the purposes of this research, fracture type was not included in the analysis of injury profiles due to time constraints; and instead, this research focused solely on fracture quantities and vehicle types. Death reports provided the demographic, date, and time data necessary for matching up cases between KCME and WTSC records. The relevant information contained in death reports was provided to the researcher by KCME staff in the form of excel spreadsheets to maintain the anonymity of the deceased.

Traffic data

Data repositories contain mass amounts of data collected from various agencies that make the information available in one place. The WTSC collision data repository contains collision specific variables in a standardized format. The standardization of data in repositories, like the one managed by the WTSC, allows for easy comparison between variables and quick identification of missing information. Traffic data were coded using integers for categorizing. Variables such as vehicle year, make, and model, posted speed limits, vehicle maneuvers before impact, weather conditions, road conditions, type of roadway, roadway lighting, date and time of collisions, and more are contained within the database. Many traffic variables are related to the changes (or lack thereof) a vehicle undergoes while navigating the roadway; these changes can be made intentionally or unintentionally by the vehicle operator. Research around these variables focuses more on the severity of the outcomes of a collision rather than the injury profile specifically (Li, Liu, & Ding, 2013). The severity of collision outcomes ranges from minor injury to fatal, and since all outcomes were fatal in this project, it was decided to focus on vehicle type as the only traffic-related variable. Additionally, some traffic variables controlled themselves. Specifically, the type of roadway was listed as some form of pavement across the sample and landscape, which indicated where a collision took place was listed as urban—the lack of variation in a variable essentially controlled for these variables in the analysis.

A simplified code was utilized for the data because the coding system used by WTSC was more complex and included options that did not exist in the subsample of data obtained from the WTSC database. The vehicle type was recorded within the WTSC database according to 99 different categories. These choices were subdivided into eight categories: passenger auto, SUV, truck, van, motorcycles, motorhome, other, and unknown. Within these categories, the vehicles were further divided by weight. Based on the cases in the population sample, each case fell into either the passenger auto, small/midsize SUV, full/large SUV, light truck, bus, motorhome, and heavy truck. These categories were then recategorized according to factors such as gross vehicle weight rating (GVWR) and front-end shape into the groups utilized in this project (Table1). Passenger auto was renamed as “Car” because it contained vehicles like sedan, hatchbacks, and limousine (all with similar front ends). The small/midsize SUV and lightweight (GVWR<4500lbs) trucks were grouped into the “Lightweight/small Truck/SUV” category. The full/large SVU and heavier (GVWR 4500-10000lbs) trucks also from the light truck category were grouped into the “Large/heavyweight Truck/SUV” group. Four out of five vans in the van category were minivan body and the fifth a step/walk-in van, which made up the “Van” group. Lastly, the “Other” vehicle type category included vehicles that ranged from the bus, motorhome, and heavy truck categories; these were all vehicles with a GVWR of over 10000lbs.

Table 1. Collected variables and data treatment

Variable	Data Treatment	Datapoint Categories
Fracture Quantity	Numerical	Number of total fractures in each skeletal region
Pedestrian Age	Numerical	Age in years
Pedestrian Sex	Coded	1. Male 2. Female
Vehicle Type	Coded	1. Car 2. Lightweight/small Truck/SUV 3. Heavy/large Truck/SUV 4. Van 5. Other
Date/Time of Collision	To match KCME & WTSC cases	Eliminated after cases were matched

Data Analytical Methods

Statistical data analysis was completed using XLSTAT (v. 2019.4.2.64053) (Addinsoft, 2019). Demographic data were analyzed for the distribution of the sample according to age and sex. The distribution of vehicle types was also modeled. A Shapiro-Wilk test of normality was selected to test the normal distribution of each variable. This test was selected because it is generally recommended as the best choice for normality testing (Ghasemi & Zahediasl, 2012; Thode, 2002). Correlation tests using ordinary least squares linear regression were performed on all variables to identify possible relationships; Pearson's r (correlation coefficient) was reported. Since the actual speed was unknown or not initially collected and only posted speed was available, posted speed was not included in the analysis. Research has shown that the posted speed zone is not a suitable replacement of actual vehicle speed when analyzing the relationships between speed and injury profiles (Harruff, Avery, & Alter-Pandya, 1998).

A Kruskal-Wallis test was selected to test for differences among vehicle type groups for each skeletal region. This test was selected as it is best for ranked data, non-normally distributed data, multiple samples; additionally, this test reduces the probability of a type I error (Dytham, 2011). A limitation is that vehicle type is not strictly ranked/ordinal, though vehicles were organized by weight within this project. Post-hoc tests, including a Bonferroni correction and Dunn's test, were selected to protect against error. The Bonferroni correction protects against the increased risk of type I error when multiple statistical tests are performed and to establish if any tests are significant

(Armstrong, 2014). Dunn's test was selected as it shows which groups have significant differences. This test specifically tested the second research question: Are there differences in the injury profile according to vehicle type for skeletal regions separately?

A Partial Least Squares Discriminant Analysis (PLS-DA) was selected to determine if the variation of fractures for multiple skeletal regions among vehicle types was enough to confidently categorize an unknown individual into the correct vehicle type category based on the injury profile. In XLSTAT, PLS-DA can be used over Discriminant Analysis when the individuals of a group are equal to or less than the number of explanatory variables. In this case, the number of explanatory variables (n=5) is equal to the number of cases in the van vehicle type group. The significance level was set at a 95% confidence interval.

Known issues with discriminant analysis tests include over-fitting data and when data sets have uneven numbers of individuals per group. Over-fitting is when classification success rates are a lot higher than chance expectations. A procedure called cross-validation helps to overcome this problem. Jackknife cross-validation was selected as it is associated with lower, but more realistic success rates (Kovarovic, Aiello, Cardini, & Lockwood, 2011). Jackknife cross-validation is when one individual is left out of the discriminate analysis when it is calculated; this is repeated for all individuals in a sample. This model specifically tested the last research question: Can the frequencies of fractures in the lower extremities and pelvis be used to assign an individual to the correct vehicle type?

RESULTS

The final sample size of 59 individuals included 37 (63%) males and 22 (37%) females with a mean age of 51.3 years and an age range of 19-95 years (Table 2). The mean age of the males was 46.8 years, with an age range of 19-87 years. The mean age of the females was 58.8 years, with an age range of 23-95 years. Females were found to have a weak positive correlation with more fractures than males in the pelvis and femora skeletal regions and a weak negative correlation with fewer fractures than males in the tibiae and fibulae skeletal regions (Table 3). Distribution of fracture frequencies by sex for each skeletal region can be found in Table 10 and Figures 3-7 within Appendix C.

Table 2. Pedestrian demographics

Summary Statistic	Male	Female	Total
Sample Size	37	22	59
Percentage of sample	63%	37%	100%
Mean age (years)	46.8	58.8	51.3
Median age (years)	44	58	53
Range age (years)	19-87	23-95	19-95

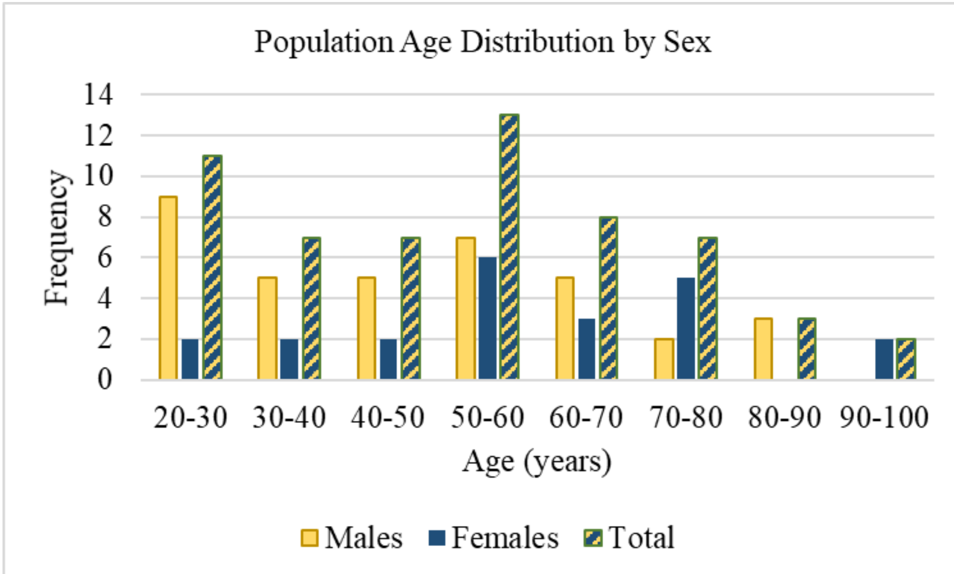

Figure 1. Bar chart of the age distribution in the total sample identified by the total (striped), male (yellow), and female (blue)

A slight positive correlation was identified between the number of pelvic fractures and an increase in age (Table 3). Weak and almost zero correlations between the number of fractures and remaining skeletal regions were also identified. Scatter plots for individual regions can be found in Appendix D. Weak positive correlations were identified between the pelvis and patellae skeletal regions and almost zero correlation between the remaining skeletal regions (Table 3). A strong positive correlation between tibiae and fibulae fractures was found with a correlation coefficient of 0.817 and a Pearson's correlation p-value of <0.05.

Table 3. Correlation coefficients for sex, age and fracture quantities by skeletal region

Variable	Pelvis	Femora	Patellae	Tibiae	Fibulae
Sex	0.128	0.122	0.017	-0.095	-0.096
Age	0.202	0.011	0.149	-0.034	0.014
Pelvis	1	0.202	0.227	0.290	0.272
Femora		1	0.192	0.241	0.445

Variable	Pelvis	Femora	Patellae	Tibiae	Fibulae
Patellae			1	0.192	0.327
Tibiae				1	0.817*
Fibulae					1
* indicates significant p-value					

Vehicle types involved in the cases are distributed, as shown in Figure 2. The "Car" vehicle type group (n=20) had the highest number of cases, and the "Van" vehicle type group (n=5) had the lowest number of cases.

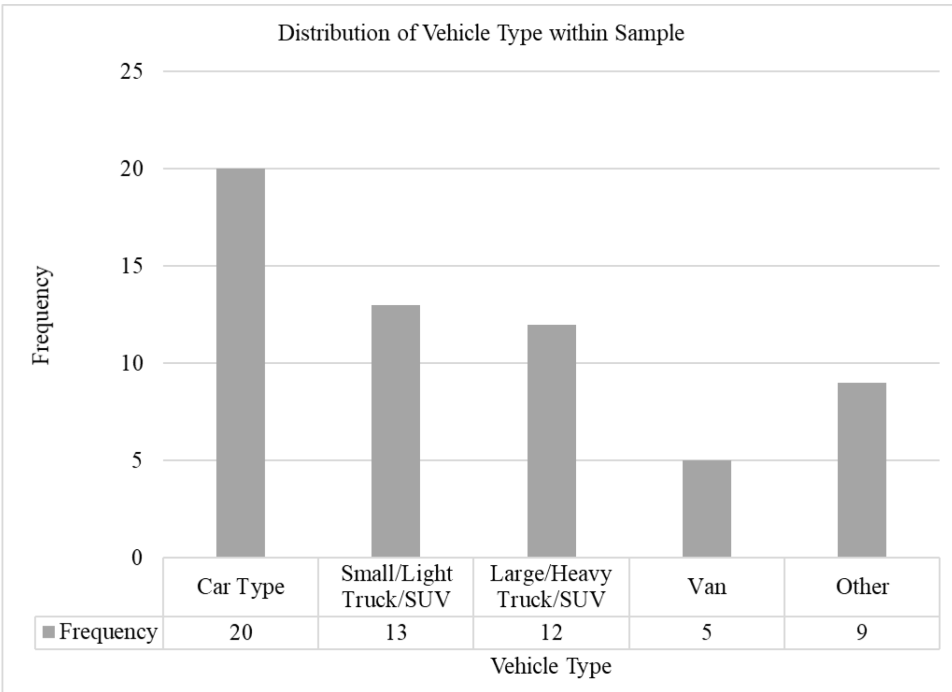

Figure 2. Frequency distribution of vehicle types for the total sample

Shapiro-Wilk test for normality revealed that all variables except age do not follow a normal distribution (Tables 4 and 5).

Table 4. Shapiro-Wilk p-values for normality distribution for the age, sex, and vehicle type variables

Shapiro-Wilk test	Age	Sex	Vehicle Type
p-value	0.061	<0.0001	<0.0001

A p-value <0.05 indicates non-normal distribution.

Table 5.Shapiro-Wilk test for a normal distribution of the fracture quantity by skeletal regions

Shapiro-Wilk Test	Pelvis	Femora	Patellae	Tibiae	Fibulae
p-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

A p-value <0.05 indicates non-normal distribution.

When analyzing each skeletal region separately, a Kruskal-Wallis test found no significant difference in fracture quantity among vehicle type groups, except for the pelvis (Table 6). With a Bonferroni corrected significance ($p < 0.005$), the “Other” vehicle type group showed significant p-values in the fracture pattern from the fracture patterns of vehicle type groups “Car” and “Heavy” (Table 7). However, a multiple pairwise comparison using Dunn’s procedure found that the fracture differences within the pelvis skeletal region were not significant enough to separate the fracture pattern of the “Other” vehicle type group from the other four vehicle type groups (Table 8).

Table 6. Kruskal-Wallis test p-values among vehicle types for fracture quantity by skeletal region

Skeletal Region	Pelvis	Femora	Patellae	Tibiae	Fibulae
p-value	0.038*	0.152	0.438	0.053	0.191

*indicates significant p-value

Table 7. Pairwise comparison for the pelvis skeletal region with a Bonferroni corrected significance level (0.005)

Vehicle Type	Car	Small/Light Truck/SUV	Large/Heavy Truck/SUV	Van	Other
Car	1	0.882	0.685	0.464	0.009*
Small/Light Truck/SUV		1	0.616	0.426	0.022
Large/Heavy Truck/SUV			1	0.682	0.007*
Van				1	0.011
Other					1

*indicates significant p-value (0.005)

Table 8. Multiple pairwise comparison using Dunn's Procedure

Sample	Frequency	Sum of ranks	Mean of ranks	Groups
Van	5	110.000	22.000	A
Large/Heavy Truck/SUV	12	308.000	25.667	A
Car	20	563.000	28.150	A
Small/Light Truck/SUV	13	377.500	29.038	A
Other	9	411.500	45.722	A

A PLS-DA analysis found that only 37.29% of cases were correctly classified into their respective vehicle type groups based on injury profiles (Table 9). These results did not meet the 95% confidence criteria. The “Car” vehicle type had the highest success rate of classification with 80% correct. All cases belonging to the “Small/lightweight

Truck/SUV" vehicle type, "Van" vehicle type, and "Other" vehicle type had a 0% correct classification percentage. The "Large/heavy Truck/SUV" vehicle type group had a 50% correct classification rate. A more detailed version of the reclassification for each case can be found in Table 11 (Appendix E).

Table 9.Confusion Matrix for correctly classified individuals into vehicle type

from \ to	Car	Small/Light Truck/SUV	Large/Heavy Truck/SUV	Van	Other	Total	% correct
Car	16	0	4	0	0	20	80.00%
Small/Light Truck/SUV	12	0	1	0	0	13	0.00%
Large/Heavy Truck/SUV	6	0	6	0	0	12	50.00%
Van	3	0	2	0	0	5	0.00%
Other	8	0	1	0	0	9	0.00%
Total	45	0	14	0	0	59	37.29%

Outliers Analysis

The PLS-DA analysis also identified five cases that were outliers from the sample: observations 2, 12, 30, 35, and 49 (Table 12, Appendix E). The "Car" vehicle type group had two cases with patellae region fractures. The outlier case (observation 35) only had fractures in the pelvis and patellae, whereas the other case with a patella fracture had fractures in all other skeletal regions.

The "Small/lightweight Truck/SUV" vehicle type group had two outlier cases. The first outlier case (observation 2) in this group had fractures in the fibulae region but not the tibiae region. All other cases in this group had the presence or absence of fractures in these paired regions, except one, non-outlier, case where there were fractures of the tibiae but not the fibulae. The other outlier case (observation 12) was the only one in the group with a patellae fracture while also having no fractures of the pelvis and fractures in the femora, tibiae, and fibulae regions.

The “Large/heavyweight Truck/SUV” vehicle type group had one outlier case (observation 30), which had the highest number of pelvis and femora fractures with no fractures were present in the other regions.

Lastly, in the “Other” vehicle type group, there were two cases with fractures of the patellae region. The outlier case (observation 49) only had fractures in the patellae, tibiae, and fibulae regions, whereas the other, non-outlier, case had fractures in all skeletal regions. A discussion of these outliers will follow.

DISCUSSION

Interpretation and Comparison of Results

The Kruskal-Wallis test showed no significant differences in the fracture quantities of a specific skeletal region across vehicle type. The results from this test suggest that fracture quantities within a single skeletal region are not good predictors of vehicle type. The Bonferroni corrected significance p-values did show significant values; however, this correction imposes a penalty when sample sizes are small, or a large number of tests are being carried out (VanderWeele & Mathur, 2019). That, in combination with insignificant results from Dunn's procedure, suggests that one vehicle type cannot be separated from other types according to the fracture quantities in individual skeletal regions.

The results of the PLS-DA model had a low overall success rate and did not meet the 95% confidence interval criteria for the classification of the injury profile into a specific vehicle type category. These results indicate that injury profiles made from the pelvis and lower extremities are poor predictors of vehicle type. The Jackknife cross-validation technique often lowers success rates by amplifying issues that are already present when an injury profile is used as a predictive variable, which also avoids the error of over-fitting the data into the model (Kovarovic et al., 2011). While the "Car" vehicle type group had the highest success rate of classification with 80% after cross-validation, the results did not meet a 95% confidence interval. These rates also suggest that there is missing information that is necessary to discriminate injury profiles among vehicle type groups. This information may exist in a combination of variables such as age, sex, actual vehicle speed, more detailed vehicle types, or fracture data from other regions of the body (Harruff et al., 1998; Li et al., 2013; Roudsari et al., 2004).

The identification of outliers from the sample suggests that there is additional information that is needed to explain how a vehicle type produced an injury profile that was so different from the rest of the injury profiles in the same vehicle category. These cases are outliers because they had fractures in body regions that were in different combinations than cases within the same vehicle type. The most predominant pattern was three of the five cases with patellae fractures were flagged as outliers; however, this may also be an artifact of the small sample size of patellae fractures and thus artificially identifying fractures of the patellae as atypical. Since fracture patterns are dependent on extrinsic and intrinsic mechanisms and it is difficult to differentiate between run-under and run-over mechanisms when only dealing with the fractures themselves, let alone only fracture quantity. It is difficult, if not impossible, to identify what circumstance created this result exactly (DiGangi & Moore, 2012; Dirkmaat, 2015; Galloway, 2014; Johnson, 1985; Martin et al., 2015; Symes et al., 2012). Other variables such as actual speed, fracture data for other regions of the body, or bumper height of the vehicle could provide more context in the case of outliers such as these.

Theoretical Framing

Reconstruction of past events is only as reliable as the information or evidence available at the time of reconstruction. In archaeology, reconstruction theory is used to generate snapshots in time to get a better understanding of what materials were available to the people living at that time and potentially as far as how those people interacted with those materials and their environment (Schiffer, 1988). In forensics, these concepts are utilized to piece together multiple snapshots from different lines of evidence and create a circumstantial narrative (Dirkmaat et al., 2008).

As previously mentioned, skeletal trauma analysis is one of those lines of evidence that can be used to add to this larger picture of incident circumstances. For example, in instances where there are multiple injuries to a pedestrian, each injury is a snapshot of the entire incident mechanism. The results from the Kruskal-Wallis test, examining fracture quantities of skeletal regions separately, were not significant in statistical value; however, this does not mean the results have no value to add to the understanding of injury profiles. These results highlight the fact that injury profiles require multiple pieces to be used together. The results also suggest that focusing on the pelvis and lower extremities may just be the wrong skeletal regions to focus on when collecting snapshots of injuries in AVP collisions.

While considering the quantities, types, and mechanics of skeletal fractures provides numerous points of data to build injury profiles, the lack of fractures in a skeletal region can provide equally essential data to the profile (Cohen et al., 2016;

Dirkmaat, 2015; Galloway, 2014; Symes et al., 2012). A lack of fractures indicates that the forces, if any, applied to that body region were not severe enough to cause deformation or failure of bone. During reconstruction, this information, the lack of fractures, could suggest that the area was not impacted, which provides details of the extent or size of the impacting object.

The PLS-DA test analyzed the fracture quantities as a complete profile, as opposed to skeletal regions individually, to provide more detailed information related to the relationship between injuries and vehicle type. This analysis also provided insight into what the circumstances of injury may be. Although this statistical test had a low overall classification rate, these findings are still informative for forensic reconstruction. The value of knowing when more information is necessary for making conclusions related to injury profiles is incredibly important to avoid overstating the evidence (Galloway, 2014; Wheatley, 2008). The addition of more skeletal regions to an analysis of injury profiles according to vehicle type would provide even more information as to the variation that exists within injury profiles and how that variation compares across different vehicle types.

While statistical analysis and forensic investigations rely on ‘hard’ evidence, facts, and numbers, it is important to acknowledge the human element involved in all aspects of investigations and analyses. Each investigator or forensic practitioner is different from the next, even if there was a standardization of policies and procedures. However, with a lack of standardization, those individual differences can magnify the differences in investigative though processes and approaches and thus impact how evidence is collected or interpreted. The way an AVP collision is experienced by the involved individuals can be influenced by both the environment and the events. Some brief examples include a perceived sense of safety a pedestrian feels when walking on the sidewalk or crossing the street. This safety exists based on the trust of others using the roads properly. Or perhaps how the operator of a vehicle is traveling down a road where there is no sidewalk or shoulder, so the risk of seeing a pedestrian on the side of the road is assumed to be lower than those areas with designated pedestrian walkways. It is also possible that the surroundings, such as a tunnel, city center, or forested area, play a role in how a vehicle operator perceives the speed in which they are traveling. These different factors can have a substantial effect on the circumstances of the collision and may influence how evidence and information are collected by investigators. This influence can appear as information being deemed as less important because it did not directly cause or did not appear to be directly involved in the incident. This bias, whether it is intentional or not, impacts the objective data that is the primary focus of statistical analysis and may limit the depth of a comprehensive analysis. While it is never possible to include all factors and eliminate bias, comprehensive injury profiles will allow for better, more useful analyses.

Limitations

The fragmentation of the overall sample size by vehicle type was the greatest limiting factor of this project. The lack of comprehensive full-body imaging, the limited number of cases over many years, and consolidation of vehicle types to create workable sample sizes all impacted the information that could be pulled and analyzed from the data set and the size of the sample itself. According to the central limit theorem, smaller sample sizes (>30-40) tend to be less likely to follow a normal distribution (Ghasemi & Zahediasl, 2012). While this population consisted of 59 individuals, the largest group, when separated by vehicle type, only contained 20 individuals. This sample fragmentation, in turn, limits the number or strength of statistical tests that can be performed on the data and therefore limits interpretations (Ghasemi & Zahediasl, 2012).

The unknown speed of vehicles at the time of impact eliminated the ability to test for correlation of speed with fracture quantity for each vehicle type and within specific skeletal regions. Speed is likely a confounding factor in evaluating injury profiles by vehicle type as multiple studies have shown that speed/velocity is an important factor in fracture characteristics (Ballesteros et al., 2004; Harruff et al., 1998; Maeda, Higuchi, Imura, Noguchi, & Yokota, 1993; Tanno et al., 2000).

Analyzing lower extremity injuries from AVP collisions is also a limitation because regions outside the pelvis and lower extremities are substantially affected in AVP collisions. By not including the head and neck, torso, and upper extremities in this analysis, an understanding of AVP collisions is weakened. Also, since the body is made up of more than just bones, organs and other soft tissues are typically considered when analyzing AVP collisions in osteological cases (Ankarath et al., 2002; Ballesteros et al., 2004; Harruff et al., 1998). The head, neck, and torso are the regions of the body, which include those vital organs, and fractures can be interpreted according to their severity based on association with vital organs (Baker et al., 1974). Additionally, studies have shown that lower extremity injuries are often associated with injuries elsewhere in the body (Ballesteros et al., 2004; Calosevic & Lovric, 2015; Hannon, Hadjizacharia, Chan, Plurad, & Demetriades, 2009; Roudsari et al., 2004).

Future Research

Due to the limiting factors of this research project, it has left many directions open for future research to build from this project. Firstly, by simply expanding this project into larger sample sizes of lower extremity data, a larger sample more likely to follow a normal distribution can be obtained for expanded statistical testing. Second, by including full-body fracture data from either more sources (i.e., autopsy records) or more comprehensive data repositories (i.e., multi-county, state, national, etc.), more complete injury profiles can be created. This inclusion would not only create more comprehensive injury profiles but also allow the application of grading fracture quantities by severity or association with vital organs. Third, the inclusion of those injury profiles of pedestrians who are involved in non-fatal collisions would create a more holistic examination of AVP injuries. The results from testing for associated injuries of non-fatal collisions could be applied to emergency medical services and the medical field. Lastly, for the most ambitious of future research projects, an analysis of all traffic-related injuries (i.e., soft tissue) could be used to create a statistical model of anticipated injuries. This analysis could allow for the input of an individual injury profile from a collision with unknown circumstances and be able to classify that individual into the most likely vehicle type group, and thus aid in investigative efforts.

CONCLUSIONS

Concluding statements

The purpose of this project was to examine the relationship between vehicle types and the injury profiles of pedestrians in fatal AVP collisions. Based on the Partial Least Squared Discriminant Analysis, this project was unsuccessful in having a high classification success rate of pedestrian injury profile for all vehicle types. It was as successful in classifying injury profiles to the “Car” vehicle type group. This project was also successful in demonstrating that fractures of the tibiae are strongly correlated with fractures of the fibulae.

RECOMMENDATIONS

Applications and Best Practices

Overall, it is not recommended that the results of this project be applied in a forensic setting. However, the results indicate that further research into this topic is necessary to have successful real-world applications to emergency medicine, hospitals, law enforcement, medicolegal investigations, and forensic anthropology. The high number of variables related to traffic fatalities leaves room for improvement to data collection and standardization.

The numerous constraints and limitations that were experienced during this project highlight some areas where data collection by law enforcement and medical examiner personnel can be improved upon. The constraints related to a lack of original information eliminated the ability to construct a comprehensive pedestrian injury profile or include variables that are known to impact fracture patterns in AVP collisions. It is recommended that when tools are available and accessible for MVC investigations, to record or estimate the actual speed of the vehicle at the time of impact to overcome these constraints in future research projects (Brach, Brach, & Mink, 2015; Han, 2018; Xu, Li, Lu, & Zhou, 2009). Additionally, it is recommended to record clearly if the vehicle was breaking or not breaking at the time of impact as a separate record from the vehicle maneuver variables. This separation is essential because breaking and turning are two separate actions a vehicle operator can make and should not be combined under one variable. In the case of WTSC records, the type of impact (i.e., front/head-on, side/broadside, rear, rollover, or left the roadway) is not recorded in pedestrian-related incidences. Therefore, it is recommended to include this variable because the type of impact has variation within groups of the same vehicle type.

In medicolegal investigations, it is recommended to have standardization practices related to imaging techniques. As demonstrated in this study, limiting radiographs to the pelvis and lower extremity in AVP fatalities limits a researcher or investigator's ability to construct a comprehensive injury profile. Therefore, it is recommended that Medical Examiner or Coroner agencies move towards a practice where the entire body is radiographically imaged before a postmortem examination, when fiscally possible. Also, it is recommended that the collection of postmortem images be standardized by the view. Collecting the same views, anterior-posterior and lateral views, for all body regions and that care be taken by imaging technicians to confirm that individual skeletal elements are clear and contained within the borders of the image, and not overlapping with other skeletal elements.

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APPENDICES

Appendix A

HUMBOLDT STATE UNIVERSITY
Institutional Review Board for the Protection of Human Subjects
707-826-5165 | irb@humboldt.edu | www.humboldt.edu/human_subjects

MEMORANDUM

Date: 1/15/2019

To: **Ariel M Gruenthal-Rankin**
Jacqulyn Scheer

From: **Susan Brater**
Institutional Review Board for the Protection of Human Subjects

IRB #: **IRB 18-106**

Subject: **ANALYZING INJURY PROFILES IN PEDESTRIAN TRAFFIC FATALITIES ACCORDING TO VEHICLE TYPE**

Thank you for submitting your application to the Committee for the Protection of Human Subjects in Research. After reviewing your proposal I have determined that your research can be categorized as Exempt by Federal Regulation 45 CFR 46.101 (b) because of the following:

Your research will involve the collection or study of existing data, documents, records, pathological specimens, or diagnostic specimens, and the sources are publicly available or the information is recorded by the investigator in such a manner that subjects cannot be identified, directly or through identifiers linked to the subjects.

The Exempt designation of this proposal will expire on 1/14/2020. By Federal Regulations, all research related to this protocol must stop on the expiration date and the IRB cannot extend a protocol that is past the expiration date. In order to prevent any interruption in your research, please submit a renewal application in time for the IRB to process, review, and extend the Exempt designation (at least one month).

Important Notes:
- Any alterations to your research plan must be reviewed and designated as Exempt by the IRB prior to implementation.
  - Change to survey questions
  - Number of subjects
  - Location of data collection,
  - Any other pertinent information
- If Exempt designation is not extended prior to the expiration date, investigators must stop all research related to this proposal.
- Any adverse events or unanticipated problems involving risks to subjects or others must be reported immediately to the IRB (irb@humboldt.edu).

cc: Faculty Adviser (if applicable)
Institutional Review Board for the Protection of Human Subjects

The California State University

Appendix B

4/29/2019 Gmail - RARC Approval Letter for 19-666 Analyzing Injury Profiles in Pedestrian Traffic Fatalities According to Vehicle Type

Gmail

Jaci Scheer <jaci.scheer@gmail.com>

RARC Approval Letter for 19-666 Analyzing Injury Profiles in Pedestrian Traffic Fatalities According to Vehicle Type

PH, RARC <PHResearchAdmin.ReviewCommittee@kingcounty.gov> Tue, Apr 16, 2019 at 4:02 PM
To: "jaci.scheer@gmail.com" <jaci.scheer@gmail.com>

Compliance Office
401 5th Avenue, Suite 900
Seattle, WA 98104
206-263-8255 Fax 206-205-3945
TTY Relay: 711
www.kingcounty.gov/health

Public Health
Seattle & King County

April 16, 2019

Jacqulyn Scheer

RE: 19-666 Analyzing Injury Profiles in Pedestrian Traffic Fatalities According to Vehicle Type

Dear: Jaci Scheer

The Research Administrative Review Committee reviewed your research proposal, 19-666 Analyzing Injury Profiles in Pedestrian Traffic Fatalities According to Vehicle Type. After completing a review of the implementation of administrative operations, the committee recommends proceeding with your research. We will keep a file of your study in our records, and ask that you submit any modification and renewals to the committee for our files and review.

Thank you for being responsive to our inquiries and we look forward to hearing about the results of your study.

Sincerely,

Jeffrey Neil Weldon

https://mail.google.com/mail/u/0?ik=a435291b2b&view=pt&search=all&permmsgid=msg-f%3A1631013591581358681&simpl=msg-f%3A16310135915... 1/2

Appendix C

Table 10. Frequency of fracture quantities comparing male (M), female (F), and total sample (T)

Number of fractures	Pelvis			Femora			Patellae			Tibiae			Fibulae		
	T	M	F	T	M	F	T	M	F	T	M	F	T	M	F
0	19	11	8	33	22	11	54	34	20	30	19	11	28	17	11
1	4	4	0	14	8	6	5	3	2	10	4	6	12	7	5
2	12	10	2	8	5	3				10	8	2	7	5	2
3	7	4	3	2	2	0				6	3	3	7	4	3
4	6	2	4	2	0	2				3	3	0	4	3	1
5	4	2	2										0	0	0
6	3	2	1										0	0	0
7	2	1	1										1	1	0
8	1	1	0												
9	0	0	0												
10	1	0	1												

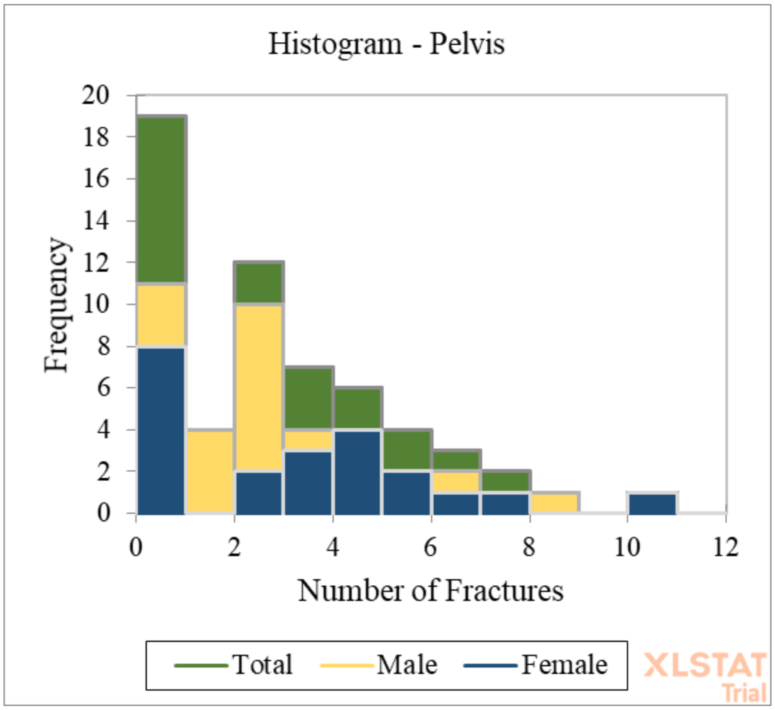

Figure 3. Histogram of the fracture frequency distribution for the pelvis skeletal region

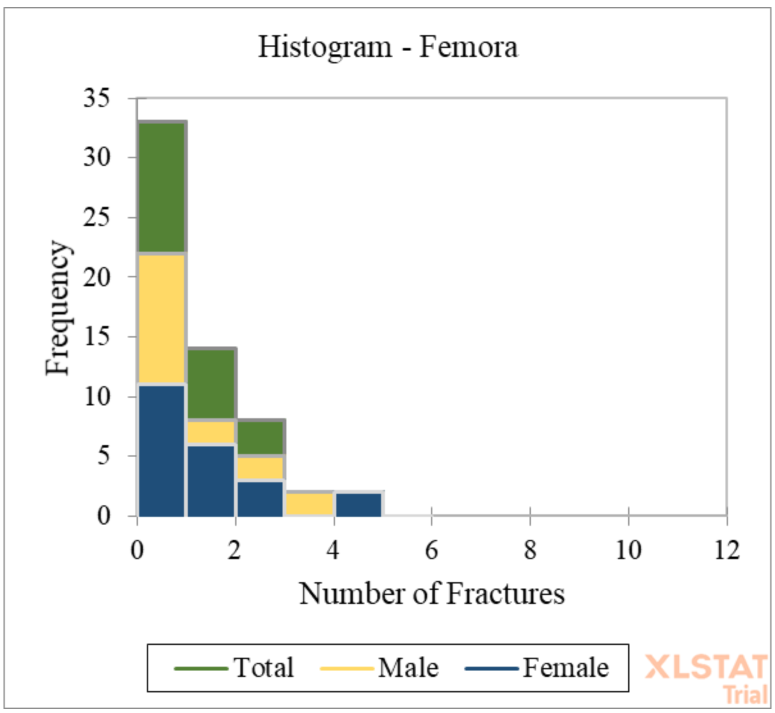

Figure 4. Histogram of the fracture frequency distribution for the femora skeletal region

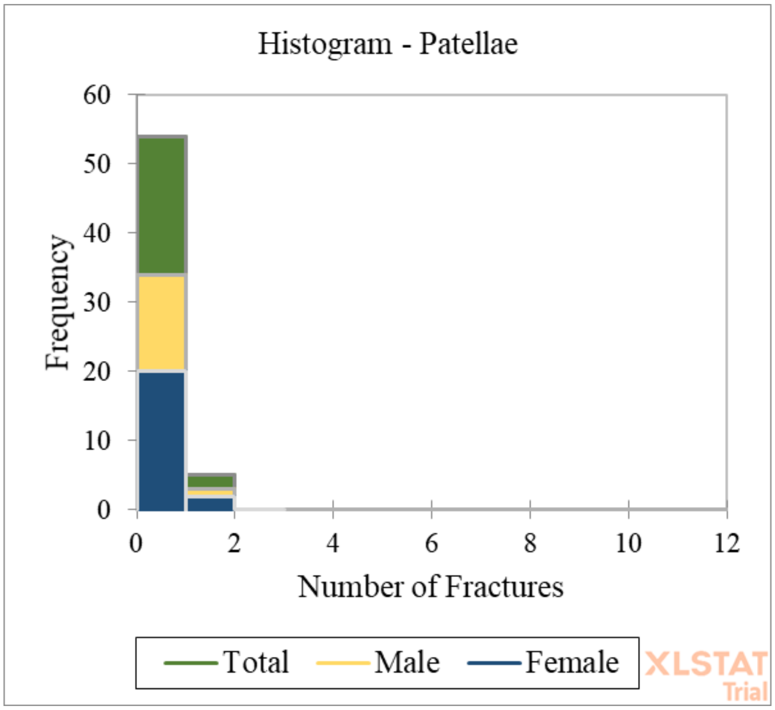

Figure 5. Histogram of the fracture frequency distribution for the patellae skeletal region

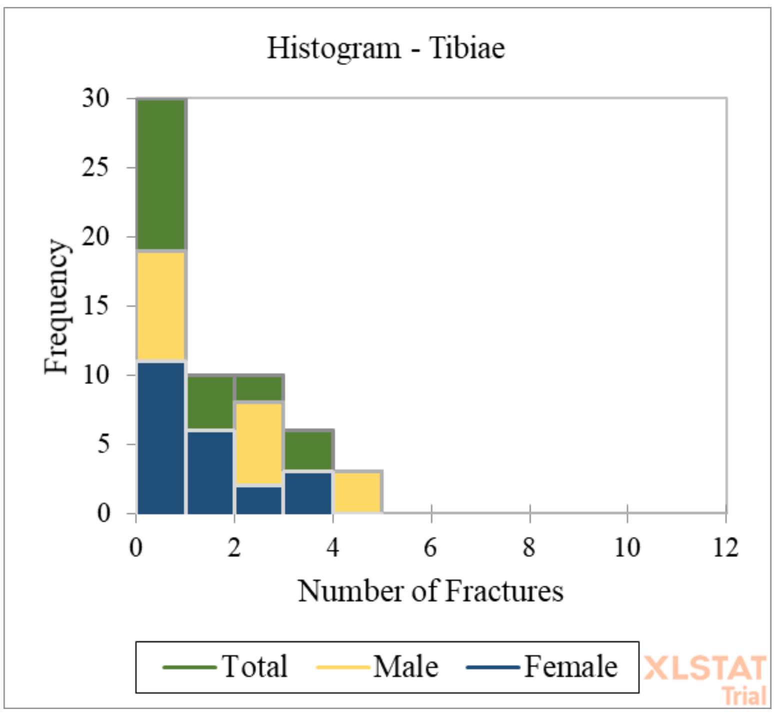

Figure 6. Histogram of the fracture frequency distribution for the tibiae skeletal region

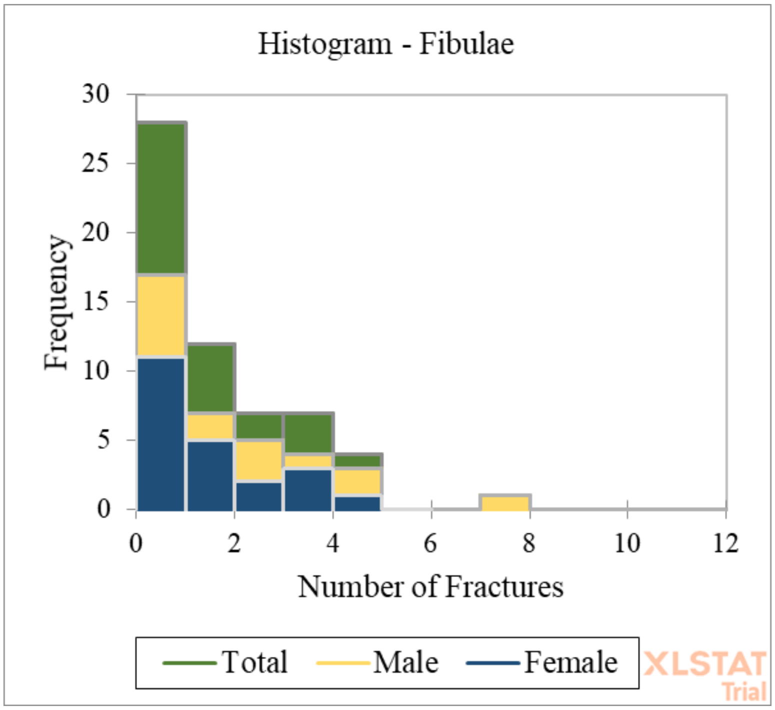

Figure 7. Histogram of the fracture frequency distribution for the fibulae skeletal region

Appendix D

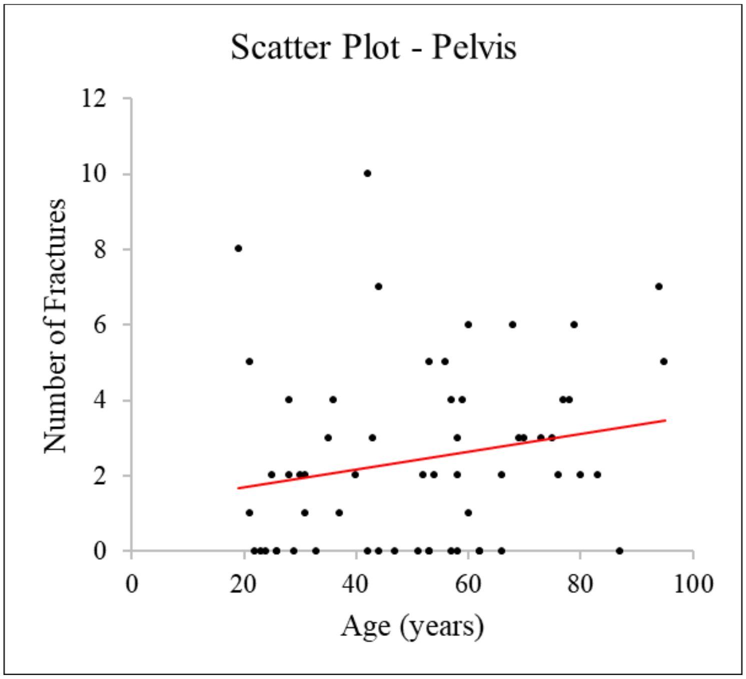

Figure 8. Scatter plot of pelvic fractures by age with the trendline in red

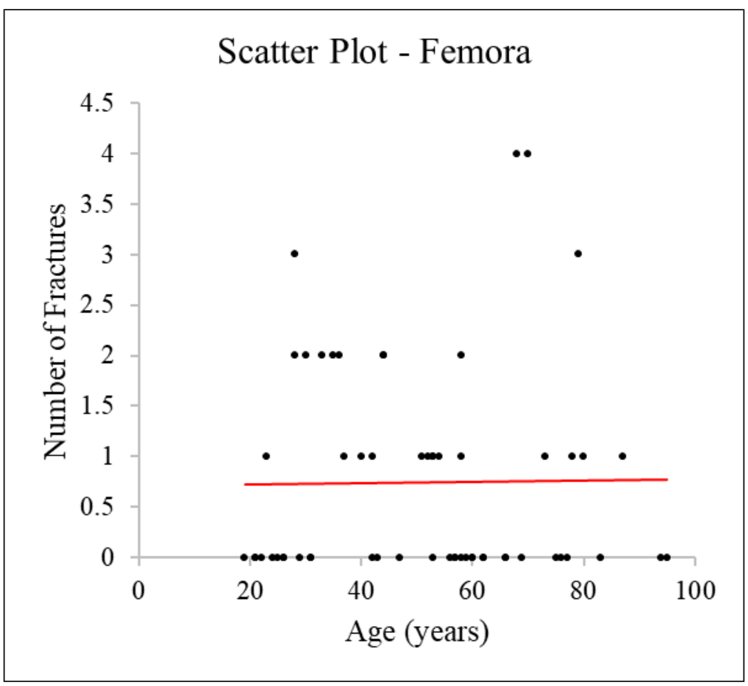

Figure 9. Scatter plot of femora fractures by age with the trendline in red

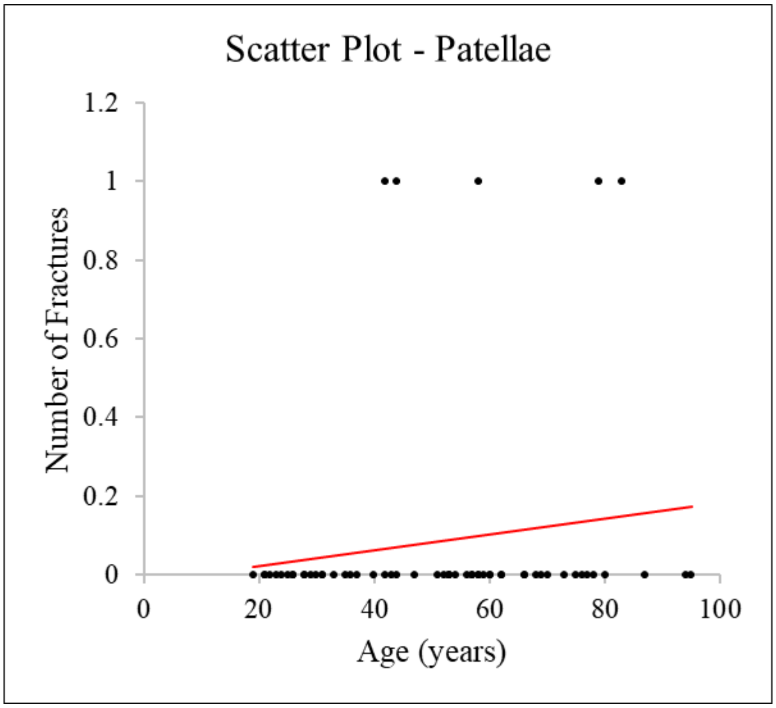

Figure 10. Scatter plot of patellae fractures by age with the trendline in red

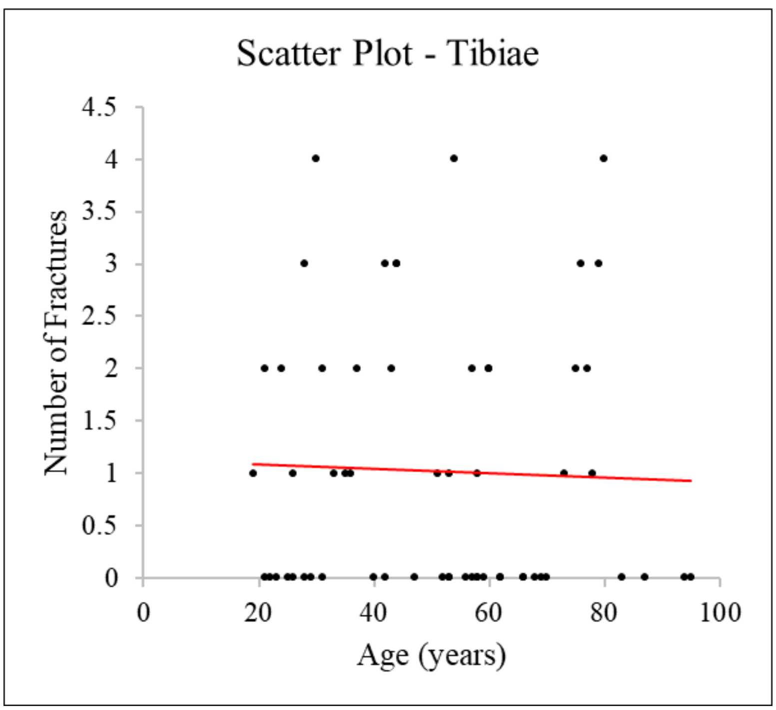

Figure 11. Scatter plot of tibiae fractures by age with the trendline in red

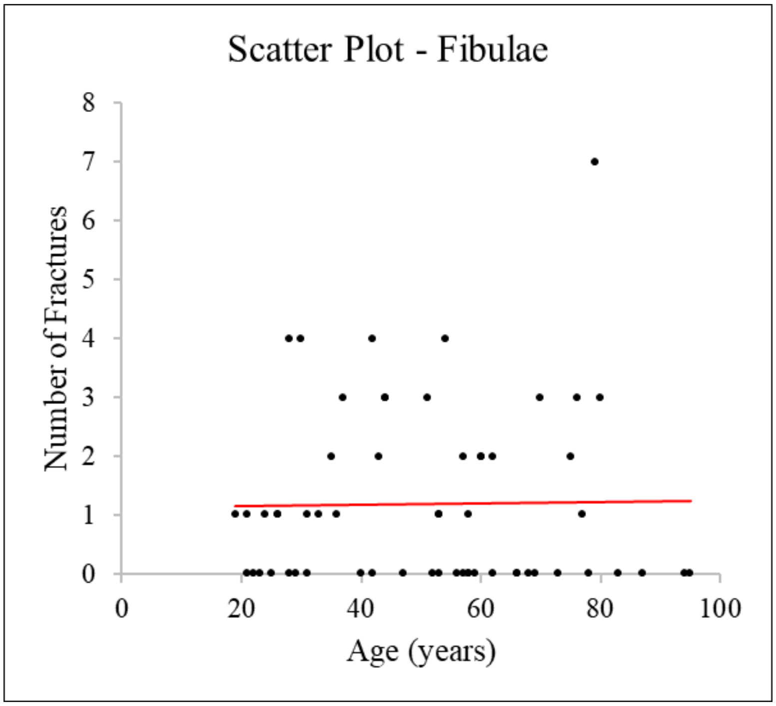

Figure 12. Scatter plot of fibulae fractures by age with the trendline in red

Appendix E

Table 11. Prior and posterior classification of vehicle type

Observation	Vehicle Type	Predicted Vehicle Type	F(1)	F(2)	F(3)	F(4)	F(5)	P(1)	P(2)	P(3)	P(4)	P(5)
Obs1	3	**1**	0.356	0.238	0.162	0.065	0.179	0.233	0.207	0.192	0.174	0.195
Obs2	2	**1**	0.367	0.248	0.136	0.053	0.196	0.235	0.209	0.186	0.172	0.198
Obs3	1	**3**	0.294	0.175	0.313	0.136	0.082	0.219	0.194	0.223	0.187	0.177
Obs4	5	**1**	0.356	0.238	0.162	0.065	0.179	0.233	0.207	0.192	0.174	0.195
Obs5	1	1	0.326	0.207	0.235	0.099	0.132	0.226	0.201	0.206	0.180	0.186
Obs6	3	3	0.287	0.167	0.331	0.144	0.070	0.217	0.193	0.227	0.188	0.175
Obs7	3	3	0.287	0.167	0.331	0.144	0.070	0.217	0.193	0.227	0.188	0.175
Obs8	2	**1**	0.321	0.202	0.248	0.106	0.124	0.225	0.200	0.209	0.181	0.185
Obs9	2	**3**	0.287	0.167	0.331	0.144	0.070	0.217	0.193	0.227	0.188	0.175
Obs10	4	**3**	0.287	0.167	0.331	0.144	0.070	0.217	0.193	0.227	0.188	0.175
Obs11	3	**1**	0.307	0.188	0.281	0.121	0.102	0.222	0.197	0.216	0.184	0.181
Obs12	2	**1**	0.418	0.301	0.009	-0.006	0.278	0.245	0.218	0.163	0.161	0.213
Obs13	3	**1**	0.308	0.189	0.280	0.120	0.103	0.222	0.197	0.216	0.184	0.181
Obs14	1	1	0.326	0.207	0.236	0.100	0.132	0.226	0.201	0.207	0.180	0.186
Obs15	1	1	0.342	0.224	0.195	0.081	0.158	0.230	0.204	0.198	0.177	0.191
Obs16	3	3	0.287	0.167	0.331	0.144	0.070	0.217	0.193	0.227	0.188	0.175
Obs17	1	**3**	0.294	0.175	0.313	0.136	0.082	0.219	0.194	0.223	0.187	0.177
Obs18	5	**1**	0.334	0.216	0.215	0.090	0.145	0.228	0.202	0.202	0.179	0.189
Obs19	1	1	0.360	0.241	0.153	0.061	0.185	0.233	0.207	0.190	0.173	0.196
Obs20	1	1	0.300	0.181	0.298	0.129	0.092	0.220	0.196	0.220	0.186	0.179
Obs21	1	**3**	0.287	0.167	0.331	0.144	0.070	0.217	0.193	0.227	0.188	0.175
Obs22	1	**3**	0.297	0.177	0.307	0.133	0.086	0.219	0.195	0.222	0.186	0.178
Obs23	1	1	0.353	0.235	0.168	0.068	0.175	0.232	0.206	0.193	0.175	0.194
Obs24	4	**1**	0.308	0.189	0.280	0.120	0.103	0.222	0.197	0.216	0.184	0.181
Obs25	2	**1**	0.314	0.195	0.265	0.113	0.113	0.223	0.198	0.213	0.183	0.183
Obs26	5	**1**	0.488	0.372	-0.163	-0.086	0.388	0.258	0.229	0.134	0.145	0.233
Obs27	1	1	0.360	0.241	0.152	0.061	0.185	0.233	0.207	0.190	0.173	0.196
Obs28	1	1	0.374	0.256	0.119	0.045	0.207	0.236	0.210	0.183	0.170	0.200
Obs29	3	3	0.294	0.174	0.315	0.137	0.081	0.219	0.194	0.223	0.187	0.177

Observation	Vehicle Type	Predicted Vehicle Type	F(1)	F(2)	F(3)	F(4)	F(5)	P(1)	P(2)	P(3)	P(4)	P(5)
Obs30	3	**1**	0.357	0.239	0.158	0.064	0.182	0.233	0.207	0.191	0.174	0.195
Obs31	3	**1**	0.300	0.181	0.298	0.129	0.092	0.220	0.196	0.220	0.186	0.179
Obs32	3	**1**	0.363	0.244	0.145	0.058	0.190	0.234	0.208	0.188	0.173	0.197
Obs33	1	1	0.506	0.390	-0.205	-0.106	0.416	0.261	0.232	0.128	0.141	0.238
Obs34	2	**1**	0.396	0.278	0.064	0.020	0.242	0.241	0.214	0.173	0.165	0.207
Obs35	1	1	0.344	0.225	0.192	0.079	0.160	0.230	0.204	0.198	0.177	0.191
Obs36	5	**1**	0.376	0.258	0.112	0.042	0.211	0.237	0.211	0.182	0.170	0.201
Obs37	4	**1**	0.307	0.187	0.283	0.122	0.101	0.222	0.197	0.217	0.184	0.181
Obs38	4	**1**	0.353	0.234	0.170	0.069	0.174	0.232	0.206	0.193	0.175	0.194
Obs39	2	**1**	0.326	0.207	0.235	0.099	0.132	0.226	0.201	0.206	0.180	0.186
Obs40	1	1	0.353	0.234	0.169	0.069	0.174	0.232	0.206	0.193	0.175	0.194
Obs41	3	3	0.294	0.175	0.313	0.136	0.082	0.219	0.194	0.223	0.187	0.177
Obs42	2	**1**	0.338	0.220	0.205	0.085	0.152	0.229	0.203	0.200	0.178	0.190
Obs43	1	1	0.339	0.221	0.203	0.084	0.153	0.229	0.203	0.200	0.178	0.190
Obs44	5	**1**	0.356	0.238	0.161	0.065	0.180	0.233	0.207	0.191	0.174	0.195
Obs45	1	1	0.405	0.288	0.040	0.009	0.258	0.243	0.216	0.169	0.163	0.209
Obs46	2	**1**	0.300	0.181	0.298	0.129	0.092	0.220	0.196	0.220	0.186	0.179
Obs47	5	**1**	0.336	0.217	0.211	0.088	0.148	0.228	0.203	0.201	0.178	0.189
Obs48	3	3	0.297	0.177	0.307	0.133	0.086	0.219	0.195	0.222	0.186	0.178
Obs49	5	**1**	0.358	0.240	0.157	0.063	0.182	0.233	0.207	0.191	0.174	0.196
Obs50	2	**1**	0.315	0.196	0.261	0.112	0.115	0.224	0.199	0.212	0.183	0.183
Obs51	1	1	0.422	0.305	-0.001	-0.011	0.284	0.246	0.219	0.161	0.160	0.214
Obs52	2	**1**	0.329	0.210	0.227	0.096	0.137	0.227	0.201	0.205	0.180	0.187
Obs53	4	**3**	0.287	0.167	0.331	0.144	0.070	0.217	0.193	0.227	0.188	0.175
Obs54	5	**1**	0.365	0.247	0.139	0.055	0.194	0.235	0.209	0.187	0.172	0.198
Obs55	1	1	0.321	0.202	0.248	0.106	0.124	0.225	0.200	0.209	0.181	0.185
Obs56	5	**3**	0.294	0.174	0.315	0.137	0.081	0.219	0.194	0.223	0.187	0.177
Obs57	2	**1**	0.413	0.296	0.022	0.000	0.269	0.244	0.217	0.165	0.162	0.212
Obs58	2	**1**	0.419	0.302	0.006	-0.007	0.280	0.246	0.218	0.162	0.160	0.213
Obs59	1	1	0.311	0.192	0.271	0.116	0.109	0.223	0.198	0.214	0.183	0.182

Car (1), Small/lightweight Truck/SUV (2), Large/heavyweight Truck/SUV (3), Van (5), Other (5)

Table 12. Outliers analysis PLS-DA: outliers bolded

Observation	DModX	DModY	Standardized dModX	Standardized dModY
Obs1	0.589	2.373	0.715	2.399
Obs2	1.649	2.100	**2.003**	2.123
Obs3	0.437	1.831	0.531	1.851
Obs4	0.589	2.536	0.715	2.564
Obs5	0.817	1.712	0.992	1.730
Obs6	0.252	1.913	0.306	1.934
Obs7	0.252	1.913	0.306	1.934
Obs8	0.797	2.212	0.968	2.237
Obs9	0.252	2.341	0.306	2.367
Obs10	0.252	3.297	0.306	3.333
Obs11	0.422	2.038	0.513	2.061
Obs12	1.612	2.073	**1.958**	2.095
Obs13	0.364	2.043	0.442	2.065
Obs14	0.735	1.713	0.893	1.732
Obs15	0.690	1.668	0.838	1.686
Obs16	0.252	1.913	0.306	1.934
Obs17	0.437	1.831	0.531	1.851
Obs18	1.182	2.633	1.435	2.662
Obs19	0.760	1.635	0.923	1.653
Obs20	0.253	1.805	0.307	1.825
Obs21	0.252	1.865	0.306	1.885
Obs22	0.434	1.821	0.527	1.841
Obs23	0.673	1.645	0.817	1.663
Obs24	0.364	3.372	0.442	3.409
Obs25	0.607	2.235	0.738	2.260
Obs26	1.386	2.261	1.683	2.286
Obs27	0.700	1.635	0.850	1.652
Obs28	0.931	1.619	1.131	1.637
Obs29	0.160	1.954	0.195	1.975
Obs30	1.825	2.384	**2.217**	2.410
Obs31	0.253	1.996	0.307	2.017
Obs32	0.629	2.422	0.764	2.449
Obs33	1.121	1.945	1.362	1.966
Obs34	1.000	2.072	1.215	2.094
Obs35	1.796	1.665	**2.182**	1.683
Obs36	0.850	2.457	1.033	2.483

Observation	DModX	DModY	Standardized dModX	Standardized dModY
Obs37	0.685	3.367	0.832	3.403
Obs38	0.561	3.560	0.681	3.599
Obs39	0.817	2.195	0.992	2.219
Obs40	0.647	1.646	0.786	1.664
Obs41	0.437	1.958	0.531	1.980
Obs42	0.822	2.160	0.999	2.184
Obs43	0.572	1.675	0.695	1.693
Obs44	0.608	2.534	0.738	2.562
Obs45	1.064	1.622	1.292	1.639
Obs46	0.253	2.286	0.307	2.310
Obs47	0.549	2.625	0.667	2.653
Obs48	0.434	1.973	0.527	1.994
Obs49	1.750	2.528	**2.126**	2.556
Obs50	0.791	2.230	0.961	2.255
Obs51	0.790	1.644	0.960	1.662
Obs52	0.421	2.186	0.511	2.210
Obs53	0.252	3.297	0.306	3.333
Obs54	1.229	2.498	1.493	2.525
Obs55	0.797	1.729	0.968	1.748
Obs56	0.160	2.844	0.195	2.875
Obs57	1.051	2.071	1.277	2.093
Obs58	0.953	2.074	1.158	2.096
Obs59	0.496	1.763	0.603	1.782