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A Biomechanical Assessment Of Canine Body Armor

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A BIOMECHANICAL ASSESSMENT OF CANINE BODY ARMOR

by

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DEDICATION

To my parents: who taught me from a young age that anything is possible and to follow my dreams. To my husband: for turning my dreams into reality and providing much needed guidance and encouragement throughout this process. I would also like to dedicate this to the men and women whose sacrifice, honor, and courage help to protect our communities and our country. And to all the animals that stand beside them as partners and protectors, together they are guardians of the night.

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CHAPTER 1 – INTRODUCTION

1.1 Statement of Problem

Military and law enforcement agencies have seen an increase in the utilization of working canines both domestically and in foreign deployments. The canine is critical in the detection of drugs and explosives, search and rescue, and deterrence. Canines have proven to be an effective tool and will continue to be utilized in the future. Although protective body armor is commercially available, current designs are thought to be cumbersome and may contribute to fatigue and heat injuries in the working canines. Also, the armor available is not tested to a canine specific standard. For a safety system to be effective, it is imperative that canine protective equipment be designed, tested, and certified based on the anatomy and biomechanical response of a canine.

1.2 Background and Significance

1.2.1 Working Canines – History and Current Roles

During World War I the main duties of the enlisted canines included casualty canines, messenger canines, and sled canines. Casualty canines traveled war zones looking for lost, injured, or deceased soldiers. When a soldier was found, canines would pull the soldier to safety before alerting others. Messenger canines were used for the exclusive purpose of getting messages, orders, or requests from one unit to another working between two handlers. Sled canines were used in packs to deliver equipment, food, and supplies to mountainous regions. These canines also searched for plane crash survivors and brought them to safety. During this time the U.S. military did not train or breed the canines used.

After the attack on Pearl Harbor the U.S. created the "Dogs for Defense" program which trained canines for military utilization. Initially, the military asked U.S. citizens to donate their pet dogs to the war effort. The canines were trained and used for purposes similar to those used in WWI with the addition of sentry and patrol duties. Sentry canines were trained as guard dogs. These canines would alert their handler to unrecognized movement or potential threats of a highly protected area. Patrol canines led troops, traveling ahead to detect potential enemy snipers or possible ambushes. They were trained to alert handlers by stiffening their bodies and tail, raising their hackles, and keeping their ears up.

During the Korean War canines were employed mainly for sentry duty. It was during the Vietnam War that their use became more sophisticated. With a canine's keen senses of smell and hearing they were used to detect enemy snipers and ambushes. With their heightened senses they were also used to track fugitives and locate mines. During this time their duties continued to include guarding protected areas and alerting soldiers to potential dangers.

Following the Vietnam War, the need for military working dogs decreased markedly. However, the drop in demand was not permanent since the demand from non-DoD (Department of Defense) government agencies began to increase. The enhanced sensory characteristics of a canine made them appealing to agencies such as the Department of Justice, Department of Transportation and Treasury Department (Frost, 1990). Detecting illegal drugs and explosives at airports became a new demand for military working dogs and the trainers. Drug-sniffing canines are able to detect a broad range of illegal drugs despite efforts at concealment and are typically used at airports, checkpoints, and other places where there is heightened security. Explosive-sniffing canines have the ability to detect small amounts of a variety of explosives. This makes them very useful at checkpoints and entry points that must be made secure. Explosive-sniffing canines perform at or above 95 percent accuracy rate and can detect odors in many different areas such as offices, theaters, barracks, warehouses, luggage, and vehicles (Dawson, Marchand et al., 2001).

This increase in demand was also felt throughout civilian law enforcement agencies. Since they were proven to be loyal soldiers they were implemented into the law enforcement community. Canines are used in civilian law enforcement to apprehend suspects, track suspects or missing persons, and/or to guard a suspect once he/she is caught. Police canines are also used as a non-lethal force and may also be trained to detect various narcotics and explosive materials.

The German Shepherd Dog was the predominant breed acquired for military service until 1984, at which time the decision was made to also purchase the Belgian Malinois breed (Peterson, Frommelt et al., 2000). German Shepherd Dogs have been the preferred standard because of the combination of their unique characteristics. Desirable characteristics for a working dog include intelligence, dependability, predictability, easy to train, usually moderately aggressive, and adaptable to almost any climatic condition. For specialized roles, detector dogs in particular, other breeds have been identified and used including smaller breeds. Retrievers and some small-breed terriers have been used for their keen sense of smell, energy, and size.

1.2.2 Efficacy of Protective Body Armor in Humans

The nature of most injuries resulting from military or law enforcement (Local, State, and Federal) activity reflects the weapon(s) predominately used in that region. The threats that are most common will dictate which protective body armor would be appropriate in preventing or mitigating injuries. Flak jackets were used in previous wars and were effective against shrapnel but not bullets. In an effort to address this, Kevlar® was developed following the Vietnam War. This fiber revolutionized protective armor, exhibiting desirable characteristics such as strength, weight, and flexibility. The fibers could be woven together to create sheets which could then be layered to create a flexible ballistic resistant panel. The layers would vary depending on the level of threat protection required. Some vests may be supplemented with metal, ceramic, or polyethylene plates to provide additional protection.

Personal body armor is designed to cover the torso, protecting vital organs from penetrating ballistic injuries. When impacted by a bullet or shrapnel, the woven fibers absorb and dissipate the energy over a large area, reducing injury severity and reducing the risk of the object entering the body. Armor is designed to not only prevent life threatening injuries but also allow officers or soldiers to move to a safer position and return fire.

The most common threats faced by military personnel include explosives (IED and non-IED), gunshot wounds, blunt trauma, and burns (Mabry, Holcomb et al., 2000; Kotwal, Montgomery et al., 2011). Gunshot wounds and shrapnel are the most common causes of injury in the battlefield. Studies have been published investigating the effectiveness of body armor in a military setting (Mabry, Holcomb et al., 2000;

Kosashvili, Hiss et al., 2005; Peleg, Rivkind et al., 2006). A study analyzed casualty data collected during a conflict involving the U.S. Army Rangers in Somalia in 1993. This study found the wounding mechanisms of the casualties were bullets (55%), fragments (31%), blunt trauma (12%), and burns (2%) (Mabry, Holcomb et al., 2000). Most fatalities were caused by bullets entering through areas not covered by armor. According to the study, no projectiles entered through the anterior chest or upper abdomen where solid armor plates were worn. Body armor reduced the mortality rates of injuries to the chest and prevented small fragment wounds to the abdomen (Mabry, Holcomb et al., 2000).

A study by Peleg et al. evaluated civilian and military injury and outcome data to determine whether body armor proved to be effective (Peleg, Rivkind et al., 2006). This study investigated records from the Israeli national trauma registry from October 1, 2000 to December 31, 2003. When comparing the unprotected civilians to the protected soldiers it was determined that armor reduces the presence and severity of injuries to the chest and the abdomen. In a military setting protective helmets are also worn. It was noted that the occurrence of head injury was more frequent in the unprotected civilians. Unfortunately, in this study the types of armor worn by the military personnel were not available in the database; therefore, the individual effectiveness of hard or soft armor against high velocity bullets cannot be confirmed based on this data set.

Threats affecting civilian law enforcement vary from those experienced by military personnel. According to the Law Enforcement Officers Killed and Assaulted (LEOKA) database, from 2004-2013 the weapons that law enforcement officers encountered most frequently included firearms, vehicles, and personal weapons (hands, feet, etc.) (FBI-LEOKA). Of the officers assaulted and injured during this time the most commonly reported injuries resulted from personal weapons (28.6%), other dangerous weapons (23.9%), knife or other cutting objects (12.7%), and firearms (9.3%). Law enforcement officers are most often feloniously killed by firearms (92.8%), more specifically handguns. Of the 474 officers feloniously killed with a firearm from 2004 through 2013, 72.8% of those officers lost their lives as a result of a handgun, followed by a rifle (18.4%), and a shotgun (8.4%). The most frequently reported handgun was a 9 millimeter (26.7%) followed by the .40 caliber (19.4%).

Although there are efforts to improve body armor and increase its use, there are few studies reporting the effectiveness of armor in civilian law enforcement. LaTourette evaluated the effectiveness of armor for police officers and found that body armor more than triples the likelihood a police officer will survive a shooting to the torso (LaTourrette, 2010). This study estimated that providing body armor to all police officers nationwide would save at least 8.5 lives per year. According to the LEOKA database, of the officers that were feloniously killed by a firearm from 2004 to 2013, 35.0% were not wearing body armor (FBI-LEOKA). Body armor use is also actively promoted by police organizations such as International Association of Chiefs of Police (IACP). The IACP started an organization to bring recognition to those officers whose body armor saved their life. The IACP/DuPont™ Kevlar® Survivors' Club® is a collaboration between IACP and DuPont which began in 1987 and has recognized over 3,100 lives saved as a result of body armor (DuPont, 2013).

The majority of law enforcement officer fatalities from a firearm while wearing body armor (2004 to 2013) are the result of a projectile entering above the shoulders (head and neck) (68.8%) followed by anterior or posterior torso (30.5%) (FBI-LEOKA). The most common area of thoracic entry was reported to be the armhole or shoulder area (38.3%). The second most common cause was attributed to the bullet exceeding the certification level of the vest (velocity and/or caliber of bullet) and penetrating completely through the armor panel (18.1%). Other areas of entry causing fatal injuries from torso wounds included between side panels, above or below the vest, or armor failure resulting in vest penetration.

Researchers have proven that body armor is effective at minimizing the severity and preventing life threatening injuries to the thoracic cavity and upper abdomen (FBI-LEOKA; Mabry, Holcomb et al., 2000; Peleg, Rivkind et al., 2006; LaTourrette, 2010). There is a continuing effort between researchers, manufacturers, and end users to investigate new body armor designs for both military and law enforcement to improve protection while still allowing the soldier or officer to be effective in the field.

1.2.3 Injuries to Working Canines and Behind Armor Trauma

Although the United States military has conducted studies regarding the cause of death in the military working canines, traumatic causes are not reported as major concerns (Dutton and Moore, 1987; Jennings and Butzin, 1992; Moore, Burkman et al., 2001). One study did investigate gunshot wounds in military canines and found the most common site of injury to be the thorax followed by extremity wounds (Baker, Havas et al., 2013). Baker et al. investigated 29 injury cases resulting in a 38% survival rate. Wounds to the thoracic cavity were most likely to result in death of the canine. A recently published study investigated causes for emergency veterinary visits for police canines (Parr and Otto, 2013). German Shepherd Dogs (GSD) from police departments, government, or security agencies that sought veterinary treatment at The Ryan Veterinary Hospital of the University of Pennsylvania were compared the pet GSD in the medical database from 2008 - 2010. Orthopedic injuries were significantly more common in law enforcement canines when compared to the pet canines. Both groups of canines presented with trauma or wounds but there was no significant difference between the two cohorts. Both studies are important in identifying the injuries that are experienced by military and law enforcement canines in the field. Further data should be collected to identify in more detail the traumatic injuries sustained by military or law enforcement working canines as a result of their responsibilities.

Even though body armor protects from life-threatening penetrating injuries, there is still a possibility of a less severe blunt trauma injury (Cannon, 2001). Blunt trauma injuries occur as the bullet's energy is distributed over a larger area, generally resulting in injuries such as bruising, rib fractures, backface signature injuries, and/or lung contusions. Backface signature injuries are lacerations that occur because of blunt trauma (Wilhelm and Bir, 2007). When the armor deformation is more localized the resulting injury is an open penetrating wound. This occurs when the vest does not successfully distribute the energy over a large enough area. Behind armor blunt trauma has also been evaluated with animal and computer models to determine internal injuries that may occur as a result (DeMuth, 1968; Moseley, Vernick et al., 1970; Carroll and Soderstrom, 1978; Linden, Berlin et al., 1988; Roberts, O'Connor et al., 2005; Roberts, Ward et al., 2007; Merkle, Ward et al., 2008). In a previously published study using a swine model, a variety of bullet calibers and velocities were used along with varying layers of Kevlar® protecting the swine thorax to ensure no penetration of the rounds

(Linden, Berlin et al., 1988). This study found that as energy transfer increased the severity of pulmonary contusions and lacerations also increased. The severity of underlying injuries (e.g. life-threatening lung injuries) may not correlate with the external injuries such as thoracic wall contusions (Carroll and Soderstrom, 1978). Despite the armor stopping the projectile from entering the thoracic cavity, internal organs such as the heart, lungs, liver, spleen, and spinal cord are still at risk for potential injury in humans and should be evaluated following a behind armor blunt trauma.

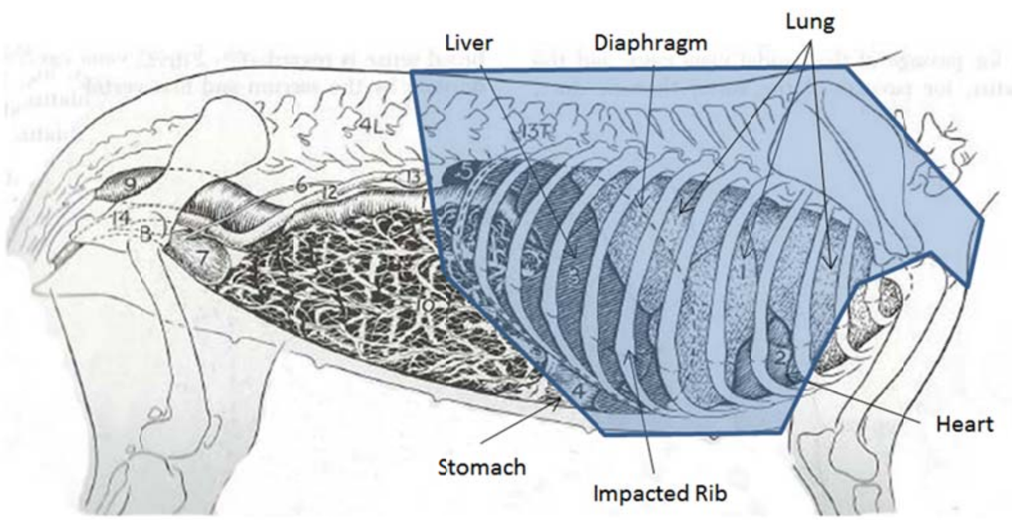


Figure 1.1: Typical armor coverage for canine (adapted from (Evans, 1993))

Manufacturers are currently producing canine armor; however, there is no mandate for canines to wear protective armor in either the military or law enforcement. The percentage of working canines that wear canine ballistic armor in the field is not known and accounts of canines being saved by the armor, to the author's knowledge, have not been reported. With the increased availability of canine specific armor, similar caution, with respect to internal injury, should be taken if working canines experience behind armor blunt trauma. Various coverage designs and ballistic threat level protections are available with the primary coverage area focusing on the thorax and upper abdomen (Figure 1.1). The currently manufactured armor is comprised of material which has been tested to the NIJ standard for ballistic resistance (NIJ-0101.06, 2008). This standard was developed using an anesthetized goat model for human protection. There is no canine specific standard in place and testing the armor materials to NIJ 0101.6 standard may over-protect or under-protect the canines. Given the immense expense incurred by Local, State, and Federal governments in acquiring, training, and maintaining these highly-skilled animals, it would seem advisable to establish the behind armor blunt trauma response for the canine thoracic cavity in order to determine the most effective way to protect these vital animals.

1.3 Specific Aims

Overall, there is very limited information in the literature regarding injuries sustained by canines used in civilian law enforcement and ways to protect them. For a canine specific standard to be developed, the biomechanical response of a canine must be determined. With this knowledge, improvements can be made to better the protection for working canines. The specific aims for this project include:

1.) Compile a database of canine casualties to determine commonly reported causes of death or need for euthanasia while in service for civilian law enforcement canines.
2.) Evaluate the biomechanical response of the canine thorax to a behind armor blunt impact.
3.) Identify an injury criterion that will best predict canine thoracic injuries resulting from behind armor blunt impact.

4.) Measure the correlation between the behind armor blunt trauma response and the standard backface testing medium (clay) to evaluate the current armor standard.

5.) Evaluate currently manufactured canine body armor to determine if the armor inhibits the canine from performing tasks.

CHAPTER 2 – CANINE THORACIC ANATOMY

2.1 Introduction

Commercially available canine armor typically covers the rib cage, protecting the vital organs beneath. The armor will not only protect organs in the thorax but could also protect vital organs in the abdominal cavity which are also protected by the rib cage. Before discussing the response of the canine thoracic cavity, a brief overview of the anatomy of a canine is essential for understanding methods and results of this study. Directional terms used when referencing quadrupeds vary from those pertaining to humans (Figure 2.1). For a canine, the anatomical position of standing is with four paws on the ground and the abdomen positioned ventrally.

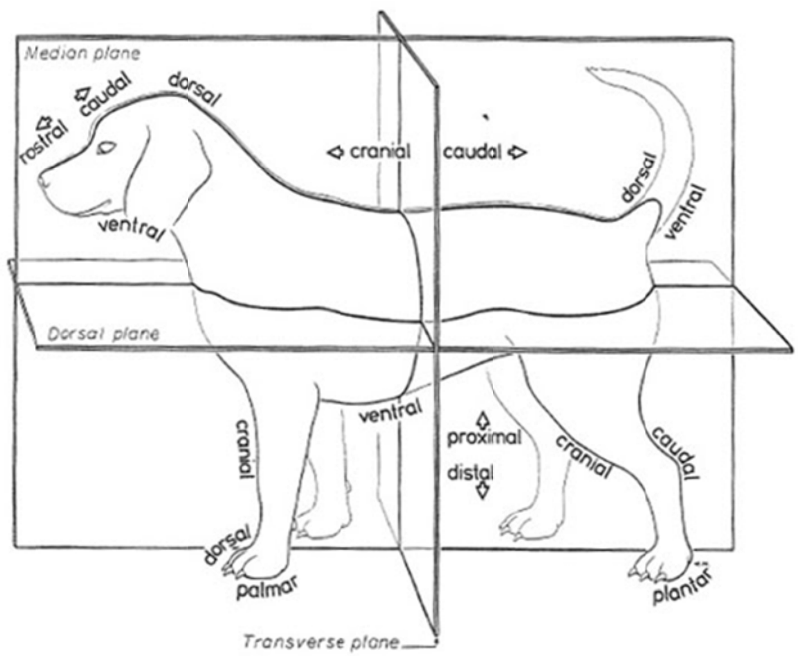


Figure 2.1: Anatomical terms of location for canines (Evans, 1993)

The shape of the thorax of a canine is also different from that of humans since its walls are laterally compressed. A canine's average dorsoventral measurement is greater than either the average lateral or craniocaudal measurement (Evans, 2013). Figure 2.2, adapted from (Huelke, Nusholtz et al., 1987), illustrates a comparison between the human and canine thoracic cavity. The canine thoracic cavity is roughly oval in shape, narrower below than above, and long dorsoventrally.

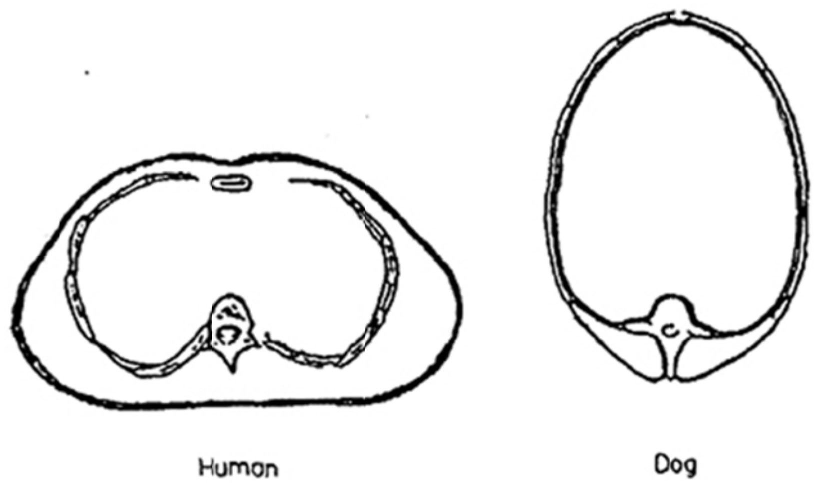


Figure 2.2: Comparison of human and canine thoracic cavity shape (Huelke, Nusholtz et al., 1987)

The thoracic cavity walls are created, in a general sense, by muscles, bones, and ligaments. Bilaterally the thoracic walls are formed by intercostal muscles and ribs, and dorsally by thoracic vertebrae. Ventrally, the sternum and transversus thoracis muscles contribute to the floor of the thoracic wall. And caudally, the base of the thoracic cavity is formed by the diaphragm.

The thoracic cavity contains the heart, lungs, lymph nodes, and thymus gland (Figure 2.3). The structures that partly or completely transverse the thoracic cavity are the aorta, cranial vena cava and caudal vena cava, azygos and hemiazygos veins, thoracic duct and smaller lymph vessels, esophagus, and vagal, phrenic, and sympathetic nerves (Evans, 2013).

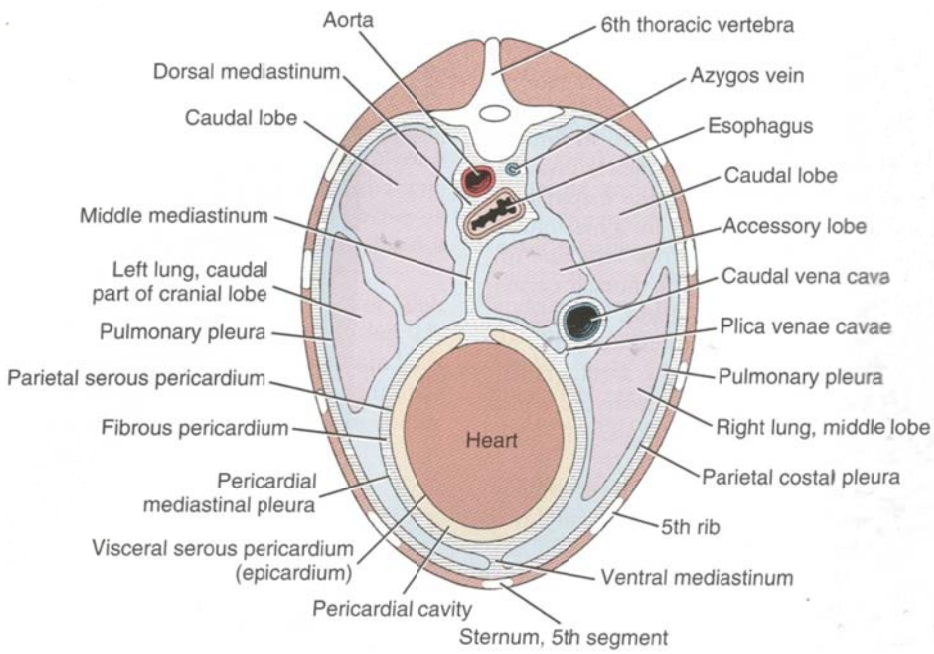


Figure 2.3: Cross section view of the thoracic cavity (Evans, 2013)

2.2 Thoracic Wall

The bony structures that make up the thoracic walls of a canine are similar to that of a human. The vertebral column, ribs, and sternum protect the thoracic organs (Figure 2.4).

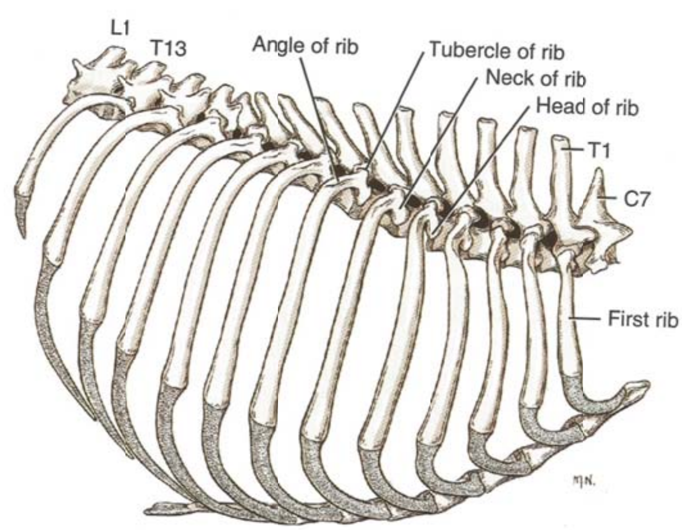


Figure 2.4: Thoracic bony structures of a canine (Evans, 2013)

2.2.1 The Vertebral Column

The vertebral column is arranged in five groups: cervical (C), thoracic (T), lumbar (L), sacral (S), and caudal (Cd). The number of vertebrae in each group can be explained with the following formula: C_7 T_{13} L_7 S_3 Cd_{20}. The number of caudal vertebrae can vary depending on breed of canine (Evans, 2013). The vertebrae protect the spinal cord and roots of the spinal nerves, aid in the support of the head, and supply attachment for the muscles directing body movement. A typical vertebra consists of a body, a vertebral arch, and various processes for muscular or articular attachments, which could include transverse, spinous, articular, accessory, and mamillary processes (Evans, 2013).

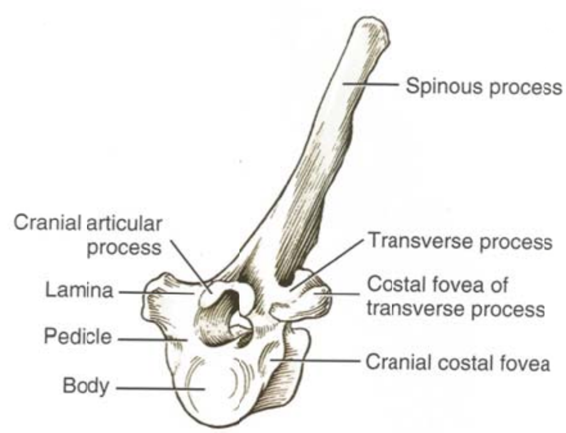


Figure 2.5: Sixth thoracic vertebra, lateral aspect (Evans, 2013)

For the current study, the focus is on the thoracic region. There are 13 thoracic vertebrae. The nine most cranial are rather similar, while the four more caudal have slight differences (Figure 2.5 and Figure 2.6). The bodies of the thoracic vertebrae are shorter than those of the cervical or lumbar regions. The pedicles of the vertebral arch are short. The laminae give rise to a spinous process, which is the most obvious feature of the first nine thoracic vertebrae. There is little change in length or direction of the spinous processes until the seventh or eighth thoracic vertebra is reached. They then become progressively shorter and are inclined increasingly through the ninth and tenth segments (Figure 2.6). The spinous process of the eleventh vertebra is almost perpendicular to the long axis of the bone.

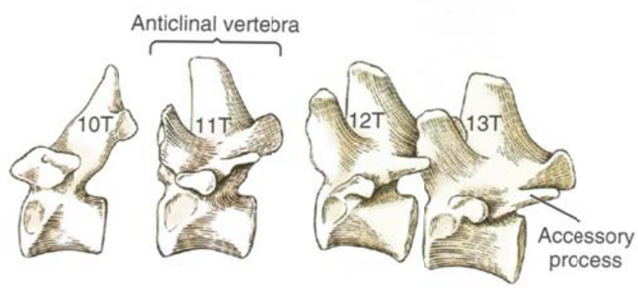


Figure 2.6: The last four thoracic vertebrae, lateral aspect (Evans, 2013)

The heads of the first pair of ribs articulate with the first thoracic and sometimes the last cervical vertebra. Tubercles of the ribs articulate with the transverse processes of the thoracic vertebrae of the same number. The transverse processes of the thoracic vertebrae are short, irregular, and blunt.

2.2.2 The Ribs

There are 13 pairs of ribs that form the bilateral limits of the thoracic cavity. Each rib is divided into a dorsal bony part and a ventral cartilaginous part (costal cartilage) (Figure 2.4 and Figure 2.7) (Evans, 2013). The sternal ribs are defined as the first nine ribs articulating with the sternum followed by the asternal ribs. The costal cartilage of the tenth, eleventh, and twelfth asternal ribs unite with the cartilage of the rib directly above to form the costal arch on each side of the thoracic cavity. The cartilages of the last pair of ribs end in the musculature and are sometimes referred to as the floating ribs, similar to the human anatomy. The ninth ribs are the longest, with the longest costal cartilages (Evans, 2013). The space between adjacent ribs is known as the intercostal space. These spaces tend to be two to three times wider than the adjacent ribs.

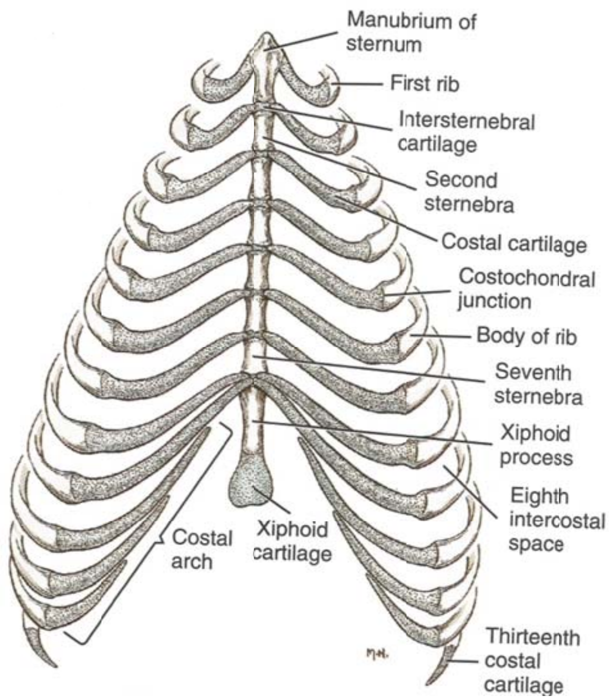


Figure 2.7: Ventral Aspect of ribs and sternum (Evans, 2013)

A typical rib consists of a vertebral extremity (consisting of head, neck, and tubercle), sternal extremity, and body (Figure 2.4). The body of the rib is slightly enlarged at the costochondral junction and generally cylindrical in shape. The third, fourth, and fifth ribs exhibit some lateral compression of the distal halves of the bony part (Evans, 2013). Typically, in larger breeds the ribs are flatter when compared to smaller breeds.

2.2.3 The Sternum

The sternum is an unpaired, segmented row of eight bones (sternebrae) that form the thoracic cavity base (Figure 2.7) (Evans, 2013). The consecutive sternebrae are joined by intersternebral cartilage (short blocks of cartilage). The sternum of the canine is laterally compressed. The first and the last sternebrae are unique. The first sternebra is expanded and has lateral projections for the attachment of the first costal cartilage. It is also longer than the others and is referred to as the manubrium. The last sternebra, called the xiphoid process, is wide horizontally and thin vertically (Evans, 2013). A thin cartilaginous plate prolongs the xiphoid process caudally.

The sternal edge of the rib articulates with the intersternebral cartilage of the sternum, with the exception of the first pair, which articulates with the first sternebra. Succeeding rib cartilages articulate with successive intersternebral cartilages (Evans, 2013). However, the eighth and ninth costal cartilages articulate with the cartilage between the seventh sternebra and the xiphoid process.

2.2.4 Musculature

The muscles of the vertebrae, for the most part, represent the trunk muscles. Aside from the cutaneous musculature, the muscles of the vertebrae are grouped into five layers (Figure 2.8). The two superficial and part of the third layers control movement of the limbs, shoulder and neck. The serratus ventralis, part of the third layer, supports the trunk and the movement of the trunk. The musculature that comprises the remaining layers aid in inspiration and expiration, head and neck movement, lateral movement of the trunk, and fixation of vertebral column (Hermanson, 2013).

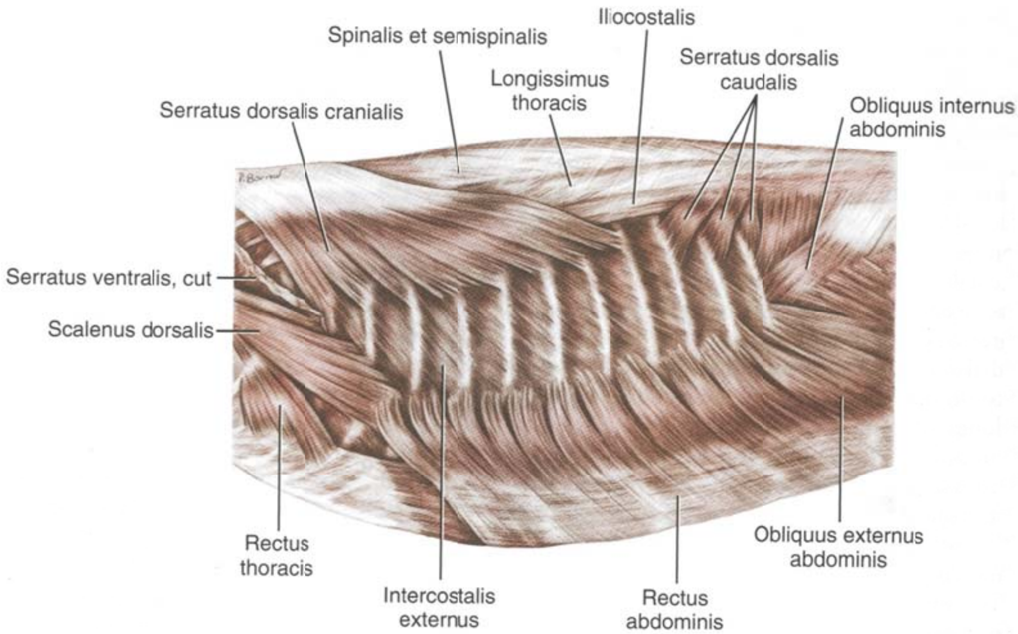


Figure 2.8: Superficial muscles of thoracic cage (Hermanson, 2013)

The spaces between the ribs are filled by the double layer of intercostal muscles (internal and external), which cross each other (Figure 2.9). External intercostal muscles give rise to the levator costae proximally. The fibers come from the transverse process of the corresponding thoracic vertebra. During the inspiratory phase of the breathing cycle, these muscles elevate the ribs and expand the rib cage. Cranially on the thorax, the rectus thoracis covers the superficial ends of the first ribs; the transversus thoracis crosses the cartilage of the sternal ribs and the sternum deeply. These muscles also aid inspiration and expiration.

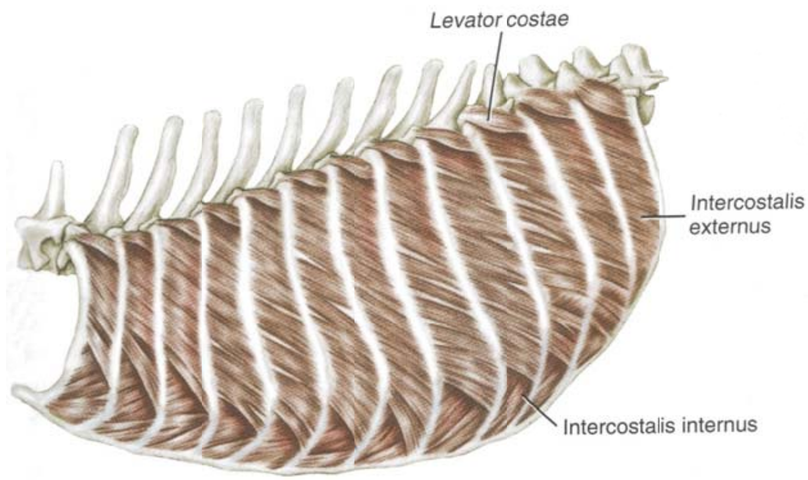


Figure 2.9: Deep muscles of thoracic cage (Hermanson, 2013)

2.3 Thoracic Cavity

2.3.1 The Mediastinum and Pleurae

The mediastinum is the space between the right and left pleural sacs that encloses the thymus, heart, aorta, trachea, esophagus, the vagus nerves, and other nerves and vessels. In humans, the mediastinum is quite strong, due to a significant amount of collagenous tissue, so that one lung can collapse independently of the other. In dogs, the tissue of the mediastinum tends to be extremely limited.

The pleurae are the serous membranes that cover the lungs, line the walls of the thoracic cavity, and cover the structures in the mediastinum (Evans, 2013). The pleurae form two complete sacs, the parietal and pulmonary. Each cavity is essentially only a prospective cavity because it contains only a capillary film of fluid. Only when gas or fluid collects between the pulmonary and parietal pleurae, preventing a lung from expanding, does it exist as a real cavity.

2.3.2 The Lungs

The respiratory system of the canine serves two purposes. The first basic function, just as in humans, is to bring in oxygen to the body and remove carbon dioxide. The second purpose of the respiratory system in canines is to help cool down the body. In humans, body temperature can be controlled by sweating; however, this is not the case for canines. In order to decrease the body temperature of a canine, heavy breathing (panting) is necessary.

The canine respiratory system consists of the upper and lower respiratory tract. The upper includes nasal cavities, nasopharynx, larynx, and trachea. The lower portion contains bronchi and lungs. When oxygen is needed, the diaphragm contracts which increases the pleural cavity by moving caudally. The intercostal muscles contract and draw the ribs cranially, increasing the size of the thoracic cavity and thus air is drawn into the lungs from the upper respiratory tract. The abdominal muscles aid in the expulsion of the air from the lungs. Inside the lungs, the bronchi divide into decreasing divisions of tubes, called bronchioles. At the microscopic level, the bronchioles end in small structures called aveoli where the blood makes contact with the cells in the lungs and oxygen is exchanged for carbon dioxide.

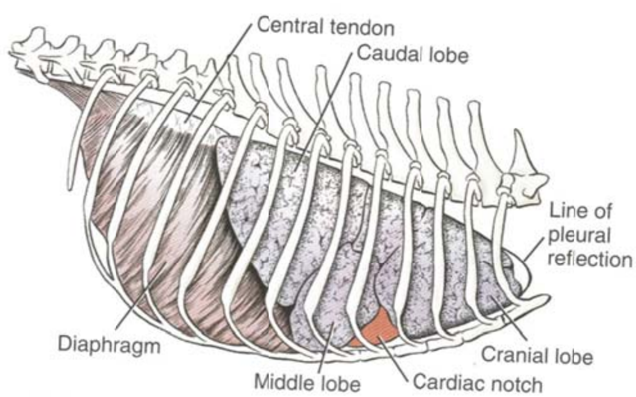


Figure 2.10: Thoracic cage and lungs (Evans, 2013)

The left lung of the canine is divided into two main lobes: the cranial and caudal lobe. The cranial lobe is further divided into the cranial and caudal part. The right lung is divided into cranial, middle, accessory, and caudal lobes. The lungs span from the first rib to the diaphragm (Figure 2.10). In the healthy canines, the greatest cranial encroachment of the diaphragm can be to the sixth intercostal space. However, in certain conditions the diaphragm can be pushed farther into the thorax.

2.3.3 The Heart

The heart is covered in a fibrous, thin, tough sac called the pericardium and is the muscular pump of the cardiovascular system. The cardiovascular system includes the heart and blood vessels and performs the function of pumping and carrying the blood to the rest of the body. The heart is located between the lungs beginning at the level of the third rib through the sixth rib. Blood vessels form an intricate system throughout the body, carrying blood to all organs, tissues and cells.

The canine's heart is very similar to the human heart. The heart has four chambers: a right and left atrium and a right and left ventricle. The chambers on the right side receive blood from the body and send it out to the lungs to be replenished with oxygen. Blood returns from the lungs to the left side of the heart, then the strong left ventricle pumps the oxygen enriched blood to the body. Arteries are muscular blood vessels that move the oxygen rich blood to the body, while veins bring the oxygen depleted blood back to the heart and lungs. Capillaries are the smallest of all blood vessels and are the site of the greatest exchange material between the blood and tissue of the body.

2.4 Abdominal Cavity

The abdomen is the portion of the canine’s body that extends from the diaphragm to the pelvis. The abdominal cavity is the largest cavity in their body. The abdomen can be grouped into three regions as determined by transverse planes: cranial abdominal region, middle abdominal region, and caudal abdominal region (Evans, 1993). The cranial abdominal region is still for the most part protected by the rib cage while the other regions are primarily muscle bound. The liver, spleen, and stomach are included in the cranial region of the abdomen and are protected by the rib cage and diaphragm.

2.5 Discussion

There are a few differences in the thoracic cavity anatomy between humans and canines. One obvious difference is the fact that canines are quadrupeds. The normal, gravitational forces resulting from the mass of each anatomical structure are in the ventral-dorsal direction (anatomical equivalent of anterior-posterior in humans) in contrast to humans in which these are in the superior-inferior direction. The general shape of the thoracic cavity of a canine is oval where the greatest measurement is in the ventral-dorsal direction. For humans, the greatest thoracic cavity measurement is in the lateral direction.

Due to these differences there is a potential that the canine thoracic response will differ from the human thoracic response. In the literature, biomechanical response, injury mechanism, and tolerance studies have been aimed at preventing injuries in humans. Therefore, canine specific data must be collected to establish a testing standard tailored the response of canines.

CHAPTER 3 – Review of Canine Deaths While in Service in Civilian Law Enforcement (2002 – 2012)

A portion of this chapter was published in the Journal of Special Operations Medicine by Stojsih S, Baker J, Les C, and Bir C. The full manuscript can be found in Appendix B.

3.1 Introduction

The use of databases to track traumatic injuries in both civilian law enforcement and military has been well established (FBI-LEOKA; Eastridge, Costanzo et al., 2009; LaTourrette, 2010; Kotwal, Montgomery et al., 2011). Compiling these data assists in identifying common injuries and in more severe cases, causes of death. With this knowledge, efforts to reduce or prevent these issues can be made. For instance, protective armor has been proven to mitigate injuries and risk of human casualties (Mabry, Holcomb et al., 2000; LaTourrette, 2010). Collecting and tabulating these data not only helps identify lifesaving procedures but it is also essential in developing ways to improve protective equipment. Although injury databases are fairly well developed for human medicine, they are lacking for veterinary medicine more specifically, the working canine population.

Currently, there is no centralized method of tracking traumatic injuries or illnesses in working canines used in civilian law enforcement. However, there has been established a working canine memorial website that has created an extensive list of canines that have died or were euthanized while in service (CPWDA, 1991). At the time of this review, according to the website, 1,867 military working and law enforcement working canines have reportedly died in service from 1940-present (CPWDA, 1991).

There are obvious limitations with lists created from non-clinical sources when generating a scientific database. However, given the lack of availability of this information, some useful generalizations may be obtained from compiling and analyzing these data. The current study consolidates the type of data that is available from the existing websites and reports the results based on traumatic and non-traumatic causes of death or euthanasia. Gathering canine casualty data can potentially assist in better prevention and treatment of injuries in this specialized population of working canines.

3.2 Methodology and Materials

In an effort to delineate the key factors related to fatal outcomes, causes of death were investigated for working canines used in civilian law enforcement in the United States between the years of 2002-2012. The primary website reporting these incidents is maintained by the Connecticut Police Work Dog Association (CPWDA) (CPWDA, 1991). Canines listed were killed or euthanized, while in service, from agencies across the U.S., various countries, and military. The Officer Down Memorial Page (ODMP) also has a program dedicated to fallen law enforcement canines in the U.S. that was launched in September 2012 (ODMP, 2012). Cases not listed on the CPWDA website but listed on ODMP were combined for the current study. Both websites are used as memorials and the data made available were self-reported by the handler or other contributors familiar with the incident (another handler, friend, spouse, etc.).

Data listed on the websites are organized by year of incident. Additional data that can be found on these websites include canine name, location, and cause of death. Data on the CPWDA website dates back to the Vietnam War, however, these data were difficult to verify and therefore all events that occurred before 2002 and/or outside the

United States were excluded from the study. Military working dogs were also excluded since these websites are directed toward the law enforcement community and thus the military canines may be underrepresented. Finally, the time frame of the study was limited to create a more manageable and representative population of law enforcement canines by removing incidents occurring before 2002, two years after the CPWDA memorial site went on-line.

Remaining data were organized and causes of death were tabulated and compared. Causes of death were separated into two main categories “non-traumatic” and “traumatic”. Deaths attributed to an illness or pathophysiology (i.e. cancer, gastric dilatation-volvulus (GDV), degenerative diseases, other medical conditions) were categorized as “non-traumatic.” Deaths caused by an external circumstance that may have been prevented (i.e. blunt trauma, gunshot wound (GSW), falls, other accidents) were categorized as “traumatic.” An attempt to gather further data from other online sources was made for each case. Key criteria were used to ensure the incidents were identical when investigating for further information on the internet. If two or more incidents shared the same date, canine name, location, and incident description, the incidents were considered to be coincident, and additional information was extracted. Details such as breed, age, and further description of incident or cause of death were the main focus. In some cases, generally involving a traumatic cause of death such as ballistic trauma or heatstroke, detailed descriptions of the circumstance surrounding the incident (e.g. friendly fire, confinement heat injury) could be found and were recorded. There were a number of cases reported on the websites that had “unknown” listed as the cause of death. If further information could not be obtained, the case was not included in the data set.

3.3 Results

Between the years of 2002 and 2012, there were 867 law enforcement canines reported to the CPWDA or ODMP K9 databases as being killed or euthanized while in service in the US with a known cause of death. Although breed information was not available for all cases (10.0%, n = 87), the majority of the cases of where breed information was obtained involved the German Shepherd Dog (48.7%, n = 422) followed by the Belgian Malinois (23.4%, n = 203).

Traumatic causes of death made up 36.7% (n = 318) of those canines killed or euthanized (Table 3.1). Cases that were placed into the "Other" category include deaths caused by animal attack (n = 7), drowning (n = 5), fire or smoke inhalation (n = 3), and electrocution/lightning (n = 1) (Table 3.1). Non-traumatic causes of death made up 63.3% (n = 549) of those killed or euthanized while in service (Table 3.2). Cases that were placed in the "Other" category include digestive (n = 14), hematopoietic problems (n = 9), neurological (n = 8), and respiratory (n = 7). There was one case of accidental euthanasia (n = 1), euthanasia due to aggression (n = 10), autoimmune diseases (n = 5), and allergic reactions (n = 4).

Table 3.1:
Traumatic causes of death in law enforcement canines

Traumatic Cause	Number Of Cases	Percent
Non-Penetrating Blunt Trauma		
Struck by Vehicle	82	25.8%
Vehicle Crash	22	6.9%
Fall	16	5.0%
Localized Impact	2	0.6%
Penetrating Trauma		
Ballistic	73	23.0%
Sharp Non-ballistic	5	1.6%
Heat Injury	79	24.8%
Airway Obstruction	12	3.8%
Ingested Toxin	11	3.5%
Other	16	5.0%

Table 3.2:
Non-traumatic causes of death in law enforcement canines

Non-Traumatic Cause	Number Of Cases	Percent
Cancer	251	45.7%
Gastric Dilatation Volvulus	66	12.0%
Non-Specific	53	9.7%
Cardiac		
Disease or Failure	31	5.6%
Heartworm	2	0.4%
Musculoskeletal		
Degenerative	16	2.9%
Spine/Bone	12	2.2%
Bacterial/Viral Infection	24	4.4%
Anesthesia-related or Surgical Complications	20	3.6%
Other Specific Organ Systems	16	2.9%
Other	58	10.6%

Ballistic deaths could be additionally classified as: hostile ballistic attack while on duty, friendly fire while on duty, and hostile ballistic attack while the canine was not on duty (Table 3.3). Working canines used in civilian law enforcement are trained for various purposes (detection, apprehension, search and rescue, and sentries) but approximately 38% (n = 28) of the fatal incidents occurred while apprehending or tracking a suspect. In the cases that involved friendly fire, the majority (69.6%, n = 16) involved a canine that identified a police officer/handler as the suspect or showed signs of aggression toward police officer/handler leading to a police officer/handler fatally wounding the canine. The remaining cases include accidental shootings or a canine caught in crossfire. Cases involving hostile off duty shootings include incidents not related to their work duties.

Table 3.3:
Descriptive details for ballistic death

Ballistic Deaths	**Number Of Cases**	**Percent**
Hostile – On Duty	28	38.4%
Friendly Fire – On Duty	23	31.5%
Hostile – Off Duty	22	30.1%

Figures 3.1 - 3.3 illustrate the annual breakdown of the cases included in this study. The annual reported number of traumatic death in law enforcement dogs remained fairly consistent until 2010 and 2011 where there was an increase. However, the data indicated a return to previous levels in 2012.

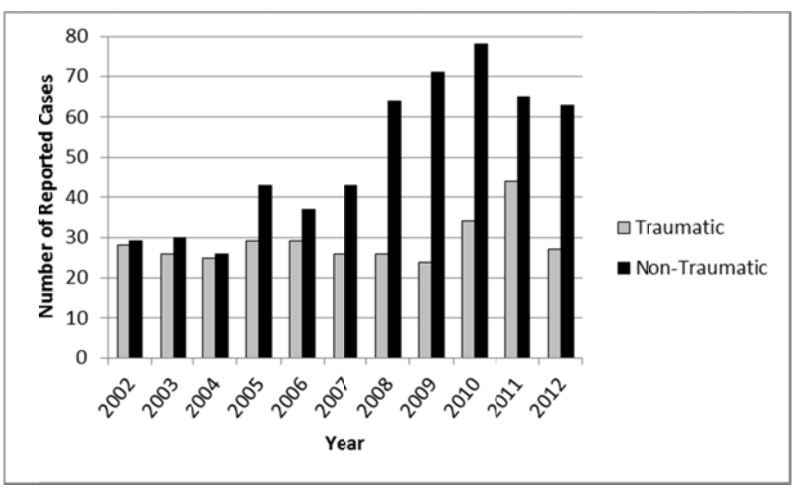


Figure 3.1: Overall number of reported canine deaths for 2002-2012

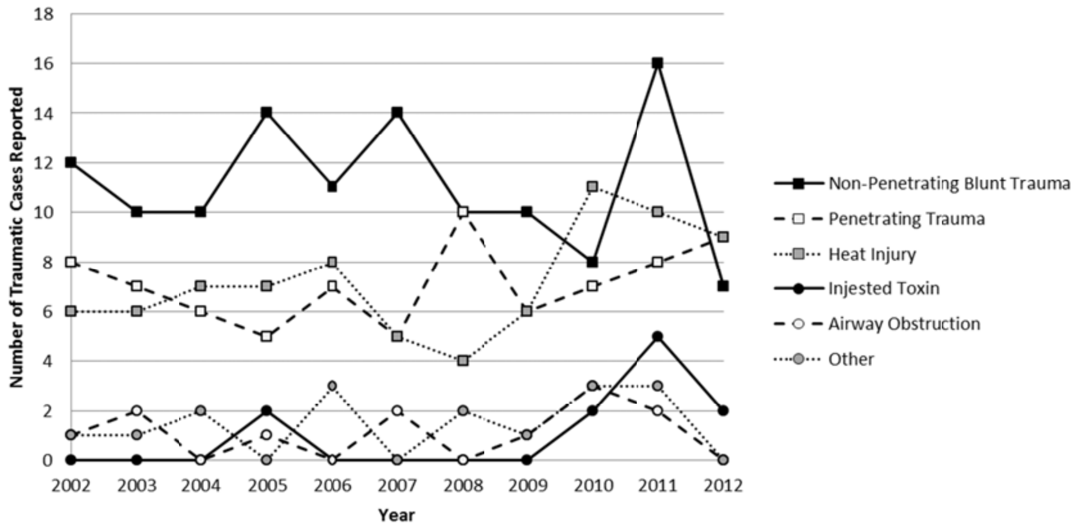


Figure 3.2: Number of traumatic causes of death reported annually

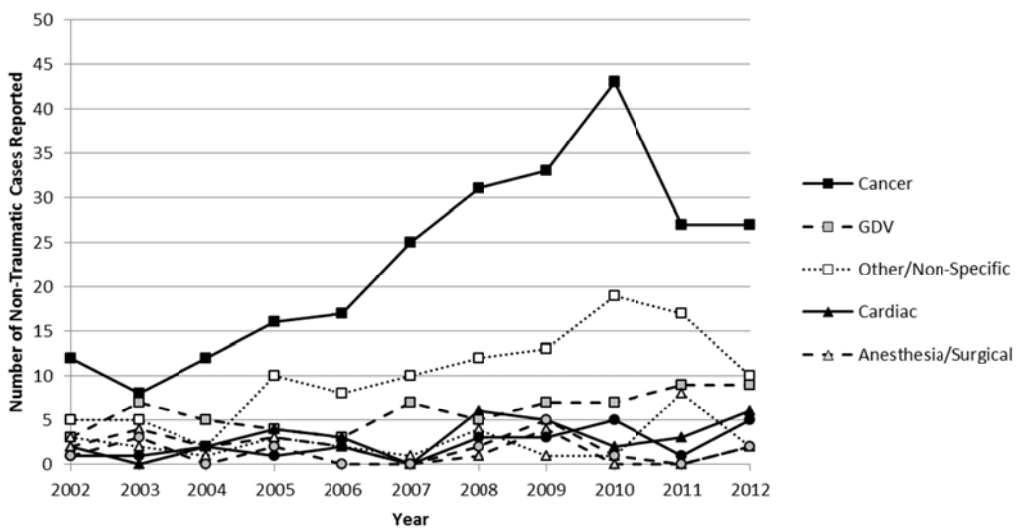


Figure 3.3: Number of non-traumatic causes of death reported annually

3.4 Discussion

Although there are studies investigating military working canines, there is a lack of data investigating civilian law enforcement canines (Dutton and Moore, 1987; Jennings and Butzin, 1992; Moore, Burkman et al., 2001; Evans, Herbold et al., 2007; Baker, Havas et al., 2013). The current study compiled self-reported cases of working canines used in civilian law enforcement that died or were euthanized while in service in the United States. Overall, the current study found the most commonly reported causes of death to be cancer, blunt trauma caused by a vehicle strike, heat injury, and ballistic penetrating trauma. Most of the non-traumatic causes of death are common issues with the canine in general, particularly for the specific breeds that are utilized in law enforcement. A recently published study investigated the occupational hazards and emergency room visits of police dogs. The study compiled emergency veterinary records from law enforcement working canines, specifically German Shepherd Dogs, to one university veterinary hospital that had been contracted to provide all veterinary care to certain police departments, government, and security agencies (Parr and Otto, 2013) Primary complaints were explored; however, if deaths occurred during the study time frame these cases were not reported.

The three most commonly reported non-traumatic causes of death in this study were cancer, gastric dilatation-volvulus (GDV), and non-specific causes. In a previously published study, researchers investigated breed-specific causes of death, retrospectively utilizing data recorded in the Veterinary Medical Database (VMDB) (Fleming, Creevy et al., 2011). The cases were organized in two categories, pathophysiologic processes (PP) and organ systems (OS). For German Shepherds, gastrointestinal causes (OS) contributed to death most frequently. The most frequent PP cause of death for German Shepherd Dogs was found to be cancer. The Belgian Malinois was not investigated in that study. Cancer is a common cause of death in the general canine population; this is not an isolated issue with working canines. In previously published studies that have investigated the military working canine, neoplasia is in the top three causes of death or euthanasia (Dutton and Moore, 1987;

Moore, Burkman et al., 2001). These findings are comparable to the data reported in the current study. The majority of the canines reported in the current study were German Shepherd Dogs and overall the leading reported cause of death or euthanasia while in service was cancer. Although cancer appears to be a commonly reported cause of death in canines, there is no definitive way to protect them from developing it unless research can show that there are specific risk factors inherent in the use to which these specialized canines are exposed (e.g., exposure to environmental carcinogens).

Gastric dilatation-volvulus (GDV) is a disease where fluid or gas creates a gross distension of the stomach, rotation of the stomach, failure to empty, increased gastric pressure and shock. Mortality rates that can be expected, despite medical care, to range from 15-24% (Brockman, Washabau et al., 1995; Glickman, Lantz et al., 1998). Several retrospective studies have investigated cause of death in military working dogs and the frequency of GDV (Dutton and Moore, 1987; Jennings and Butzin, 1992; Moore, Burkman et al., 2001). Two of these studies evaluated cause of death that occurred during the 1980's (Dutton and Moore, 1987; Jennings and Butzin, 1992). Both studies found the occurrence of GDV to be below 5% in the military working dog population. A more recently published study found an increased risk of GDV in the military working canine in the 1990's. Moore et al. found that 9.1% of deaths could be attributed to GDV or its complications (Moore, Burkman et al., 2001). In the current study all reported causes of death categorized as bloat, torsion, or volvulus were grouped together as gastric dilatation-volvulus as a way to normalize the self-reported data. There were 66 cases (12.0%) of death reportedly caused by GDV or its complications. Although 12% is higher than what was reported in previously published studies, these findings are comparable to what was reported by Moore et al. (Moore, Burkman et al., 2001). Gastric dilatation-volvulus is a potentially preventable and surgically correctable condition. Continued research and gathering of working canine casualty data may ideally lead to changes in management and prevention that may help lower the risk of GDV in both the law enforcement canine population, and in the general pet population.

All cases that were reported as "natural causes" were placed in the non-specific category since the exact cause of death was not known. Death by a natural cause could potentially be any illness not directly influenced by external forces. Senility or old age is typically thought of if the cause of death is listed as natural causes for a canine. Additionally, natural causes could be used to describe a geriatric canine that died from unknown causes with no specific sign of disease or trauma. One limitation of the current study is that causes of death compiled were self-reported and verification or clarification was unattainable. There could be variations in the way individuals define the term "natural causes" leading to artificially lower totals in other non-traumatic categories. All causes of death that were compiled for the current study were recorded precisely as they were reported to CPWDA and ODMP.

Previously published studies that have reviewed the cause of death or euthanasia in military working canines have reported senility or geriatrics in the top five most common causes of loss (Dutton and Moore, 1987; Moore, Burkman et al., 2001). The primary reason for euthanasia in one study was due to locomotion problems, affecting the musculoskeletal system, which inhibited their ability to perform tasks (Dutton and Moore, 1987). The average age of these canines were reportedly 10.5 and 11.3 years (Dutton and Moore, 1987; Moore, Burkman et al., 2001). Geriatrics could be attributed to a marked decrease in performance or quality of life resulting in discharge and was found to be the third top cause of discharge for military working canines over the age of 5 (Evans, Herbold et al., 2007). Although the current study has its limitations by only evaluating the causes of death for law enforcement canines still in service, the results are comparable to what has previously been published. A database following the veterinary care and eventual cause of death of law enforcement canines through retirement would provide a complete representation of this unique population.

Working canines are exposed to different circumstances when compared to the general population of canines. Military and police canines are subjected to threats similar to those experienced by their human counterparts. Potential threats include ballistic, blunt, and explosive resulting traumas in addition to the potential for ingesting hazardous substances. These canines may be at a higher risk of hostile action or being involved in dangerous situations as a result of their duties. In this study, the most commonly reported cause of traumatic death to the CPWDA and ODMP for working canines was due to injuries caused by motor vehicle accidents (MVA). Studies that have investigated causes of trauma in canines have found that motor vehicle accidents were frequent causes of trauma and fatalities (Kolata, Kraut et al., 1974; Kolata and Johnston, 1975; Simpson, Syring et al., 2009). Kolata and Johnston published an article investigating injuries in 600 dogs involved in MVAs, where the dog was struck by a vehicle (Kolata and Johnston, 1975). Overall, 12.5% of the dogs died or were euthanized as a result of their injuries. A more recent study reported 91.1% of the canine blunt trauma cases investigated were as a result of a motor vehicle accident

(Simpson, Syring et al., 2009). The mortality rate associated with severe blunt trauma related to MVAs was determined to be 12%.

Working canines could be at an increased risk of injury and even death caused by MVA since their job requires apprehending and tracking of suspects. This could make the dogs more vulnerable than the normal canine population. In situations where a suspect attempts to evade capture, the canine will pursuit the suspect which could involving running through urban and suburban areas with moderate to high traffic levels. Although the mortality rate reported in previously published studies was rather low for MVAs, this was the most common cause of traumatic death reported in the current study (Kolata and Johnston, 1975; Simpson, Syring et al., 2009).

The second most commonly reported traumatic cause of death or euthanasia for in service canines was heatstroke. Heatstroke in working canines may be instigated by many factors, none of which are well-documented in the scientific literature. However, it is generally accepted that lack of acclimation to hot environments or hard work, sudden changes in environmental temperature or workload, and confinement in hot vehicles all play major roles in fatal heatstroke in working dogs (Taylor, 2009). Further detailed information was found for the majority of the cases through various online news reports. The majority of the heatstroke cases in the current study (n = 48, 60.8%) could be classified as confinement heat injury. This means the canine was left unattended in a patrol car causing the canine's body temperature to increase resulting in their death. With canine units, it is rather common in many situations to leave the canine in the patrol car while the engine and the air conditioning are running. There are times where the car will be more comfortable and cooler than the ambient temperature and it tends to be a good place for the canine to cool down and rest. Alarm systems are available that will sound the horn, call, page, or otherwise alert the officer, and roll down the windows if the interior temperature of the car exceeds a certain threshold. This alerts officers and allows additional air circulation in the car. However, these systems can malfunction. Out of the 79 heatstroke cases, 29.1% (n = 23) were reportedly caused by alarm systems that malfunctioned and did not alert the officers that the interior of the car reached dangerous temperatures.

The other causes of confinement heat injury could be attributed to the handler becoming distracted or delayed. Twenty-five cases (31.6%, n = 25) included police officers that forgot to remove the canine from the car for an extended period of time. Only 20.3% (n = 16) of the cases were caused by exertion (n = 8) or environmental conditions (n = 8). The remaining cases could not be attributed to a cause since details were not available (n = 15, 19%). Confinement heat injury is a cause of death that is preventable. With further research and identifying the potential factors involved, this may help identify specific risk factors and thus more specific means to mitigate them.

The third most commonly reported cause of traumatic death to the CPWDA and ODMP for working canines was as a result of the penetrating ballistic trauma of a gunshot wound (GSW). Very few studies have looked at the occurrence of ballistic trauma in working canines. A recently published study by Baker et al. investigated 29 cases of GSW injury in military working dogs between 2003 and 2009 and reported a survival rate of 38% (Baker, Havas et al., 2013). According to this study, the most common site for injury appeared to be the thorax and extremities. Fifty-nine percent (59%) of the canines were categorized as killed in action (KIA). Although, extremity wounds were found to be the second most common injury location, all of the dogs that had extremity wounds as their only injury survived. All dogs that received wounds to the neck or abdomen died as a result of the injuries. In the cases with abdominal wounds, all of the dogs had additional life threatening injuries; however, it was determined that the cause of death was not the abdominal wound. In a combat scenario, extremity wounds in humans can cause significant blood loss and was found to be one of the leading causes of death, however, in canines this does not appear to be the case, perhaps due to scant muscle in the extremity of a canine compared to a human (Baker, Havas et al., 2013).

In 2012, the second leading cause of death in on-duty police officers was as a result of firearms (NLEOMF, 2012). According to the data collected by the National Law Enforcement Memorial Fund (NLEOMF), of the police officers that were killed, 38.6% were killed with a firearm. Although, to the author's knowledge there currently are no studies listing the frequency of gunshot wounds in working canines, the current study is comparable to the data available for human law enforcement personnel. These canines are exposed to the same risks and are sometimes sent into situations ahead of the police officers to locate and alert their team of hazards in order to add protection to the officers. In this study 23% (n = 77) of the canines were reportedly killed or euthanized as a result of a gunshot wounds which is slightly lower than that reported for their human counterparts in 2012.

Ballistic cases in this study were further investigated with additional online sources since the majority of the incidents were well documented by the media. According to various online reports, 38.4% (n = 28) of the penetrating ballistic trauma cases were on-duty hostile shootings (Table 3.3). The remaining cases involved friendly fire (31.5%, n = 23) and hostile shooting that occurred off-duty (30.1%, n = 22). The friendly fire cases can be further broken down into accidental or intentional shootings. Remarkable, 69.6% (n = 16) of the friendly fire cases were intentional shootings. In these cases, the canine aggressed or bit a law enforcement officer and in response, the officer intentionally shot the canine out of fear for their own safety. Six cases (26.1%, n = 6) involved a canine that was caught in the crossfire or was accidentally shot by a police officer. One case resulted from a friendly fire but the exact circumstance was not clear. Cases that were categorized as hostile shootings that occurred off-duty generally involved a canine that escaped the kennel or home of the handler and was shot for a variety of reasons.

The implementation of civilian trauma systems or injury databases have been effective at improving care delivered to injured patients, injury prevention, supplying data for clinical research, documenting effects of trauma, and policy development (Mann and Mullins, 1999; Olson, Arthur et al., 2001; Zehtabchi, Nishijima et al., 2011). In the past, significant improvements in civilian trauma care have resulted from data and experiences in combat casualty care. On the contrary, applying civilian standards to military trauma care proved to expose significant medical differences in the 1990’s, therefore, exposing deficiencies on the battlefield (Mabry, Holcomb et al., 2000; Eastridge, Costanzo et al., 2009). Trauma registries not only help improve trauma outcomes but also improve advances in personal protective equipment and pre-hospital care standards (Eastridge, Costanzo et al., 2009; Kotwal, Montgomery et al., 2011).

A study that investigated US Army Ranger combat casualties in Somalia noted the need for a comprehensive combat casualty registry allowing evidence based validation of surgical and resuscitative intervention (Mabry, Holcomb et al., 2000). The Joint Theater Trauma Registry (JTTR) was developed to better organize and coordinate battlefield care. One study analyzed the JTTR data from July 2003 through July 2008 comparing data to the civilian trauma system equivalent, National Trauma Data Bank (NTDB) (Eastridge, Costanzo et al., 2009). As a result the evidence based guidelines put in place for a military setting were associated with improvements in outcome for hypothermia prevention and management, burn resuscitation, and massive transfusion mortality. Following the inception of the JTTR, an additional study investigated the outcomes from implementing pre-hospital trauma care guidelines customized for the battlefield (Tactical Combat Casualty Care, TCCC) and a pre-hospital trauma registry (PHTR) (Kotwal, Montgomery et al., 2011). Comparisons were additionally made with casualty data from the regiment which supported and applied the guidelines to the military as a whole. It was reported that the 75th Ranger Regiment had a decrease in cases identified as killed in action (KIA) and died of wounds (DOW) when compared the US military ground troops. Continually improving and implementing guidelines for battlefield trauma care will continue to lower casualty rates. A comprehensive working canine database could be used in a similar manner to potentially lower fatality rates as demonstrated by the human population.

The current study compiled and compared causes of death for in-service working canines in law enforcement. However, there are limitations to this study. The data presented in the current study were compiled from online sources. The information were collected and reported as a memorial to the fallen canines. The causes of death are reported by handlers or other contributors affected by the death of the canine. None of the cases could be verified with veterinary records, however, additional information could be found if there was media coverage of the incident. There are no specifications as to where the canine units must seek veterinary care making it difficult to access veterinary records and verify causes of death. If veterinary records were available additional information such as breed, sex, age, and cause of death could also be compiled and analyzed.

With the causes being reported by non-clinical personnel, it is possible the causes were not correctly understood or reported. Errors in reporting the cause correctly, and potentials for certain types of causes not to be reported at all, could cause inaccurately represented categories. Additionally, in an effort to compile the information, causes of death were grouped together in an attempt to normalize the data. For instance, there were cases in which the cause of death was listed as “heart attack.” In general, the myocardial infarction that is generally referred to in this terminology does not have the same catastrophic effects in the canine as it can in humans, quite possibly because of the differences in the two species’ cardiac collateral circulation (Weirich, Bisgard et al., 1971; Fregin, Luginbuhl et al., 1972; Liu, Tilley et al., 1986; Driehuys, Van Winkle et al., 1998). Additionally, such a cause of death would be difficult to definitively diagnose in the absence of a full necropsy. Therefore, these cases were grouped with “cardiac disease” and “cardiac failure.” Furthermore, if the cause of death would carry additional scrutiny of the officer, when the death could be attributed to the officer’s actions or attention to care of the canine, then the handler may not contact the websites. If the handler is unaware of the websites existence, there is a potential for missing data points as well.

In conclusion, the current study casts some light on the risks that civilian law enforcement canines undergo as part of the tasks to which they are assigned; in addition to those risks to which they are subject simply due to their particular breed characteristics. The databases from which these conclusions are drawn were never designed to yield high-quality epidemiologic conclusions: these databases are in general set up as memorials to animals with whom their handlers have worked closely, and to whom many handlers may owe their lives. They are, at best, incomplete death records. However, given the immense expense incurred by Local, State, and Federal governments in acquiring, training, and maintaining these highly-skilled animals, it would seem advisable to recommend the establishment of a wider database, taken across governmental levels and including living (working and retired) as well as deceased animals, in order to determine, more rigorously than is currently possible, the full extent of the risk profile to which these animals are subjected. As more subtle epidemiologic patterns become more clear, it may be thus possible to alter selection, training, and deployment strategies in order to more efficiently maintain this valuable resource.

CHAPTER 4 – BIOMECHANICAL RESPONSE OF THE CANINE THORACIC CAVITY TO BLUNT BALLISTIC IMPACTS

4.1 Introduction

In the United States from 2004 to 2013, there were a reported 511 police officers feloniously killed in the line of duty and of those deaths, 92.8% (n = 474) were killed with a firearm (FBI-LEOKA). Only 65% (n = 308) of these officers were wearing ballistic protective armor. Of the officers that were wearing armor, only 5.8% (n = 18) were shot in areas that were covered by the ballistic vest and died as a result of the injuries sustained. It has been reported that an officer not wearing armor is 3.4 times more likely to be killed from a shot to the thorax (LaTourrette, 2010). In addition to saving lives, armor has also been shown to reduce the severity of injury (Peleg, Rivkind et al., 2006). Although these findings have been established for humans, armor efficacy has not been explored for canines even though canine specific armor is commercially available.

The impact and injury response is a complex interaction of soft and hard tissue responding to contact from an external source. The importance of compression and speed of deformation have been reported for high velocity thoracic impacts (Viano and Lau, 1988; Viano, King et al., 1989). Additionally, the response of the human thoracic cavity to blunt ballistic impact has been documented (Bir and Viano, 2004; Bir, Viano et al., 2004; Bass, Salzar et al., 2006; Roberts, Ward et al., 2007). With the differences in anatomical structures and general differences between humans and canines, there will likely be a difference in terms of mechanism and severity of injury for a similar impact condition. The human thorax is much wider than it is deep, while the opposite is true for canines. In order to better protect, mitigate life-threatening injuries, and develop canine specific standards, the mechanisms of injury must first be understood.

The aim of this study was to evaluate the mechanism of thoracic injury of a canine during blunt ballistic impact. This was achieved by quantifying the response at two impact conditions and determining the response at which the rib bones failed to recover. Impact force, thoracic deflection, spine/sternum/rib acceleration, and rib strain were collected for each specimen. Necropsies were performed following the impact events to verify injury severity.

4.2 Methodology and Materials

4.2.1 Ballistic Armor

Typically, armor is chosen based on the threat that is expected. Since injury and mortality data are not available for working canines, especially in law enforcement, understanding the most common threat to their human counterparts will start the effort to better understanding how to protect the canine. According to the Law Enforcement Officers Killed and Assaulted (LEOKA) database, the majority of officers killed in the line of duty from 2004 – 2013, were killed with a firearm (92.8%, n = 474) (FBI-LEOKA). Handguns were reported as the most common firearm used (72.8%, n = 345); the 9 mm handgun (26.7%, n = 92) was the most frequently reported weapon used in felonious killings of law enforcement officers. In order to protect against the most common threat to law enforcement officers, a NIJ Level II armor (designed and tested to 9 mm and .357 magnum threats) was chosen as the focus and guideline for this study.

Sheets of Kevlar® XP™ S102 (Figure 4.1) were donated to Wayne State University by DuPont Protection Technologies (Richmond, VA, DuPont™). Ballistic panels of 30.5 x 30.5 cm (12 x 12 in) were received with an areal density of 0.51 kg/m^2 and thickness of 0.46 mm for each individual panel. The panels were cut to 15.2 x 30.5 cm (6 x 12 in) panels in order to allow a fit without gaps for the narrow anatomy of the canine specimens tested. Ballistic armor packets were constructed for each test. Layers of Kevlar® XP™ were placed unidirectionally, tacked in the four corners, and placed inside a nylon cover. DuPont™ recommended, for a vest made with Kevlar® XP™, a NIJ level II would be designed with 9 layers of Kevlar® XP™ S102. The ballistic limit (V_{50}) or velocity at which 50% of the shots will penetrate the armor for this design is approximately 500 m/s with a 9 mm (information provided by DuPont™ personnel).

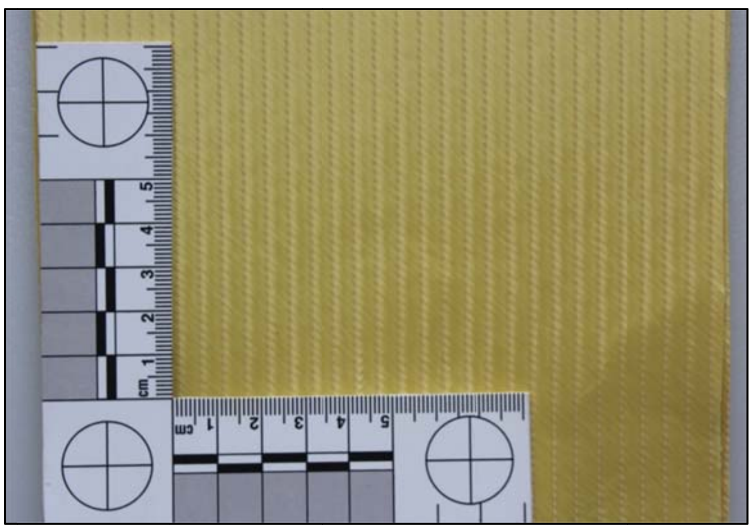


Figure 4.1: Kevlar® XP™ S102 sheet

4.2.2 Specimen Details

Fourteen (14) unembalmed post-mortem canine specimens (PMCS) were tested, four female and twelve male (Table 4.1). The average specimen weight was 29.9 ± 4.5 kg. Specimens were procured from the Detroit Animal Control and were euthanized previously for reasons not related to this study. Prior to obtaining the specimens, approval was granted by Wayne State University's Institutional Animal Care and Use Committee (IACUC) (Appendix A). Detailed measurements were taken of each specimen including thoracic circumference, lateral depth of thorax, and dorsal-ventral length (spine to sternum). Lateral depth was a measurement taken at the site of impact. The thoracic ratio was used to further describe the shape of the thoracic cavity (dorsal-ventral length/lateral depth). Age and exact breed could not be verified. The majority of the canines were a mixture of Rottweiler, German Shepherd Dog, and/or "Pit bull" breeds. Canines over 30 kilograms were selected when possible.

Pre-test x-rays were taken to ensure there was no presence of skeletal fractures. If fractures or other issues were detected the canine was not tested. Once the canines were x-rayed and weighed, the specimens were stored at 0ºF until testing. Specimens were allowed to return to room temperature for at least 18-24 hours prior to applying instrumentation. Once sufficiently thawed the instrumentation process began, at least 24 hours prior to testing.

Table 4.1:
Detailed description of post mortem canine specimens tested

ID	Gender	Breed	Weight (kg)	Thorax		
				Circumference (cm)	Depth (cm)	Thoracic Ratio
2	F	Rottweiler Mix	34.6	72.0	20.7	1.15
3	M	Pit bull Mix	31.3	67.0	21.3	1.06
4	M	Pit bull Mix	30.4	65.0	21.0	1.00
5	M	Rottweiler Mix	37.7	69.5	21.7	1.01
6	F	Shepherd Mix	25.2	63.0	19.8	1.11
7	M	German Shepherd	38.5	82.0	22.1	1.14
8	M	Shepherd Mix	25.2	62.0	17.8	1.17
9	M	Pit bull Mix	26.8	65.0	20.0	0.99
10	M	Pit/Shepherd Mix	26.8	64.0	17.1	1.23
11	M	Pit bull Mix	28.5	63.5	17.7	1.22
12	F	Pit bull Mix	28.8	71.0	21.3	1.02
13	M	Pit bull Mix	26.5	68.0	19.0	1.11
14	M	Akita	31.8	69.0	19.0	1.18

4.2.3 Data Collection and Instrumentation

A TDAS Pro data acquisition system (DTS Inc., Seal Beach, CA) was used for collecting all data. The data were sampled at 38,000 Hz with a four-pole Butterworth anti-aliasing hardware filter with a cutoff frequency of 4,300 Hz. Tri-axial accelerometers blocks and strain gages were mounted to skeletal structures (Figure 4.2). Three single axis accelerometers (7264D/C 2K Endevco, Meggitt Sensing Systems, Irvine, CA) were mounted to each custom aluminum tri-axial block to measure accelerations in the x-, y-, and z-axes (Figure 4.3). Tri-axial blocks were screwed to a custom aluminum mount with channels for plastic cable ties to then secure the mount and accelerometer block to the bone. Six accelerometer blocks were mounted to the following skeletal structures for each canine: seventh and eighth ribs (bilaterally), the spinous process of T7, and the seventh sternebra. Accelerometers were used to determine rib acceleration during impact and were located ventral to the angle of the rib. The sternum and spine accelerations were used to understand the global motion of the canine during impact.

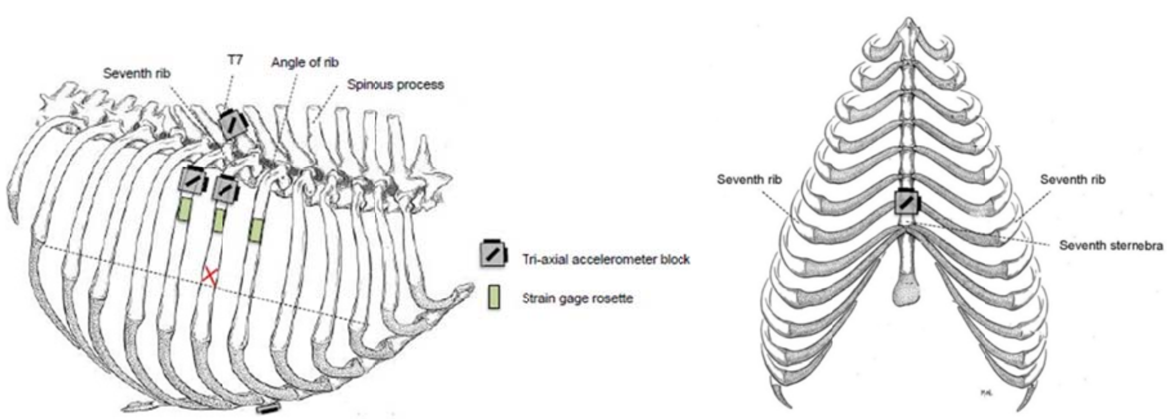


Figure 4.2: Instrumentation locations on bony structures

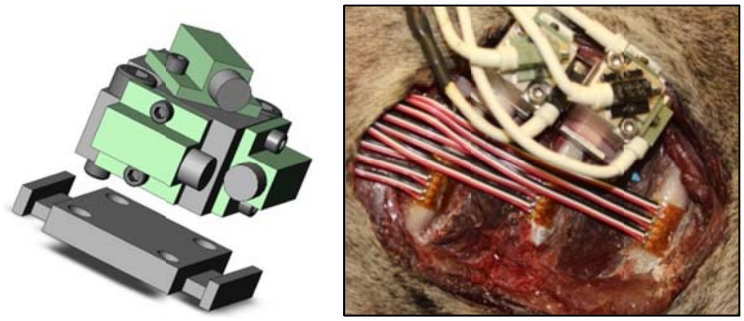


Figure 4.3: Tri-axial accelerometer block and mount

Rectangular rosette strain gages (Vishay Micro-Measurements, Raleigh, NC) were secured to the sixth, seventh, and eighth ribs bilaterally to determine bone strain during impact and potentially identify timing of fracture (Figure 4.2 and Figure 4.3). A temporary line parallel to the spine was marked from the costochondral junction of the twelfth rib. The line intersection with the seventh rib indicated the point of aim which aided in positioning for instrumentation. Tissue was left intact at impact locations. Cable ties for the accelerometer mounts and strain gage adhesion to the surface of the ribs were assessed after each test.

A coordinate system was developed for the canine to ensure consistency when collecting and analyzing acceleration data (Figure 4.4). Polarities of the measured external movement were also defined. Acceleration in the x-axis was defined as cranial-caudal movement with positive indicating cranial direction. Acceleration in the z-axis was defined as dorsal-ventral with positive indicating dorsal movement. Acceleration in the y-axis was defined as right-left where positive y was movement to the right side of the canine.

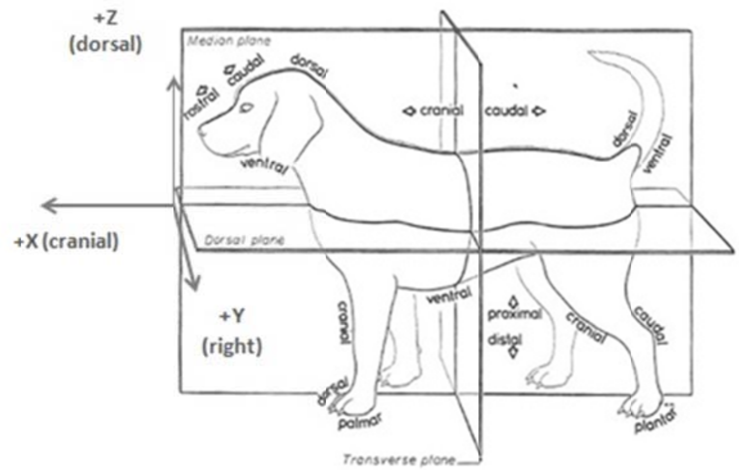


Figure 4.4: Canine coordinate system (adapted from (Evans, 1993))

A chestband was wrapped, externally, around the thoracic cavity at approximately the level of the ninth rib to measure thoracic deflection. The chestband contained 40 piezoresistive bridge strain gages mounted on a thin metal band which was covered with a flexible urethane coating (Figure 4.5) (Eppinger, 1989). The strain gages were evenly spaced at 25.4 mm (1 inch) apart. The chestband was sutured to the epidermis to ensure it remained in the desired position. The chestband was located 2.5 cm (1 inch) caudally from the impact location. Although the chestband was created for direct impact, the speed and energy imparted into this system would likely damage strain gages if it was impacted directly under ballistic conditions. The chestband output is used to calculate the maximum deflection, compression, and velocity of deflection.

Figure 4.5: Forty-gage chestband schematic

Impact force between the armor panel and the skin was determined using a thin film polymer-on-polymer force sensor (SensorTech Corp, SC) which was secured at impact site (Figure 4.6). The conductive polymer materials are pressed together as force is applied increasing the current that passes through the material thereby dropping the resistance of the material. Each sensor was individually calibrated by the manufacturer. These sensors were calibrated to 30 kN initially, however, the sensors were calibrated to 9 kN for the last four PMCS (n = 8) because of limitations at the manufacturer. This range was determined to be adequate based on the data previously collected.

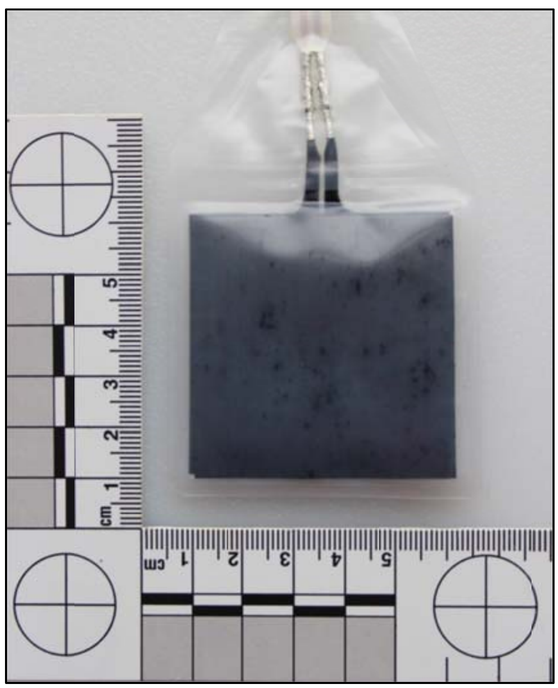
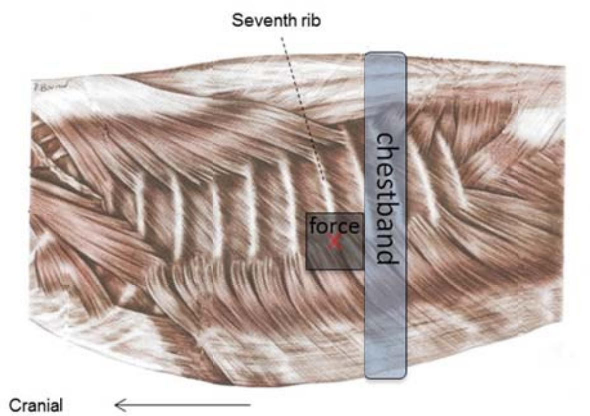


Figure 4.6: Polymer-on-polymer force sensor

The force sensors were a one-time use piece of instrumentation, a new sensor was used for each test. The force sensor was secured with Gaffer's Tape to the skin of the specimen at the impact site. The sensor was positioned so that the shot path was centered on the force sensor and the seventh rib (transversely). The chestband was positioned directly adjacent to force sensor (Figure 4.7).



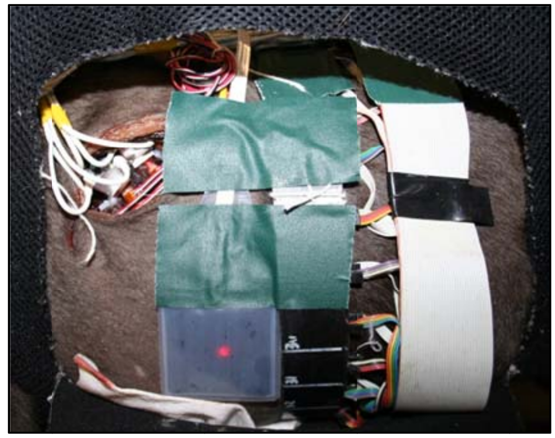


Figure 4.7: Positioning of chestband and force sensor with respect to impact site

High speed video was collected for each test. Two camera views were recorded, a camera (10,000 fps, Redlake MotionXtra HG-100K) was located perpendicular to the shot path and a second camera (1,000 fps, Kodak EktraPro HG Imager Model 2000) was located overhead to record the global movement of the specimen during the impact.

4.2.4 Experimental Design

A harness was created to allow a natural “standing” position (spine horizontal) for a quadruped. Specimens were placed in the harness and suspended from an adjustable system (Figure 4.8). Following the NIJ 0101.06 standard, a 9 mm 124 grain FMJ RN bullet traveling at 398.0 ± 9.1 m/s (1306 ± 30 fps) was used for all tests (NIJ-0101.06, 2008). Commercially available ammunition was purchased and the rounds were uploaded to achieve the desired velocity. The ammunition was fired using a Universal

Receiver (UR-01, Rapid City, SD, H.S. Precision Inc.) which allowed for laser sighting and remote firing. The shot path was aligned such that the bullet struck perpendicular to the armor packet. A chronograph (Model 35P Austin, TX, Oehler Research Inc.) with three photo-electric screens (Model 57 Austin, TX, Oehler Research Inc.) was used to measure the velocity of each shot.

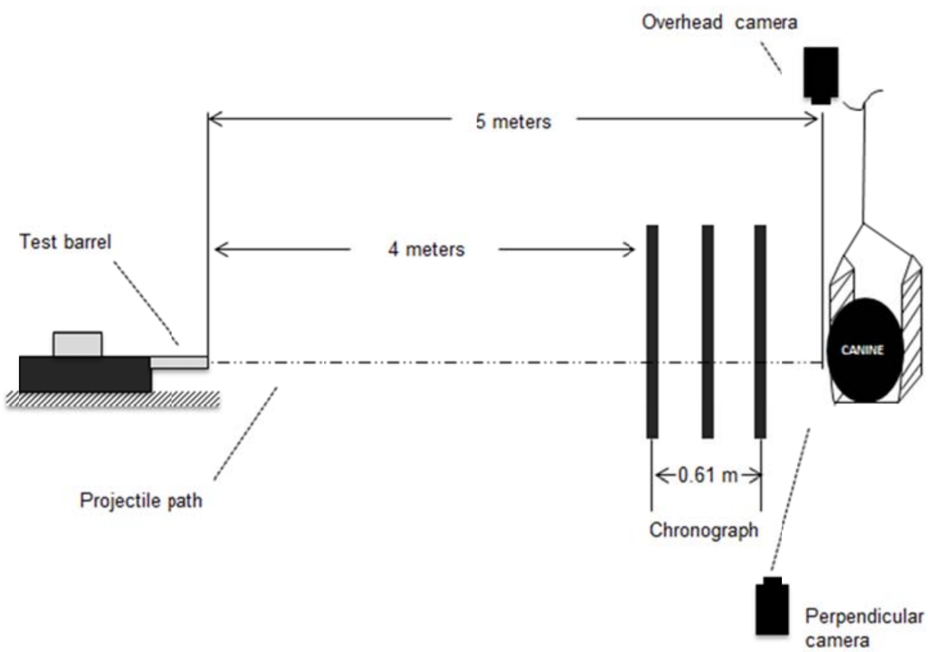


Figure 4.8: PMCS test setup

Two impact conditions were performed on each specimen; one to each of the bilateral seventh ribs. The first condition was “non-injurious” with an armor packet of 15 layers of Kevlar® (15-ply). The second condition was “injurious” with an armor packet of 8 layers of Kevlar® (8-ply). Even though soft tissue was not assessed since the specimens were frozen prior to testing, vital organs could sustain injury as a result to behind armor trauma (Figure 4.9). Organs located closest, medially, to the impact site include the lungs, diaphragm, and liver.

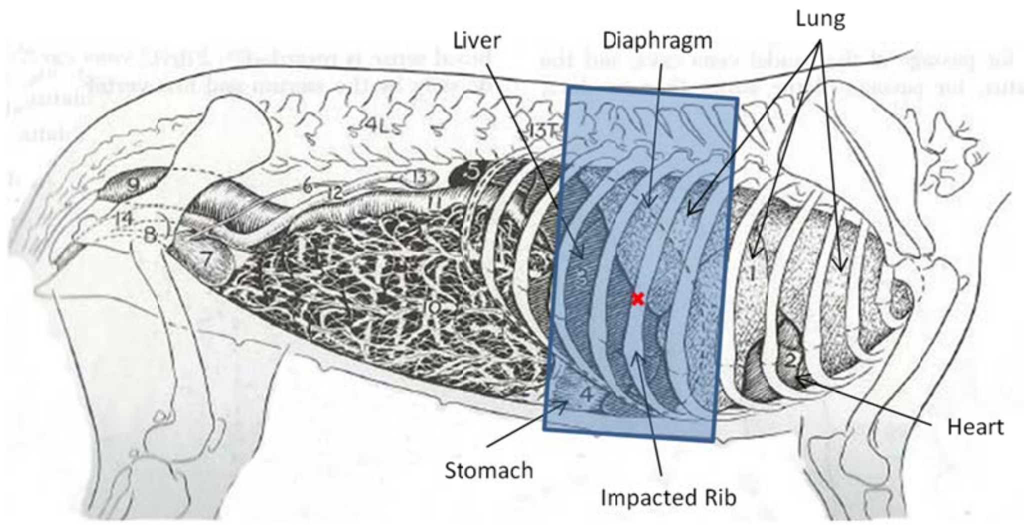


Figure 4.9: Anatomy of canine with respect to armor panel and shot location (Shaded area indicates approximate location of armor panel, adapted from (Evans, 1993))

4.2.5 Filter Determination

Hardware anti-aliasing filter (TDAS Pro, DTS Inc., Seal Beach, CA) was set with a cutoff frequency of 4,300 Hz, filtering transducer output. To determine appropriate filter to reduce signal noise, analysis of transducer outputs with Fast Fourier Transform (FFT) helped to identify frequency limits following the hardware filtering. Accelerometer data were initially filtered using a four-pole Butterworth low-pass filter (phaseless) with a -3dB limit frequency of 6,500 Hz. As recommended in SAE J211, the filter -3dB frequency is approximately one sixth of the data sample rate (38,000 Hz) which is consistent with existing engineering standards for filtering accelerometer data (SAE-J211-1, 1995). However, a frequency analysis of the acceleration data from the impacted seventh rib indicated that the accelerometer signal in the lateral direction (y-axis) included relevant data at frequencies above 6,500 Hz (Figure 4.10). Relevant data was not observed in non-impacted ribs, sternum, or spine acceleration data above 6,500 Hz.

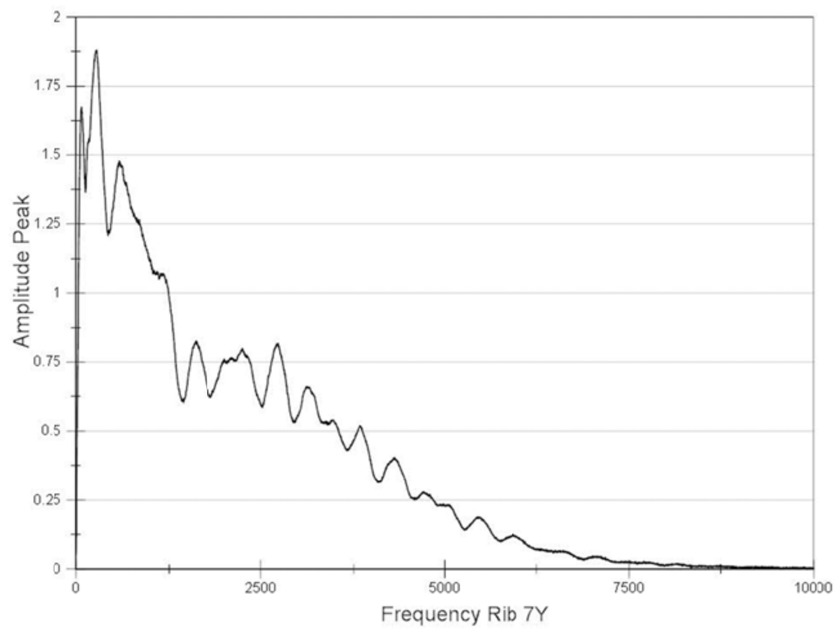


Figure 4.10: FFT plot of impacted rib acceleration in the lateral direction (y-axis)

To preserve the relevant high-frequency data, the thoracic acceleration data were filtered with a four-pole Butterworth low-pass filter (phaseless) with a -3dB limit frequency of 7,500 Hz, which effectively diminished noise in the off-axes (x-axis, z-axis) and non-impacted rib accelerometers while only slightly attenuating the peak acceleration (1.27 ± 0.77% reduction) in the lateral direction (y-axis) of the impacted rib. Overall the filtered peaks remained relatively close. It was determined to filter rib, sternum, and spine acceleration data with four-pole Butterworth low-pass filter (phaseless) with a -3dB limit frequency of 7,500 Hz since it retained the meaningful data and had the smallest peak attenuation.

A similar approach was taken when considering filter options for the chestband output and rib strains. Chestband output is commonly filtered using a CFC 600 prior to post-processing (Maltese, Eppinger et al., 2002; Yoganandan, Pintar et al., 2008; Yoganandan, Humm et al., 2013). Data collected during this testing exhibited relevant data through approximately 3,000 Hz (Figure 4.11). A four-pole Butterworth low-pass filter (phaseless) with a -3dB frequency limit of 3,000 Hz was chosen to minimize the attenuation of the peak deflection (2.52 ± 4.83% reduction). Rosette strain gage data were also filtered with the four-pole Butterworth low-pass filter (phaseless) with a -3dB frequency limit of 3,000 Hz (Figure 4.12).

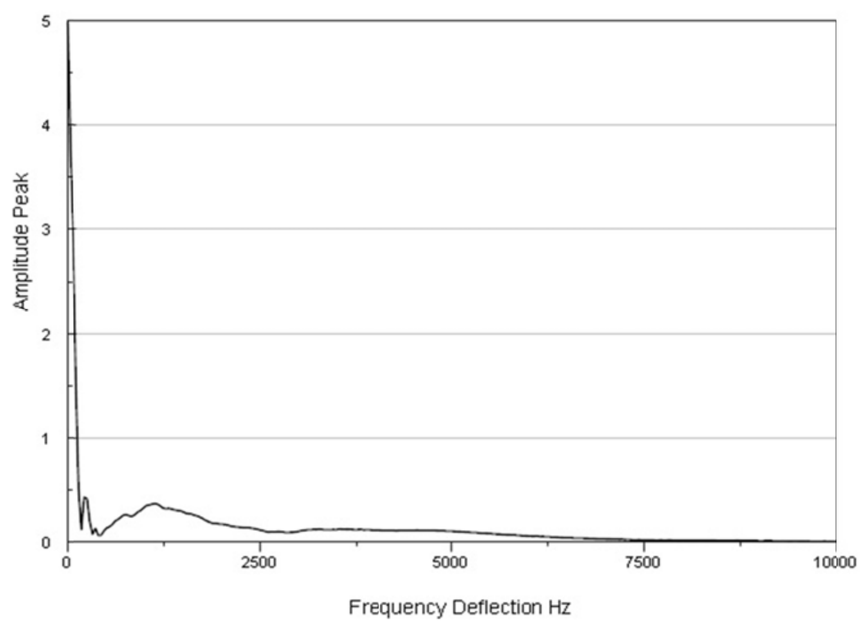


Figure 4.11: FFT of chestband output

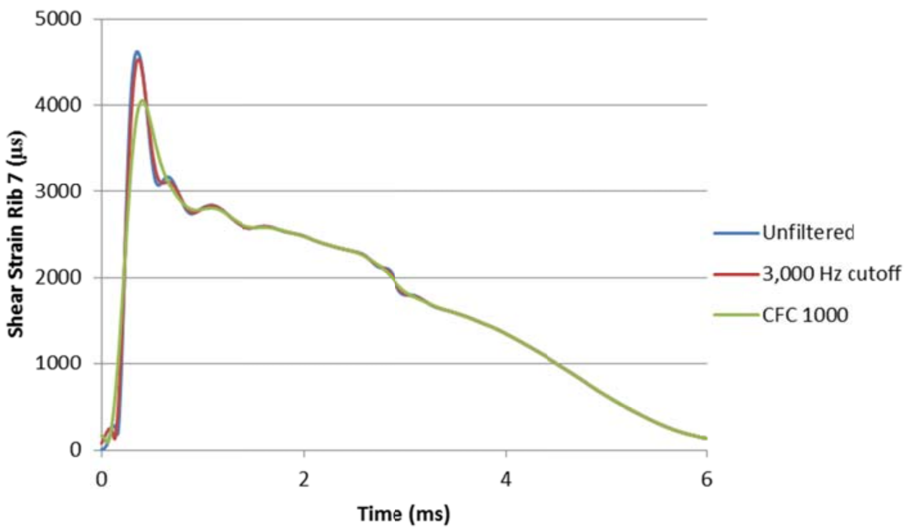


Figure 4.12: Filter comparison for shear strain of impacted rib

4.2.6 Analysis

Time zero was determined by the force sensor signal. Post-processing of data output from the force sensor was needed to calculate the impact force. The response of the force sensor was non-linear; therefore, the sensor sensitivity was dependent on the maximum output expected. Sensitivities were calculated based on the manufacturer's calibration data for each sensor with maximum range of 9 kN. Acceleration data were filtered and the resultant was calculated.

Rosette strain gage data were filtered and principal and shear strains were computed using the following formulas:

$$\varepsilon_1 = \frac{1}{2}(\varepsilon_A + \varepsilon_C) + (\frac{1}{2}[(\varepsilon_A - \varepsilon_C)^2 - (2\varepsilon_B - \varepsilon_A - \varepsilon_C)^2]^{\frac{1}{2}}$$

$$\varepsilon_2 = \frac{1}{2}(\varepsilon_A + \varepsilon_C) - (\frac{1}{2}[(\varepsilon_A - \varepsilon_C)^2 - (2\varepsilon_B - \varepsilon_A - \varepsilon_C)^2]^{\frac{1}{2}}$$

$$\gamma_{max} = \frac{1}{2}[(\varepsilon_A - \varepsilon_C) - (2\varepsilon_B - \varepsilon_A - \varepsilon_C)]^{\frac{1}{2}}$$

where $\varepsilon_{A,}$ ε_B and ε_c represent the three gages of the rectangular Rosette.

Prior to processing, the chestband output was filtered. The chestband data were further analyzed using custom software, CrashStar V2.5 (Transportation Research Center Inc., East Liberty, OH). This software has never been used with a canine model. Since the chestband can be installed at any point along the circumference of the chest, the program requires the user to input a “sternum” or “spine” location from the band placement on the specimen. For the current study, the “spine” location was identified based on the initial position of the chestband on the specimen. This orientation allows the chestband to plot the thoracic motion and deformation resulting from the lateral impact at each time point.

The program output is the x- and y-axis position (mm) of each of the active gages for each point in time. The deflection of the thorax was calculated using a half-chest method (Maltese, Eppinger et al., 2002; Kuppa, Eppinger et al., 2003). For this method the “spine” is known and the “sternum” location was identified as the gage diametrically opposite the spine gage (Figure 4.13). A line was constructed between the spine and the sternum. The perpendicular distance between the gages near the impact site and the spine-sternum line was calculated for each time point. It was determined that the sternum does accelerate during impact creating movement with the sternum gage; therefore, the spine-sternum line is adjusted at each time point following the sternum gage movement. Half-chest compression was calculated using the initial magnitude from the gage generating peak deflection to the spine-sternum line. The time to peak deflection (T_D) was determined based on the point of contact as established by the force sensor. Rate at which the thoracic cavity reached peak deflection (V_D) was calculated by dividing the peak deflection by the time to peak deflection (T_D).

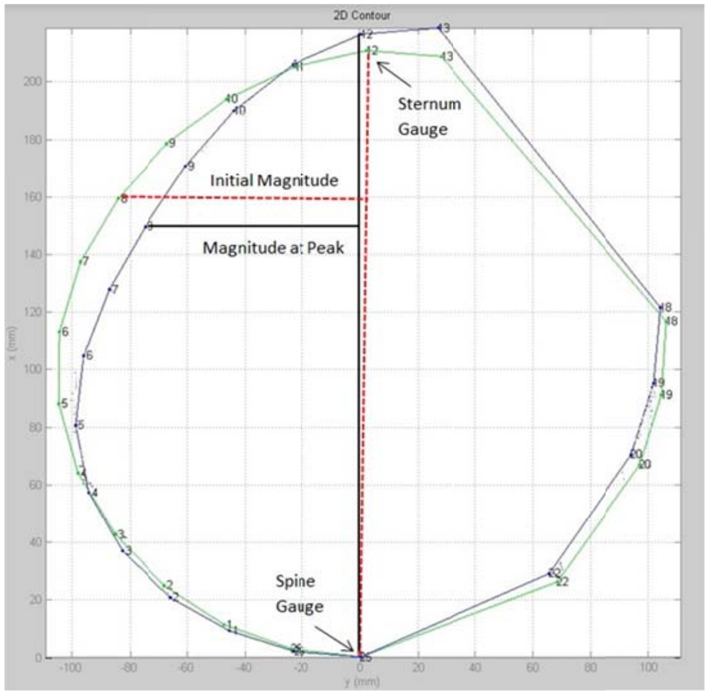


Figure 4.13: Spine-sternum method used for deflection analysis

The sixth, seventh, and eighth rib bones, bilaterally, were removed from each specimen during necropsy. A veterinarian evaluated each impacted seventh rib and injury classifications were developed (Table 4.2).

Table 4.2:
Fracture classification descriptions

Score	Fracture Classification
1	No visible fracture
2	Non-displaced fracture, transverse or oblique
3	Displaced fracture, both non-comminuted and comminuted

4.2.7 Statistical Analysis

Statistical analyses were conducted using SPSS Statistics software (IBM SPSS, Version 22). A Spearman's Correlation was run to determine the relationships between all variables. Engineering parameters included peak force, seventh and eighth peak resultant rib accelerations, sternum and spine peak resultant accelerations, peak deflection, and peak shear strain. The Two-Way ANOVA was used to measure the interaction between armor packets (8-ply, 15-ply) or injury outcome (fracture, not fracture) and independent variables on measured engineering variables. The independent variables were defined as: weight, thoracic circumference, lateral depth, dorsal-ventral length, and thoracic ratio. If an interaction was present, a post-hoc One-Way ANOVA test was used to compare the mean differences of grouped data. Due to the small sample size, a One-Way ANOVA was used to compare the mean differences between armor packet or injury outcome and rib strain. Independent variable interactions could not be evaluated for the rib strain data. The significant level for these analyses was set at $\alpha = 0.05$.

Binomial logistic regressions were performed to determine whether the presence of a rib fracture could be predicted from the measured engineering variables (Table 4.3). Independent variables (weight, thoracic circumference, lateral depth, dorsal-ventral length, and thoracic ratio) were added to the logistic regression model, in addition to the measured engineering variables, to determine if the independent variables aided in the models ability to predict a rib fracture. All tests with no visible fracture were grouped into category “no fracture” or fracture = 0, all tests with a visible fracture (either fracture classification 2 or 3) were grouped in the category “fracture” or fracture = 1.

Table 4.3:
List of variables evaluated as fracture predictors

Predictor	Description
Force	Behind armor impact force
Deflection	Peak half-chest deflection
Compression	Peak half-chest compression
A_{R7}	Resultant acceleration of impacted rib
A_{R8}	Resultant acceleration of eighth rib
A_{Sp}	Resultant acceleration of spine
A_{St}	Resultant acceleration of sternum
T_D	Time to peak deflection from contact
V_D	Rate of deflection - peak

The logistic regression model for the probability of fracture (P) takes the form:

$$P = \frac{e^{t(x)}}{e^{t(x)} + 1} = \frac{1}{1 + e^{-t(x)}}$$

$$t(x) = \alpha + \sum_{i}^{n} \beta_i x_i$$

where: α = intercept
x_i = variables used in the model
β_i = corresponding coefficients with each variable

The maximum likelihood method is used for coefficient determination. The -2 log likelihood (-2LL) statistic was used to assess the overall fit of the model and the relative improvement of the models ability to predict the injury outcome accurately with the addition of each variable. The difference between the initial -2LL measurement and the -2LL measurement after the variables are added to the model is defined as the Chi-squared value of the model which is tested for statistical significance. Significance levels were set at $\alpha = 0.05$. A Chi-squared value resulting in a p-value below 0.05 indicates a significant relationship between the injury outcome and the variables included. Another model assessment tool, the Nagelkerke R^2 value, evaluates the strength of the relationship between the injury outcome and the variables. This can be interpreted as the percentage of the variation of data explained by the model. Models were then assessed for variable significance using the Wald Chi-squared statistic. The null hypothesis tested was that the coefficient associated with the variable was zero or that there was no association between fracture and the variables (engineering variables and independent variables).

4.3 Results

Fourteen (14) canines were tested for this study. The first three canines were evaluated to establish testing methodology and the appropriate number of armor layers to create an “injurious” and “non-injurious” response without complete perforation of the armor packets. The second test from Canine 2 and the second test from Canine 3 were included in the analysis since conditions were consistent with final methodology. The first test with Canine 6 (15-ply) was removed from the study due to a data acquisition system trigger failure during testing and therefore data were not collected. Peak deflection illustrations for each test are located in Appendix C. Pictures of the impacted rib for each test are located in Appendix D.

4.3.1 Biomechanical Data – Comparison based on Armor Packet

Detailed descriptions of the biomechanical data collected during the tests are included in Tables 4.4 and 4.5. The peak impact force for the 8-ply and 15-ply conditions were 3,090.2 ± 851.3 N and 2,786.7 ± 960.2 N, respectively. The PMCS experienced peak force within 0.25 ms from contact.

ID	Velocity (m/s)	Peak Force (N)	Peak Deflection (mm)	Peak Resultant Acceleration (g)				Peak Shear Strain (µs)		Fracture Classification
				Rib 7	Rib 8	Spine	Sternum	Rib 7	Rib 8	
2R	411.5	2450.3	23.2	1625.1	1074.2	230.7	111.9	-	-	2
4R	396.8	2784.0	12.2	-	799.4	111.4	-	-	-	2
5R	385.3	1643.7	10.5	1074.1	711.0	97.2	202.1	7178.5	1429.8	2
6L	395.0	2728.3	12.5	-	549.4	68.1	349.4	7065.0	4552.3	1
7L	387.7	2568.7	17.7	655.7	703.8	71.7	870.9	6372.6	1072.3	2
8R	398.1	4577.1	11.8	1315.3	1493.5	196.6	957.7	-	-	3
9R	402.9	4048.1	7.7	1058.8	698.1	301.0	796.4	8059.2	5770.2	3
10R	405.4	2699.8	10.9	1180.7	789.0	123.5	1045.0	-	9622.0	3
11R	387.1	3233.8	7.2	929.5	828.0	355.6	230.3	-	2543.1	2
12R	385.6	3877.7	19.0	1322.7	418.3	176.4	370.9	7189.4	-	1
13R	382.5	3945.7	15.2	1772.3	1399.7	150.2	337.0	-	2871	3
14R	397.8	2525.3	50.3	1582.3	2845.7	294.8	462.4	-	-	3
Ave.	**394.6**	**3090.2**	**16.5**	**1251.6**	**1025.8**	**181.4**	**521.3**	**7172.9**	**3980.1**	
St.Dev	**9.1**	**851.3**	**11.6**	**343.5**	**655.4**	**96.0**	**332.6**	**599.6**	**2989.4**	

Table 4.4:
Detailed thoracic data with 8-ply armor

ID	Velocity (m/s)	Peak Force (N)	Peak Deflection (mm)	Peak Resultant Acceleration (g)				Peak Shear Strain (µs)		Fracture Classification
				Rib 7	Rib 8	Spine	Sternum	Rib 7	Rib 8	
3R	393.5	2945.8	16.3	1686.8	81.2	137.3	244.3	-	-	2
4L	387.1	4489.9	11.0	1166.1	282.7	77.4	277.6	-	-	1
5L	394.7	1616.6	9.2	1420.7	1195.4	93.4	196.3	4525.0	-	1
6R	-	-	-	-	-	-	-	-	-	-
7R	399.6	2775.1	8.4	1848.6	997.2	110.2	208.3	-	-	1
8L	391.7	2437.2	25.6	2761.3	3527.1	529.0	125.7	-	3403.7	2
9L	396.5	2311.6	12.0	1804.7	1728.4	195.1	505.3	-	-	2
10L	401.7	3053.1	16.6	1038.7	732.5	79.1	897.2	-	-	1
11L	392.9	1283.7	6.8	1073.1	1022.9	67.7	1037.2	6667.3	6687.9	1
12L	381.9	3907.9	7.7	610.3	591.0	151.5	325.4	4436.6	3739.0	1
13L	394.1	-	7.3	855.0	838.7	330.6	294.3	6971.6	5044.1	1
14L	394.1	3046.0	31.4	1203.1	688.3	147.8	345.3	6467.8	1899.0	2
Ave.	**393.4**	**2786.7**	**13.8**	**1406.2**	**1062.3**	**174.5**	**405.2**	**5813.7**	**4154.7**	
St.Dev.	**5.4**	**960.2**	**8.1**	**596.0**	**929.2**	**139.2**	**296.1**	**1230.3**	**1805.1**	

Table 4.5:
Detailed thoracic data with 15-ply armor

A Spearman's correlation was used to test the relationship between weight, circumference, lateral depth of thoracic cavity, dorsal-ventral length of thoracic cavity, and thoracic ratio. Weight had a positive correlation with circumference ($\rho = 0.781$, $P < 0.001$), dorsal-ventral length ($\rho = 0.705$, $P < 0.001$), and lateral depth ($\rho = 0.671$, $P < 0.001$). The thoracic ratio did not prove to have correlation with weight. Since circumference and dorsal-ventral length were well correlated with weight they were not explored further. The weight, thoracic ratio, and lateral depth were included in a Two-Way ANOVA to determine if there was an interaction between armor packet and independent variables on measured engineering parameters. Although a significant correlation was measured between lateral depth and weight, it was included in the analysis since the relationship was not as strong with a ρ value less than 0.7. For the Two-Way ANOVA, categorical variables were created for each independent variable (weight, thoracic ratio, and lateral depth) because of the small sample size, meaning the measured value was either 'greater' or 'less' than the median of the measurements. No interactions were present with lateral depth or thoracic ratio for any of the measured engineering variables.

Mean differences between armor packets (8-ply, 15-ply) and measured variables were also compared. The impacted rib experienced the highest acceleration responses with an average peak acceleration of 1,251.6 ± 343.5 g for 8-ply and 1,406.2 ± 596.0 g for 15-ply. The eighth rib on the impacted side experienced peak accelerations of 1,025.8 ± 655.4 g for 8-ply and 1,062.3 ± 929.2 g for 15-ply. There was no statistical difference between the means for the seventh rib ($P = 0.457$) and the eighth rib ($P = 0.994$) with regards to armor packet (Figure 4.14). Impact location was typically closer to the sternum, resulting in higher accelerations in the sternum when compared to the spine (Figure 4.14). The average peak sternum acceleration for 8-ply and 15-ply armor packets were 521.3 ± 332.6 g and 405.2 ± 296.1 g, respectively. The average peak spine acceleration was 181.4 ± 96.0 g for 8-ply and 174.5 ± 139.2 g for 15-ply. A statistical difference was not present when comparing armor for spine (P = 0.813) or sternum (P = 0.337) average peak accelerations with regards to armor. Peak rib accelerations occurred closely in time to peak force after contact (Figure 4.15). Peak spine and sternum accelerations occurred less than 1 ms after impact.

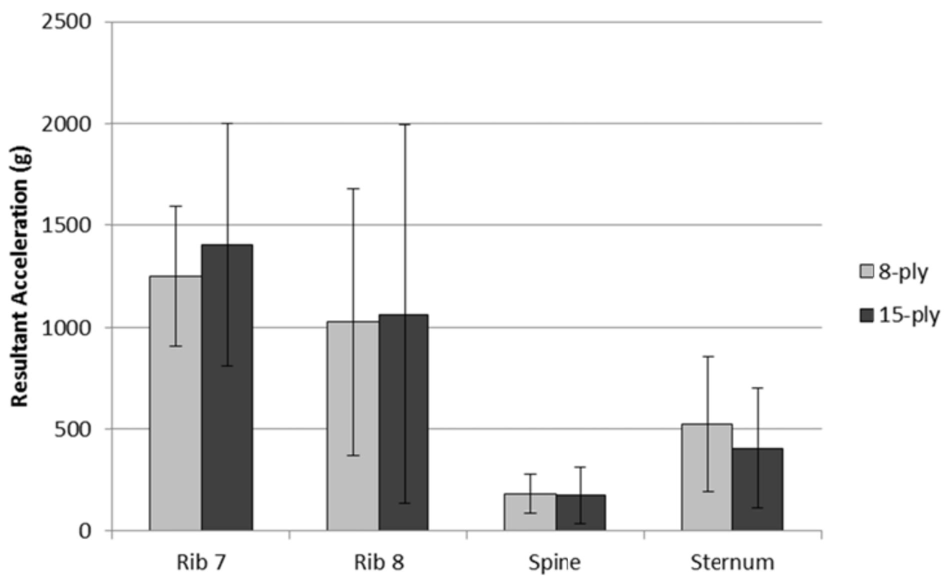


Figure 4.14: Resultant acceleration of thoracic regions during impact

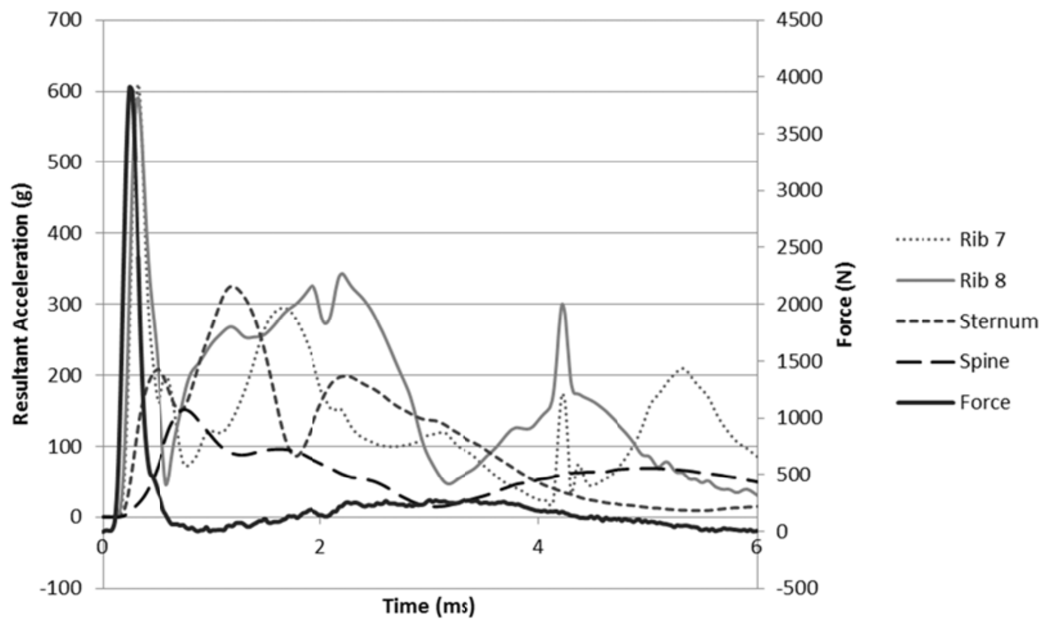


Figure 4.15: Typical timing comparison of impact force and acceleration data

Peak principal strains (ε_1 and ε_2) and peak shear strains (γ_{max}) are listed for each test in Table 4.6. Rib strain data were not captured for all impacts. With the nature of the impact and location of strain gages, complete adhesion throughout the impact was difficult to obtain. Peak shear strains, when collected, also proved to not be statistically different when comparing means for 8-ply and 15-ply (Figure 4.16). The average peak shear strain for the seventh rib was 7,172.9 ± 599.6 μs for 8-ply and 5,813.7 ± 1,230.3 μs for 15-ply (P = 0.057). The average peak shear strain for the eighth rib was 3,980.1 ± 2,989.4 μs for 8-ply and 4,154.7 ± 1,805.1 μs for 15-ply (P = 0.910).

Table 4.6:
Detailed list of peak principal (ε_1 ,ε_2) and peak shear (γ_{max}) strains for seventh and eighth ribs

ID	Armor	Seventh Rib			Eighth Rib		
		ε_1 (μs)	ε_2 (μs)	γ_{max} (μs)	ε_1 (μs)	ε_2 (μs)	γ_{max} (μs)
2R	8	-	-	-	-	-	-
3R	15	-	-	-	-	-	-
4L	15	-	-	-	-	-	-
4R	8	-	-	-	-	-	-
5L	15	2604.2	-6466.8	4525.0	-	-	-
5R	8	4485.4	-9871.5	7178.5	1046.9	-1851.3	1429.8
6L	8	4140.5	-9989.6	7065.0	3204.6	-5919.1	4552.3
7L	8	4114.6	-8769.2	6372.6	366.6	-2364.2	1072.3
7R	15	-	-	-	-	-	-
8L	15	-	-	-	7219.5	-1762.2	3403.7
8R	8	-	-	-	-	-	-
9L	15	-	-	-	-	-	-
9R	8	5724.2	-11049.0	8059.2	6951.7	-4593.3	5770.2
10L	15	-	-	-	-	-	-
10R	8	-	-	-	7131.4	-12120.0	9622.0
11L	15	4143.6	-9196.9	6667.3	4152.6	-9231.1	6687.9
11R	8	-	-	-	1802.1	-3284.0	2543.1
12L	15	2850.8	-6022.3	4436.6	2226.5	-5258.7	3739.0
12R	8	4899.0	-9521.4	7189.4	-	-	-
13L	15	4702.8	-9245.1	6971.6	3226.8	-6861.3	5044.1
13R	8	-	-	-	2275.6	-4213.4	2871.0
14L	15	4466.1	-8499.9	6467.8	2549.7	-1714.8	1899.0
14R	8	-	-	-	-	-	-

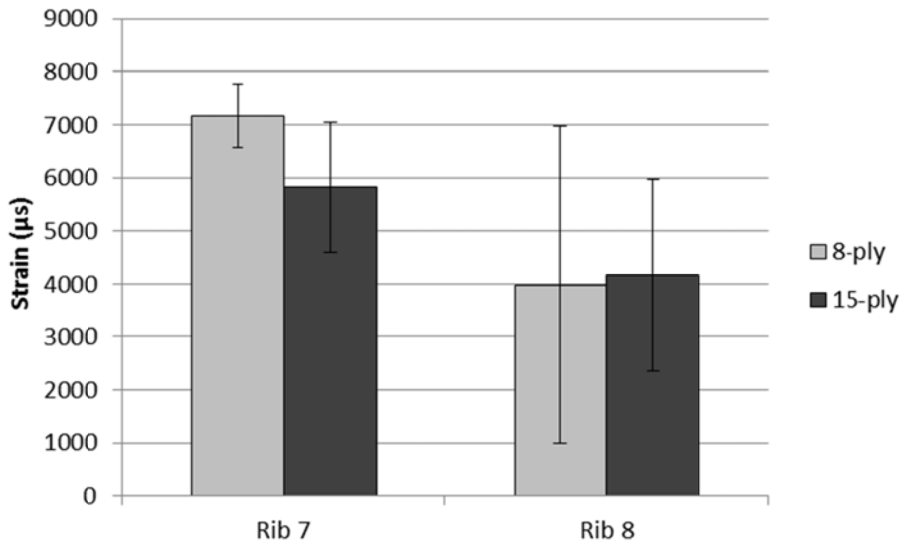


Figure 4.16: Average peak shear strain of the seventh and eight ribs during impact

The peak shear strains for the seventh and eighth ribs typically occurred less than 2 ms after impact (Figure 4.17). The seventh rib reached peak strain before the eighth rib which was expected since that was the impacted rib. The peak shear strains for the seventh rib were also larger in magnitude which was expected as well.

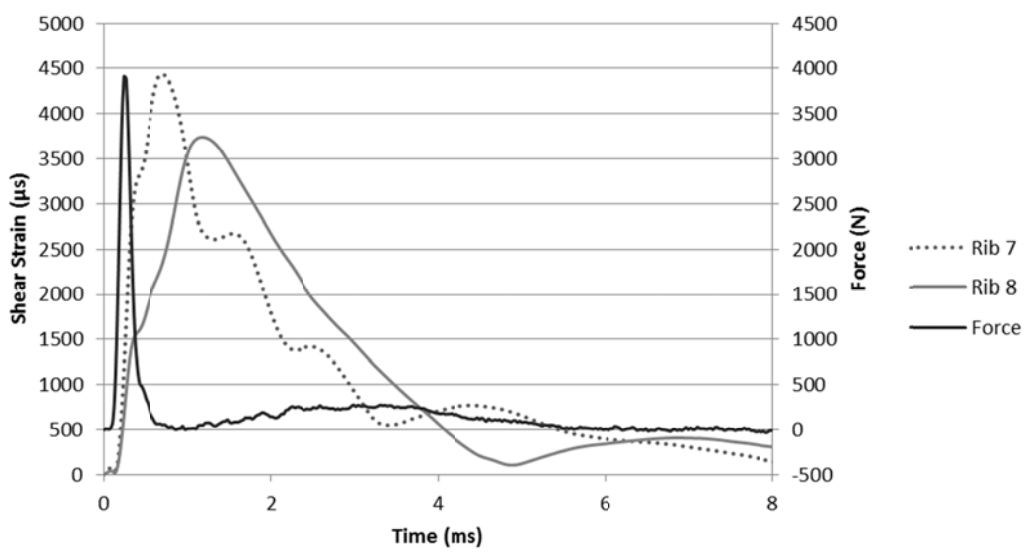


Figure 4.17: Typical timing comparison of impact force and rib strain

There was a statistically significant weight interaction present with impact force when comparing 8-ply and 15-ply (P = 0.044), therefore, force was grouped based on median weight of the specimens. The mean differences between armor packet or weight and impact force were compared using a post-hoc One-Way ANOVA test. The median weight of the tested canines was 28.8 kg. Canines that fell below the median weight experienced average peaks forces of 3,587.2 ± 713.6 N with 8-ply armor and 2,598.7 ± 969.3 N for 15-ply armor (P = 0.068) (Figure 4.18). The average peak force for canines above the median weight for 8-ply and 15-ply were 2,394.4 ± 437.6 N and 2,974.7 ± 1,023.0 N, respectively (P = 0.277). The peak forces for the canines under the median weight proved to be significantly higher than the forces experienced by the canines above the median weight for 8-ply armor tests (P = 0.008). This was to be expected since the 8-ply armor packet provided less distribution of the impact force combined with the smallest specimens; this was a worst-case scenario.

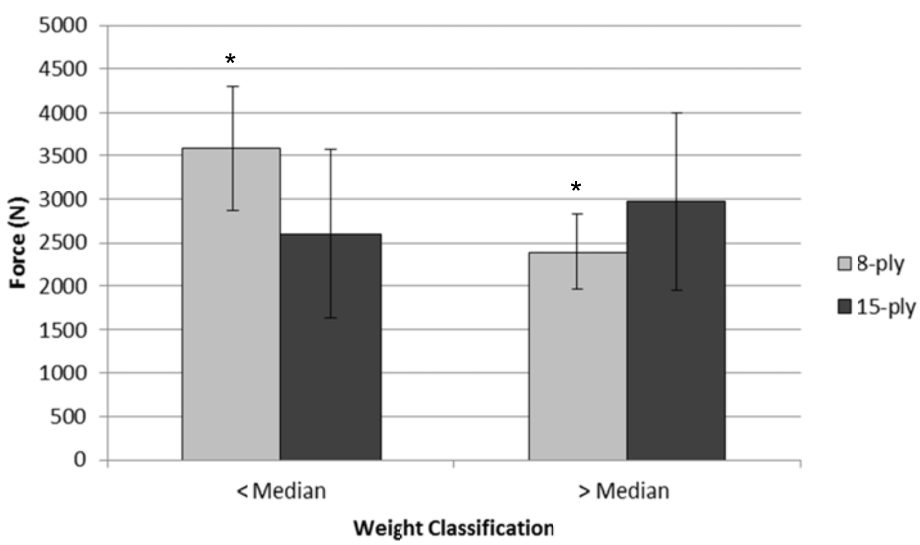


Figure 4.18: Impact force classification by weight (* P-value < 0.05)

The average peak deflections at the level of impact and 2.5 cm (1 inch) towards the posterior part of the body for 8-ply and 15-ply were 16.5 ± 11.6 mm and 13.8 ± 8.1 mm, respectively (P = 0.259). A correlation was detected between peak deflection measurements and resultant rib acceleration from the eighth rib (ρ = 0.39, P = 0.008) (Figure 4.19 and Figure 4.20). As the eighth rib acceleration increased so did the peak deflection.

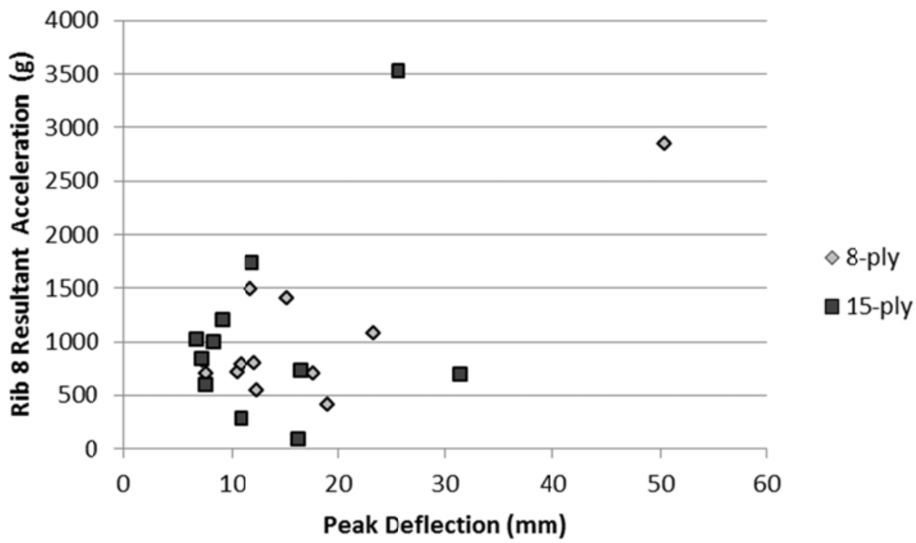


Figure 4.19: Peak eighth rib acceleration versus peak deflection

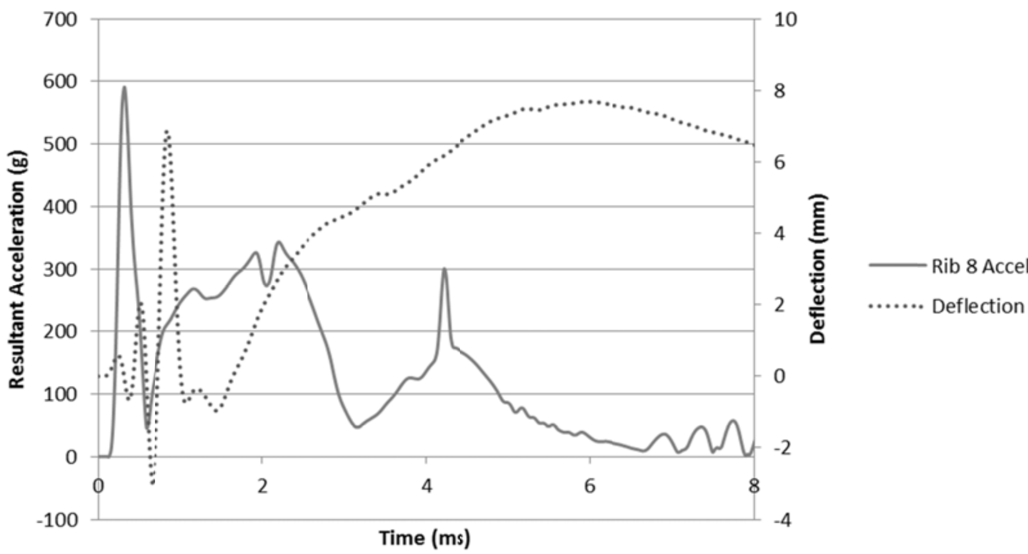


Figure 4.20: Example of timing comparison of the eighth rib acceleration and peak deflection

4.3.2 Injury Data – Comparison based on Injury Outcome

The armor packet conditions were used to generate an "injurious" and "non-injurious" response. The 8-ply packet did not exclusively create rib fractures in the PMCS, similarly, the 15-ply packet did not solely prevent against rib fracture. There was a significant association between injury severity and armor layers based on the Chi-Squared Likelihood Ratio (P = 0.007). The 8-ply packet which was used as the "injurious" condition resulted in more severe injuries when compared to the 15-ply. For the impact condition with the 8-ply armor (n = 12), 41.7% (n = 5) of the impacts resulted in a level 2 fracture classification and 41.7% (n = 5) resulted a level 3 classification. The remaining two (2) cases were classified a level 1 with no visible fractures. For the 15-ply impact condition (n = 11) the majority of the cases were classified as a level 1 with no visible fracture on the seventh rib (63.6%, n = 7). The remaining cases were classified as a level 2 fracture classification (36.4%, n = 4). There were no observed level 3 fracture classifications resulting from the 15-ply impact condition.

Injuries for each test were classified based on observations of the seventh rib (impacted rib) during the necropsy. Three fracture classifications were developed to group the injury outcome: (1) no visible fracture, (2) visible fracture with the bone being non-displaced or continuous after removing tissue, or (3) visible fracture with bone being displaced or discontinuous and in some cases comminution of the rib bone (Figures 4.21 - 4.23). There were no cases where additional ribs were fractured; only the seventh rib was affected.

Figure 4.21: Typical fracture classification level 1 – no visible fracture (medial aspect of bone)

Figure 4.22: Typical fracture classification level 2 – fracture with continuity of bone (medial aspect of bone)

Figure 4.23: Typical fracture classification level 3 – fracture with discontinuity of bone and comminution (medial aspect of bone)

A Two-Way ANOVA was performed to measure the interaction between injury outcome (fracture, no fracture) and independent variables (weight, lateral depth, and thoracic ratio) on measured engineering variables. No fracture cases (classification 1) were compared to fracture cases (classifications 2 and 3) for measured engineering parameters. There were no significant interactions noted between the injury outcome and independent variables on measured engineering variables. Additionally there were no significant mean differences between the injury outcome and the average peak values of the measured parameters (Table 4.7). Although no statistical difference was noted, the resultant acceleration of the spine and peak deflection appear to be potentially promising varialbes for future studies.

Table 4.7:
Biomechanical data based on fracture classification

	No Fracture (Class 1)	**Fracture (Classes 2, 3)**	**P-value**
A_{Sp} (g)	128.3 ± 84.9	210.1 ± 124.4	0.068
Deflection (mm)	10.9 ± 4.3	18.0 ± 11.6	0.078
V_D (m/s)	4.0 ± 7.3	20.5 ± 27.2	0.102
Compression (%)	12.6 ± 4.3	19.2 ± 12.9	0.128
A_{R8} (g)	736.5 ± 303.0	1240.5 ± 929.9	0.170
T_D (ms)	7.1 ± 4.3	4.8 ± 5.2	0.224
γ_{maxR7} (μs)	6142.5 ± 1298.9	7019.5 ± 780.8	0.265
γ_{maxR8} (μs)	5005.8 ± 1243.8	3576.4 ± 2844.8	0.368
A_{R7} (g)	1166.9 ± 375.3	1434.6 ± 532.2	0.375
A_{St} (g)	439.6 ± 306.7	479.6 ± 328.6	0.547
Force (N)	2966.5 ± 1120.7	2944.1 ± 783.3	0.959

*Abbreviated measurements: A_{R7}-Resultant Acceleration rib 7, A_{R8}-Resultant Acceleration rib 8, A_{Sp}-Resultant Acceleration of spine, A_{St}-Resultant Acceleration of sternum, γ_{maxR7} -Shear strain rib 7, γ_{maxR8}-Shear strain rib 8

4.3.3 Injury Prediction

In addition to the measured responses, additional variables were calculated that may help predict the occurrence of injury (Table 4.8). Logistic regression analysis was performed to determine whether the presence of rib fractures could be predicted from the measured and calculated engineering variables. Lateral depth and weight were included in the model as independent variables.

Table 4.8:
Test results evaluated for potential fracture prediction

ID	Armor	Deflection (mm)	T_D (ms)	V_D (m/s)	Compression (%)	Fracture (Y/N)
2R	8	23.2	0.95	24.3	20.4	Y
3R	15	16.3	3.0	5.4	15.5	Y
4L	15	11.0	9.1	1.2	12.8	N
4R	8	12.2	11.6	1.1	11.9	Y
5L	15	9.2	11.7	0.8	10.8	N
5R	8	10.5	15.4	0.7	9.6	Y
6L	8	12.5	14.9	0.8	13.2	N
7L	8	17.7	0.9	19.1	18.7	Y
7R	15	8.4	7.1	1.2	7.2	N
8L	15	25.6	0.6	46.0	29.2	Y
8R	8	11.8	3.2	3.7	14.1	Y
9L	15	12.0	0.4	30.2	13.5	Y
9R	8	7.7	8.3	0.9	8.1	Y
10L	15	16.6	3.8	4.4	18.9	N
10R	8	10.9	9.6	1.1	12.7	Y
11L	15	6.8	3.7	1.9	9.1	N
11R	8	7.2	11.2	0.6	7.5	Y
12L	15	7.7	5.9	1.3	8.0	N
12R	8	19.0	0.8	23.2	18.2	N
13L	15	7.3	6.9	1.1	15.4	N
13R	8	15.2	0.5	30.2	15.7	Y
14L	15	31.4	1.3	23.7	40.6	Y
14R	8	50.3	0.5	100.0	51.8	Y

Predictor	α	β	SE	Model X^2	Model p-value	R^2	-2LL	Wald X^2	Wald p-value	Sensitivity (%)	Specificity (%)	Correct Prediction (%)
V_D	6.474	0.100	0.059	7.390	0.060	0.372	23.399	2.843	0.092	78.6	66.7	73.9
Deflection	5.449	0.190	0.124	6.419	0.093	0.330	24.370	2.350	0.125	78.6	66.7	73.9
A_{Sp}	2.767	0.012	0.008	6.177	0.103	0.319	24.612	2.514	0.113	78.6	44.4	65.2
A_{R8}	2.857	0.001	0.001	4.026	0.259	0.218	26.763	1.181	0.277	78.6	44.4	65.2
A_{R7}	5.439	0.002	0.001	3.730	0.292	0.221	24.180	1.402	0.236	84.6	50.0	71.4
Compression	4.349	0.111	0.098	4.496	0.213	0.241	26.293	1.278	0.258	78.6	55.6	69.6
T_D	6.868	-0.098	0.098	3.325	0.344	0.182	27.464	1.012	0.315	78.6	55.6	69.6
A_{St}	8.840	0.000	0.002	2.886	0.409	0.166	26.881	0.062	0.804	69.2	55.6	63.6
Force	6.768	0.000	0.001	2.011	0.570	0.120	26.830	0.120	0.741	78.6	25.0	59.1

Table 4.9:
Logistic regression results

Logistic regression results indicate that the engineering variables do not affect the likelihood that a fracture will occur (Table 4.9). The velocity of deflection seemed to have the most encouraging results (model $P = 0.060$ and variable $P = 0.092$). Weight and lateral depth of the specimens did help improve the models, however, they were not found to be significant factors in predicting rib fractures ($P > 0.05$). Thoracic ratio was initially explored as an additional independent variable but did not improve the model so it was removed from the analysis.

4.4 Discussion

Biomechanical assessments and establishing a response is the first step to understanding injury mechanisms and identifying methods for protection. These responses have been well established for automotive impacts, but blunt ballistic impacts are not the same kind of loading event. Ballistic impacts involve lower mass and higher rate considerations making force and deflection evaluation difficult. Previously published biomechanical response studies involving blunt ballistic impacts have utilized larger, instrumented projectiles allowing for force determination (Bir and Viano, 2004; Bir, Viano et al., 2004; Eck, 2006; Wilhelm and Bir, 2007; Raymond, Van Ee et al., 2009). Additionally, deflection is generally determined by high speed video and tracking markers. During this study, force and thoracic deflection were collected using the thin film force sensor and chestband, a novice approach for a blunt ballistic response study.

Force and deflection vary based on impact velocity and mass of the projectile and stiffness of the target. In a previously published blunt ballistic thoracic study, there were three conditions evaluated: A) high mass with low velocity (140 g at 20 m/s), B) high mass with moderate velocity (140 g at 40 m/s), and C) low mass with high velocity

(30 g at 60 m/s) (Bir, Viano et al., 2004). Average peak force and peak deflection measurements that resulted from Condition A were 3,383 ± 761 N and 22.6 ± 2.8 mm, respectively. For Condition B, the average peak force was 10,620 ± 2,226 N and the average peak deflection was 52.3 ± 16.2 mm. Impact Condition C resulted in an average peak force of 3,158 ± 309 N and an average peak deflection of 17.8 ± 4.7 mm. The impact conditions for the current study differ by several orders of magnitude, using live ammunition with a bullet weight of 124 grains (8.04 g) and an average impact velocity of 394.0 ± 7.3 m/s. The resulting average peak behind armor force for the 8-ply armor condition was 3,090.2 ± 851.3 N creating an average peak thoracic deflection of 16.5 ± 11.6 mm. The resulting average peak behind armor force for the 15-ply armor condition was 2,786.7 ± 960.2 N with an average peak deflection of 13.8 ± 8.1 mm. Although, the peak forces recorded during the current study are comparable to Conditions A and C from Bir et al., the peak deflections are lower. This could be due to the location of deflection measurement for the current study or the difference between the animal and human model. Since the chestband was delicate, it could not be placed at the location of impact. If the impacts were more localized there is a chance that the true peak deflection was not captured.

An impact to the thoracic cavity compresses the rib cage, accelerating the ribs in the direction of the impact force (Viano, King et al., 1989). With sufficient compression of the thorax, tensile strain limits in the ribs can be exceeded generating fracture. As the thoracic cavity is compresses, the internal organs can become displaced from their normal positions, increasing pressure, and potentially creating damage to the organs within the thoracic cavity. Thoracic deflection, compression, and TTI (acceleration based criterion) have been identified as potential injury predictors for automotive thoracic impact conditions (Cavanaugh, Zhu et al., 1993; Kuppa and Eppinger, 1998; Chung, Cavanaugh et al., 1999; Kuppa, Eppinger et al., 2003). For example, an average peak rib deflection of 65 mm or 20% chest compression correlates to a 50% probability of an AIS 3+ injury in a 45 year old 50th percentile male (Kuppa, Eppinger et al., 2003). Peak deflections and compressions reported in this study were much lower than those reported in automotive literature. The current study found that there was an average peak deflection of 18.0 ± 11.6 mm for tests that resulted in a rib fracture and a compression of 19.2 ± 12.9% (based on half-chest methods). The duration of the impact is the main difference between ballistic and automotive impacts and the occurrence of injury. Peak thoracic forces generated during automotive impact research are approximately 4 to 6kN resulting in average peak deflections of 68.4 ± 16.1 mm and an impact duration of approximately 60 ms (Yoganandan, Humm et al., 2013). The average peak force of 2,944.1 ± 783.3 N for tests resulting in fracture was obtained in less than 0.5 ms for the current study.

For high velocity type impacts, both velocity and compression are evaluated by the Viscous Criterion (VC) which was developed for thoracic and abdominal impacts to include the rate-sensitive response of tissue (Viano and Lau, 1988). This criterion indicates that as the speed of deformation increases the body's tolerance to compression decreases. The VC demonstrated high correlation to severe soft tissue and internal organ injury (Viano and Lau, 1988). A tolerance level of VC_{max} = 1.0 m/s correlated to a 25% probability of injury for frontal chest impacts. Bir and Viano evaluated injury criteria for blunt ballistic impacts (Bir and Viano, 2004). The Blunt

Criterion (BC), taking into account five parameters (specific to the physical properties of the impactor and impacted surrogate), and VC were evaluated. Both variables were significant predictors of skeletal injury. A VC_{max} of 0.8 m/s was determined to result in a 50% probability of sustaining an AIS 2 or 3 skeletal injury. For the current study, thoracic wall thickness was not recorded and therefore BC was not calculated. The rate of deflection, VC, and VC_{max} were explored. The velocity of deflection calculated by differentiating the chestband deflection exceeded the 30 m/s suggested for VC validity (Viano and Lau, 1988). This is potentially a result of filtering since the chestband output was filtered with a frequency limit of 3,000 Hz which is higher than what is typically used for a CFC 600 (Maltese, Eppinger et al., 2002; Yoganandan, Pintar et al., 2008; Yoganandan, Humm et al., 2013). Additionally, VC was established to identify the risk to soft tissue and internal organs. The current study evaluated thoracic injury in terms of skeletal damage. As an alternative to the traditional VC calculation, the time to peak deflection (T_D) and the rate at which peak deflection was achieved (V_D) were reported. The time to peak deflection was evaluated and the average time to the peak was 7.1 ± 4.3 ms for tests resulting in no fracture and 4.8 ± 5.2 ms for tests resulting in a fracture. The rate at which the peak deflection was reached could also be calculated and it was found that the tests resulting in no rib fracture reached the peak deflection at 4.0 ± 7.3 m/s while the tests that result in a fracture reached the peak at 20.5 ± 26.2 m/s. This estimate did prove to be the most promising measurement when predicting rib fracture for this study and could be looked into further in future studies.

Rib fracture patterns are commonly complex with a relatively small amount of published research (Love and Symes, 2004; Daegling, Warren et al., 2008; Christensen and Smith, 2013). Bone tends to be stronger under compression rather than tension, meaning bone will typically fail first at the point of greatest tension (Alms, 1961). During the current testing the lateral (exterior) aspect of the rib bone was under compression and the medial (internal) aspect was under tension creating a bending force leading to fractures propagating primarily on the medial aspect of the rib bone. Love and Symes reported multiple examples of rib fractures in which there was evidence of buckling fractures, which were defined as failure that initiated at the point of compression (Love and Symes, 2004). Buckling fractures were not noted in the current study. Fourteen of the 23 cases (60.9%) resulted in a fracture where the fracture propagation began on the medial side of the rib bone. Nine cases (39.1%) resulted in incomplete fractures with four fractures having incomplete butterfly fractures as well (Figure 4.24). Five cases (21.7%) resulted in complete fracture of the rib bone with two cases resulting in a complete butterfly fracture (medial aspect of bone) and one case resulting in comminution of the rib bone. A butterfly fracture represents failure in bending that originates in tension and as the original compressed surface is encountered, the fracture surface splits, shearing off the bone fragment (Alms, 1961; Christensen and Smith, 2013). Age of the canines may have played a role in the resulting fracture patterns; however, age could not be determined from the specimens. Although soft tissue was not assessed during the current study, rib fractures can be an important indicator of soft tissue and organ injury. Future testing should evaluate the effects of blunt ballistic trauma on soft tissue.

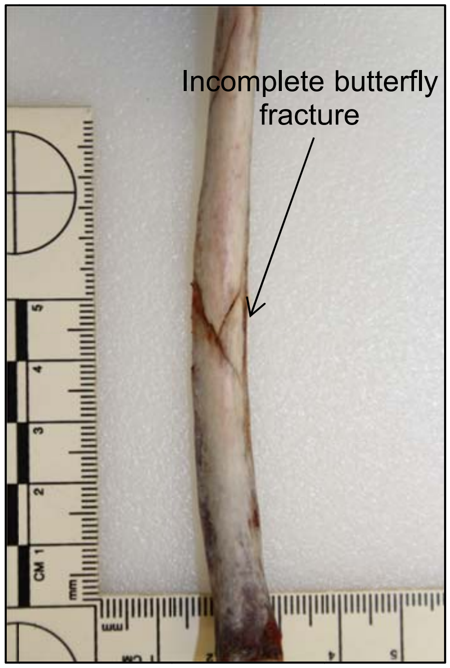


Figure 4.24: Example of an incomplete butterfly fracture from this study

There were several limitations to this study that should be noted. The chestband had several inactive gages during testing. Due to the age of the instrumentation the chestband was not repairable and funds were not available to purchase a replacement chestband since the study was self-supported. In order to utilize the chestband and ensure intact gages were at the impact site, the chestband was adjusted after the first impact. Unfortunately, this meant that for most tests the gages opposite the impact site did not collect curvature data and could not be used for analysis. The deflection data and subsequently the compression data could only be evaluated based on half-chest methods for this reason. The CrashStar software does estimate the data, however, there is error introduced to the results.

The chestband was designed for direct impact in the automotive research community. However, the band was not designed for direct ballistic type impacts and therefore was located adjacent to the site of impact. Deflection measurements were made from the level of the eighth and ninth ribs which did not result in injury. Another observation that was made regarding the chesband was sensitivity to suture site. If the suture was right at the level of impact a large peak was noticed in the deflection shortly after contact. The skin may have been pulled resulting in a sharp response of the strain gage at the suture. This perhaps is not representative of thoracic movement but primarily epidermis movement. Additionally, if there were no sutures near the impact site the deflection seemed to indicate the chestband bulged after impact creating a negative deflection or expansion of the cavity. Previous literature did not go into detail regarding methods for securing the chestband, perhaps for higher rate impacts suture placement should be taken into account. With that being said, the chestband allowed the ability to collect deflection data without extensive damage to tissue since video tracking was not a viable option with live ammunition and utilization of both side of the canine. Although, the peak deflection data did show promise in the logistic regression analysis, ballistic impacts may not be an appropriate use for the chestband.

Another interesting observation from the chestband was the peak deflections occurrence with respect to time. Generally, the thoracic wall at the point of impact accelerates to a peak velocity, which then decreases to zero at which point the peak deflection occurs. For this study, peak deflection did not always occur at that point in time. Deflections from Specimens 4, 5, and 6 experienced peak deflections approximately 10 ms after contact. Specimens 4 and 5 were above the median weight but Specimen 6 was one of the smallest canines tested. Each specimen was a different breed of canine but Specimens 4 and 5 were more barreled chested compared to Specimen 6 which was a German Shepherd Mix. Unfortunately it is not clear what may have caused the delay in peak deflection for these three canines. It is hypothesized that the issue may be related to the location of the chestband sutures. Or perhaps the external compression from the harness was greater than the deflection created from the impact, resulting in the peak deflection being created from an unrelated action.

The sample size of the current testing was small. When analyzing the mean differences between injury outcome and the engineering variables significant differences were not observed. Spinal acceleration and deflection, although not statistically significant, were close to significance and could be focused on in future studies. A power analysis indicated an approximate sample size of 90 in which to obtain significance based on the data collected during the current study.

Additionally, the order of testing typically started with the 15-ply packet and then the 8-ply packet. This order was decided on to help reduce the likelihood that there would be rib fracture resulting from the first impact. If a rib fracture was produced during the first impact, the rib cage would not be intact for the second impact and could compromise the results. There were three canines that were tested where both impacts resulted in a rib fracture (Canine ID: 8, 9, and 14). For each of these tests, the first impact with the 15-ply packet resulted in a level 2 fracture (incomplete) and the second impact with the 8-ply packet resulted in a level 3 fracture (complete). The data from these tests were further examined and there were no noted variations within these tests.

The current study generated preliminary results regarding the thoracic blunt ballistic response of a canine. A variety of techniques were evaluated for collecting biomechanical response data for behind armor blunt trauma impacts with live ammunition. Although the chest deflection measurement method had its limitations, the rate for reaching peak deflection proved to be a variable that should be evaluated further. Additionally, more layers of armor reduce the severity of injury based on the specimens tested in this study, even though there was no statistical difference in the thoracic responses.

CHAPTER 5 – EVALUATION OF THE USE OF NATIONAL INSTUTUTE OF JUSTICE (NIJ) 0101.06 BALLISTIC RESISTANCE OF BODY ARMOR

5.1 Introduction

Initial body armor research began with a few objectives: develop armor that could stop the most common threats officers would face, prevent penetration and reduce life-threatening injuries, and allow the officer to physically walk away (Hanlon and Gillich, 2012). In order to work towards these objectives and evaluate behind armor blunt trauma (BABT), testing was conducted at Edgewood Arsenal in the late 1970's (Montanarelli, Hawkins et al., 1973; Goldfarb, Ciurej et al., 1975). Impacts with a .38 Special, 244 m/s (800 fps), were performed on anesthetized goats covered with 7-ply Kevlar-29 material. Impact locations varied to assess different vital organs and evaluate the injury response.

In order to translate these data to determine the risk of BABT injury, a standard methodology for measuring backface signatures (BFS) needed to be developed. BFS is defined as the maximum deformation of the soft body armor as a result of ballistic impact. A number of materials were evaluated to create a repeatable, inexpensive, and easy to conduct testing method which would also respond similarly to human tissue (Metker, Prather et al., 1975; Prather, Swann et al., 1977). After much consideration and testing of various materials, a standard methodology, and BFS limit were established. The recommendation has been correlated to both the gelatin data and the goat model (Goldfarb, Ciurej et al., 1975; Metker, Prather et al., 1975). It was determined that 44 mm of deformation into a ROMA Plastilina modeling clay, No. 1, backing material correlated to a 6% probability of lethality. These reports concluded that humans would be even less likely to sustain serious injuries under similar conditions. This BFS limit of 44 mm in clay is still used today to evaluate and certify armor. Currently in the U.S., soft body armor is assessed and certified using the NIJ 0101.06 standard which evaluates a number of requirements in addition to BFS (NIJ-0101.06, 2008).

Although this standard was developed using an animal model and was designed to be species-independent, the standard was meant to represent a 70 kg man. Validation was not performed to determine the risk of injury for smaller individuals or smaller animals. It is possible that smaller individuals would be at greater risk of injury when exposed to the same impact conditions. Additionally, the testing represented one ballistic threat and one level of armor protection. Currently there are three levels of soft armor protection (NIJ Level IIA, II, IIIA) available and certified, each tested to two different ballistic threats and velocities (NIJ-0101.06, 2008). The .38 Special is no longer the most common threat that civilian law enforcement will encounter and is not included in the current standard.

The goal of the current study was to evaluate the correlation between injuries recorded in PMCS testing to BFS measurements in clay. Two armor packet designs, 8-ply and 15-ply, were tested on conditioned clay backing material. Depth and volume of indentation were recorded and compared to injury data from PMCS testing to determine if the BFS is a good predictor of injury in the canine.

5.2 Methodology and Materials

5.2.1 Ballistic Armor

Sheets of Kevlar® XP™ S102 were donated to Wayne State University by DuPont Protection Technologies (Richmond, VA, DuPont™). Ballistic sheets of 30.5 x 30.5 cm (12 x 12 in) were received with an areal density of 0.51 kg/m^2 and thickness of 0.46 mm for each sheet. The sheets were cut to 15.2 x 30.5 cm (6 x 12 in) panels in order to be consistent with PMCS testing. Layers of Kevlar® XP™ were placed together unidirectionally, tacked in the four corners, and placed inside a nylon cover. DuPont™ recommends, for a vest made with Kevlar® XP™, a NIJ level II would be designed with 9 layers of Kevlar® XP™ S102. The same two conditions used in PMCS testing (8-ply and 15-ply armor packets) were tested during the current study.

5.2.2 Experimental Design

Prior to testing, a box with dimensions 61 x 61 x 14 cm (24.0 x 24.0 x 5.5 inch) filled with ROMA Plastilina clay No. 1 was placed in a temperature and humidity chamber (ESL-2CA, ESPEC North America Inc., Hudsonville MI) for conditioning. The clay was heated to 42 ºC (107.6 ºF) with 0% relative humidity for at least 24 hours prior to testing. The clay was calibrated as outlined in the NIJ 0101.06 standard to ensure it fell within acceptable testing ranges (NIJ-0101.06, 2008). Once the clay was determined to be with the calibration thresholds, the clay box was placed 5 meters down range from the muzzle of the barrel and the armor packet was secured to the front of the box (Figure 5.1). Bullets were fired using a Universal Receiver (model UR-01, Rapid City, SD, H.S. Precision Inc.) which allowed for accurate, remote firing. The shot path was aligned such that the bullet struck perpendicular to armor packet and at least 7.6 cm (3 in) from the edges. The manufacture and model of the bullet was kept consistent with the PMCS testing. The velocities were also matched for each test; therefore, the 9 mm 124 grain FMJ RN rounds were uploaded to be within the threshold of 398 ± 9.1 m/s (1306 ± 30 fps). A chronograph (Model 35P, Austin, TX, Oehler Research Inc.) with three photo-electric screens (Model 57, Austin, TX, Oehler Research Inc.) was used to measure the velocity of each shot. Following the test shots, the clay was calibrated again to ensure the response was still within the thresholds during the testing.

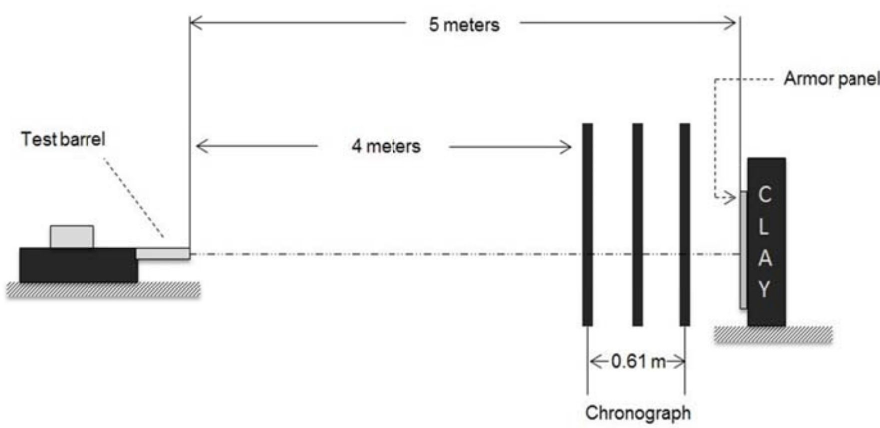


Figure 5.1: Clay test setup

5.2.3 Analysis

Backface signature (BFS) measurements were taken using digital calipers in accordance with the NIJ 0101.06 standard for each test (Figure 5.2). Molds were also created of each indentation using a two-part low viscosity polyurethane resin (EasyFlo 60, Polytek Development Corp., Easton PA). The molds allowed for a permanent capture of the indentation that could be further analyzed to determine volume of the indentation for each impact. Each clay test was matched by bullet velocity and armor packet to one PMCS test that resulted in biomechanical and injury data. For the purpose of this study only the thoracic deflection and resulting fracture classification were considered from the PMCS testing.

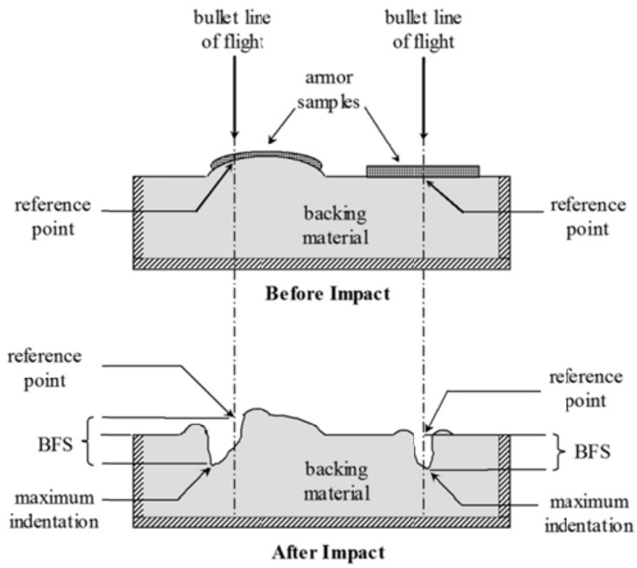


Figure 5.2: BFS measurement (NIJ-0101.06, 2008)

Statistical analyses were conducted using SPSS Statistics software (IBM SPSS, Version 22). A One-way ANOVA was used for comparing mean differences between armor packet (8-ply, 15-ply) and clay and PMCS measurements. Significance levels were set at $\alpha = 0.05$. Binomial logistic regression analysis was performed to determine whether the presence of rib fracture could be predicted from clay measurements (Table 5.1). All PMSC tests with no visible fracture were grouped into category “no fracture” or fracture = 0, all tests with a visible fracture (either classification 2 or 3) were grouped in the category “fracture” or fracture = 1.

Table 5.1:
List of variables evaluated as fracture predictors

Predictor	**Description**
Depth	Depth of indentation in clay behind armor
Volume	Volume of indentation in clay behind armor

The logistic regression model for the probability of fracture (P) takes the form:

$$P = \frac{e^{t(x)}}{e^{t(x)} + 1} = \frac{1}{1 + e^{-t(x)}}$$

$$t(x) = \alpha + \sum_{i}^{n} \beta_i x_i$$

where: α = intercept
x_i = variables used in the model
β_i = corresponding coefficients with each variable

The maximum likelihood method was used for coefficient determination. The -2 log likelihood (-2LL) statistic was used to assess the overall fit of the model and the relative improvement of the models ability to predict the injury outcome accurately with the addition of each variable. The difference between the initial -2LL measurement and -2LL the measurement after clay measurement variables are added to the model is defined as the Chi-squared value of the model which is tested for statistical significance. Significance levels were set at $\alpha = 0.05$. A Chi-squared value resulting in a p-value below 0.05 indicates a significant relationship between the injury outcome and the variables included. Another model assessment tool, the Nagelkerke R^2 value, evaluates the strength of the relationship between the injury outcome and measured clay variables. This can be interpreted as the percentage of the variation of data explained by the model. Models were then assessed for variable significance using the Wald Chi-squared statistic. The null hypothesis tested was that the coefficient associated with the measured clay variable was zero or that there was no association between fracture and the measured variables. The 95% confidence intervals of the probability of fracture were calculated if models and variables proved to be significant predictors (Kuppa and Eppinger, 1998).

5.3 Results

5.3.1 Clay and PMCS depth comparison

One clay test was performed for each PMCS test (n = 23). Velocities were paired, as close as possible, to each PMCS test resulting in an average change of velocity of 1.5 ± 1.0 m/s. Injury outcomes from each PMCS test were matched with BFS depths in clay and volumes of the clay indentations. The bullet was captured by the armor packet (8-ply and 15-ply) during both PMCS and clay testing with no complete penetrations noted. The bullet penetrated the first three layers of armor and the fourth layer was mechanically damage. A comparison of PMCS testing data to depth and volume in clay can be found in Table 5.2 for 8-ply armor and Table 5.3 for 15-ply armor. The average BFS depth for the 8-ply tests was 41.2 ± 3.7 mm and the average volume of the indentation was 73.9 ± 8.3 mL. The average BFS depth for the 15-ply armor packet was 24.1 ± 1.8 mm and the average volume of the indentation was 48.2 ± 5.4 mL. Both depth and volume of the indentation in the clay are significantly larger for the 8-ply armor when compared to the indentation resulting from 15-ply ($P < 0.001$). Pictures of the impacted rib for each PMCS test are located in Appendix D.

Table 5.2:
Clay and PMCS data paired for 8-ply tests

ID	PMCS Data				Clay Data		
	# of armor layers	**Velocity (m/s)**	**Deflection (mm)**	**Fracture Score**	**Velocity (m/s)**	**Depth (mm)**	**Volume (mL)**
2R	8	411.5	23.2	2	413.6	43.7	88.0
4R	8	396.8	12.2	2	394.4	39.5	77.7
5R	8	385.3	10.5	2	383.7	36.1	73.2
6L	8	395.0	12.5	1	394.4	36.9	66.9
7L	8	387.7	17.7	2	387.4	43.5	68.4
8R	8	398.1	11.8	3	399.6	45.7	62.7
9R	8	402.9	7.7	3	400.2	45.5	77.8
10R	8	405.4	10.9	3	407.8	38.4	88.2
11R	8	387.1	7.2	2	387.1	41.7	73.7
12R	8	385.6	19.0	1	387.1	41.7	73.7
13R	8	382.5	15.2	3	383.7	36.1	73.2
14R	8	397.8	50.3	3	399.6	45.7	62.7

Table 5.3:
Clay and PMCS data paired for 15-ply tests

ID	PMCS Data				Clay Data		
	# of armor layers	**Velocity (m/s)**	**Deflection (mm)**	**Fracture Score**	**Velocity (m/s)**	**Depth (mm)**	**Volume (mL)**
3R	15	393.5	16.3	2	394.4	24.4	43.9
4L	15	387.1	11.0	1	384.7	26.9	50.0
5L	15	394.7	9.2	1	394.7	24.2	46.1
7R	15	399.6	8.4	1	403.3	23.1	53.5
8L	15	391.7	25.6	2	392.3	21.2	41.6
9L	15	396.5	12.0	2	395.9	26.1	58.5
10L	15	401.7	16.6	1	404.5	25.8	53.1
11L	15	392.9	6.8	1	392.3	21.2	41.6
12L	15	381.9	7.7	1	384.7	23.9	48.7
13L	15	394.1	7.3	1	395.3	24.5	49.1
14L	15	394.1	31.4	2	394.4	24.4	43.9

The 15-ply armor packet created a larger surface area for distribution of the energy into the clay by creating a shallow yet wider indentation. The 8-ply armor packet created more of a localized distribution creating a narrower and deeper indentation in the clay (Figure 5.3).

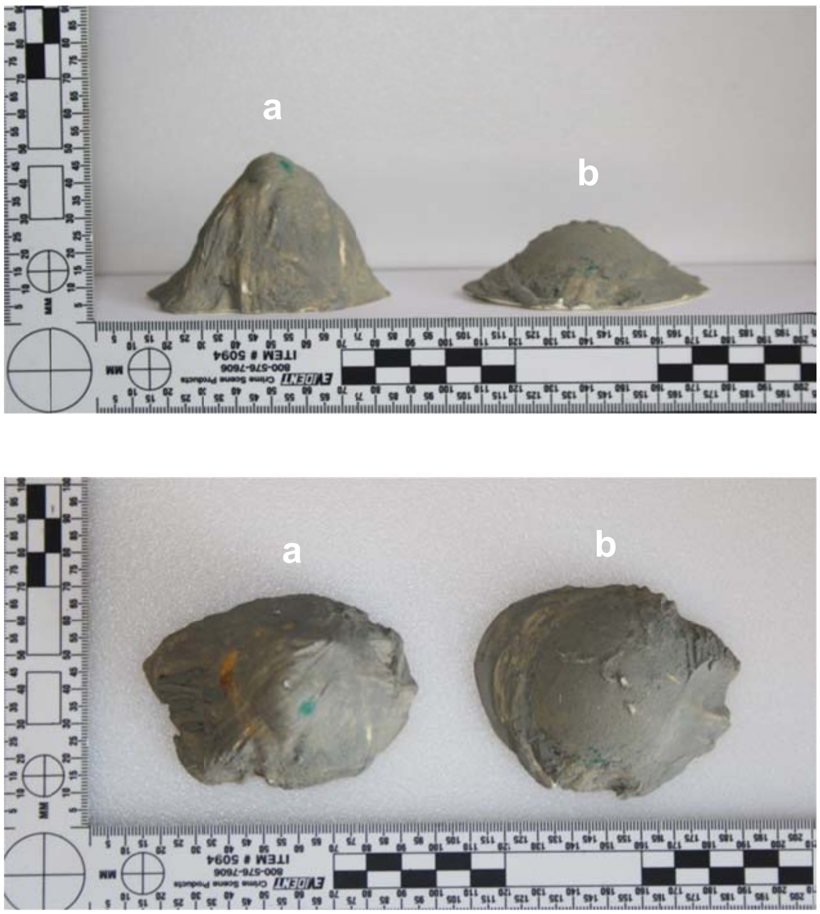


Figure 5.3: Behind armor clay indentation for a) 8-ply and b) 15-ply armor packets

When comparing the deflection measured in the clay to deflection measured in the PMCS testing there is a noticeable difference (Figure 5.4). For the 8-ply armor packet, the average BFS measurement was 41.2 ± 3.7 mm and the deflection from PMCS testing was 16.5 ± 11.6 mm. The measurement in clay was significantly higher than the measurement from the PMCS ($P < 0.001$). For the 15-ply armor packets, the average BFS depth was recorded as 24.1 ± 1.8 mm and 13.8 ± 8.1 mm. The clay measurement for the 15-ply armor pack was also significantly higher than the measurement from PMCS (P = 0.001). Indicating that the PMCS have a stiffer response compared to the clay model.

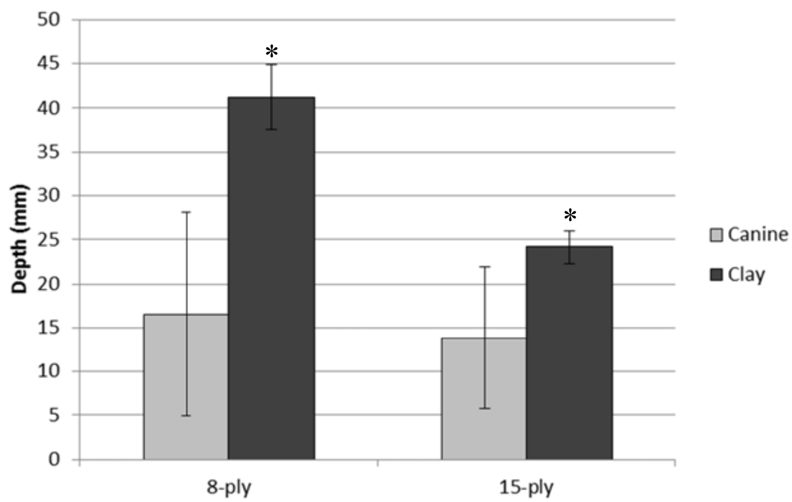


Figure 5.4: Deflection measured from PMCS with respect to Backface Signature in clay (* P < 0 .05)

5.3.2 Injury Prediction using Clay Backing Material

Since each PMCS test was matched with a clay test, the values may also be analyzed by the fracture outcome (Figure 5.5). The average depth in clay for tests resulting in no fracture were 27.6 ± 6.9 mm and for tests resulting in fracture the average depth in clay was 36.6 ± 8.9 mm. The average volume of the clay indentation for cases without the occurrence of a fracture was 53.6 ± 10.3 mL and for cases with fracture the average volume was 66.7 ± 15.4 mL. For depth and volume of clay indentation, the cases with fracture had significantly higher values (depth P = 0.018, volume P = 0.036) when compared to cases without fracture.

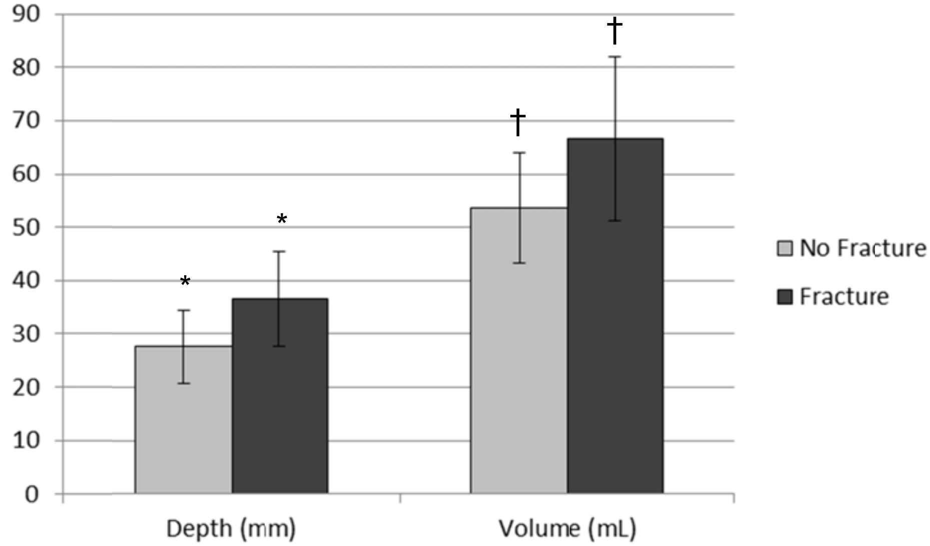


Figure 5.5: Depth and volume measurements of clay indentation for no fracture and fracture cases (* and † indicated $P < 0.05$)

Logistic regression analysis showed that both the depth in clay and the volume of the indentation were significant predictors of rib fracture, demonstrating both the model and variable significance (Table 5.4). Additional independent variables were not added to the models. Logistic regression models were presented for depth in clay and volume of the clay indentation (Figure 5.6 and Figure 5.7). A 50% risk of rib fracture is represented by a depth in clay of 28.5 mm and a volume of 54.1 mL. The 95% confidence intervals are included in both models.

Predictor	**α**	**β**	**SE**	**Model X^2**	**Model p-value**	**R^2**	**-2LL**	**Wald X^2**	**Wald p-value**	**Sensitivity (%)**	**Specificity (%)**	**Correct Prediction (%)**
Depth	-3.702	0.130	0.060	5.494	0.015	0.308	24.864	4.701	0.030	71.4	77.8	73.9
Volume	-3.949	0.073	0.037	4.834	0.028	0.257	25.956	3.852	0.050	78.6	77.8	78.3

Table 5.4:
Logistic regression results

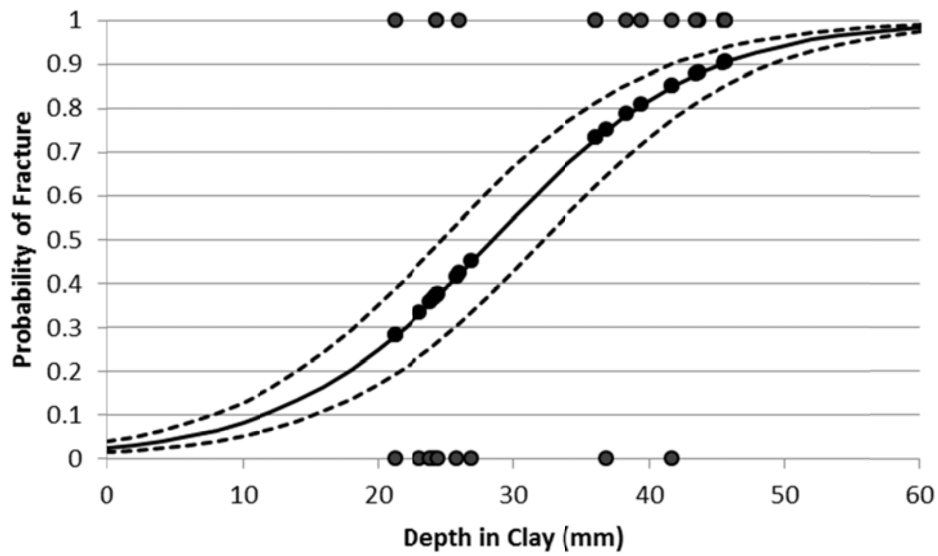


Figure 5.6: Injury risk function for the prediction of rib fracture based on BFS in clay

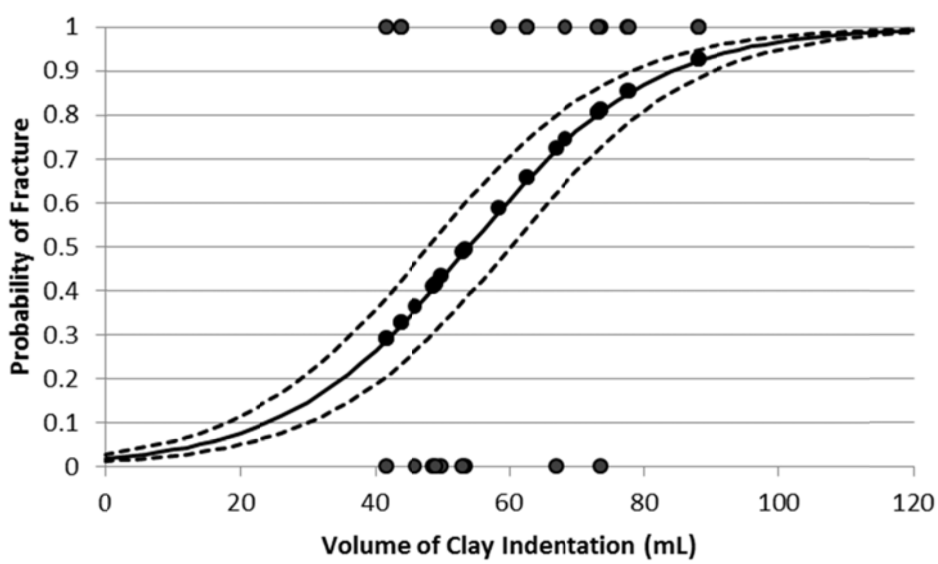


Figure 5.7: Injury risk function for the prediction of rib fracture based on volume of clay indentation

5.4 Discussion

The overall goal of injury biomechanics research is to understand the process of injury and develop ways to reduce or eliminate injury. In order to achieve this, researchers must first identify the injury mechanism, quantify the responses of tissues and structures in the body to various impact conditions (‘biomechanical response’), and determine the response at which tissue and structures may fail (‘injury tolerance’). In order to minimize injury, protective materials or structures can be developed or evaluated to minimize the force and energy delivered to the body region. For the most part, this has been accomplished for human body armor. A Standard (NIJ 01011.06) has been developed and is currently followed for certifying protective armor; however, the standard was not evaluated for small individuals or animals (NIJ-0101.06, 2008). This study took the biomechanical results from PMCS testing and evaluated whether the current standard is effective at predicting injury for a canine-specific model.

Fourteen fractures were produced from the 23 impacts in the PMCS. Although this is just a single rib fracture that may not be life-threatening, some of the fractures were rather severe. Five of the fractures were classified as discontinuous or displaced fractures. Three cases exhibited intercostal muscle damage where the rib and muscle had failed creating an opening in the thoracic cavity. This study evaluated primarily skeletal injuries, but some of the impacts may have resulted in serious organ damage. Since the PMCS were frozen prior to testing, evaluating soft tissue damage was outside the scope of this study but could be evaluated in future studies. Since there are few studies collecting data regarding ballistic injuries to canines, it is difficult to conclude what the recovery time would be for this type of injury in a canine. Previously published literature evaluating armor and its protective ability looked primarily at organ damage (Linden, Berlin et al., 1988; Roberts, O'Connor et al., 2005; Merkle, Ward et al., 2008). This agrees with the recommendation that with a higher velocity impact, internal organ injury occurs before peak compression of the thoracic cavity (Viano and Lau, 1988). This study represents a first step to evaluate canine thoracic injuries by focusing on skeletal injuries.

The average peak deflection in the PMCS with the 8-ply armor was 16.5 ± 11.6 mm while the BFS in clay with the same armor packet was 41.2 ± 3.7 mm. The average peak deflection in the PMCS with the 15-ply armor packet was 13.8 ± 8.1 mm while the BFS in clay was 24.1 ± 1.8 mm. It is evident that the clay does not reflect the deflection collected in the canine testing. Clay has been shown to agree with human response in blunt ballistic impacts, however, the indentation in the clay and BFS represent the permanent deformation (Bir, 2000). Clay does not provide the complete biomechanical representation of the impact which should be considered. The location of deflection measurement during the PMCS testing could also explain potential differences in mean values. One trend that is comparable is the deflection and BFS decreases with the increased number of ballistic material layers.

Logistic regression analysis show that based on the PMCS data and clay data the current standard, utilizing clay backing material to determine BFS, seems to predict the outcome of injury. The model was statistically significant with both BFS and volume of the indentation in clay. The volume measurement is not a requirement for armor certification based on the NIJ 0101.06 Standard but it is an additional parameter that helps identify the overall physical size of the indentation. Ballistic resistant armor is designed to distribute energy over a large area to reduce the severity of injury in the tissue. As armor has become more flexible the distribution of energy can be more localized creating more severe injuries in the underlying tissue. Soft armor can “pencil” when impacted, creating a deeper but very narrow indentation in clay and tissue (Carroll and Soderstrom, 1978; Wilhelm and Bir, 2007). The volume measurement may also help identify this occurrence.

The logistic regression model indicated that a BFS depth of 28.5 mm corresponds to a 50% probability of rib fracture. The current standard follows the threshold of a 44 mm BFS limit. This limit provided a 6% probability of lethality in a goat model of approximately 70 kg (Goldfarb, Ciurej et al., 1975; Metker, Prather et al., 1975). This may indicate that a lower BFS limit is needed when certifying canine specific armor. The sample size used for the logistic regression model (n = 23) is relatively small which should be considered when interpreting the results.

Ballistic armor has proven effective for human law enforcement and military personnel and could be beneficial to their canine counterparts. Understanding the response of the canine and the injury tolerance with regards to skeletal fracture can help improve the future development of canine armor. Further refining the minimum number of armor layers needed to prevent serious injury and allow for canine mobility to complete tasks is needed to optimize canine protection and efficacy in the field.

CHAPTER 6 – END USER EVALUATION

6.1 Introduction

Law enforcement and military working canines are utilized in a variety of different environments, some involving extreme conditions. The environmental limits of the canines and how they perform tasks efficiently, without causing harm to themselves, have yet to be defined. Military environments can be harsh and extreme, including large changes of altitude, utilization in naval operations, and desert or tropical temperature conditions (Baker and Miller, 2013). Comparatively, military working canines may experience more extremes; however, law enforcement canines do encounter potentially hazardous climates in certain areas of the United States and may also be utilized for water operations. At the same time that working dogs are being utilized more broadly, canine specific protective equipment is becoming more widely marketed. Paw protectors, muzzles, protective eyewear, tactical vests, and ballistic vests are all available for working canines. Although available, information regarding the efficacy and effect on canine performance is minimal. For this study, canine core body temperature and performance were evaluated for law enforcement canine working dogs wearing ballistic vests.

The normal body temperature of a canine ranges between 100.5 - 102.5 ºF at rest and 101.0 – 104.0 ºF during exercise (Taylor, 2009). Most veterinary personnel follow the guideline that any rectal temperature over 106^{o}F is a critical temperature indicating heat injury. However, these temperatures were derived from data collected in clinical settings after presentation to veterinary care, and significant cooling may have already occurred prior to presentation. Thus, actual body temperature causing heat injury may have been significantly higher (Taylor, 2009; Baker and Miller, 2013). When investigating working or athletic canines, the body temperatures that can be tolerated may also differ from the normal population. Several studies have investigated canine athletes and working canines and have shown that canines with rectal temperatures of 108^{o}F during moderate exercise demonstrate no adverse effects (Rose and Bloomberg, 1989; Steiss, Ahmad et al., 2004; Angle and Gillette, 2011).

The aforementioned studies collected canine body temperatures during exercise to evaluate risk of heat injury, however, the main focus of these studies were athletic canines. The aim of this study was to measure the effects of armor as it relates to core body temperature, focus, concentration, mobility, speed, and coordination. These were evaluated by monitoring law enforcement canines while they completed a typical day of training with and without armor in a non-climate controlled outdoor facility. Core body temperature, video and duration of time to complete each task were recorded. The primary hypothesis was that the armor would both increase the task completion times and increase the canines' core body temperature during the task.

6.2 Methodology and Materials

6.2.1 End User Recruitment

Handlers and canines were recruited from the Macomb County Sheriff's Department canine unit. Prior to obtaining the recruits, approval was granted by Wayne State Universities Institutional Animal Care and Use Committee (IACUC) (Appendix A). Six handlers agreed to participate in the study with their canines; however, data were only collected from five. The average weight of the five canine participants was 38.4 ±

4.3 kg (84.6 ± 9.4 lb) with service times ranging from 2.5 to 5 years. All of the canines were male German Shepherd Dogs.

One week prior to collecting data, the vests were provided to the handlers. The handlers were asked to introduce the canine to the new vest during non-working hours, allowing the canine to wear the vest for about 30 minutes each day, for the week prior to testing. This acclimation period allowed the canine to become comfortable with the fit and feel of the vest. Although most of these canines had ballistic vests available to them, new vests were purchased to ensure consistency with vest manufacturer, design, and ballistic threat level. The canines were inexperienced in completing the training course while wearing body armor vests.

6.2.2 Canine Ballistic Armor

Prior to procuring vests it was important to determine the most common ballistic threat to law enforcement officers in the US and the most commonly purchased canine ballistic vest. The researchers wanted to ensure that the canines could wear these vests on duty after testing completed. Handlers were consulted prior to purchasing the vests. According to Law Enforcement Officers Killed and Assaulted (LEOKA), the most common ballistic threat police officers face in the field is a 9 mm bullet (FBI-LEOKA). Law enforcement canines will likely face the same threats as their human counterparts. Commercially available canine armor is tested to human standards and is categorized based on the same threats. NIJ Threat Level II (tested to provide protection for 9 mm and 357 caliber rounds) ballistic vests for canines were selected for research.

To locate the most commonly purchased canine armor, a list of all available canine armor manufacturers was compiled and each was contacted. In addition, 7 non-profit organizations which raise money to purchase canine vests for officers were contacted. Sales could not be quantified when speaking with the armor manufacturers; therefore, the information given by the non-profit organizations was crucial. At the time of the study, the two most commonly purchased brands by the 7 non-profits were Point Blank and International Armor. One of the non-profits stated they had supplied over 700 vests purchased from Point Blank. This was by far the largest sample identified by the organizations. Based on these data, the most commonly purchased canine vest was determined and purchased.

The NIJ Threat Level II canine ballistic vests were purchased from Point Blank Body Armor (Model BII threat level II; Pompano Beach, FL) (Figure 6.1). The vest is constructed from a combination of Twaron and Honeywell materials. The armor packets are tested to the NIJ 0101.06 ballistic resistance of body armor standard (NIJ-0101.06, 2008). The median and dry areal densities of the armor are 4.49 kg/m^2 and 4.25 kg/m^2, respectively. The thickness of the armor panel is 0.58 cm. The overall weight of the armor panel and carrier was 2.25 kg (4.95 lbs).

Each canine was measured to determine the appropriate vest size based on manufacturers guidelines. Three measurements were used: body length (from between the scapulae to the top of the tail), circumference of the neck, and circumference of the thoracic cavity (just caudal of front legs). The average neck, chest circumference and body length were 54.6 ± 2.5 cm (21.5 ± 1.0 in), 83.8 ± 4.8 cm (33.0 ± 1.9 in), and 66.0 ± 2.8 cm (26.0 ± 1.1 in), respectively.

Figure 6.1: Point Blank Canine Armor model BII

6.2.3 Training Evaluation

To evaluate the “wearability” of the vest, the recruited canines were observed during their typical training activities. The tasks for which the canines were evaluated included: search, agility, and apprehension. First, the search task was used to assess the canine’s ability to focus, concentrate and find a hidden suspect. Next, the agility portions evaluated the canine’s mobility and coordination by running a course with 5 obstacles. Finally, the apprehension was used to evaluate the speed of the canines as they apprehended a suspect who was approximately 60 meters away. All of these tasks were conducted both with and without body armor. In addition, each activity was performed three consecutive times, if possible, in order to both obtain an average as well as to evaluate fatigue. For the canine officers evaluated in this study, the United States Police Canine Association governs the rules and training that each canine unit must complete to be certified. The training area was set up based on these specifications and the information that follows was obtained from the regional website (USPCA, 2010).

Suspect Searching

The suspect search trains canines to locate individuals based on scent and consists of six boxes with two rows of three boxes. The boxes are 12 m (40 ft) apart and 12 m (40 ft) from the centerline (Figure 6.2). There is a 1.3 cm (0.5 in) slot at the bottom of each box to allow the canine access to the scent within the box. To create a repeatable and comparable test, the suspect was concealed in the same box each time. There was concern that repeating this test more than twice per canine could create a learning effect which may produce training issues, therefore, the canines ran this activity once without the armor and once with the armor.

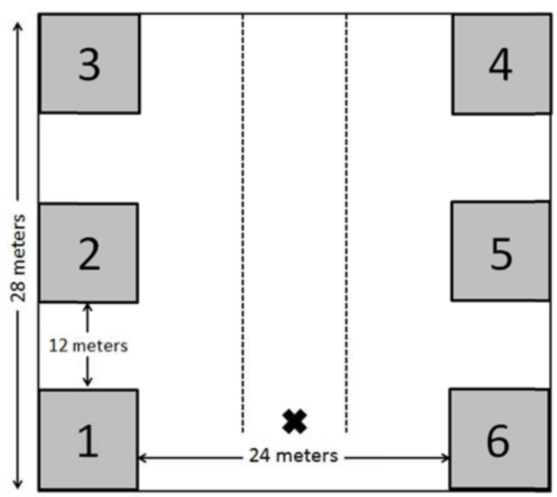


Figure 6.2: Suspect search exercise diagram

Prior to the commencement of the task, the canine was placed behind a shield while the “suspect” concealed himself in the box. The handler walked the canine to a spot between boxes 1 and 6 (Figure 6.2) and the handler issued the command to the canine to initiate the search. For each trial run, the suspect was concealed in the last box checked, box 6, creating the maximum amount of search time. The canines typically have 4 minutes to properly identify which box conceals the “suspect”. The canines either passively identified the correct box by sitting beside it or actively by barking to alert the handler.

Agility

The agility course consisted of 5 obstacles: hurdles, A-frame, broad jump, crawl, and catwalk. Canines ran the agility course three consecutive times without armor and three consecutive times with armor, when possible. The hurdle exercise consisted of six obstacles, about 1.0 m (3 ft) high; 1.2 m (4 ft) wide and spaced 4.9 m (16 ft) apart in a straight line (Figure 6.3 and Figure 6.4). The handler and canine started at a point approximately 1.5 meters from the first hurdle. The handler issued a command at each hurdle to drive the canine over the hurdles without stopping between. Upon completion of the last hurdle, the canine was called to the handler's side and both proceeded to the next obstacle.

Figure 6.3: Canine agility examples of hurdle obstacles

Figure 6.4: Hurdle portion of the agility course

The A-frame obstacle also tested the hurdling capabilities of the canine; however the conditions are more extreme (Figure 6.5). The canine began at the base of the obstacle from a heeled position. The handler commanded the canine to summit the obstacle and run down the ramp to complete. Once finished with the obstacle the handler recalled the canine to his side and they proceed to the next obstacle.

Figure 6.5: Canine agility A-frame obstacle

The broad jump consisted of four boards, graduated in height from 15.2 cm (6 in) to 30.5 cm (12 in) vertically (Figure 6.6). This obstacle tests their ability to jump a specific distance. The horizontal length of the broad jump, from low end to high end, was 1.8 m (6 ft). The canine started the obstacle from a heeled position at the low end of the jump. The handler commanded the canine to jump across the boards. Again, once completed the handler called the canine to his side and proceeded to the next obstacle.

Figure 6.6: Canine agility broad jump obstacle

Canines may also be required to crawl under objects or into small spaces. The crawl obstacle helps prepare the canine for those instances (Figure 6.7). The canine began from a heeled position at the beginning of the obstacle. The handler commanded the canine to crawl through the obstacle. Once the canine finished the obstacle, the handler called the canine to his side and then continued to the last obstacle.

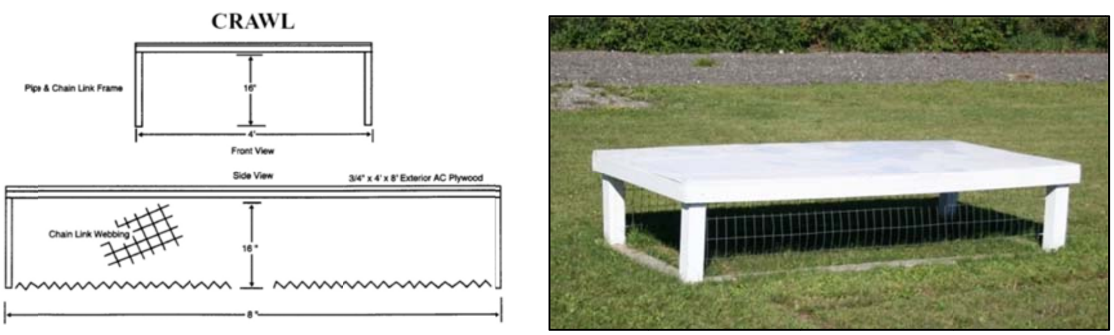


Figure 6.7: Canine agility crawl obstacle

The final obstacle was the catwalk, which consisted of a latter placed at a 25º to 30º angle onto a 61 cm (2 ft) wide platform (Figure 6.8). The stair portion of this obstacle is intended to help prepare a canine for drastically angled stairs, such as an attic. The platform is approximately 1.8 m (6 ft) above the ground with a ramp on the opposite end from the stairway. The ramp is used to aid the canine in dismounting and is about 3 m (10 ft) in length. For this obstacle the canine, again, began from a heeled position. The handler then commanded the canine to climb the ladder to the platform. Once the canine reached the platform, the handler signaled to stay in a standing position on the platform. On the handlers command, the canine proceeded across and down the ramp to the handler's side and finished in a heeled position.

Figure 6.8: Canine agility catwalk obstacle

Apprehension

The task of apprehension was assessed during a training activity that practices the "take down" of a suspect. This exercise was carried out with a decoy wearing a soft bite sleeve standing approximately 60 meters from where the canine and handler started the exercise. The hander instructed the canine to fully apprehend the decoy in their normal training manner. This required a run at full gait which was helpful to determine whether the armor causes overheating or inhibited motion of limbs. This task was conducted three times, consecutively, without the body armor and then three times, consecutively, with the body armor, when possible.

6.2.4 Experimental Design

The primary focus of this study was to evaluate the effect of ballistic vests on canine performance. Each canine was tested once over the span of two separate days. Each test day was divided into two sections: canines completing the three tasks without armor followed by canines completing the same three tasks with armor. Collecting three trials per task was not always possible. Canines 4 and 5 (collected on test day 2) had physical conditions restricting participation. The evaluation began with the suspect search (one trial per canine), followed by the agility course (three consecutive trials, if possible, per canine), and finally apprehension (three consecutive trials, if possible, per canine). Agility trials generated continuous exercise for approximately 10 minutes while the apprehension trials generated approximately 5 minutes of continuous exercise. Once the canines finished the tasks without the armor there was a break, approximately 30 minutes, to allow canines to recover and return to a baseline core body temperature prior to starting the trials with ballistic armor.

Canine 1 started the lineup completing the suspect search once without the vest. Core temperatures were taken before and after the suspect search for each canine. The pre-suspect search temperature was used as their baseline or their resting core body temperature. Canines 2 and 3 followed, completing the suspect search once without the vest. Next, canines began the agility exercise, again, starting with Canine 1. Canine 1 completed three trials of the agility, consecutively, without the vest. Core body temperature was recorded before the trials began, between each trial, and immediately after the canine completed the third trial. Canines 2 and 3 were asked to complete three trials as well, and once completed; Canine 1 started the apprehension exercise. Canine 1 completed three trials of apprehension without armor. Core body temperatures were again recorded before the trials began, between each trial, and after the final trial was completed. Canines 2 and 3 followed. To remain consistent, the same schedule was followed while the canines were wearing the armor. Sequence was continued on the second day of testing for Canines 4 and 5.

6.2.5 Data Collection

Three main parameters were collected during testing: time to complete tasks, core body temperature during the tasks, and video for further analysis. The handlers were also asked to complete a qualitative survey to aid in the understanding of how the canines performed.

Time to complete tasks

The time to complete the tasks was measured using Smartspeed gates (Fusion Sport, Australia). This system is a wireless and freely configurable timing system (Figure 6.9). The remote unit has a laser that reflects back; when the connection is broken the time will either start or stop depending on how the gate is set up. Each gate consists of a remote unit and a reflector. These gates provide an accurate and reliable method of timing the canines to within 0.01 seconds.

Figure 6.9: Smartspeed gate system

Core body Temperature

Each canine was given a CorTemp® ingestible core body temperature sensor (HQInc., FL) to measure core body temperature throughout testing. The sensor was 2.2 cm (0.88 in) in length and 1.1 cm (0.42 in) in diameter (Figure 6.10). The sensor was a single use transducer which provided an accurate and remote means to measure core body temperature. Once the sensor had been ingested, the data recorder wirelessly picked up the signal from the sensor in a digital format. The data recorder displayed temperature in real time and also stored data for download and later analysis. The data recorder could store up to 25,000 data points and collect data from up to 99 individual sensors. The sensors were administered 2 hours prior to evaluation to allow adequate time for the sensor to travel into the digestive tract.

Figure 6.10: CorTemp® sensor and data recorder

Video Analysis

Two, standard definition, handheld video cameras were used to collect video data during each task. Video was used to verify times for certain exercises and was further analyzed using Dartfish Prosuite v5.5 software (Dartfish, Switzerland). This software has been used extensively in the areas of sports motion analysis and more importantly dog agility (Birch and Lesniak, 2013). The software allows for an evaluation between the trials using the Simulcam module which blends the videos for comparison. Ambient temperature and humidity was recorded using a portable, battery operated temperature recorder (Dickson, IL: Model TH8P3).

Handler Evaluation

The last portion of this study documented the observations of the handler. It was felt that the handler could best assess their canine partner and provide insight into whether the canine was performing their tasks adequately. For the suspect search, handlers were asked to rate (on a scale from 1 to 5) the canines concentration, ability to find the suspect, overall obedience, and general mobility while wearing the body armor and without the body armor. The performance assessment for the agility exercise was broken down by obstacle and the handlers were asked to rate (on a scale from 1 to 5) the overall obedience and general mobility of the canine. The canine's ability to apprehend a suspect with and without armor was rated (on a scale from 1 to 5) based on the following categories: speed, jumping ability, overall obedience, and general mobility. Additionally, handlers were asked to judge whether the armor distracted the canine during these exercises. An example of the survey is included in Appendix E.

6.2.6 Statistical Analysis

A mixed-model ANOVA was performed to determine the overall effect of trial number (1,2,3), armor status (with and without), and interaction between both on completion times and core body temperature during the agility (each obstacle was evaluated separately when analyzing completion times) and apprehension tasks. If a significant interaction was found between trial number and armor, the post-hoc Fisher's LSD was performed. The significant level was set at $\alpha = 0.05$.

6.3 Results

Data were collected from five Macomb County Sheriff canines. Six agreed to participate, however, once the vests were received, it was determined that the vest did not properly fit one of the canines and the canine was removed from the study. The testing took place on two non-consecutive days. The first day, three canines were evaluated with average temperature during testing at 71.1 ± 4.5ºF and peak relative humidity of 28.5%. The second day, two canines were evaluated with average temperature during testing at 64.6 ± 4.4ºF and peak relative humidity of 94%.

6.3.1 Completion Time

Detailed completion times are listed in Table 6.1 - Table 6.3. Times for the suspect search exercise are listed in Table 6.1. The beginning of the suspect search was missed on video for Canine 3 while not wearing armor. Although statistical analysis could not be run, the general trend seemed to be an increase in time when armor was added.

Table 6.1:
Time for suspect search completion with and without armor

	Suspect Search Time (s)
Canine 1	
No Armor	21.77
Armor	21.20
Canine 2	
No Armor	29.90
Armor	34.90
Canine 3	
No Armor	-
Armor	39.67
Canine 4	
No Armor	28.00
Armor	42.63
Canine 5	
No Armor	37.30
Armor	46.43

Some completion time data points were either not collected or were removed for apprehension or agility tasks (Table 6.2 and Table 6.3). Canines 4 and 5 had physical issues that the handlers did not want to push for fear of injury, therefore 5 data points for agility were missed for each canine and 1 apprehension data point was missed for Canine 5. Additionally, Canine 4 had issues with the A-frame obstacle while wearing the vest leading to 2 data points not being collected. Canine 2 had similar issues with the A-frame, also missing 2 data points. Data points were removed if the time recorded did not accurately represent the time it took the canine to complete the task. Canines 1, 2, and 4 stopped after the third hurdle (testing included 6 hurdles), thus creating a longer completion time for the hurdles. Three data points were removed.

Table 6.2:
Detailed completion time for each canine and trial during agility

		No Armor Time (s)			Armor Time (s)			No Armor	Armor
ID	**Obstacle**	**Trial 1**	**Trial 2**	**Trial 3**	**Trial 1**	**Trial 2**	**Trial 3**	**Average**	**Average**
Canine 1	**Hurdle**	7.13	6.77	**10.00**[a]	8.10	6.83	7.37	7.97 ± 1.77	7.43 ± 0.64
	A-frame	5.63	3.93	4.93	6.07	10.37	6.33	4.83 ± 0.85	7.59 ± 2.41
	Jump	1.07	1.03	1.13	0.97	1.17	1.30	1.08 ± 0.05	1.14 ± 0.17
	Crawl	2.03	2.00	2.00	1.77	2.27	2.27	2.01 ± 0.02	2.10 ± 0.29
	Catwalk	10.37	10.57	11.03	11.60	15.27	17.40	10.66 ± 0.34	14.76 ± 2.93
Canine 2	**Hurdle**	6.87	6.90	6.83	**13.63**[a]	6.97	6.97	6.87 ± 0.03	9.19 ± 3.85
	A-frame	2.57	2.37	2.33	-	3.07	-	2.42 ± 0.13	3.07
	Jump	1.00	1.00	1.03	1.00	1.27	1.17	1.01 ± 0.02	1.14 ± 0.13
	Crawl	1.33	1.37	1.43	2.60	2.40	1.53	1.38 ± 0.05	2.18 ± 0.57
	Catwalk	9.97	10.07	11.97	18.27	15.37	11.17	10.67 ± 1.13	14.93 ± 3.57
Canine 3	**Hurdle**	6.67	6.60	6.60	8.80	6.90	6.83	6.62 ± 0.04	7.51 ± 1.12
	A-frame	2.73	3.00	2.67	3.97	3.53	3.87	2.80 ± 0.18	3.79 ± 0.23
	Jump	1.30	1.67	1.23	1.57	1.53	1.30	1.40 ± 0.23	1.47 ± 0.15
	Crawl	1.77	1.73	1.67	2.57	3.83	3.00	1.72 ± 0.05	3.13 ± 0.64
	Catwalk	12.83	11.23	11.60	11.83	11.80	12.43	11.89 ± 0.84	12.02 ± 0.36
Canine 4	**Hurdle**	**10.80**[a]	7.30	7.00	8.50	8.80	-	8.37 ± 2.11	8.65 ± 0.21
	A-frame	4.63	5.60	3.77	-	-	-	4.67 ± 0.92	-
	Jump	1.30	1.37	1.10	1.33	1.27	-	1.26 ± 0.14	1.30 ± 0.05
	Crawl	2.10	2.26	2.67	6.53	4.07	-	2.34 ± 0.29	5.30 ± 1.74
	Catwalk	12.63	9.20	10.86	19.60	18.03	-	10.90 ± 1.72	18.82 ± 1.11
Canine 5	**Hurdle**	6.73	6.50	6.73	9.00	8.63	-	6.66 ± 0.13	8.82 ± 0.26
	A-frame	3.07	3.17	3.23	5.83	10.03	-	3.16 ± 0.08	7.93 ± 2.97
	Jump	1.07	1.00	1.13	1.20	1.30	-	1.07 ± 0.07	1.25 ± 0.07
	Crawl	1.53	1.73	1.47	4.03	2.50	-	2.25 ± 1.08	3.27 ± 1.08
	Catwalk	9.93	10.63	7.83	13.10	17.17	-	9.47 ± 1.46	15.13 ± 2.88

[a] Data point is an outlier and was removed for analysis

Table 6.3:
Detailed completion time for each canine and trial during apprehension

	No Armor Time (s)			Armor Time (s)			No Armor	Armor
ID	**Trial 1**	**Trial 2**	**Trial 3**	**Trial 1**	**Trial 2**	**Trial 3**	**Average**	**Average**
1	4.38	3.94	3.80	4.36	4.32	4.26	4.04 ± 0.30	4.31 ± 0.05
2	3.82	3.70	3.68	3.88	3.79	3.86	3.73 ± 0.07	3.84 ± 0.05
3	3.74	3.72	3.66	3.95	3.96	4.03	3.71 ± 0.04	3.98 ± 0.04
4	4.45	4.50	4.40	4.96	5.35	4.75	4.45 ± 0.05	5.02 ± 0.31
5	3.99	4.06	4.03	4.54	4.10	-	4.03 ± 0.04	4.32 ± 0.31

In order to determine the effect of armor on apprehension and agility times, data were combined for all canines. Average time data are listed in Table 6.4. For each task there was a statistical increase in time while the canines wore armor.

Table 6.4:
Average apprehension and agility times with and without armor

Activity	Armor	N	Time (s)	P - value
Apprehension	No	14	4.0 ± 0.3	< 0.001
	Yes	14	4.3 ± 0.5	
Agility				
Hurdles	No	13	6.8 ± 0.2	< 0.001
	Yes	12	7.8 ± 0.9	
A-frame	No	15	3.6 ± 1.1	0.001
	Yes	9	5.9 ± 2.7	
Jump	No	15	1.2 ± 0.2	0.032
	Yes	13	1.3 ± 0.2	
Crawl	No	15	1.8 ± 0.4	< 0.001
	Yes	13	3.0 ± 1.3	
Catwalk	No	15	10.7 ± 1.3	< 0.001
	Yes	13	14.8 ± 3.0	

Values are mean ± SD
†Mean is significantly higher compared to without vest mean ($P < 0.05$)

To determine if there was a fatigue effect on time to complete the tasks, the data were combined and compared based on trial number. Average apprehension and agility times are listed in Table 6.5. A significant decrease was found during the trials for the hurdle obstacle. As the trial number increased the average time decreased. There was also a significant interaction between the armor and trial number for the hurdles (P = 0.023). Post-hoc analysis found a statistical decrease in time while the canines were wearing armor between trials 1 and 3 during the hurdle obstacle (Tables 6.6 and 6.7) This was not found while the canines were not wearing armor.

Table 6.5:
Average apprehension and agility times for each trial

Activity	Trial Number	N	Time (s)	P - value
Apprehension	1	10	4.2 ± 0.4	
	2	10	4.1 ± 0.5	0.160
	3	8	4.1 ± 0.4	
Agility				
	1	8	7.7 ± 1.0	
Hurdles	2	10	7.2 ± 0.8	0.007
	3	7	6.9 ± 0.2	
	1	8	4.3 ± 1.4	
A-frame	2	9	5.0 ± 3.1	0.198
	3	7	3.9 ± 1.4	
	1	10	1.2 ± 0.2	
Jump	2	10	1.3 ± 0.2	0.248
	3	8	1.2 ± 0.1	
	1	10	2.6 ± 1.6	
Crawl	2	10	2.4 ± 0.9	0.421
	3	8	2.0 ± 0.6	
	1	10	13.0 ± 3.3	
Catwalk	2	10	12.9 ± 3.2	0.667
	3	8	11.8 ± 2.7	

Values are mean ± SD
†Mean is significantly higher compared to without vest mean ($P < 0.05$)

Table 6.6:
Post-hoc analysis of hurdle time data without armor

Hurdles	Trial Number	N	Time (s)	P - value
No Armor	1	4	6.8 ± 0.2	0.829
	2	5	6.8 ± 0.3	
	1	4	6.8 ± 0.2	0.743
	3	4	6.8 ± 0.2	
	2	5	6.8 ± 0.3	0.897
	3	4	6.8 ± 0.2	

Values are mean ± SD

Table 6.7:
Post-hoc analysis of hurdle time data with armor

Hurdles	Trial Number	N	Time (sec)	P – value
Armor	1	4	8.6 ± 0.4	0.073
	2	5	7.6 ± 1.0	
	1	4	8.6 ± 0.4	0.020†
	3	3	7.1 ± 0.3	
	2	5	7.6 ± 1.0	0.302
	3	3	7.1 ± 0.3	

Values are mean ± SD
†Mean is significantly higher compared to without vest mean ($P < 0.05$)

Evaluations of within subject differences were not analyzed. Individually the canines performed very differently. The average change in times for apprehension and agility are listed for each canine below (Tables 6.8 and 6.9). For each canine there was an increase in average time when wearing the armor for both apprehension and agility.

Table 6.8:
Change in average time for apprehension with and without armor

Average ∆ Time (s) Apprehension	
Canine 1	0.28
Canine 2	0.12
Canine 3	0.27
Canine 4	0.57
Canine 5	0.29

Table 6.9:
Change in average time for agility course with and without armor

	Average ∆ Time (s)					
	Hurdles	**A-frame**	**Jump**	**Crawl**	**Catwalk**	**Average**
Canine 1	0.5	2.8	0.1	0.1	4.1	1.5 ± 1.8
Canine 2	0.1	0.6	0.1	0.8	4.3	1.2 ± 1.7
Canine 3	0.9	1.0	0.1	1.4	0.1	0.7 ± 0.6
Canine 4	1.5	-	0.0	3.0	7.9	3.1 ± 3.4
Canine 5	2.2	2.7	0.2	1.7	4.9	2.3 ± 1.7
Average	1.0 ± 0.8	1.8 ± 1.1	0.1 ± 0.1	1.4 ± 1.1	4.3 ± 2.8	

Averages are mean ± SD

6.3.2 Core Body Temperature

In order to compare the effect of armor on core body temperature, temperatures taken before and after apprehension and agility trials were combined for all canines. Average temperature data is listed in Table 6.10. A statistical increase in core body temperature while the canines wore armor was found for the apprehension task.

Some core body temperature data points were either not collected or were removed from apprehension or agility data set. A total of three core body temperature data points were not collected. Once again, Canines 4 and 5 did not complete the third agility trial with the vest, resulting in 2 data points not being collected. Also, Canine 5 did not complete the third apprehension trial with the vest; therefore, 1 core temperature data point from the apprehension average was not collected. One core body temperature data point was removed from the apprehension data set. Canine 4 had an abnormally low temperature that the authors attribute to the canine drinking water before temperature was noted. Since this value was lowered due to water consumption, the data point was removed from analysis.

Table 6.10:
Comparison of average core body tempertures measured during apprehension and agility trials with and without armor

Activity	Armor	N	Temperature (ºF)	P - value
Apprehension	No	19	102.4 ± 1.1	< 0.001†
	Yes	19	103.1 ± 1.5	
Agility	No	20	102.7 ± 1.1	0.089
	Yes	18	103.0 ± 1.2	

Values are mean ± SD
†Mean is significantly higher compared to without vest mean (*P* < 0.05)

To determine if there was a cumulative effect on the core body temperature after multiple trials, the data were combined and compared based on the time point from which the temperature was taken. Average core body temperatures from apprehension and agility trials are listed in Table 6.11. A statistically significant increase in core body temperature was found during apprehension trials. Core body temperature increased as the canines progressed through the three trials.

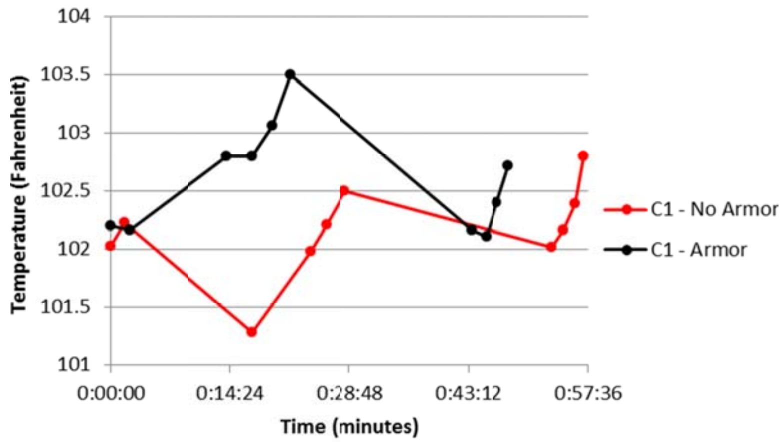
Table 6.11:
Comparison of average core body temperatures measured during apprehension and agility trials

Activity	Time Point	N	Temperature (ºF)	P - value
Apprehension	1	9	102.7 ± 1.4	0.023†
	2	10	102.6 ± 1.5	
	3	9	102.7 ± 1.4	
	4	10	103.1 ± 1.2	
Agility	1	10	102.5 ± 1.3	0.136
	2	10	102.9 ± 1.1	
	3	8	103.1 ± 1.2	
	4	10	103.5 ± 1.1	

Values are mean ± SD
†Mean is significantly higher compared to without vest mean (*P* < 0.05)

As with completion time data, evaluations of within subject differences with regards to core body temperature were not analyzed. Core body temperatures recorded throughout the testing are included below for each canine (Figure 6.11 - Figure 6.15).

The line graph in Figure 6.11 illustrates the temperature progression with time of Canine 1. The bar graph shows the percent change in temperature from the baseline temperature. The baseline temperature used to calculate the percent change was taken prior to the suspect search (102.0ºF no armor and 102.2ºF with armor). The peak temperature for Canine 1 without wearing armor was 102.8ºF. This was the final temperature reading, 57 minutes after recording baseline at 102.0ºF (0.014 degree/min). The peak temperature while wearing the armor was recorded at 103.5 ºF. This measurement occurred following the agility and was 22 minutes following baseline reading at 102.2 ºF (0.06 degree/min). Canine 1 exhibited an increasing body temperature during the activities with a cooling down period between agility and apprehension.



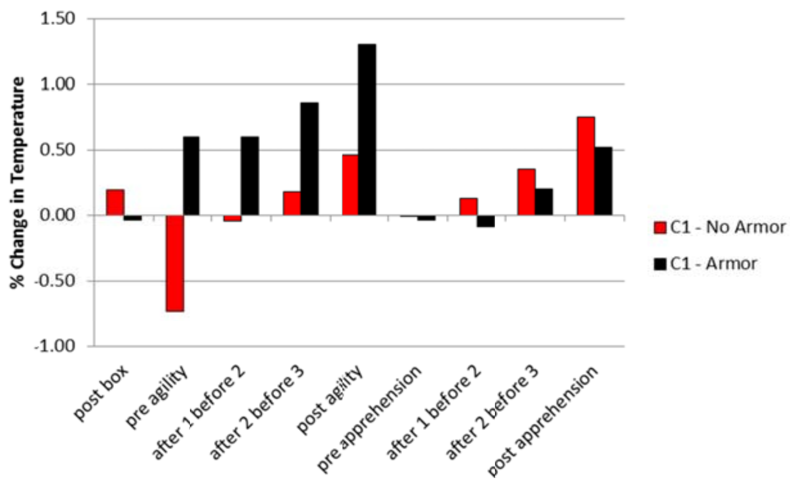


Figure 6.11: Core body temperatures recorded with and without armor - Canine 1

Overall Canine 2 experienced a higher core body temperature during the activities while wearing armor (Figure 6.12). The peak core body temperature without the armor was recorded at 103.6ºF during the trials. This was recorded 33 minutes into the course and after the baseline was recorded at 102.2ºF (0.042 degree/min). The peak core body temperature during the trials while Canine 2 was wearing armor was 104.5ºF and was recorded after the final apprehension trial 49 minutes after the baseline was recorded at 103.1ºF (0.03 degree/min). Canine 2 had an increasing core body temperature throughout the activities and did not exhibit a cool down between agility and apprehension.

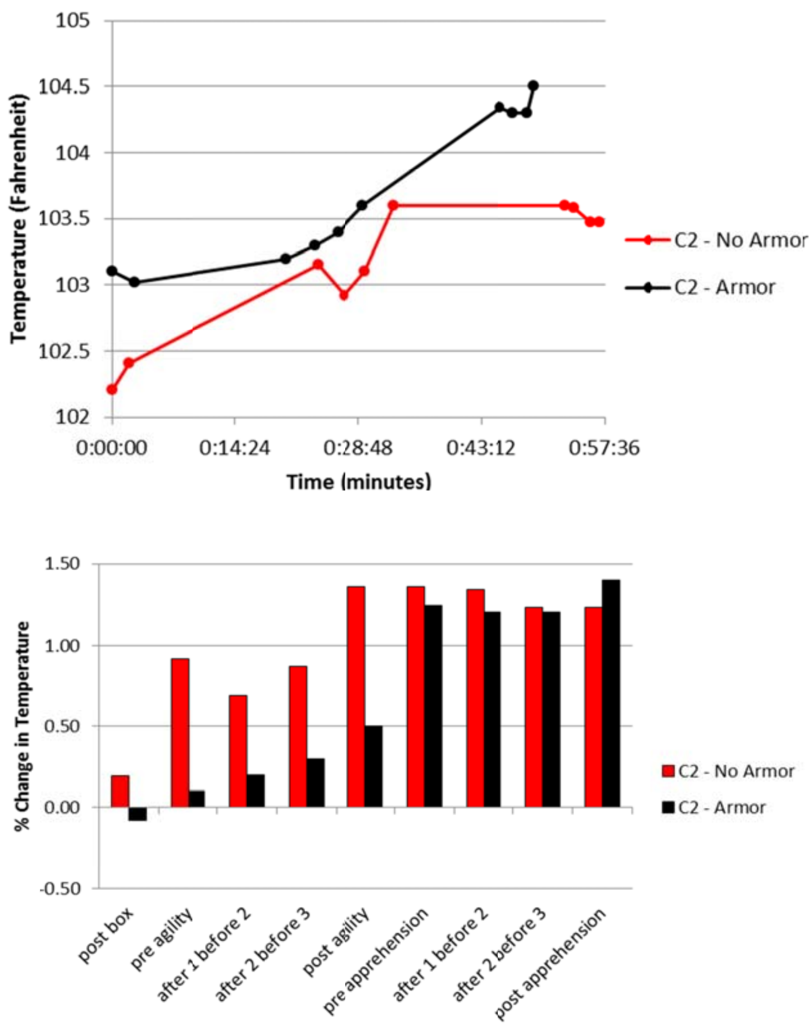


Figure 6.12: Core body temperatures recorded with and without armor - Canine 2

Temperature data for Canine 3 are illustrated in Figure 6.13. Canine 3 had the lowest baseline temperature when compared to the other canines. The peak core body temperature for Canine 3 without wearing the armor was recorded as 103.6ºF at 36 minutes following baseline recording of 100.9ºF (0.075 degree/min). The peak core temperature with the armor was the baseline temperature 101.8ºF. The core body temperature decreased throughout the trials with the armor. Canine 3 responded quite differently when compared to the other canines in this study.

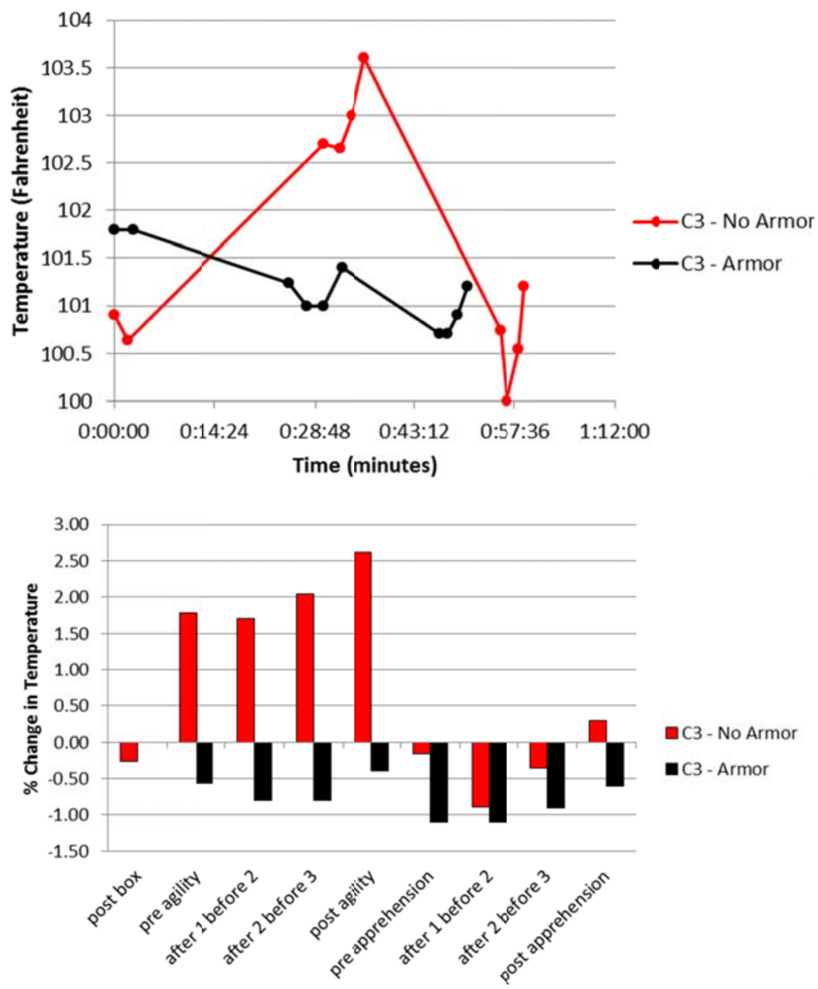


Figure 6.13: Core body temperatures recorded with and without armor - Canine 3

Temperature data for Canine 4 are illustrated in Figure 6.14. The core body temperature recorded for Canine 4 prior to the 1st apprehension trial without wearing armor was recorded as 95ºF, potentially the result of drinking water while waiting in the handler's patrol car. This point was an outlier and was removed from analysis. The peak core body temperature for Canine 4 was recorded at 105.7ºF during trials without armor. The peak temperature occurred approximately 18.5 minutes following the baseline reading of 104.1ºF (0.086 degrees/minute). The peak core body temperature recorded during trials with armor was 104.5ºF and it occurred 28 minutes following baseline measurement of 103.4ºF (0.039 degrees/minute). Canine 4 responded in a similar way to Canine 1 where both cooled down between agility and apprehension.

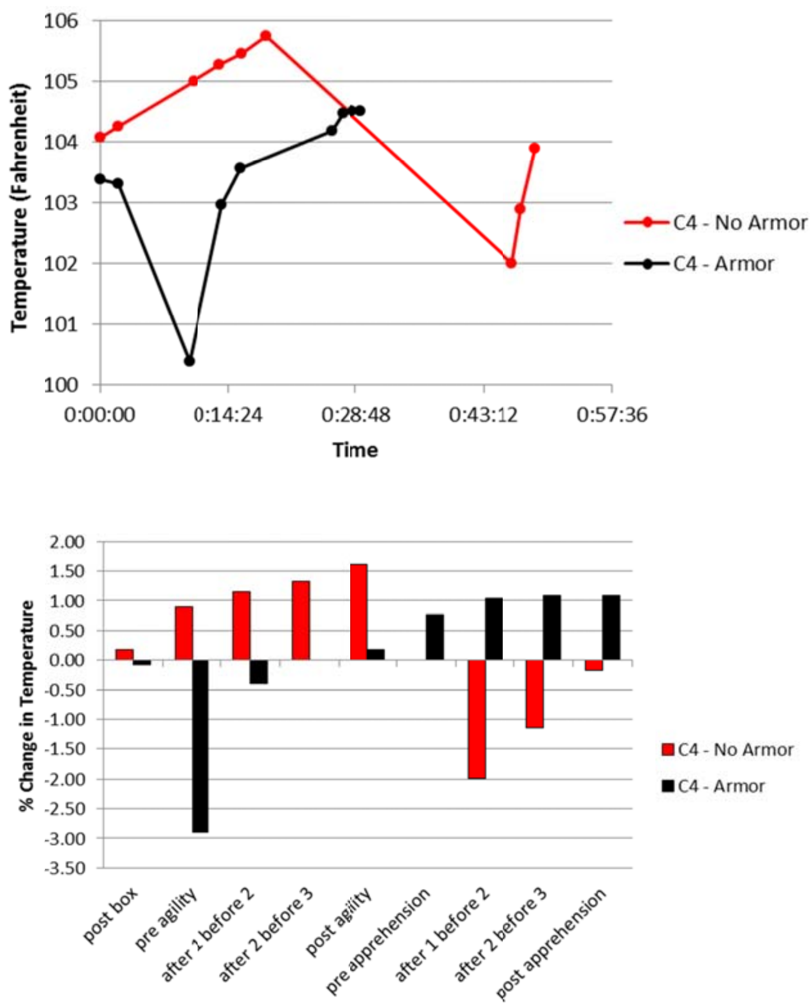


Figure 6.14: Core body temperatures recorded with and without armor - Canine 4

Temperature data for Canine 5 are illustrated in Figure 6.15. Peak core body temperature recorded during trials while the canine was not wearing armor was 103.5ºF and it occurred 32.5 minutes following the baseline measurement of 102.1ºF (0.043 degrees/minute). Peak core body temperature recorded for trials while the canine was wearing armor was 104.0ºF and was recorded 28 minutes following the baseline recording of 101.8 ºF (0.079 degrees/minute). Canine 5 responded in a similar way to

Canine 2 where both had increasing core body temperatures without a noticeable cool down while resting.

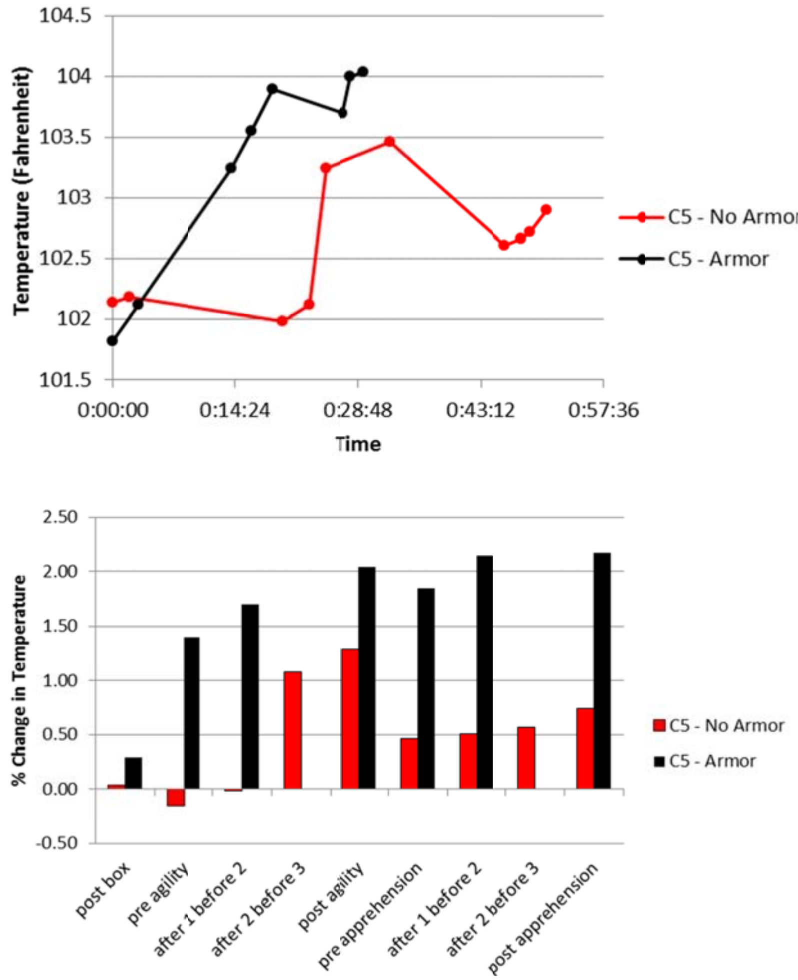


Figure 6.15: Core body temperatures recorded with and without armor - Canine 5

6.3.3 Handler Evaluation

Once the canines completed all the exercises, handlers were asked to evaluate their canines' performance. Handlers were asked to rate the performance from 1 to 5, where 1 was poor (difficult) and 5 was excellent (easy), for each activity based on several questions regarding performance with and without armor. An average of the score given by each handler, for their own canine, is provided in Table 6.12.

Table 6.12:
Average score for canine performance based on handler assessment

	Suspect Search	Agility	Apprehension
Canine 1			
No Armor	5.0 ± 0.0	5.0 ± 0.0	4.5 ± 0.6
Armor	5.0 ± 0.0	3.6 ± 0.8	3.0 ± 0.0
Canine 2			
No Armor	5.0 ± 0.0	4.7 ± 0.8	5.0 ± 0.0
Armor	5.0 ± 0.0	2.3 ± 1.1	4.0 ± 0.8
Canine 3			
No Armor	4.0 ± 0.0	4.1 ± 0.4	4.8 ± 0.5
Armor	4.0 ± 0.0	4.0 ± 0.8	4.0 ± 0.0
Canine 4			
No Armor	5.0 ± 0.0	5.0 ± 0.0	4.0 ± 0.0
Armor	4.0 ± 0.0	2.7 ± 1.0	4.0 ± 0.0
Canine 5			
No Armor	5.0 ± 0.0	4.1 ± 0.9	4.3 ± 1.0
Armor	5.0 ± 0.0	1.9 ± 1.1	4.0 ± 1.0

Overall the handlers felt the suspect search was an easy task for the canines and that the armor was not a distraction. The handlers noticed difficulties with the agility obstacles, primarily the crawl, catwalk, and A-frame obstacles. Two handlers felt the armor was a distraction during the agility but felt it could be resolved with time and training. During the apprehension trials the handlers did not feel the armor was a distraction but it did cause the canines to run slower and perhaps not jump as high.

6.4 Discussion

This study aimed to measure the effects of armor as it relates to core body temperature, focus, concentration, mobility, speed, and coordination. Evaluation was conducted by having the canines complete a typical day of training. Training was performed in an outdoor, non-climate controlled facility. Tasks were completed with and without armor. During the trials: time, core body temperature, and video were recorded.

Suspect search and the handler evaluation were used to help evaluate the focus and concentration of the canines. Based on the small sample size and data collected, it was difficult to draw substantive conclusions. Overall, the suspect search was a simple task for all the canines. Additionally, searching for objects and people encompass a large portion of their job. It is important to study whether armor could hinder that capability. One limitation of this task was that it was not as controlled as the other exercises. The times were not as consistent and there was only one trial for comparison. There was some variation in techniques and how each canine checked the boxes and alerted to the correct box, therefore, it was challenging to determine when the canines found the suspect. Even when comparing the data from one canine, there was variation in the manner of each trial. The times for the suspect search are difficult to compare and draw conclusions due to these inconsistencies which were unexpected.

The handler evaluations gave insight into canine performance; however, it would have been helpful to evaluate the handlers' preconceived notions regarding canine body armor. If handlers believed armor would hinder the ability to perform a task prior to testing, there could potentially be a bias in the evaluation. Generally the handlers scored their canine lower when wearing the armor. For future studies perhaps involving a third party judge, such as a certification judge, in evaluations would give a neutral perspective on performance. For the purpose of this study, the evaluation revealed how the handlers felt about the armor and the canines' performance with the armor.

Overall this study found that the armor increased the time to complete both apprehension and agility tasks for these canines. When evaluating the core body temperatures, there was a significant difference during the apprehensions trials. Collectively, the mean temperatures were higher while the canines were wearing armor. Even though the temperatures were statistically higher, the core body temperatures were still below those generally thought to be life threatening. The average core body temperature during agility trials, approximately 10 minutes of excursion, without wearing the armor was 102.7 ± 1.1ºF and 103.0 ± 1.2ºF with armor. The overall core body temperature during the apprehension trials, approximately 5 minutes of excursion, without wearing the armor was 102.4 ± 1.1ºF and 103.1 ± 1.5ºF while wearing armor. Peer reviewed articles have found that the rectal body temperature of racing, sporting, and detection canines can vary between 104ºF and 108ºF during strenuous activities without detectable adverse effects (Rose and Bloomberg, 1989; Steiss, Ahmad et al., 2004; Angle and Gillette, 2011). Rectal temperature was not collected during this study which is the standard for recording temperature in canines. However, a differential may be present when comparing core body temperature to a rectal temperature at the same time point. Observations made of military working dogs being monitored during bite and explosive detection work found rectal temperatures reached in excess of 108ºF while the core body temperatures were between 103-104ºF (Baker and Miller, 2013). This may explain why some canines can perform and are not affected by higher rectal temperature.

Both core body temperature and performance time were affected by the armor during the apprehension exercise. Core body temperature and time had a statistically significant increase. Since the trials were not randomized, it cannot be concluded whether the apprehension trial created the higher temperatures and longer trial times or if it was due to the task always being last. To visually confirm the increase in time during apprehension, Dartfish Prosuite 6.0 was used to compare the video from with and without armor trials; videos were overlapped using SimulCam. Figure 6.16 illustrates a comparison of Canine 1 apprehending with and without armor. This is a comparison of the video from trial 3 with armor and trial 3 without armor. The picture on the left is the beginning of the run, the trial with the armor is slightly behind the trial without. The armor has "SHERIFF" written in yellow letters which helps indicate which canine has on the armor. As the canine progresses down the 60 yard path the separation distance between the two increases.

Figure 6.16: Comparison of apprehension trial with and without armor

The canines encountered a few challenges worth noting while wearing the armor. The obstacles that proved to be the most challenging while the canines were wearing armor were the contact obstacles: A-frame, catwalk, and crawl. Some of the canines needed physical assistance from their handlers to complete these obstacles. The climbing obstacles were especially challenging. Four of the five canines needed assistance from their handlers to make it over the peak of the A-frame while wearing the vest. Canine 2 was only able to complete the obstacle once while wearing the armor.

Canine 4 was not able to complete any of the A-frame attempts while wearing the armor. Canines 1 and 5 were assisted by their handlers which allowed them to get over the peak of the A-frame. This increased the time it took for them to complete the obstacle. Canine 3 did not need assistance however his average time increased by approximately 1.0 second to complete the obstacle with the armor.

The catwalk required assistance in the beginning for the majority of the canines to get up the ladder while none needed assistance when they were not wearing armor. The most common issue was losing their footing on the ladder. Canine 2 started to hesitate on the trial 3 and needed two attempts to make it up the stairs. Canine 3 did not need his handlers' assistance and his average times were very similar with and without the armor. Canines 1, 2, 4, and 5 had an increased time of more than 4 seconds when wearing the armor.

The crawl obstacle helped identify a potential issue with the design of the canine armor. The top of the crawl obstacle was 40.6 cm (16 in) from the ground. The canines would lower themselves to slip under the obstacle, however, they did not lower themselves enough and the portion of the carrier between their scapulae impeded further movement (Figure 6.17). This caused hesitation for most of the canines. Canines 1, 2, and 4 needed a "toy" thrown through the obstacle at least once to compel them to complete the obstacle. Canine 3 needed no assistance from his handler. The canines experienced no issues with the crawl obstacle while they were not wearing the canine armor. Due to the inconsistencies the hesitations caused for each canine, the time was determined based on when the canines head went under the obstacle (during the successful attempt) to the point where the canine was fully out of the obstacle.

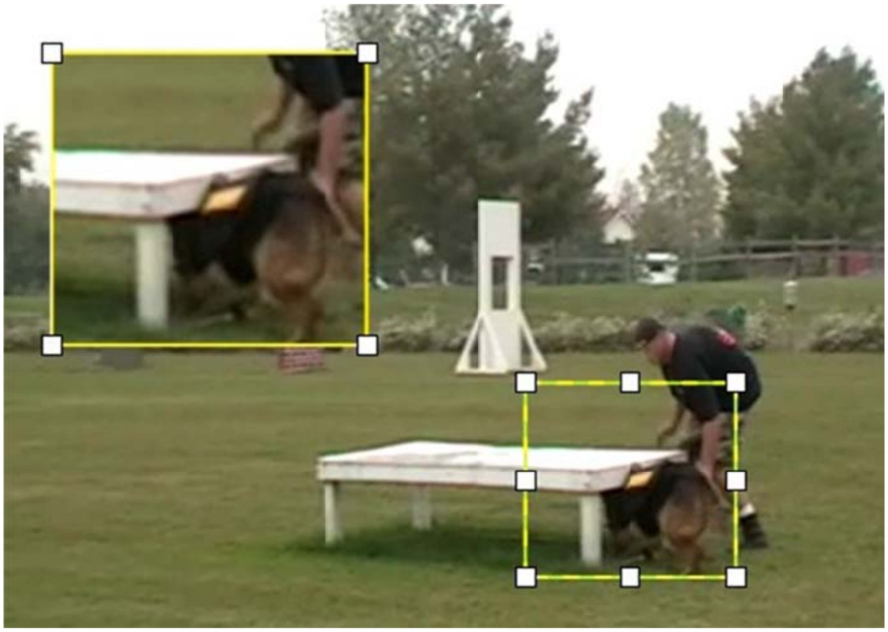


Figure 6.17: Illustration of Canine 4 catching the top of the armor on the crawl obstacle

The authors attempted to control as many variables as possible through study design however, there were variables that could not be controlled or were unexpected. Working within the confines of the handlers training schedule, testing days could not be missed due to undesirable weather conditions. The high humidity on the second day of testing was not ideal but was unavoidable. Although the core body temperature capsules allowed for easy access to recording this valuable information, there were a few limitations. Access to drinking water was not restricted during rest periods for the canines in this study. The recorded temperatures from Canine 4 seemed to be affected more by drinking water than the other canines. It was determined that the canine drank water just before the pre-apprehension without armor temperature was recorded; this outlier was removed from the data set. It has been noted that during the first 5 hours post-consumption of the capsule, water will cause a decrease in the core body temperature reading (Wilkinson, Carter et al., 2008). If water is consumed, Wilkinson et al. recommends waiting 30-60 minutes after ingestion of cool fluids to obtain an accurate core body temperature if the GI temperature pill was ingested just prior to exercise. In humans, it was recommended that individuals ingest the pill approximately 12 hours prior to the start of the measurement period and the effect of water ingestions was decreased. In this study, the canines ingested the pills 2 hours before the start of the measurement period.

The lack of funding led to a small sample size since vests needed to be purchased for each canine to ensure all canines were wearing the same model vest. Although the sample size was small, valuable information has been noted from this study and more data should be collected in this area. Despite the fact that the canines were allowed to acclimate to the armor from a behavioral standpoint, they were not familiar with training in the armor. Additionally, according to the handlers, situations where a canine will need to climb ladders or jump up tall walls are rare. Therefore, this may not be an issue in real world situations; however, if the canines are trained in armor they could be more prepared.

The armor did increase the time it took for the canine to complete both apprehension and agility tasks and the core body temperature did increase during apprehension trials. The increase in core body temperature was still within a clinically acceptable range and was not considered injurious. The increase in time should be evaluated further in future testing to determine if the increase diminishes with practice and training. It is crucial to train in equipment that may be needed in the field. Additionally, for future testing, the experimental design should be randomized to better evaluate the performance while wearing armor.

CHAPTER 7 – EVALUATION OF PROPOSED CANINE BODY ARMOR TESTING PROTOCOL

7.1 Introduction

Canine armor is currently being manufactured and purchased by a variety of organizations. One interesting aspect of the working canine is their positive public perception. Communities want to ensure that the canines working with their local law enforcement agencies have protection. Funds are typically raised to help defray the cost of canine armor resulting in the body armor being donated to the agency and canine. There has yet to be any published research evaluating the efficacy of canine armor at preventing serious injuries.

The armor panels used in available canine armor are currently tested to the NIJ ballistic resistant standard (NIJ-0101.06, 2008). It was determined that 44 mm of deformation into a ROMA Plastilina modeling clay, No. 1, backing material correlated to a 6% probability of lethality. These reports concluded that humans would be even less likely to sustain serious injuries under similar conditions (Goldfarb, Ciurej et al., 1975; Metker, Prather et al., 1975; Prather, Swann et al., 1977). This standard was not evaluated for its effectiveness at protecting small individuals or small animals from life-threatening injuries as a result of behind armor blunt trauma.

The aim of this study was to evaluate behind armor canine thoracic response of a commercially available canine armor that has been tested to the current armor standard. This was achieved by quantifying the biomechanical response and resulting injury severity. Impact force, thoracic deflection, spine/sternum/rib acceleration, and rib strain were collected for each specimen. Necropsies were performed following the impact events to verify injury severity.

7.2 Methodology and Materials

7.2.1 Canine Ballistic Armor

Prior to procuring vests it was important to determine the most common ballistic threat to law enforcement officers in the U.S. and the most commonly purchased canine ballistic vest. The researchers wanted to ensure that the canines could wear these vests on duty after testing completed. Handlers were consulted prior to purchasing the vests. According to Law Enforcement Officers Killed and Assaulted (LEOKA), the most common ballistic threat police officers face in the field is a 9 mm bullet (FBI-LEOKA). Law enforcement canines will likely face the same threats as their human counterparts. Commercially available canine armor is tested to human standards and is categorized based on the same threats. NIJ Threat Level II (designed and tested to provide protection for 9 mm and 357 caliber rounds) ballistic vests for canines were selected for research.

To locate the most commonly purchased canine armor, a list of all available canine armor manufacturers was compiled and each was contacted. In addition, 7 non-profit organizations which raise money to purchase canine vests for officers were contacted. Sales could not be quantified when speaking with the armor manufacturers; therefore, the information given by the non-profit organizations was crucial. At the time of the study, the two most commonly purchased brands by the 7 non-profits were Point Blank and International Armor. One of the non-profits stated they had supplied over 700 vests purchased from Point Blank. This was by far the largest sample identified by the organizations. Based on these data, the most commonly purchased canine vest was determined and purchased.

The NIJ Threat Level II canine ballistic vests were purchased from Point Blank Body Armor (Model BII threat level II; Pompano Beach, FL) (Figure 7.1). The vest is constructed from a combination of Twaron and Honeywell materials. The armor packets are tested to the NIJ 0101.06 ballistic resistance of body armor standard (NIJ-0101.06, 2008). The median and dry areal densities of the armor panel are 4.49 kg/m^2 and 4.25 kg/m^2, respectively. The thickness of the armor panel is 0.58 cm. The overall weight of the armor panel and carrier was 2.25 kg (4.95 lbs).

Figure 7.1: Point Blank canine armor model BII

7.2.2 Specimen Details

Two (2) unembalmed post-mortem canine specimens (PMCS) were tested (Table 7.1). The average specimen weight was 31.5 ± 4.1 kg. Specimens were procured from the Detroit Animal Control and were euthanized previously for reasons not related to this study. Prior to obtaining the specimens, approval was granted by

Wayne State University's Institutional Animal Care and Use Committee (IACUC) (Appendix A). Detailed measurements were taken of each specimen including thoracic circumference, lateral depth of thorax, and dorsal-ventral length (spine to sternum). Lateral depth was a measurement taken at the site of impact. The thoracic ratio was used to further describe the shape of the thoracic cavity (dorsal-ventral depth/lateral length). Age and exact breed could not be verified.

Pre-test x-rays were taken to ensure there was no presence of skeletal fractures. If fractures or other issues were detected the canine was not tested. Once the canines were x-rayed and weighed, the specimens were stored at 0ºF until testing. Specimens were allowed to return to room temperature for at least 18-24 hours prior to applying instrumentation. Once sufficiently thawed the instrumentation process began, at least 24 hours prior to testing.

Table 7.1:
Detailed description of post mortem canine specimens tested

ID	Gender	Breed	Weight (kg)	Thorax		
				Circumference (cm)	Depth (cm)	Thoracic Ratio
15	M	Rottweiler	28.6	64.5	18.5	1.07
16	M	Rottweiler	34.4	69.0	20.5	1.09

7.2.3 Data Collection

A TDAS Pro data acquisition system (DTS Inc., Seal Beach, CA) was used for collecting all data. The data were sampled at 38,000 Hz with a four-pole Butterworth anti-aliasing filter with a cutoff off frequency of 4,300 Hz. Tri-axial blocks of single axis accelerometers and strain gages were mounted to skeletal structures (Figure 7.2). Three single axis accelerometers (7264D/C 2K Endevco, Meggitt Sensing Systems, Irvine, CA) were mounted to each custom aluminum tri-axial block to measure accelerations in the x-, y-, and z-axes (Figure 7.3). Tri-axial blocks were screwed to a custom aluminum mount with channels for plastic cable ties to then secure the mount and accelerometer block to the bone (Figure 7.3). Six accelerometer blocks were mounted to the following skeletal structures for each canine: seventh and eighth ribs (bilaterally), the spinous process of T7, and the seventh sternebra. Accelerometers were used to determine rib acceleration during impact and were located ventral to the angle of the rib. The sternum and spine accelerations were used to understand the global motion of the canine during impact.

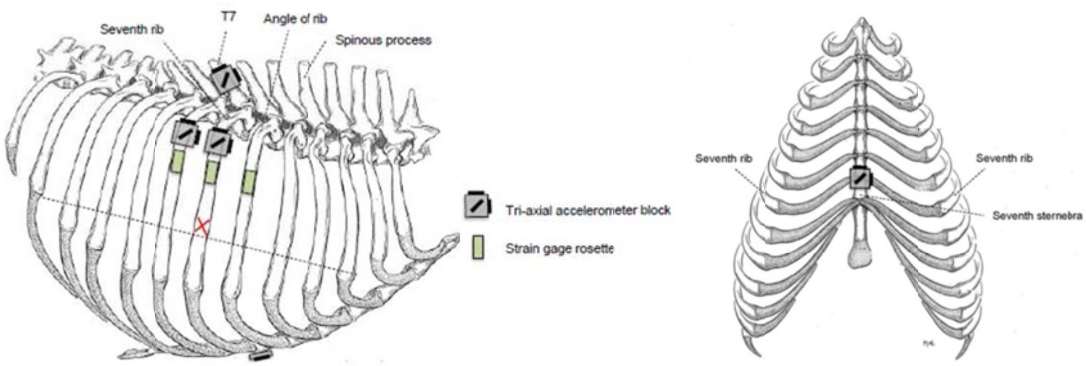


Figure 7.2: Instrumentation locations on bony structures

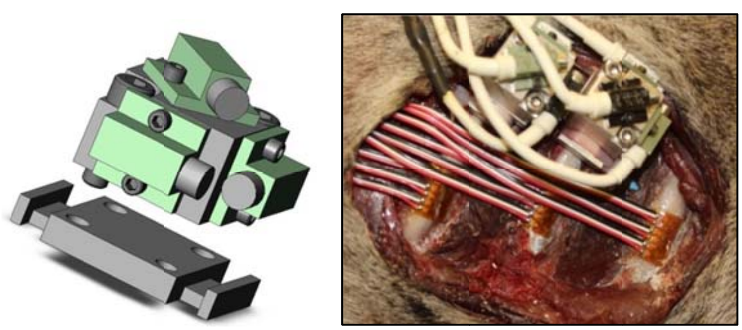


Figure 7.3: Tri-axial accelerometer block and mount

Rectangular rosette strain gages (Vishay Micro-Measurements, Raleigh, NC) were secured to the sixth, seventh, and eighth ribs bilaterally to determine bone strain during impact and potentially identify timing of fracture (Figure 7.2 and Figure 7.3). A temporary line parallel to the spine was marked from the costochondral junction of the twelfth rib. The line intersection with the seventh rib indicated the point of aim which aided in positioning for instrumentation. Tissue was left intact at impact locations. Cable ties for the accelerometer mounts and strain gage adhesion to the surface of the ribs were assessed after each test.

A coordinate system was developed for the canine to ensure consistency when collecting and analyzing acceleration data (Figure 7.4). Polarities of the measured external movement were also defined. Acceleration in the x-axis was defined as cranial-caudal movement with positive indicating cranial direction. Acceleration in the z-axis was defined as dorsal-ventral with positive indicating dorsal movement. Acceleration in the y-axis was defined as right-left where positive y was movement to the right side of the canine.

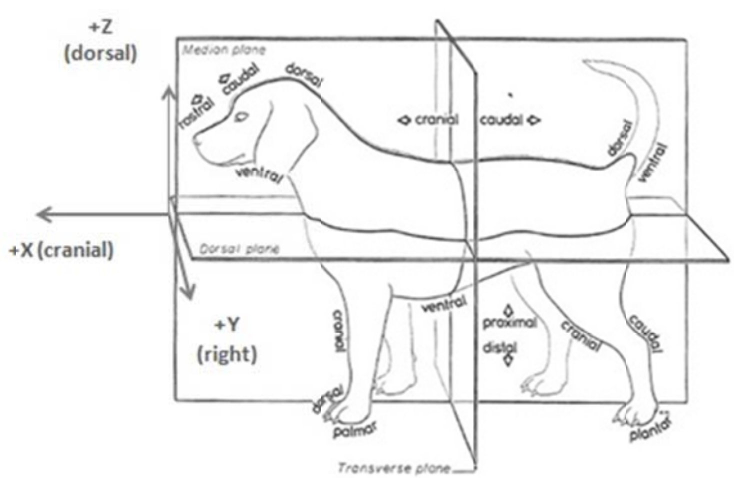


Figure 7.4: Canine coordinate system (adapted from (Evans, 1993))

A chestband was wrapped, externally, around the thoracic cavity at approximately the level of the ninth rib to measure thoracic deflection. The chestband contained 40 piezoresistive bridge strain gages mounted on a thin metal band which was covered with a flexible urethane coating (Figure 7.5) (Eppinger, 1989). The strain gages were evenly spaced at 2.5 cm (1 inch) apart. The chestband was sutured to the epidermis to ensure it remained in the desired position. The chestband was located 2.5 cm (1 inch) caudally from the impact location. Although the chestband was created for direct impact, the speed and energy imparted into this system would likely damage strain gages if it was impacted directly under ballistic conditions. The chestband is used to calculate the maximum deflection, compression, and velocity of deflection.

Figure 7.5: Forty-gage chestband schematic

Impact force between the armor panel and the skin was determined using a thin film polymer-on-polymer force sensor (SensorTech Corp, SC) which was secured at impact site (Figure 7.6). The conductive polymer materials are pressed together as force is applied increasing the current that passes through the material thereby dropping the resistance of the material. Each sensor was individually calibrated by the manufacturer to a maximum range of 9 kN based on previously collected data.

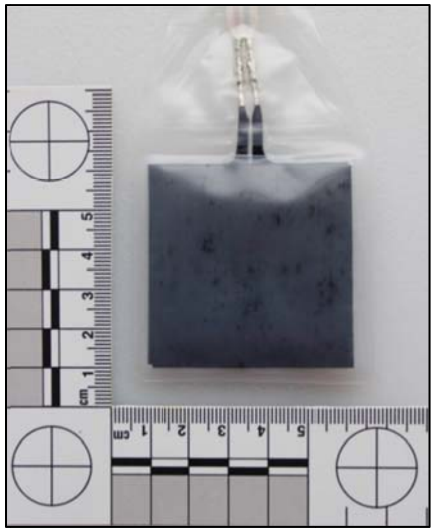


Figure 7.6: Polymer-on-polymer force sensor

The force sensors were a one-time use piece of instrumentation, a new sensor was used for each test. The force sensor was secured with Gaffer's Tape to the skin of the specimen at the impact site. The sensor was positioned so that the shot path was centered on the force sensor and the seventh rib (transversely). The chestband was positioned directly adjacent to force sensor (Figure 7.7).

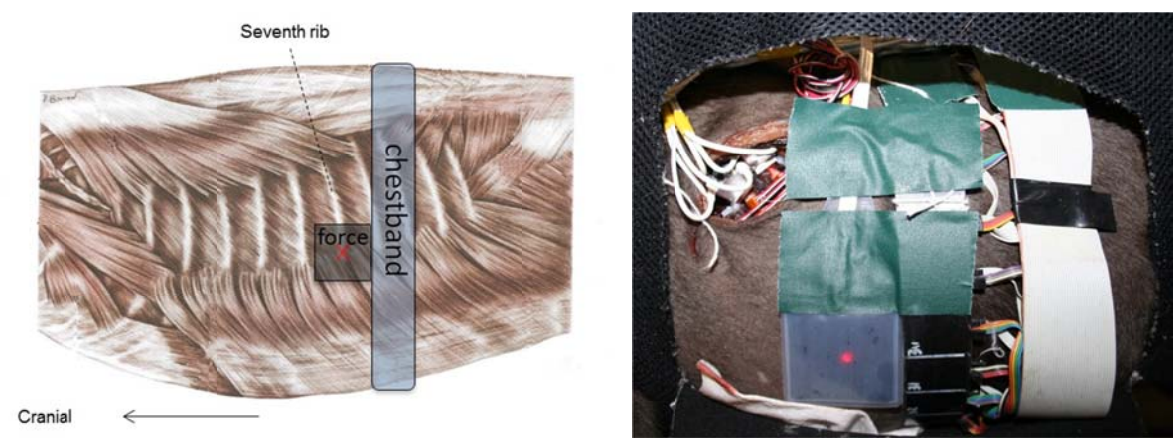


Figure 7.7: Positioning of chestband and force sensor with respect to impact site

High speed video was collected for each test. Two camera views were recorded, a camera (10,000 fps, Redlake MotionXtra HG-100K) was located perpendicular to the shot path and a second camera (1,000 fps, Kodak EktraPro HG Imager Model 2000) was located overhead to record the global movement of the specimen during the impact.

7.2.4 Experimental Design

A harness was created to allow a natural standing position (spine horizontal) for a quadruped. Specimens were placed in the harness and suspended from an adjustable system (Figure 7.8). Following the NIJ 0101.06 Standard, 9 mm 124 grain FMJ RN bullet traveling at 398 ± 9.1 m/s (1306 ± 30 fps) was used for all tests (NIJ-0101.06, 2008). Commercially available ammunition was purchased and the rounds were uploaded to achieve the desired velocity. The ammunition was fired using a Universal Receiver (UR-01, Rapid City, SD, H.S. Precision Inc.) which allowed for laser sighting and remote firing. The shot path was aligned such that the bullet struck perpendicular to the armor packet. A chronograph (Model 35P, Austin, TX, Oehler Research Inc.) with three photo-electric screens (Model 57, Austin, TX, Oehler Research Inc.) was used to measure the velocity of each shot.

Two impacts were performed on each specimen; one to each of the bilateral seventh ribs. Both impacts were tested under the same conditions with the Point Blank armor covering the impact site.

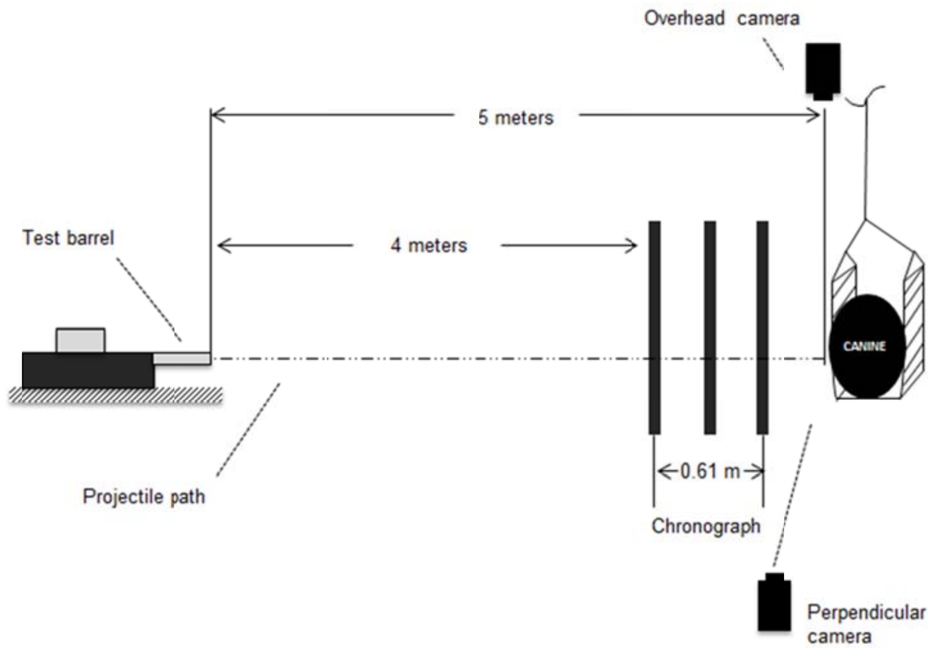


Figure 7.8: PMCS test setup

7.2.5 Filter Determination

Hardware anti-aliasing filter (TDAS Pro, DTS Inc., Seal Beach, CA) was set with a cutoff frequency of 4,300 Hz, filtering transducer output. To determine appropriate filter to reduce signal noise, analysis of transducer outputs with Fast Fourier Transform (FFT) helped to identify frequency limits following the hardware filtering. Accelerometer data were initially filtered using a four-pole Butterworth low-pass filter (phaseless) with a -3dB limit frequency of 6,500 Hz. As recommended in SAE J211, the filter -3dB frequency is approximately one sixth of the data sample rate (38,000 Hz) which is consistent with existing engineering standards for filtering accelerometer data (SAE-J211-1, 1995). However, a frequency analysis of the acceleration data from the impacted seventh rib indicated that the accelerometer signal in the lateral direction (y-axis) included relevant data at frequencies above 6,500 Hz (Figure 7.9). Relevant data was not observed in non-impacted ribs, sternum, or spine acceleration data above 6,500 Hz. The required filter needed to remove high frequency noise from accelerometer data and retain valuable data. The same filter was applied to all accelerometer data.

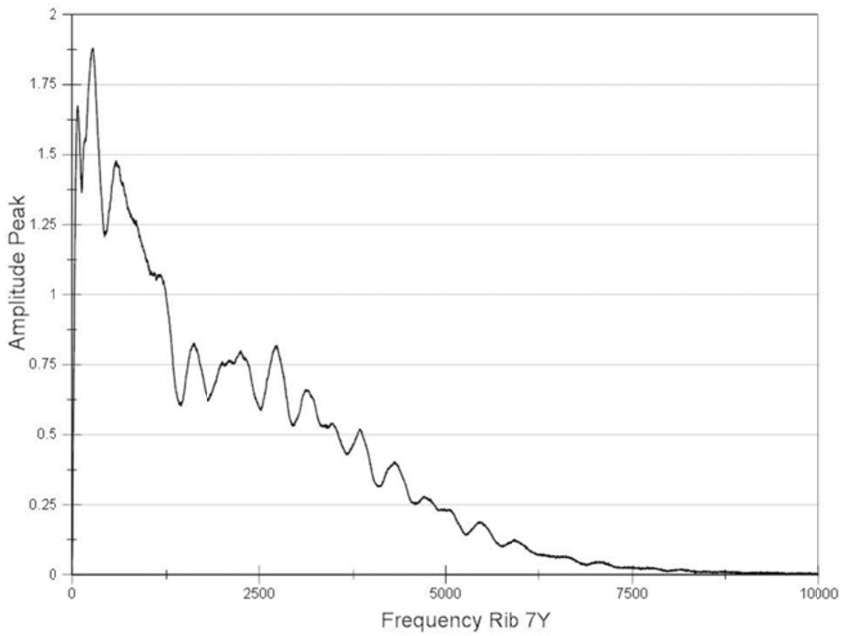


Figure 7.9: FFT of impacted rib acceleration in the lateral direction (y-axis)

To preserve the relevant high-frequency data, the thoracic acceleration data were filtered with a four-pole Butterworth low-pass filter (phaseless) with a -3dB limit frequency of 7,500 Hz, which effectively diminished noise in the off-axis (x-axis, z-axis) and non-impacted rib accelerometers while only slightly attenuating the peak acceleration (1.27 ± 0.77%) in the lateral direction (y-axis) of the impacted rib. Overall the filtered peaks remained relatively close. It was determined to filter rib, sternum, and spine acceleration data with the four-pole Butterworth low-pass filter (phaseless) with a

-3dB limit frequency of 7,500 Hz since it retained the meaningful data and had the smallest peak attenuation.

A similar approach was taken when considering filter options for the chestband output and rib strains. Chestband output is commonly filtered using a CFC 600 prior to post-processing (Maltese, Eppinger et al., 2002; Yoganandan, Pintar et al., 2008; Yoganandan, Humm et al., 2013). Data collected during this testing exhibited relevant data through approximately 3,000 Hz (Figure 7.10). A four-pole Butterworth low-pass filter (phaseless) with a -3dB limit frequency of 3,000 Hz was chosen to minimize the attenuation of the peak deflection (2.52 ± 4.83% reduction). Rosette strain gage data were also filtered with the four-pole Butterworth low-pass filter (phaseless) with a -3dB limit frequency of 3,000 Hz (Figure 7.11).

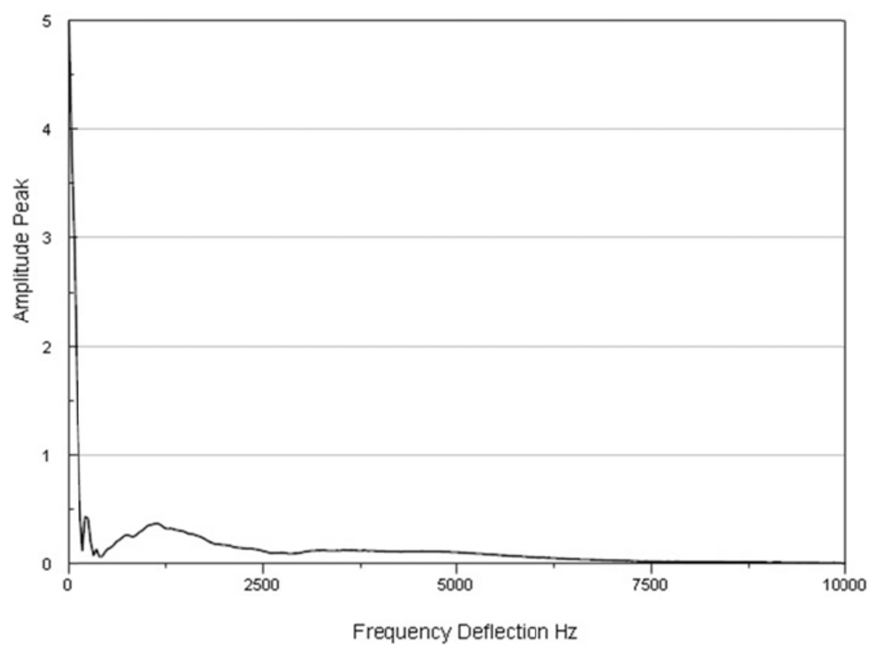


Figure 7.10: FFT of chestband output

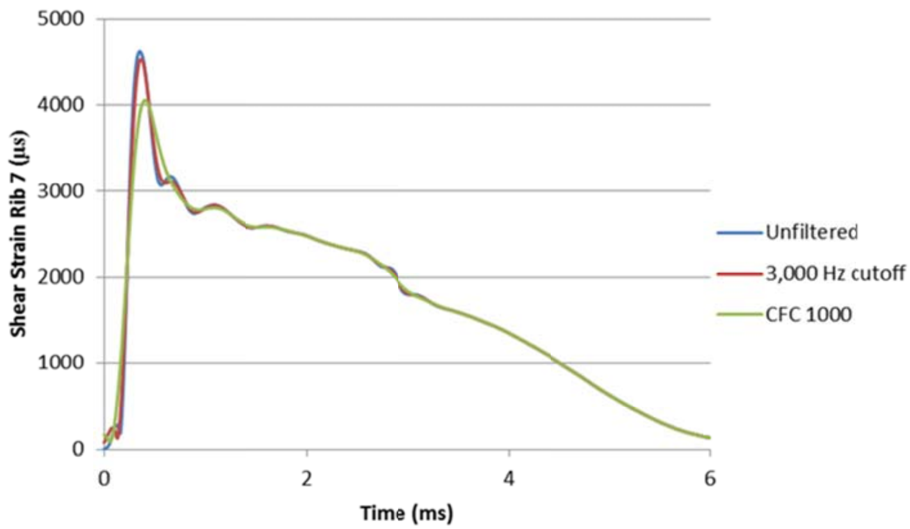


Figure 7.11: Filter comparison for shear strain of impacted rib

7.2.6 Analysis

Time zero was determined by the force sensor signal. Post-processing of data output from the force sensor was needed to calculate the impact force. The response of the force sensor was non-linear; therefore, the sensor sensitivity was dependent on the maximum output expected. Sensitivities were calculated based on the manufacturer's calibration data for each sensor. Acceleration data were filtered and resultant was calculated.

Rosette strain gage data were filtered and principal strains (maximum and minimum) and maximum shear strain were computed using the following formulas:

$$\varepsilon_1 = \frac{1}{2}(\varepsilon_A + \varepsilon_C) + (\frac{1}{2}[(\varepsilon_A - \varepsilon_C)^2 - (2\varepsilon_B - \varepsilon_A - \varepsilon_C)^2]^{\frac{1}{2}}$$

$$\varepsilon_2 = \frac{1}{2}(\varepsilon_A + \varepsilon_C) - (\frac{1}{2}[(\varepsilon_A - \varepsilon_C)^2 - (2\varepsilon_B - \varepsilon_A - \varepsilon_C)^2]^{\frac{1}{2}}$$

$$\gamma_{max} = \frac{1}{2}[(\varepsilon_A - \varepsilon_C) - (2\varepsilon_B - \varepsilon_A - \varepsilon_C)]^{\frac{1}{2}}$$

where $\varepsilon_{A,}$ ε_B and ε_c represent the three gages of the rectangular Rosette.

Prior to processing, the chestband output was filtered. The chestband data were then post-processed using custom software, CrashStar V2.5 (Transportation Research Center Inc., East Liberty, OH). This software has never been used with a canine model. Since the chestband can be installed at any point along the circumference of the chest, the program requires the user to input a “sternum” or “spine” location from the band placement on the specimen. For this study, the “spine” location was identified based on the initial position of the chestband on the specimen. This orientation allows the chestband to plot the thoracic motion and deformation resulting from the lateral impact at each time point.

The program output is the x- and y-axis position (mm) of each of the active gages at each time point. The deflection of the thorax was found using a half-chest method (Maltese, Eppinger et al., 2002; Kuppa, Eppinger et al., 2003). For this method the “spine” is known and the “sternum” location was identified as the gage diametrically opposite the spine gage (Figure 7.12). A line was constructed between the spine and the sternum. The perpendicular distance between the gages near the impact site and the spine-sternum line was calculated for each time point. It was determined that the sternum does accelerate during impact creating movement with the sternum gage; therefore, the spine-sternum line is adjusted at each time point following the sternum gage movement. Half-chest compression was calculated using the initial magnitude from the gage generating peak deflection to the spine-sternum line. The time to peak deflection (T_D) was determined based on the point of contact as established by the force sensor. Rate at which the thoracic cavity reached peak deflection (V_D) was calculated by dividing the peak deflection by the time to peak deflection (T_D).

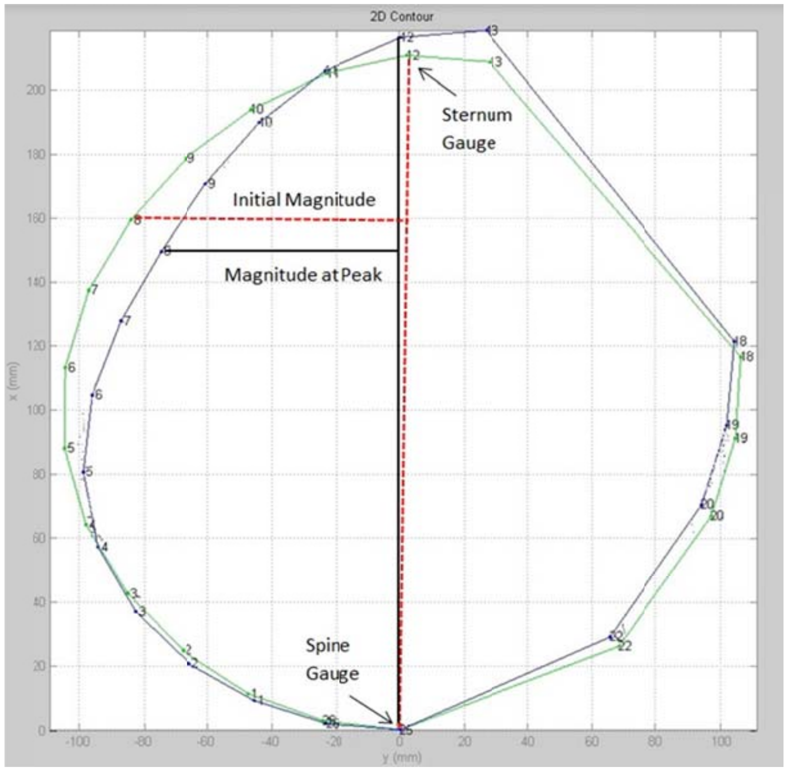


Figure 7.12: Spine-sternum method used for deflection analysis

The sixth, seventh, and eighth rib bones, bilaterally, were removed from each specimen during necropsy. A veterinarian evaluated each impacted seventh rib and injury classifications were developed (Table 7.2).

Table 7.2:
Fracture classification descriptions

Score	Fracture Classification
1	No visible fracture
2	Non-displaced fracture, transverse or oblique
3	Displaced fracture, both non-comminuted and comminuted

7.2.7 Statistical Analysis

An ANOVA was used to compare mean differences between armor types (8-ply, 15-ply, and Point Blank) and measured engineering variables. Significance was set at $\alpha = 0.05$. If there was significance between the armor types, post-hoc Tukey test was used to further analyze the difference.

7.3 Results

Detailed descriptions of the thoracic canine response while wearing the Point Blank canine armor are listed in Table 7.3. Average peak impact force behind the Point Blank armor was 5,746.8 ± 1,405.1 N. The average peak deflection was determined to be 15.4 ± 6.0 mm and average peak compression was 17.5 ± 7.9%. The average time to peak deflection was 4.1 ± 1.1 ms and the average rate at which peak deflection was achieved was 4.2 ± 2.4 m/s. Peak deflection illustrations for each test are located in Appendix C. Pictures of the impacted rib for each test are located in Appendix D.

ID	Velocity (m/s)	Peak Force (N)	Peak Deflection (mm)	Peak Resultant Acceleration (g)				Peak Shear Strain (µs)		Fracture Classification
				Rib 7	Rib 8	Spine	Sternum	Rib 7	Rib 8	
15L	394.4	6253.7	22.8	1441.2	-	90.7	102.0	-	-	2
15R	395.9	4725.9	18.0	2045.5	1781.1	189.5	92.7	-	-	2
16L	392.9	4505.4	10.7	1796.9	626.1	73.2	313.3	7971.1	3716.9	2
16R	400.2	7502.5	10.2	2097.7	837.9	79.4	192.3	7327.3	3761.3	1
Ave.	**395.9**	**5746.9**	**15.4**	**1845.3**	**1081.7**	**108.2**	**175.1**	**7649.1**	**3739.1**	
St.Dev	**3.2**	**1405.1**	**6.0**	**299.7**	**614.9**	**54.7**	**102.5**	**455.4**	**31.4**	

Table 7.3:
Detailed thoracic data for Point Blank armor

Comparisons of the average biomechanical responses with respect to the armor type were completed using an ANOVA (Table 7.4). The majority of the means were found to have no significant difference. The force behind the armor did seem to differ between the armor types ($P < 0.001$). Further analysis of the force means were tested with a post-hoc Tukey method. The average peak force behind the Point Blank armor was statistically higher when compared to the 8-ply packet ($P < 0.001$) and the 15-ply packet ($P < 0.001$).

Table 7.4:
Armor comparison of thoracic response

	8-ply	**15-ply**	**Point Blank**	**P-value**
Force (N)	3090.2 ± 851.3	2786.7 ± 960.2	5746.9 ± 1405.1	<0.001†
γ_{maxR7} (μs)	7172.9 ± 599.6	5813.7 ± 1230.3	7649.1 ± 455.4	0.057
A_{R7} (g)	1251.6 ± 343.5	1406.2 ± 596.0	1845.3 ± 299.7	0.127
A_{St} (g)	521.3 ± 332.6	405.2 ± 296.1	175.1 ± 102.5	0.155
A_{Sp} (g)	181.4 ± 96.0	174.5 ± 139.2	108.2 ± 54.7	0.522
V_D (m/s)	17.1 ± 28.4	10.6 ± 15.5	4.0 ± 2.1	0.547
T_D (ms)	6.5 ± 5.9	4.8 ± 3.6	4.2 ± 1.1	0.586
Deflection (mm)	16.5 ± 11.6	13.8 ± 8.1	15.4 ± 6.1	0.803
γ_{maxR8} (μs)	3980.1 ± 2989.4	4154.7 ± 1805.1	3739.1 ± 31.4	0.979
Compression (%)	16.8 ± 11.8	16.5 ± 10.1	17.5 ± 8.0	0.986
A_{R8} (g)	1025.8 ± 655.4	1062.3 ± 929.2	1081.7 ± 614.9	0.991

*Abbreviated measurements: A_{R7}-Resultant Acceleration rib 7, A_{R8}-Resultant Acceleration rib 8, A_{Sp}-Resultant Acceleration of spine, A_{St}-Resultant Acceleration of sternum, γ_{maxR7}- Shear strain rib 7, γ_{maxR8}-Shear strain rib 8

†Armor type generated statistical significance with respect to mean values ($P < 0.05$)

Three of four tests with the Point Blank armor resulted in fracture classification 2 and the remaining test resulted in no fracture. Similar to the 8-ply and 15-ply packets, damage occurred to the seventh rib only.

7.4 Discussion

The canine thoracic response was evaluated for behind armor blunt trauma using a certified canine ballistic vest. The armor proved to protect the canine thoracic cavity from the 9 mm threat similar to the 8-ply and 15-ply armor packets previously tested. The ammunition was captured by the armor panels for all 4 tests conducted. The Point Blank BII armor is made of 16 layers of Twaron aramid material (quilted) and 21 layers of Honeywell Spectra Shield®. Although the accelerations, rib strains, and peak deflections were comparable to those collected with the 8-ply and 15- ply packets, the behind armor force resulting from the Point Blank armor was significantly higher. The Point Blank armor may have allowed for more flexibility which could explain the higher force behind the armor. The current study included a rather small sample size and significant results should be interpreted with care. The injuries resulting from the increased force, based on observation, were not more severe. Three of the four impacts resulted in a non-displaced fracture while none of the impacts resulted in a displaced fracture.

The armor tested was certified to the NIJ 0101.06 standard and according the manufacturer, BFS from a new BII model armor with a 9 mm of comparable velocity ranges from 27 – 29 mm depending on the armor size. A conditioned armor resulted in BFS measurements ranging from 28 - 31 mm. As previously determined from PMCS and clay testing the recommended depth in clay for a 50% probability of rib fracture in a canine was found to be 28.5 mm (Chapter 5). Although the Point Blank armor was not tested on clay during this study, the manufacture claims and the resulting injuries during the current test could support the finding that there is a reasonable risk of rib fracture for a canine with the current standard. Similar to their human counterpart, if a canine is shot in the area protected by armor, even if no visible indication of injury exists, there is a likelihood of skeletal injury and veterinary care should be sought shortly after the incident occurs.

The study was not without limitation. The sample size was rather small with only two canines being tested and a total of 4 shot were evaluated. Even though the weight of the canines were considered reasonable with one above median and one below median of all PMCS specimens, future testing should investigate a range of weights. Further testing should be conducted to evaluate additional armor threat levels and ballistic threats since injuries and injury severity will likely vary.

CHAPTER 8 - CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

The overall goal of this research was to further the understanding of canine ballistic armor and the biomechanical thoracic response of a canine to blunt ballistic impacts. The focus of this research was to determine if ballistic penetration is a concern for law enforcement canines in the field, evaluate the thoracic response of the canine to various conditions of blunt ballistic impact, and determine whether commercially available canine armor restricts the abilities of the canine and their efficacy.

Civilian law enforcement canines are at risk for ballistic penetrating trauma. The third leading cause of traumatic death from 2002 – 2012 was found to be as a result of ballistic penetration. Post-mortem canine specimens were used to establish biomechanical response and injury tolerance of the canine thorax. The biomechanical response was determined for three armor conditions: 8-ply Kevlar® packet, 15-ply Kevlar® packet, and Point Blank Level II canine armor. Fracture of the impacted rib occurred as a result of behind armor blunt trauma in over half of the tests. Fourteen of the 23 impacts to the 8 and 15-ply packets resulted in a fracture, 5 of which were complete displacements of the rib bone. The majority of non-displaced rib fractures and all of the displaced rib fractures occurred with the 8-ply. The Point Blank armor tests (n = 4) resulted in 3 non-displaced fractures of the impacted rib. The greater the number of layers the greater the protective ability of the armor against behind armor blunt trauma which was expected.

Measured and calculated engineering parameters were not found to be significant predictors of rib fracture. Measuring the backface signature (BFS) in clay of the armor packets did, however, prove to predict rib fractures in the post-mortem canine specimens. Both depth and volume of BFS were significant predictors. The current NIJ 0101.06 standard sets the BFS limit at 44 mm while this study found that a 50% probability of rib fracture for canines could occur at 28.5 mm. This finding was possibly supported by the PMCS testing with Point Blank armor. According to the manufacture the BFS for armor used should have been 27-29 mm in clay and the testing did result in rib fracture during 3 of the 4 tests.

The performance and core body temperature of canines were evaluated with the Point Blank Level II canine armor, resulting in increased mean completion times for apprehension and agility tasks and increased mean core body temperature during apprehension tasks. Although the temperature increase was statistically significant, the core body temperature remained below temperatures that are thought to be life-threatening. Overall, the armor tested protected the canine thoracic cavity from a penetrating bullet wound. Behind armor blunt trauma was recorded and in some cases resulting rib fractures were rather severe. Additional testing should be done to evaluate the thoracic response to higher energy rounds and different levels of armor protection which may be more applicable to military canines. Further testing should also evaluate the soft tissue and internal organ damage that may occur as a result of behind armor blunt trauma.

This study provides preliminary data to an area of research that is lacking valuable information. Canines have proven to be effective partners in both military and law enforcement applications. Evaluating ways to improve training and protection is beneficial to those they work besides and the communities they help protect.

APPENDIX A

Wayne State University IACUC Approval

WAYNE STATE UNIVERSITY

INSTITUTIONAL ANIMAL
CARE AND USE COMMITTEE
87 E. Canfield, Second Floor
Detroit, MI 48201-2011
Telephone: (313) 577-1629
Fax Number: (313) 577-1941

ANIMAL WELFARE ASSURANCE # A 3310-01

PROTOCOL # A 08-09-10

Protocol Effective Period: **September 21, 2010 – August 31, 2013**

TO: Dr. Cynthia Bir
Department of Bioengineering
2215 Bioengineering Center

FROM: Lisa Anne Polin, Ph.D. Lisa Anne Polin
Chairperson
Institutional Animal Care and Use Committee

SUBJECT: Approval of Protocol # A 08-09-10
"VIP Protection - Phase III Canine Body Armor"

DATE: September 21, 2010

Your animal research protocol has been reviewed by the Wayne State University Institutional Animal Care and Use Committee, and given final approval for the period effective **September 21, 2010** through **August 31, 2013**. The listed source of funding for the protocol is **CTTSO BAA No. 09-Q-4554 VIP-2494-ARMORWORKS20-1874-FPCanine Body Armor (Phase III)**. The species and number of animals approved for the duration of this protocol are listed below.

Species	Strain	Qty.	USDA Cat.
NO LIVE ANIMALS TO BE USED ON CAMPUS UNDER THIS PROTOCOL..................		....	

Be advised that this protocol must be reviewed by the IACUC on an annual basis to remain active. Any change in procedures, change in lab personnel, change in species, or additional numbers of animals requires prior approval by the IACUC. Any animal work on this research protocol beyond the expiration date will require the submission of a new IACUC protocol form and full committee review.

The Guide for the Care and Use of Laboratory Animals is the primary reference used for standards of animal care at Wayne State University. The University has submitted an appropriate assurance statement to the Office for Laboratory Animal Welfare (OLAW) of the National Institutes of Health. The animal care program at Wayne State University is accredited by the Association for Assessment and Accreditation of Laboratory Animal Care International (AAALAC).

APPENDIX B

Reprint of Stojsih S, Baker J, Les C, and Bir C

Review of Canine Deaths While in Service in US Civilian Law Enforcement (2002–2012)

Sarah E. Stojsih, MSE; Janice L. Baker, DVM; Clifford M. Les, DVM, PhD; Cynthia A. Bir, PhD

ABSTRACT

Background: Working dogs have been proven effective in multiple military and law enforcement applications. Similar to their human counterparts, understanding mortality while still in service can help improve treatment of injuries, and improve equipment and training, to potentially reduce deaths. This is a retrospective study to characterize mortality of working dogs used in civilian law enforcement. **Methods:** Reported causes of death were gathered from two working dog and law enforcement officer memorial websites. **Results:** Of the 867 civilian law enforcement dogs reported to these memorial websites from 2002 to 2012 with reported causes of death while in service, the deaths of 318 were categorized as traumatic. The leading reported causes of traumatic death or euthanasia include trauma as a result of a vehicle strike, 25.8% (n = 82); heatstroke, 24.8% (n = 79); and penetrating ballistic trauma, 23.0% (n = 73). **Conclusion:** Although the information gathered was from online sources, this study casts some light on the risks that civilian law enforcement dogs undergo as part of the tasks to which they are assigned. These data underscore the need for a comprehensive database for this specialized population of working dogs to provide the robust, reliable data needed to develop prevention and treatment strategies for this valuable resource.

KEYWORDS: *canine, mortality, law enforcement, trauma*

Introduction

The use of databases and guidelines to track traumatic injuries and improve survival in both civilian law enforcement and military applications has been well established.[1–6] For instance, the Joint Theater Trauma System was developed to provide a universal and integrated approach to battlefield care, resulting in optimization of casualty care capabilities and minimization of mortality.[2–4] While injury and mortality databases are fairly well developed for human medicine, they are lacking for veterinary medicine—more specifically, the working dog population. Although working dogs face threats similar to those experienced by their human counterparts, their quadruped stance and smaller mass may affect injury severity and treatment, resulting in the need for canine-specific casualty care guidelines. Compiling causes of injury or death data can assist in developing new strategies for enhanced canine-specific treatment, equipment, and training that may increase survival.

Previous research has been published highlighting the working canine.[7–13] Studies reporting cause of death or euthanasia, primarily for the military working dog population, emphasize duty-limiting causes to diseases such as osteoarthritis, degenerative joint disease, neoplasia, and senility.[8,11] One recent study investigated common reasons for emergency medical visits in police working dogs.[12] This population presented more frequently with orthopedic injuries, compared to pet German Shepherd Dogs; gastrointestinal disease was commonly present for both populations. Collecting morbidity and mortality data is crucial to improving canine units and their efficacy. Additionally, understanding mortality related to unexpected events, such as heat injury or ballistic-related trauma, is crucial to ensuring medics and handlers are properly trained for current needs.

Currently, there is no centralized method of tracking traumatic injuries or illnesses in working dogs used in law enforcement or military. A working dog memorial website has been established, however, creating an extensive list of dogs that have died or were euthanized while in service.[14] At the time of this review, according to the memorial website, there were 1,867 working dogs from government, security agencies, military, and law enforcement that reportedly died in service from 1940 to the present, with new cases being added regularly.[14] There are obvious limitations with lists created from nonclinical sources when generating a scientific database. However, given the lack of availability of this information, some useful generalizations may be obtained from compiling and analyzing these data collected from online sources. The current study consolidates the type of data available from the existing websites and reports traumatic causes of death or euthanasia that occurred while dogs were in service. Gathering canine casualty data can potentially assist in better prevention and treatment of injuries in this specialized population of working dogs.

Methods

To delineate the key factors related to fatal outcomes, causes of death were investigated for working dogs used in civilian law enforcement in the United States between the years 2002 and 2012. The primary website reporting these incidents in one location, established in 2000, is maintained by the Connecticut Police Work Dog Association (CPWDA).[14] Dogs listed died or were euthanized while in service, meaning the dogs were working for a police department, government, or security agency at the time of their death. The Officer Down Memorial Page (ODMP) also has a program dedicated to fallen canine officers, which launched in September 2012.[15] Cases not listed on the CPWDA website but listed on ODMP were combined for the current study. Both websites are used as memorials and the data made available were self-reported by the handler or other contributors familiar with the incident (e.g., another handler, friend, spouse).

Cases reported to the websites are from agencies across the United States, various countries, and the military. Data listed on the websites are organized by year of incident. Additional data found on this website include canine name, location, and cause of death. Data on the CPWDA website dates back to the Vietnam conflict and includes incidents from outside the United States. These data would be difficult to verify and, therefore, were not included in the study. Military working dogs were also excluded, since these websites are directed toward the law enforcement community and, thus, the military dogs may be underrepresented. A number of cases reported on the websites had "unknown" listed as the cause of death. If further information could not be obtained, the case was not included in the data set. Finally, the time frame of the study was limited to create a more manageable and representative population of law enforcement dogs by removing incidents occurring before 2002, 2 years after the memorial site went online.

Remaining data were organized and various causes of death were tabulated and compared. Causes of death were separated into two main categories: nontraumatic and traumatic. Deaths attributed to an illness or pathophysiology (e.g., cancer, gastric dilatation-volvulus, degenerative diseases, other medical conditions) were categorized as nontraumatic. Deaths caused by an external circumstance that may have been prevented (e.g., blunt trauma, gunshot wound [GSW], falls, other accidents) were categorized as traumatic. Almost two-thirds (63.3%; n = 549) of the reported deaths were categorized as nontraumatic. Only the traumatic cases were selected for inclusion in this review to ensure compliance with the goal of this study to focus on causes of death that could be considered potentially preventable, to shed light on the importance of understanding, recording, and properly preparing for current needs in working dog casualty care.

An attempt to gather further data from other online sources was made for each case, using online resources. Key criteria were used to ensure the incidents were identical when investigating for further information on the Internet. If two or more incidents shared the same date, canine name, location, and incident description, the incidents were considered to be coincident, and additional information was extracted. Details such as breed, age, and further description of incident or cause of death were the main focus. In some cases, generally involving ballistic trauma or heatstroke, detailed descriptions of the circumstance surrounding the incident (e.g., friendly fire, confinement heat injury) could be found and were recorded.

Results

Between the years of 2002 and 2012, there were 867 law enforcement dogs reported to the CPWDA or ODMP K9 database as being killed or euthanized while in service in the United States with a known cause of death (traumatic and nontraumatic). A large percentage of the cases (90%) had breed information available. Of those cases for which information was available, the majority involved the German Shepherd Dog (48.7%), followed by the Belgian Malinois (23.4%).

Traumatic causes of death made up 36.7% (n = 318) of those dogs killed or euthanized while in service (Table 1). Cases that were placed in the "Other" category include deaths caused by animal attack (n = 7), drowning (n = 5), fire or smoke inhalation (n = 3), and electrocution/lightning (n = 1). The top three traumatic causes of death include being struck by a vehicle, heatstroke, and ballistic penetrating trauma.

Further detailed information was found for the majority of the heatstroke cases (n = 64, 81%) through various online news reports. The majority of these cases with a known cause (n = 48, 75%) could be classified as a confinement heat injury: meaning the dog was left unattended in a patrol car causing the dog's body temperature to increase resulting in their death. The confinement heat injury deaths could be further defined by situations in which dogs were unintentionally left in the car for an extended period of time (n = 25) or were reportedly

Table 1 *Traumatic Causes of Death in Law Enforcement Dogs*

Traumatic Cause	Cases, No.	Percent
Nonpenetrating blunt trauma		
Struck by vehicle	82	25.8
Vehicle crash	22	6.9
Fall	16	5.0
Localized impact	2	0.6
Penetrating trauma		
Ballistic	73	23.0
Sharp nonballistic	5	1.6
Heatstroke	79	24.8
Airway obstruction	12	3.8
Ingested toxin	11	3.5
Other	16	5.0

Figure 1 *Number of reported traumatic deaths.*

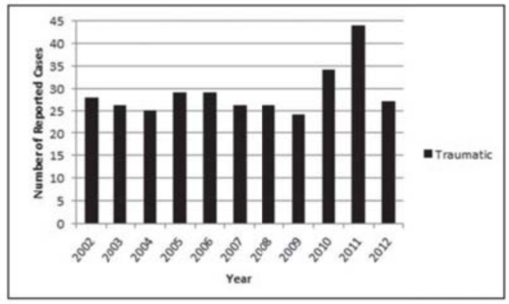
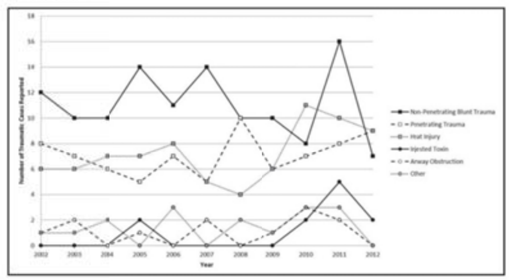


Figure 2 *Number of traumatic deaths reported annually by cause.*



caused by alarm systems that malfunctioned allowing the interior of the car to reach dangerous temperatures without notification (n = 23). The remaining 16 heatstroke cases were caused by exertion (n = 8) or environmental conditions (n = 8).

Ballistic deaths could be classified additionally as hostile ballistic attack while on duty, friendly fire while on duty, and hostile ballistic attack while the dog was not on duty (Table 2). Working dogs used in civilian law enforcement are trained for various purposes (e.g., detection, apprehension, and search and rescue), but approximately 38% of the ballistic fatalities occurred while apprehending or tracking a suspect. In the cases that involved friendly fire, the majority (n = 16) involved a dog that identified a police officer/handler as the suspect or showed signs of aggression toward a police officer/handler, leading to a police officer/handler fatally wounding the dog. The remaining cases include accidental shootings or a canine officer caught in crossfire. Cases involving hostile off-duty shootings include incidents not related to their work duties. The annual reported number of traumatic deaths in law enforcement dogs remained fairly consistent until 2010 and 2011, when there was a positive increase. However, the data indicated a return to previous levels in 2012 (Figures 1 and 2).

Table 2 *Descriptive Details for Ballistic Deaths*

Ballistic Deaths	Cases, No.	Percent
Hostile – on duty	28	38.4
Friendly fire – on duty	23	31.5
Hostile – off duty	22	30.1

Discussion

Although there are studies investigating military working dogs, there is a lack of data investigating civilian law enforcement dogs.[7-12] This is, to our knowledge, the only study that has categorized, compared, and reported these data. The current study compiled self-reported cases of working dogs used in civilian law enforcement that died or were euthanized while in service in the United States. Overall, the current study found the most commonly reported causes of death related to a traumatic event to be blunt trauma caused by a vehicle strike, heatstroke, and ballistic penetrating trauma. Although causes of death could not be verified with veterinary records or necropsy reports, this study provides a characterization of mortality in the working dog community that may benefit future research and improve treatment of life-threatening injuries, and improve equipment and training for current needs.

Working dogs are exposed to different circumstances when compared to the general population of dogs. While on duty, military, special weapons and tactics (SWAT), and law enforcement dogs are subjected to threats similar to those experienced by their human counterparts. Potential threats include ballistic, blunt, and explosive-resulting traumas, in addition to the potential for ingesting hazardous substances. These dogs may be at risk for hostile action or being involved in dangerous situations as a result of their duties. Common causes of injury or death could differ for different working dog populations.

In the current study, the most commonly reported cause of traumatic death to the CPWDA and ODMP online resources for working dogs in law enforcement was due to injuries caused by motor vehicle accidents (MVAs). Studies that have investigated causes of trauma in pet dogs have found that MVAs were frequent causes of trauma and fatalities.[16–18] Kolata and Johnston[16] published an article investigating injuries in 600 dogs involved in MVAs in which the dog was struck by a vehicle. Overall, 12.5% of the dogs died or were euthanized as a result of their injuries. A more recent study reported 91.1% of the canine blunt trauma cases investigated were the result of an MVA.[18] The mortality rate associated with severe blunt trauma was determined to be 12%.

Law enforcement dogs could be at risk for injury and even death caused by a motor vehicle due to their job requirements (e.g. apprehending and tracking suspects). This could make the dogs more vulnerable than the normal dog population. In situations where a suspect attempts to evade capture, the dog will pursue the suspect, which could involve running through urban and suburban areas with moderate to high traffic levels. Although the mortality rates involving dogs struck by vehicles were reported in previously published studies for the normal population,[16,18] these data are not available for working dogs.

Approximately one quarter of the current study's population reportedly died from heatstroke. In working dogs, heatstroke may be due to many factors, none of which are well documented in the scientific literature. However, it is generally accepted that lack of acclimation to hot environments or hard work, sudden changes in environmental temperature or workload, and confinement in hot vehicles all play major roles in fatal heatstroke in working dogs.[19] The majority of the heatstroke cases with known cause in this study could be classified as confinement heat injury. The two causes of confinement heat injury were attributed to the handler becoming distracted or delayed and unintentionally leaving the dog in the patrol vehicle or the patrol car alarm malfunctioned. With canine units, it is rather common in many situations to leave the dog in the patrol car while the engine and the air conditioning are running. There are times when the car will be more comfortable and cooler than the ambient temperature and it tends to be a good place for the dog to cool down and rest. Alarm systems are available that will sound the horn, call, page, or otherwise alert the officer, and roll down the windows if the interior temperature of the car exceeds a certain threshold. This alerts officers and allows additional air circulation in the car. However, these systems can malfunction. Of the heatstroke cases with known causes, 35.9% were reportedly caused by alarm systems that malfunctioned and did not alert the officers that the interior of the car had reached dangerous temperatures.

Exertion and confinement heat injuries, while both giving rise to similar clinical abnormalities, are caused by different physiologic and situational conditions. Thus, risk factors as well as preventive measures for each will likely vary considerably. Further research and identification of the potential factors involved may help reveal specific risk factors and, thus, more specific means to mitigate them.

The third most commonly reported cause of traumatic death to the CPWDA and ODMP for working dogs was as a result of the penetrating ballistic trauma of GSW. Very few studies have looked at the occurrence of ballistic trauma in working dogs. A study by Baker et al[7] investigated 29 cases of GSW injury in military working dogs between 2003 and 2009 and reported a survival rate of 38%. According to this study, the most common site for injury appeared to be the thorax and extremities. Fifty-nine percent of the dogs were categorized as killed in action (KIA). Although, extremity wounds were found to be the second most common injury location, all of the dogs that had extremity wounds as their only injury survived. All dogs that received wounds to the neck or abdomen died as a result of the injuries. In the cases with abdominal wounds, all of the dogs had additional life-threatening injuries; however, it was determined that the cause of death was not the abdominal wound. In a combat scenario, extremity wounds in humans can cause significant blood loss and were found to be one of the leading causes of death. In dogs, however, this does not appear to be the case, perhaps due to scant muscle in the extremity of a dog compared to a human.[7]

Currently there are no studies listing the frequency of fatal GSWs in law enforcement working dogs. According to data from 2012 collected by the National Law Enforcement Memorial Fund, there were 49 police officers (38.6%) killed with a firearm; this was the second leading cause of death in on-duty police officers.[20] Working dogs are exposed to the same risks and are sometimes sent into situations ahead of the law enforcement officers (e.g., when assisting SWAT teams) to locate and alert their team of hazards, to add protection to the officers. The current data show that 23% of the dogs were reportedly killed or euthanized as a result of GSWs, which is slightly lower than that reported for their human counterparts in 2012.

All ballistic cases in this study were further investigated with additional online sources, since the majority of the incidents were well documented by the media. According to media reporting, it appears that 38.4% of the ballistic cases were on-duty hostile shootings (Table 2). The remaining cases involved friendly fire (31.5%) and hostile shooting that occurred off duty (30.1%). The friendly fire cases can be further broken down into accidental or intentional shootings. Surprisingly, 69.6% ($n = 16$) of the friendly fire cases were intentional shootings. In these cases, the dog was aggressive or bit a law enforcement officer and, in response, the officer intentionally shot the dog out of fear for the officer's own safety. Six cases (26.1%) involved a dog that was caught in the crossfire or was accidentally shot by a police officer. One case resulted from friendly fire, but the exact circumstance was not clear. Cases that were categorized as hostile shootings that occurred off duty generally involved a dog that escaped the kennel or home of the handler and was shot for a variety of reasons.

The implementation of civilian trauma systems or injury databases has been effective for improving care delivered to injured patients, injury prevention, supplying data for clinical research, documenting effects of trauma, and policy development.[21–23] In the past, significant improvements in civilian trauma care have resulted from data and experiences in combat casualty care. On the contrary, applying civilian standards to military trauma care revealed significant medical differences in the 1990s, exposing deficiencies on the battlefield.[2,24] Trauma registries not only help improve trauma outcomes but also improve advances in personal protective equipment and prehospital care standards.[2–4,6]

A study that investigated U.S. Army Ranger combat casualties in Somalia noted the need for a comprehensive combat-casualty registry allowing evidence-based validation of surgical and resuscitative intervention.[24] The Joint Theater Trauma Registry (JTTR) was developed to better organize and coordinate battlefield care. One study analyzed the JTTR data from July 2003 through July 2008, comparing data to the civilian trauma-system equivalent, the National Trauma Data Bank.[2] As a result, the evidence-based guidelines put in place for a military setting were associated with improvements in outcome for hypothermia prevention and management, burn resuscitation, and massive transfusion mortality. Following the inception of the JTTR, an additional study investigated the outcomes from implementing prehospital trauma care guidelines customized for the battlefield (Tactical Combat Casualty Care) and a prehospital trauma registry.[3] Additional comparisons were made with casualty data from the regiment, which supported and applied the guidelines to the military as a whole. It was reported that the 75th Ranger Regiment had a decrease in cases identified as KIA and died of wounds when compared with the U.S. military ground troops. Continually improving and implementing guidelines for battlefield trauma care will continue to lower casualty rates. A comprehensive working dog database could be used in a similar manner to potentially lower fatality rates, as demonstrated by the human population.

This study compiles and compares causes of death for in service working dogs in law enforcement. However, there are limitations to this study. The data presented in this study were compiled from online sources. The information was collected and reported as a memorial to the fallen canines. The causes of death were reported by handlers or other contributors affected by the death of the dog. None of the cases could be verified with veterinary records; however, additional information could be found if there was media coverage of the incident. There are no specifications as to where the canine units must seek veterinary care, making it difficult to access veterinary records and verify causes of death. If veterinary records or necropsy reports were available, additional information such as breed, sex, age, and cause of death could also be compiled and analyzed.

With the causes being reported by nonclinical personnel, it is possible the causes were not correctly understood or reported. Errors in reporting the cause correctly, and the potential for certain types of causes not to be reported at all, could result in inaccurately represented categories. Furthermore, if the cause of death would carry additional scrutiny of the officer, when the death could be attributed to the officer's actions or attention to care of the dog, then the handler may not contact the websites. If the handler is unaware of the websites' existence, there is a potential for missing data points, as well.

In conclusion, this study casts some light on the risks that civilian law enforcement dogs undergo as part of the tasks to which they are assigned. Additionally, it is important to note that this report is not an accusation of any aspect of law enforcement and the care of the dogs, but rather an attempt to identify areas in which knowledge and resources could be improved, subsequently benefiting canine casualty care and reducing death from potentially survivable traumatic events. The databases from which these conclusions are drawn were never designed to yield high-quality epidemiologic conclusions; these databases are, in general, set up as memorials to animals with whom their handlers have worked closely and to whom many handlers owe their lives. They are, at best, incomplete death records. However, given the immense expense incurred by local, state, and federal governments in acquiring, training, and maintaining these highly skilled animals, it would seem advisable to establish a wider database, taken across governmental levels and including living (working and retired) and deceased animals, to determine more rigorously than is currently possible the full extent of the risk profile to which these animals are subjected. As more, subtle epidemiologic patterns become clearer, it may be possible to alter selection, training, and deployment strategies to maintain this valuable resource more efficiently.

Disclosures

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References

1. Deuel E, Wemmer R. Law enforcement officers killed and assaulted, 2011. http://www.fbi.gov/about-us/cjis/ucr/leoka/2011. Accessed May 20, 2013.
2. Eastridge BJ, Costanzo G, Jenkins D, et al. Impact of joint theater trauma system initiatives on battlefield injury outcomes. *Am J Surg*. 2009;198:852–857.
3. Kotwal RS, Montgomery HR, Kotwal BM, et al. Eliminating preventable death on the battlefield. *Arch Surg*. 2011;146:1350–1358.
4. Eastridge B, Hardin M, Cantrell J, et al. Died of wounds on the battlefield: causation and implications for improving combat casualty care. *J Trauma*. 2011;71:S4–S8.
5. Holcomb JB, McMullin N, Pearse L, et al. Causes of death in U.S. Special Operations Forces in the global war on terrorism 2001 - 2004. *Ann Surg*. 2007;245:986–991.
6. Eastridge B, Mabry R, Seguin P, et al. Death on the battlefield (2001–2011): implications for the future of combat casualty care. *J Trauma Acute Care Surg*. 2012;73:S431–S437.
7. Baker JL, Havas KA, Miller LA, et al. Gunshot wounds in military working dogs in Operation Enduring Freedom and Operation Iraqi Freedom: 29 cases (2003–2009). *J Vet Emerg Crit Care*. 2013;23:47–52.
8. Dutton RE, Moore GE. Clinical review of death/euthanasia in 123 military working dog necropsies. *Mil Med*. 1987;152:489–493.
9. Evans RI, Herbold JR, Bradshaw BS, et al. Causes for discharge of military working dogs from service: 268 cases (2000–2004). *J Am Vet Med Assoc*. 2007;231:1215–1220.
10. Jennings PB, Butzin CA. Epidemiology of gastric dilatation-volvulus in the military working dog program. *Mil Med*. 1992;157:369–371.
11. Moore GE, Burkman KD, Carter MN, et al. Causes of death or reasons for euthanasia in military working dogs: 927 cases (1993–1996). *J Am Vet Med Assoc*. 2001;219:209–214.
12. Parr JR, Otto CM. Emergency visits and occupational hazards in Germand Shepherd police dogs (2008–2010). *J Vet Emerg Crit Care*. 2013;23:591–597.
13. Slensky K, Drobatz K, Downend A, et al. Deployment morbidity amoung search-and-rescue dogs used after the September 11, 2001, terrorist attacks. *J Am Vet Med Assoc*. 2004;225:868–873.
14. Cortina JA. K-9's that died while still in service. http://www.cpwda.com/k9_kilod.htm. Accessed May 20, 2013.
15. K9s. Officer Down Memorial Page website. http://www.odmp.org/k9. Accessed May 20, 2013.
16. Kolata RJ, Johnston DE. Motor vehicle accidents in urban dogs: a study of 600 cases. *J Am Vet Med Assoc*. 1975;167:938–941.
17. Kolata RJ, Kraut NH, Johnston DE. Patterns of trauma in urban dogs and cats: a study of 1,000 cases. *J Am Vet Med Assoc*. 1974;164:499–502.
18. Simpson SA, Syring R, Otto CM. Severe blunt trauma in dogs: 235 cases (1997–2003). *J Vet Emerg Crit Care*. 2009;19:588–602.
19. Taylor WM. Canine tactical field care: Part two—Massive hemorrhage control and physiologic stabilization of the volume depleted, shock-affected, or heatstroke-affected canine. *J Spec Oper Med*. 2009;9:13–21.
20. Groeninger S. 127 law enforcement officers killed nationwide in 2012. National Law Enforcement Officers Memorial Fund website. http://www.nleomf.org/newsroom/news-releases/127-law-enforcement-officers.html. Accessed May 20, 2013.
21. Mann NC, Mullins RJ. Research recommendations and proposed action items to facilitate trauma system implementation and evaluation. *J Trauma*. 1999;47(3 Suppl):S75–8.
22. Olson CJ, Arthur M, Mullins RJ, et al. Influence of trauma system implementation on process of care delivered to seriously injured patients in rural trauma centers. *Surgery*. 2001;132:273–279.
23. Zehtabchi S, Nishijima DK, McKay MP, et al. Trauma registries: history, logistics, limitations, and contributions to emergency medicine research. *Acad Emerg Med*. 2001;18:637–643.
24. Mabry RL, Holcomb JB, Baker AM, et al. United States Army Rangers in Somalia: an analysis of combat casualties on an urban battlefield. *J Trauma*. 2000;49:515–529.

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APPENDIX C
Thoracic Deflection 2D Illustrations

Red Line – Initial magnitude, Black Line – Magnitude at Peak

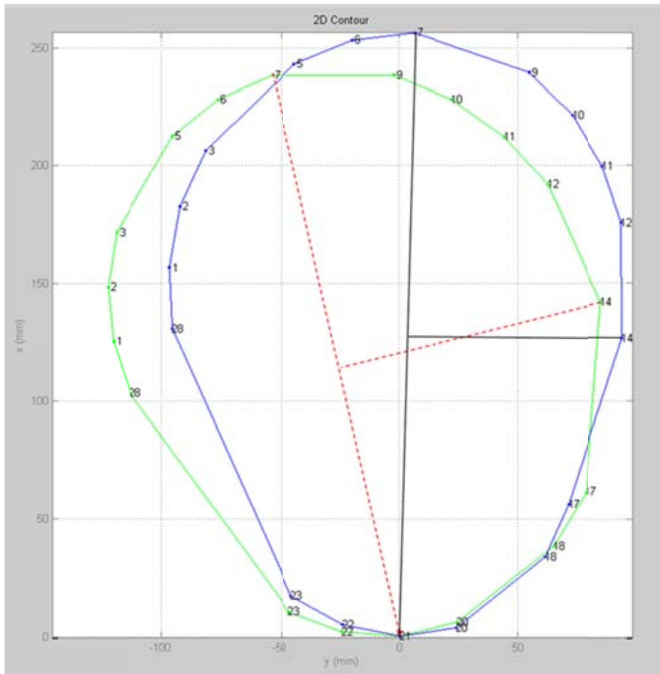

Figure C1: Peak deflection measurement Test 2-2R

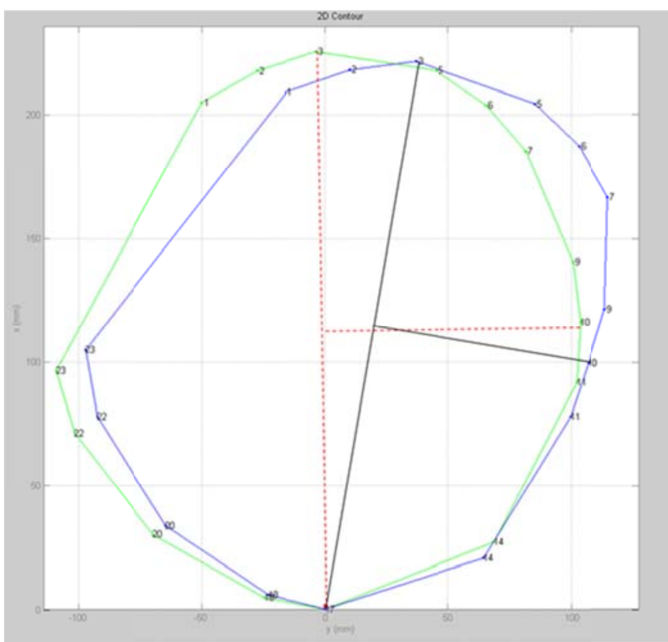

Figure C2: Peak deflection measurement Test 3-2R

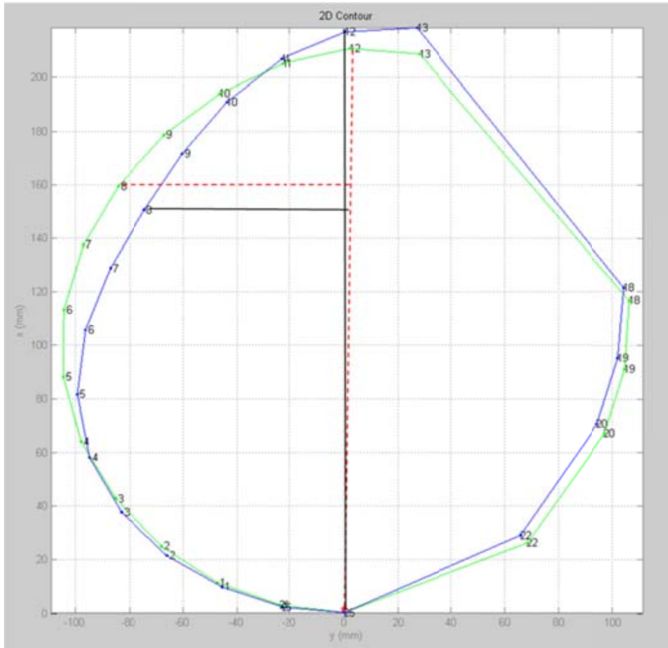

Figure C3: Peak deflection measurement Test 4-1L

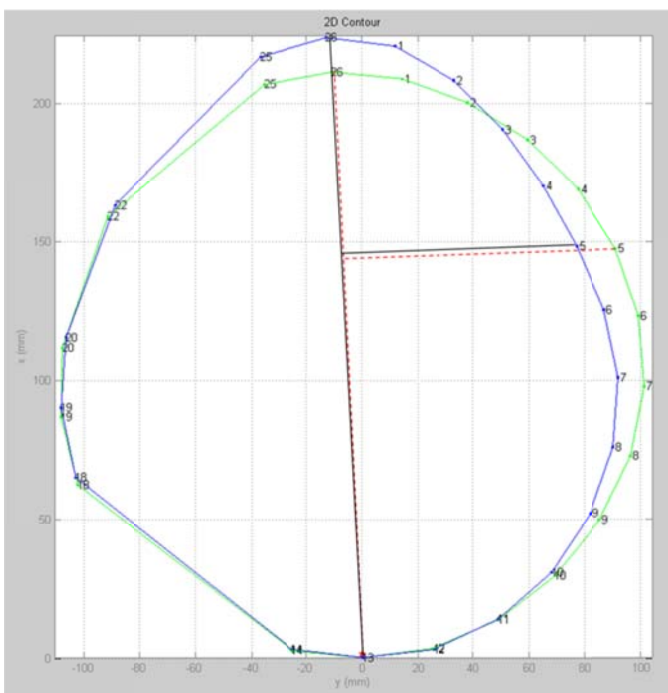

Figure C4: Peak deflection measurement Test 4-2R

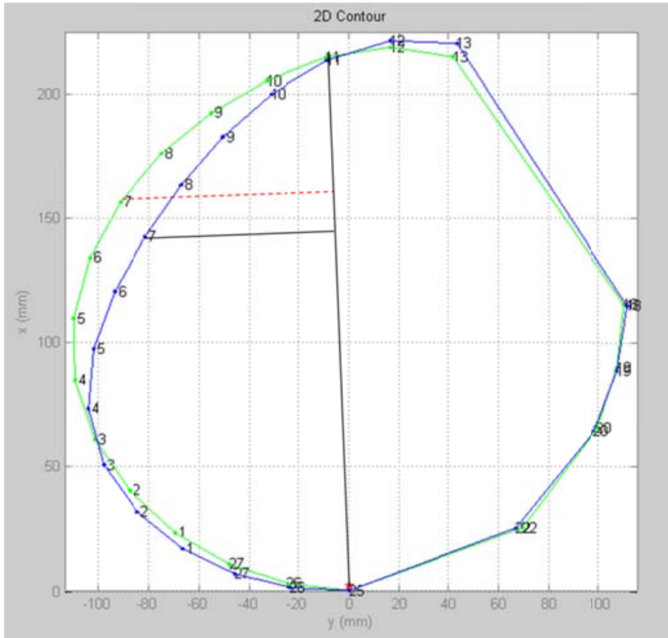

Figure C5: Peak deflection measurement Test 5-1L

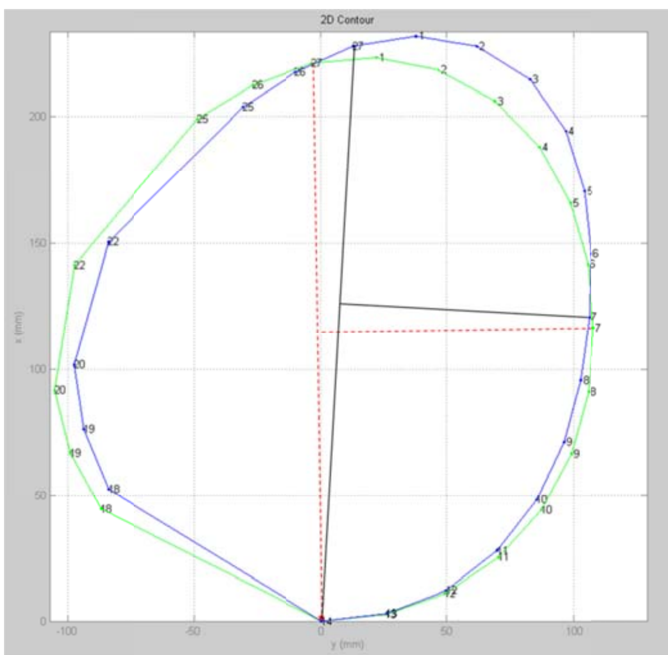

Figure C6: Peak deflection measurement Test 5-2R

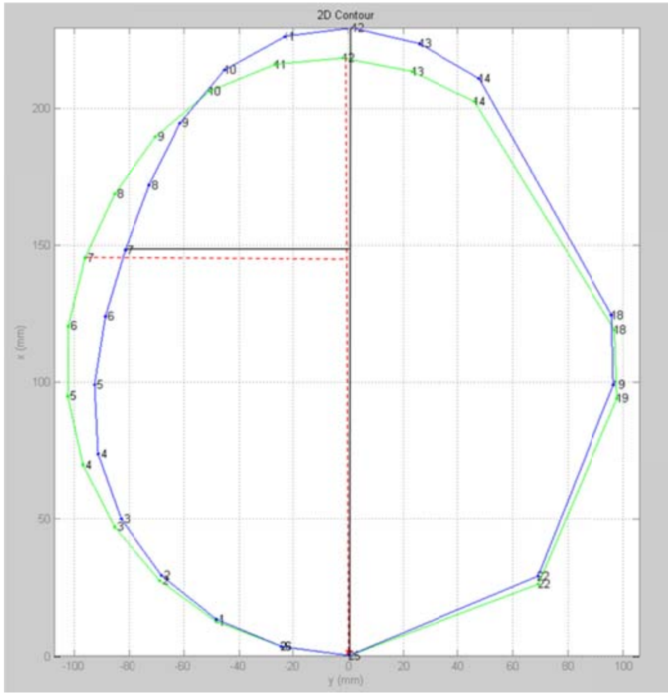

Figure C7: Peak deflection measurement Test 6-2L

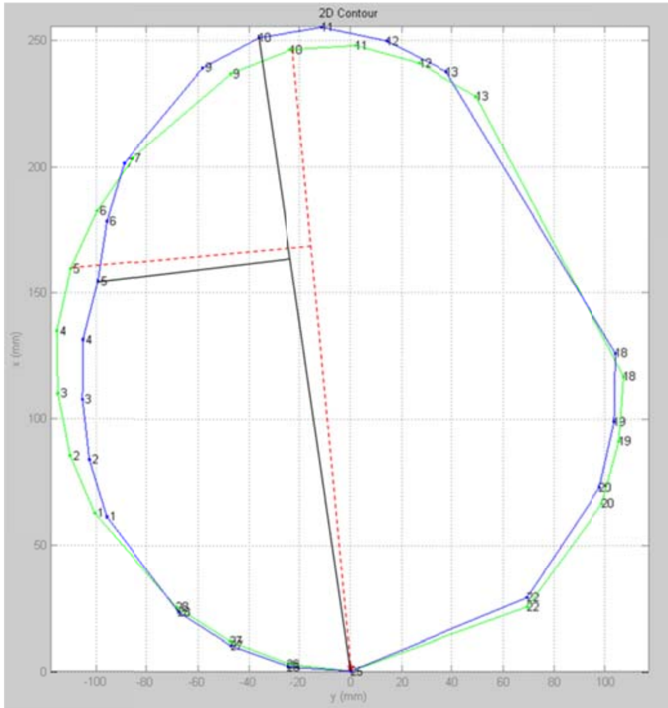

Figure C8: Peak deflection measurement Test 7-1L

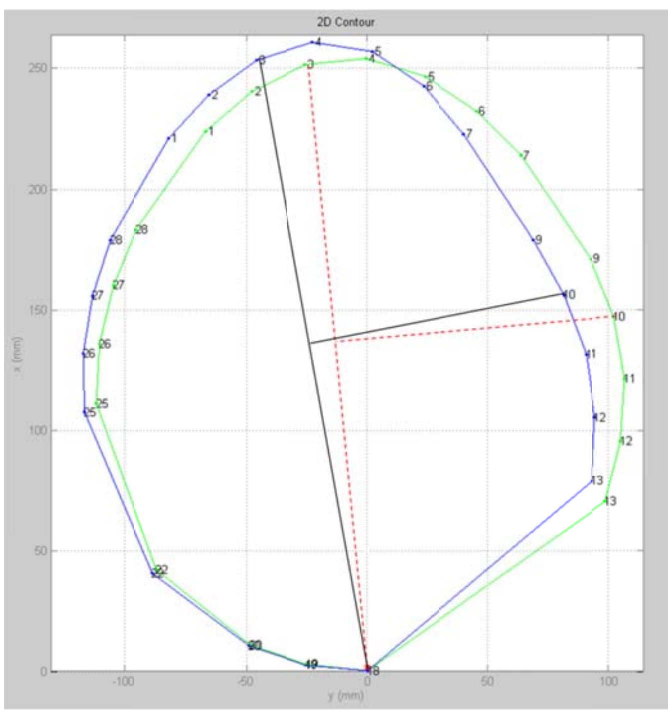

Figure C9: Peak deflection measurement Test 7-2R

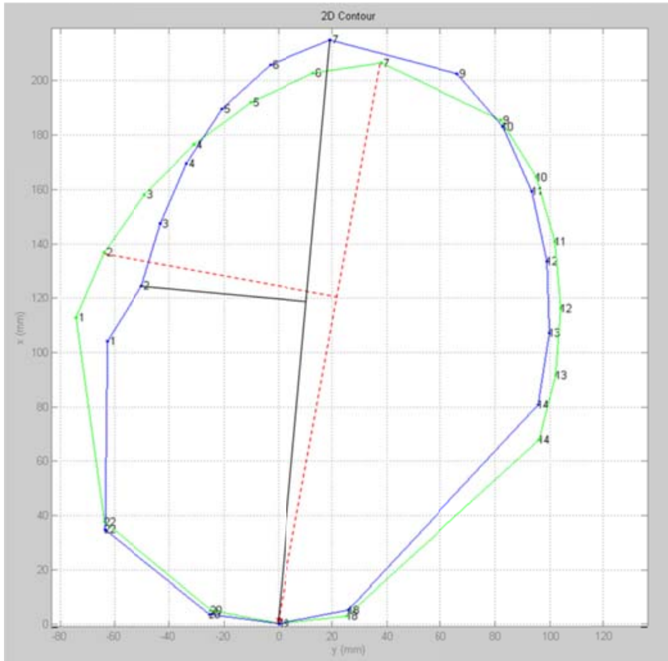

Figure C10: Peak deflection measurement Test 8-1L

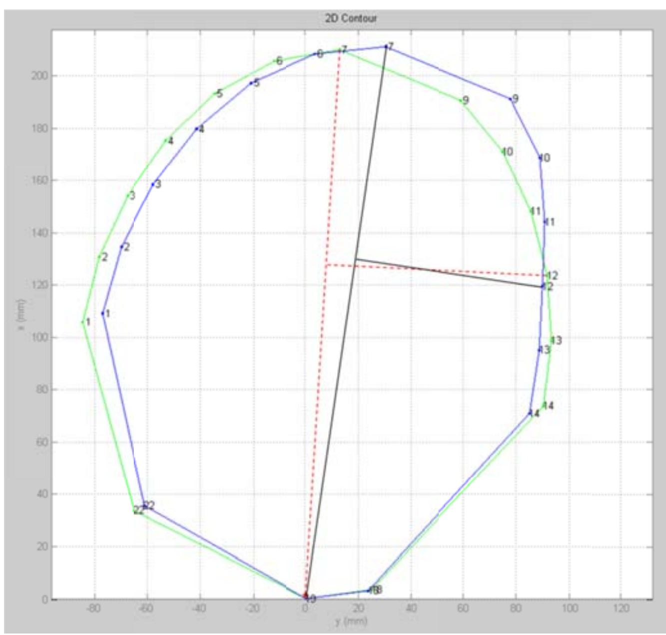

Figure C11: Peak deflection measurement Test 8-2R

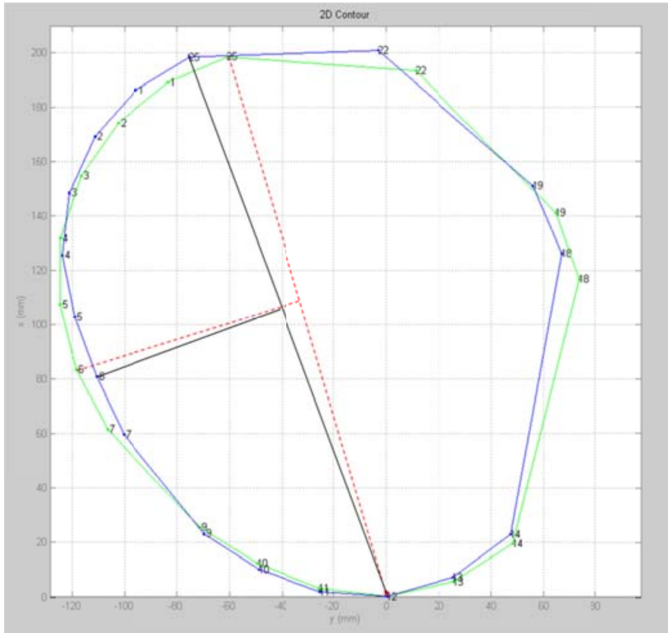

Figure C12: Peak deflection measurement Test 9-1L

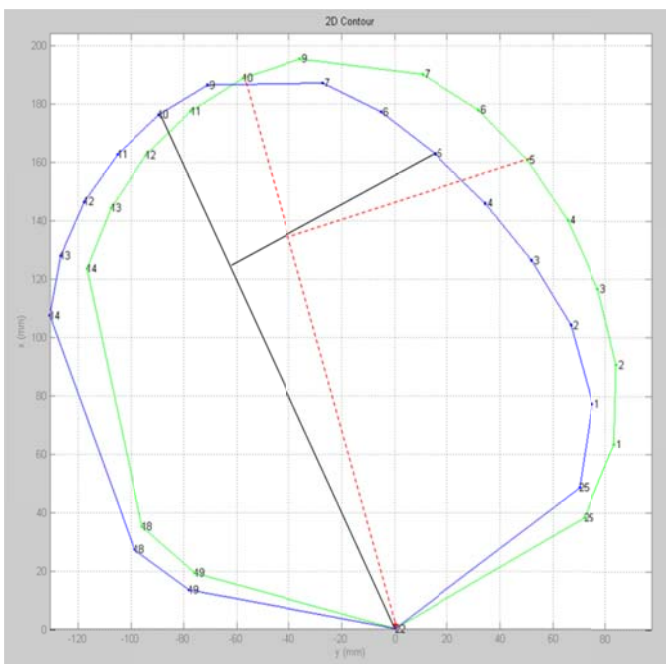

Figure C13: Peak deflection measurement Test 9-2R

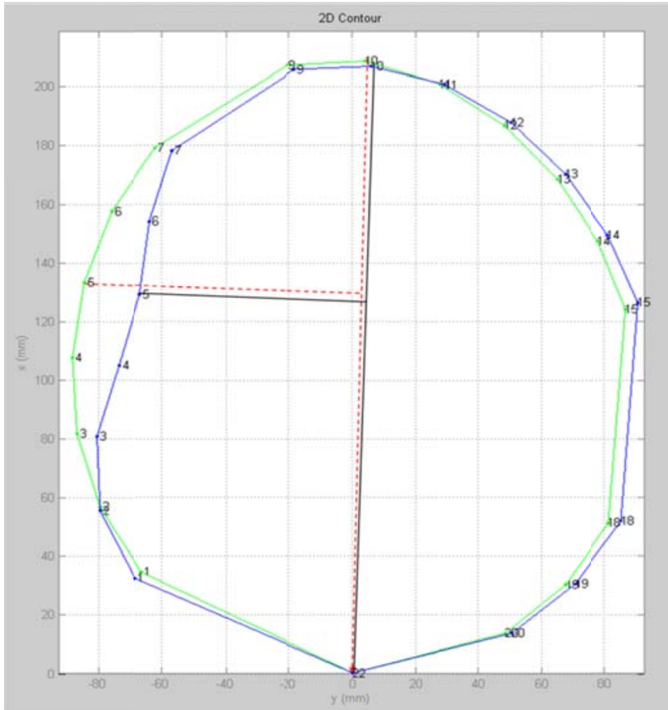

Figure C14: Peak deflection measurement Test 10-1L

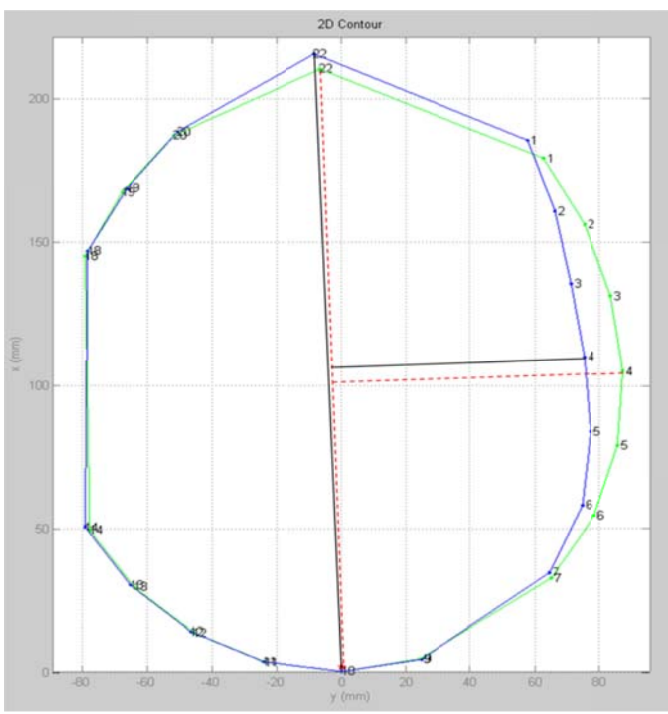

Figure C15: Peak deflection measurement Test 10-2R

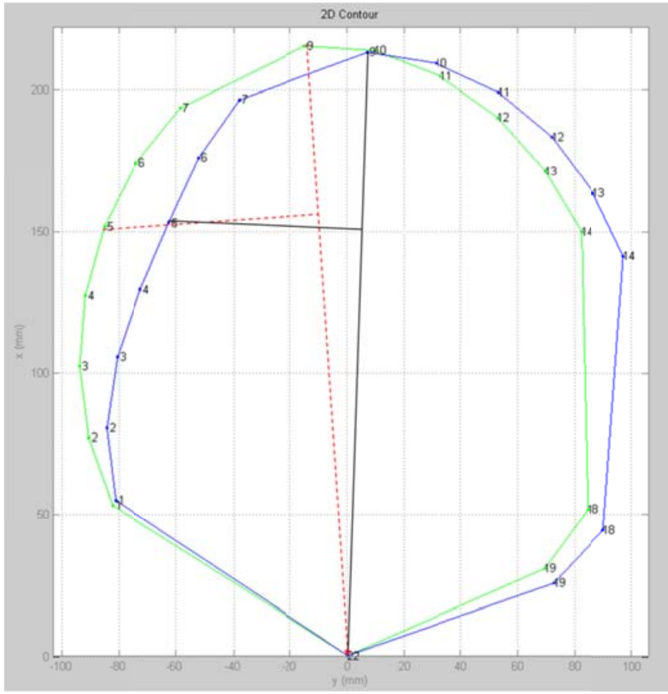

Figure C16: Peak deflection measurement Test 11-1L

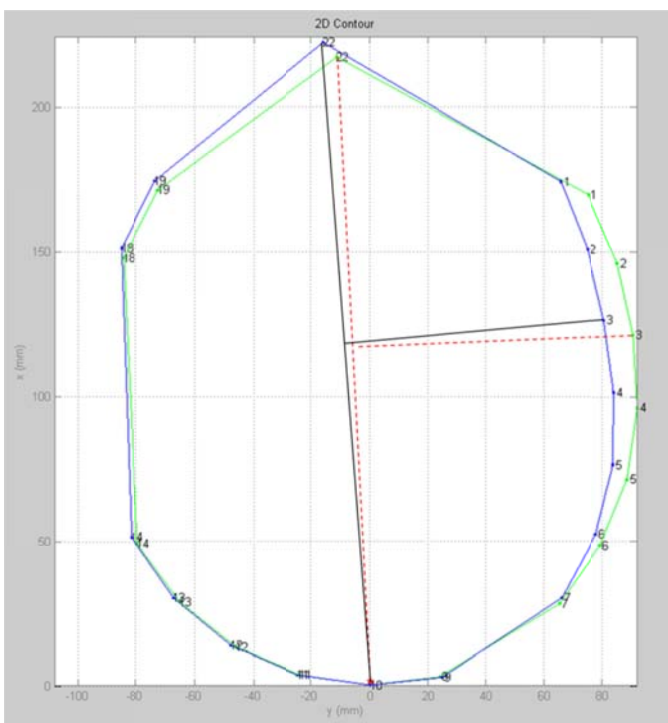

Figure C17: Peak deflection measurement Test 11-2R

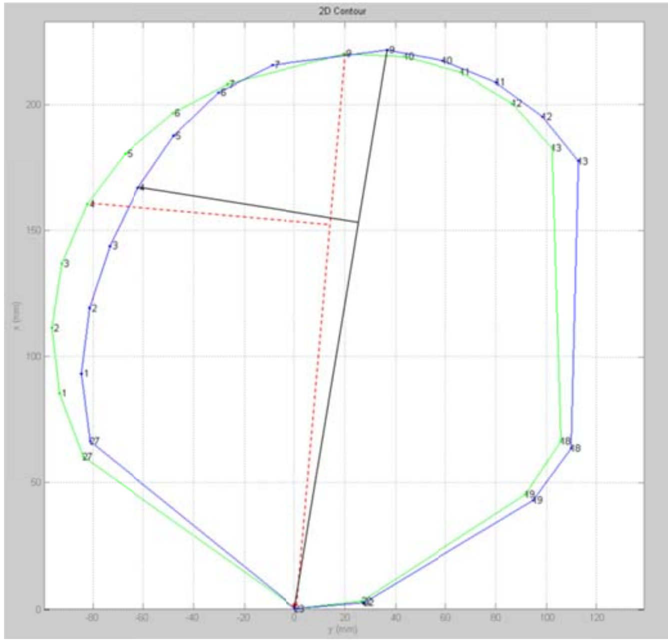

Figure C18: Peak deflection measurement Test 12-1L

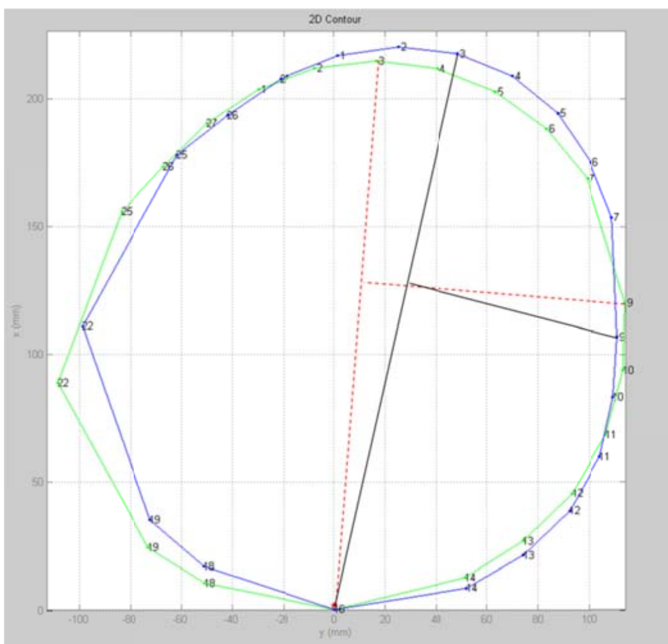

Figure C19: Peak deflection measurement Test 12-2R

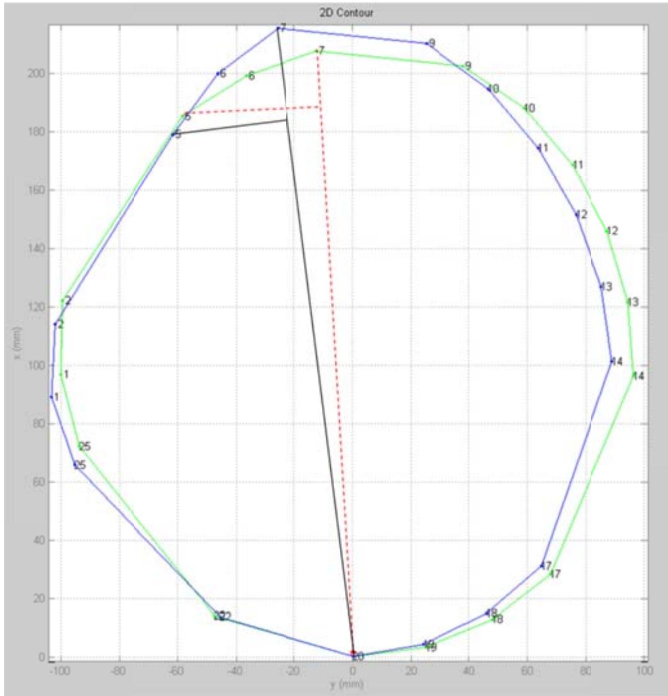

Figure C20: Peak deflection measurement Test 13-1L

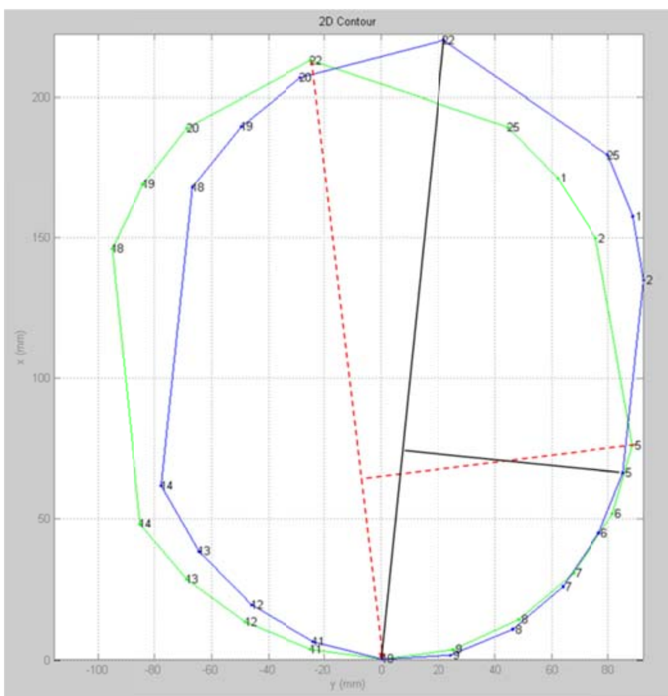

Figure C21: Peak deflection measurement Test 13-2R

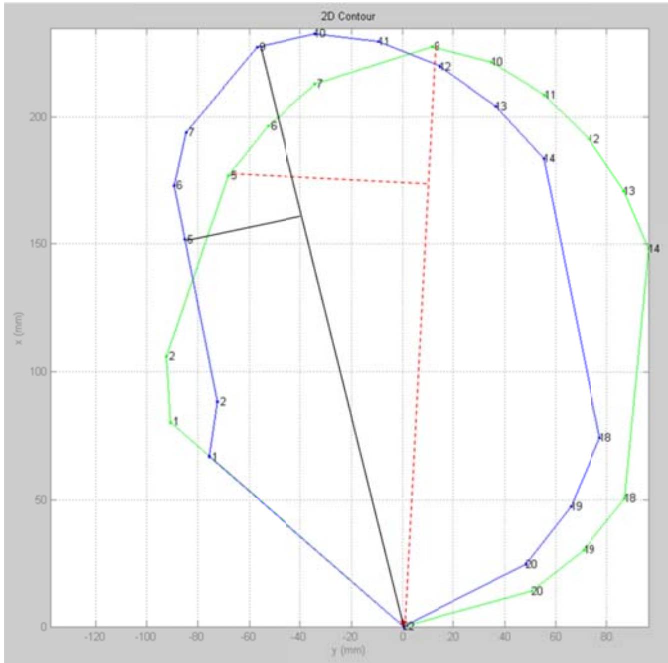

Figure C22: Peak deflection measurement Test 14-1L

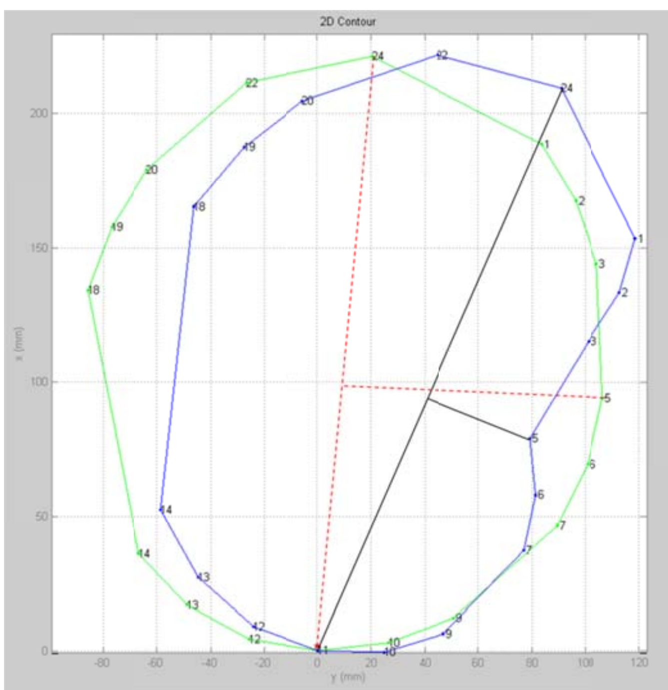

Figure C23: Peak deflection measurement Test 14-2R

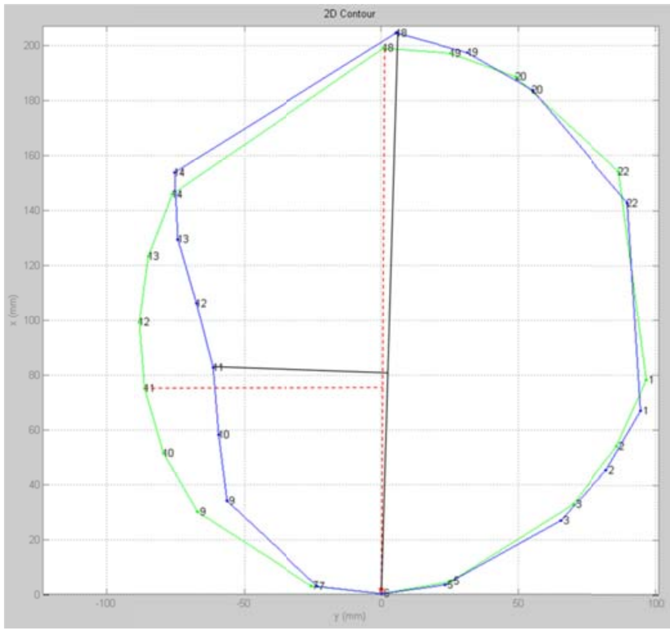

Figure C24: Peak deflection measurement Test 15-1L

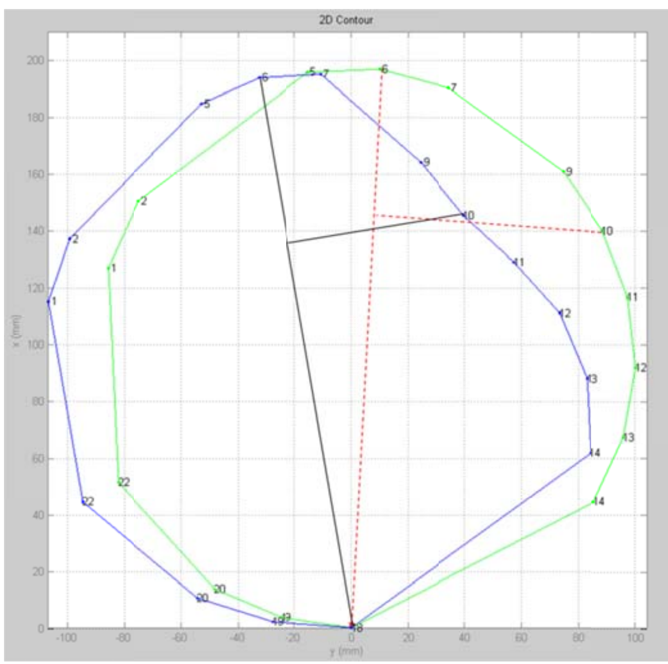

Figure C25: Peak deflection measurement Test 15-2R

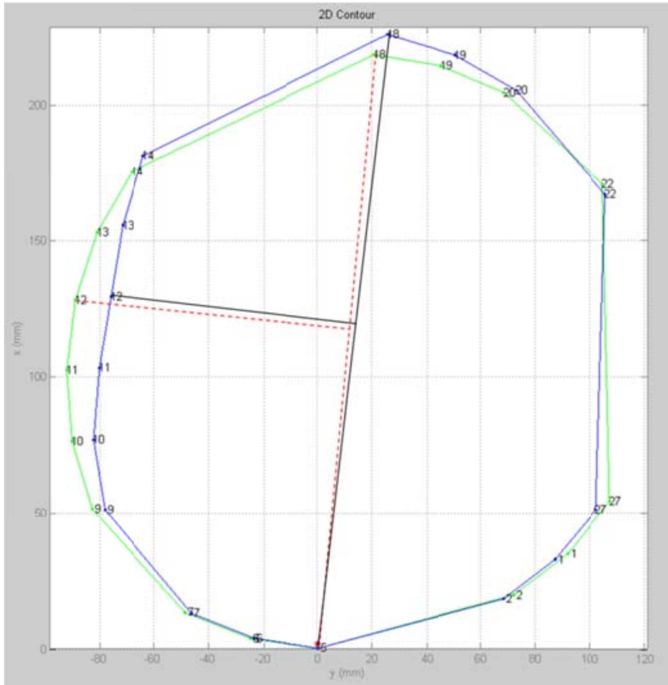

Figure C26: Peak deflection measurement Test 16-1L

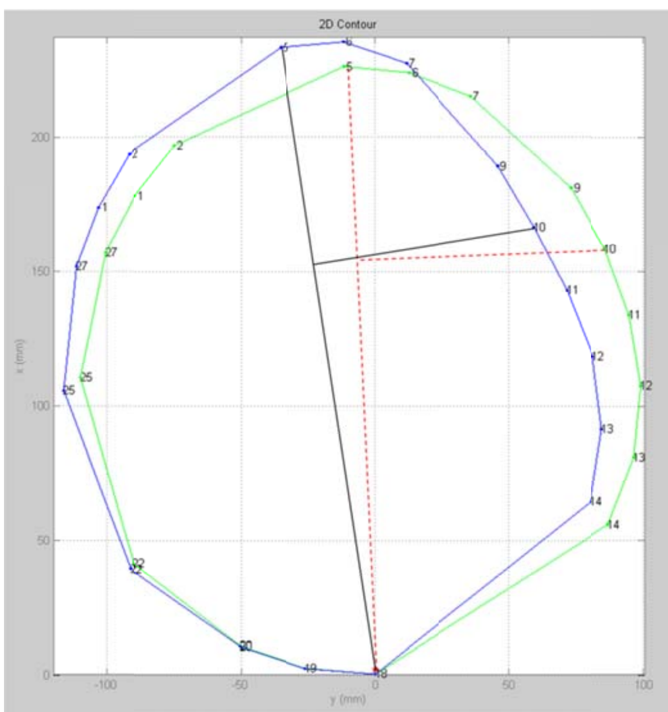

Figure C27: Peak deflection measurement Test 16-2R

APPENDIX D
Necropsy Results

Figure D1: Rib fracture a) medial and b) cranial aspect: Test 2-2R, 8-ply

Figure D2: Rib fracture a) medial, b) cranial and c) caudal aspect: Test 3-2R, 15-ply

Figure D3: No rib fracture, medial aspect: Test 4-1L, 15-ply

Figure D4: Rib fracture a) medial, b) cranial and c) caudal aspect: Test 4-2R, 8-ply

Figure D5: No rib fracture, medial aspect: Test 5-1L, 15-ply

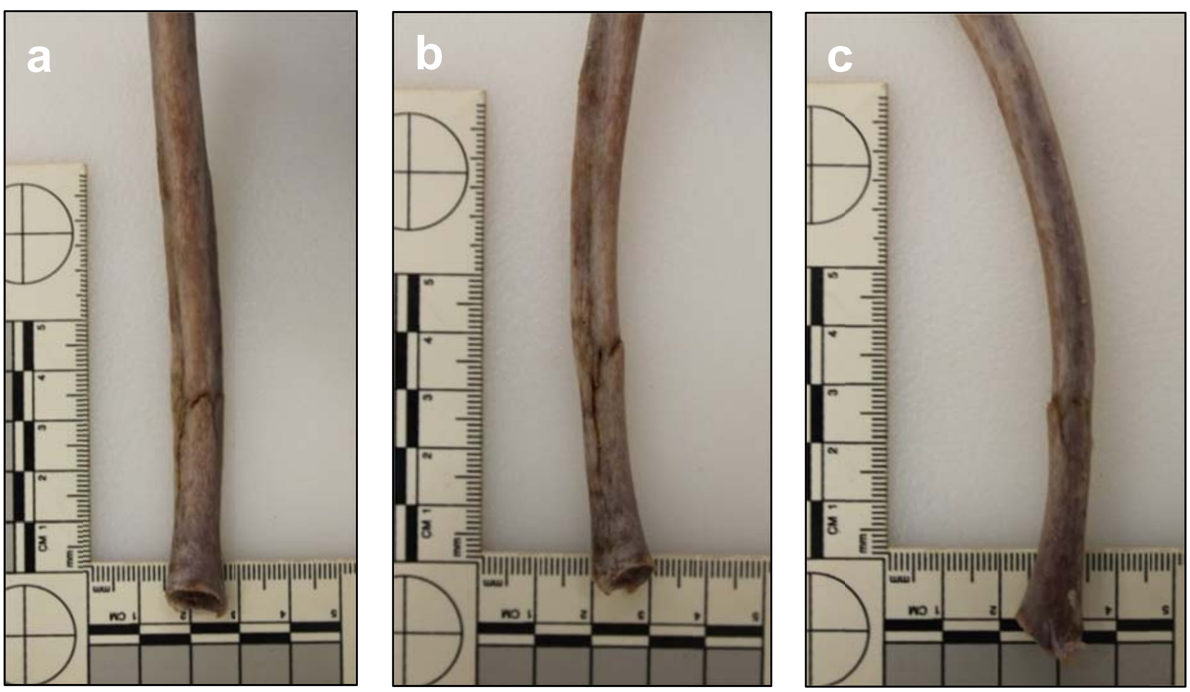

Figure D6: Rib fracture a) medial, b) cranial and c) caudal (incomplete butterfly fracture): Test 5-2R, 8-ply

Figure D7: No rib fracture, medial aspect: Test 6-2L, 8-ply

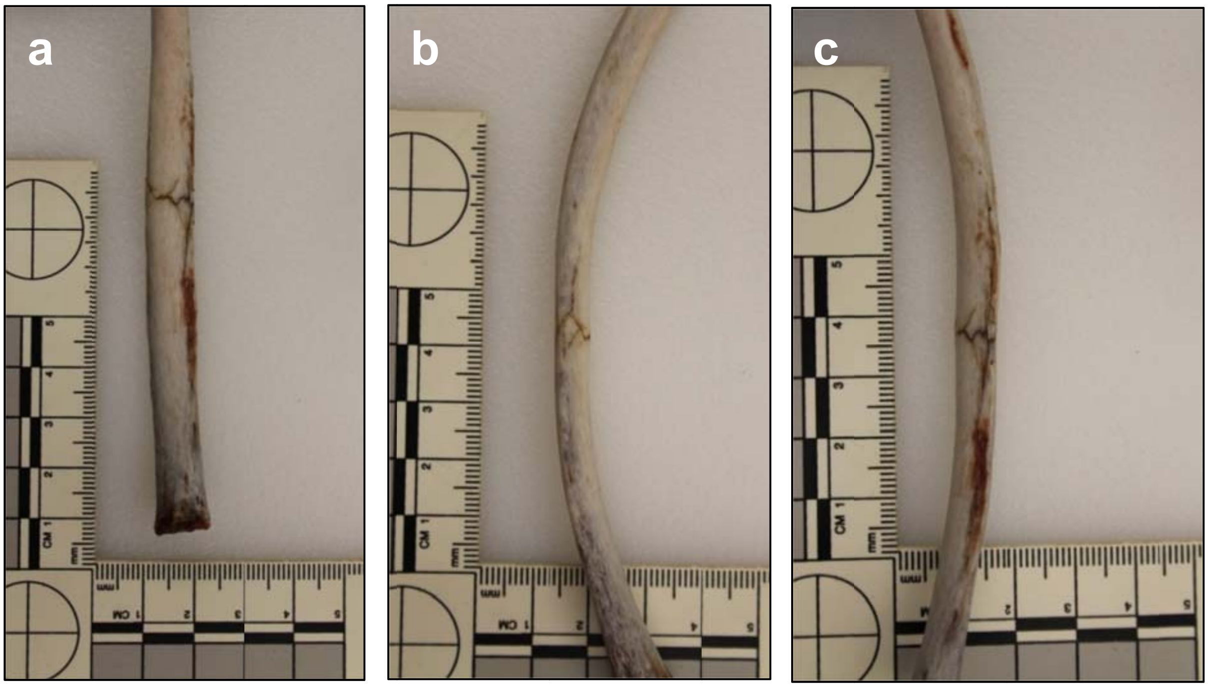

Figure D8: Rib fracture a) medial, b) caudal (incomplete butterfly fracture) and c) cranial aspect: Test 7-1L, 8-ply

Figure D9: No rib fracture, medial aspect: Test 7-2R, 15-ply

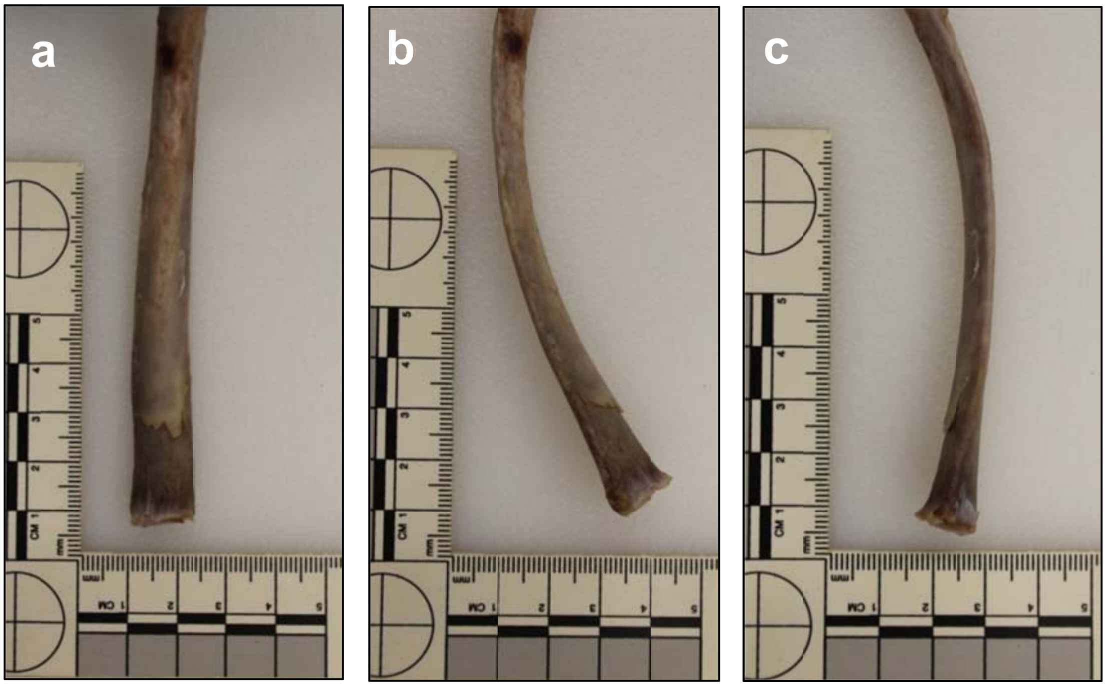

Figure D10: Rib fracture a) medial, b) caudal and c) cranial aspect: Test 8-1L, 15-ply

Figure D11: Rib fracture a) medial (butterfly fragment), b) caudal and c) lateral aspect: Test 8-2R, 8-ply

Figure D12: Rib fracture a) medial, b) cranial and c) caudal aspect: Test 9-1L, 15-ply

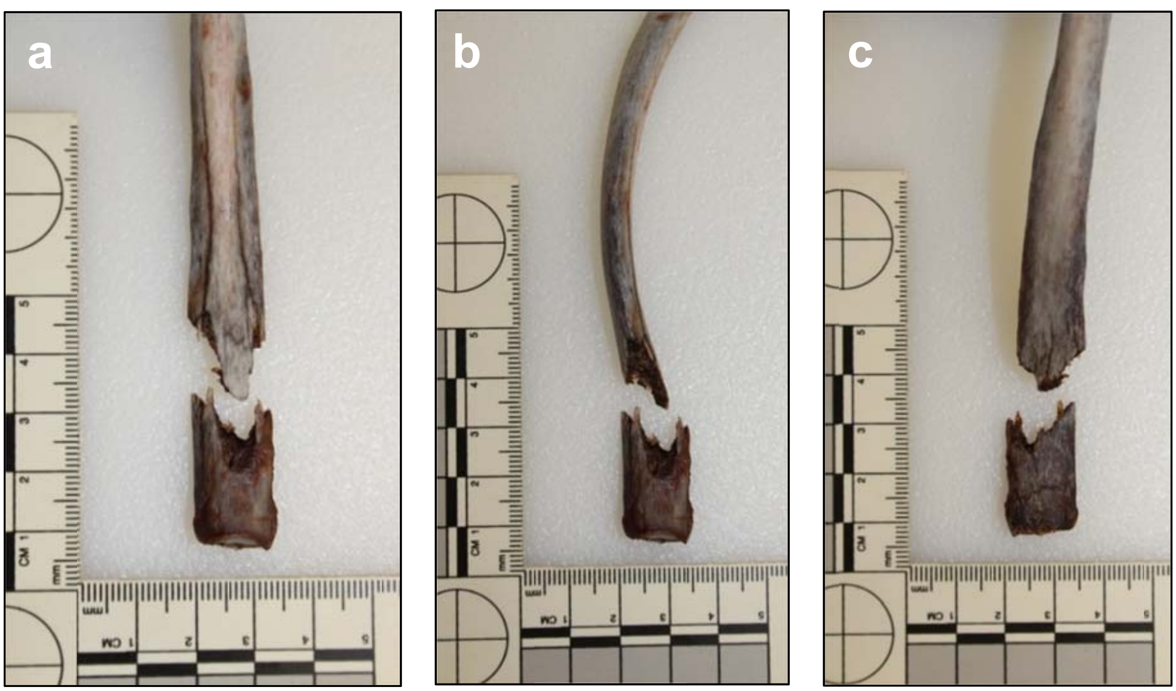

Figure D13: Rib fracture a) medial, b) cranial and c) lateral aspect: Test 9-2R, 8-ply

Figure D14: No rib fracture, medial aspect: Test 10-1L, 15-ply

Figure D15: Rib fracture a) medial and b) caudal aspect: Test 10-2R, 8-ply

Figure D16: No rib fracture, medial aspect: Test 11-1L, 15-ply

Figure D17: Rib fracture a) medial, b) cranial* and c) caudal* aspect (*incomplete butterfly fracture): Test 11-2R, 8-ply

Figure D18: No rib fracture, medial aspect: Test 12-1L, 15-ply

Figure D19: No rib fracture, medial aspect: Test 12-2R, 8-ply

Figure D20: No rib fracture, medial aspect: Test 13-1L, 15-ply

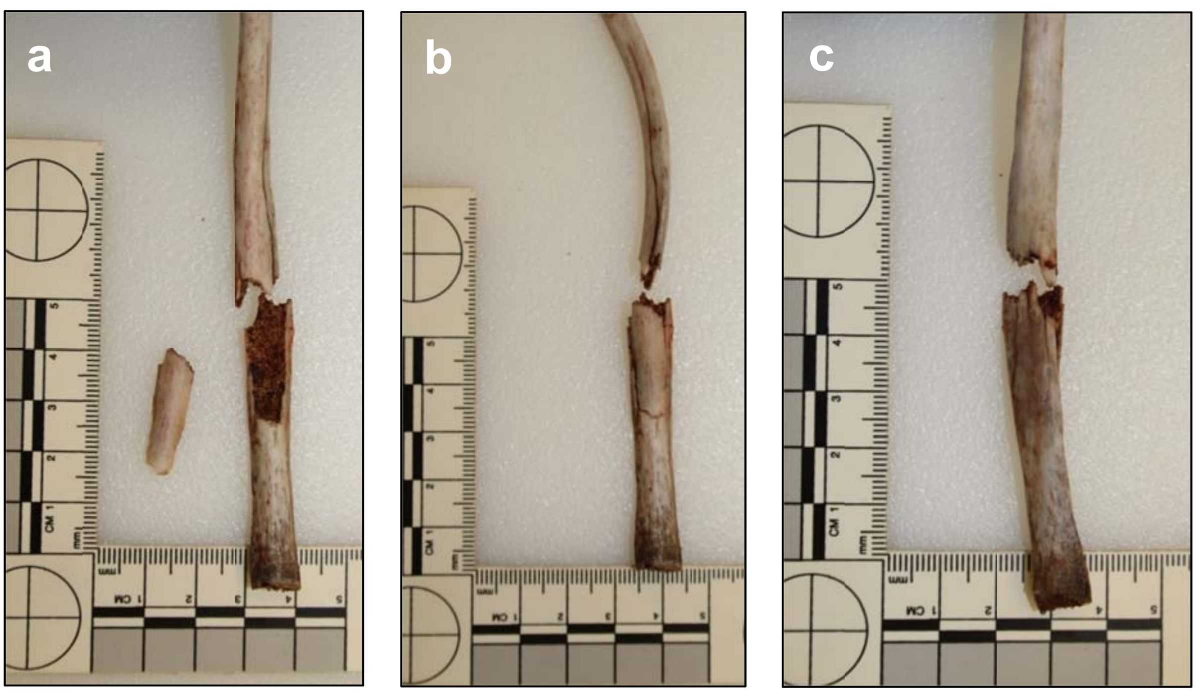

Figure D21: Rib fracture a) medial (butterfly fracture), b) caudal and c) lateral aspect: Test 13-2R, 8-ply

Figure D22: Rib fracture a) medial (incomplete butterfly fracture), b) cranial and c) caudal aspect: Test 14-1L, 15-ply

Figure D23: Rib fracture a) medial, b) caudal and c) cranial aspect: Test 14-2R, 8-ply

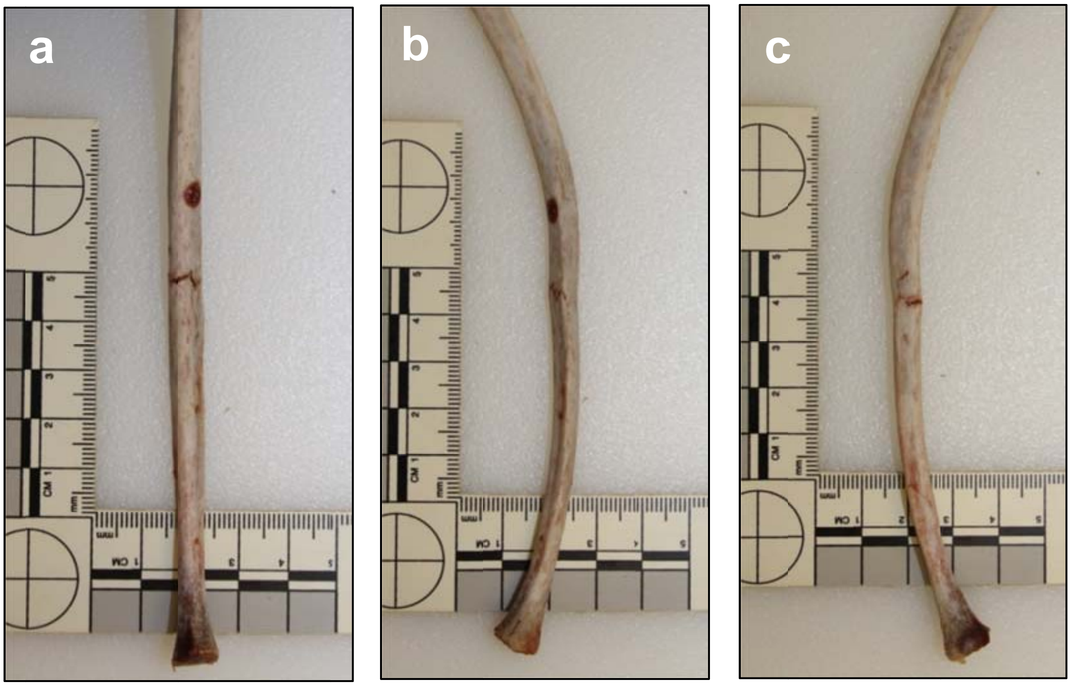

Figure D24: Rib fracture a) medial, b) cranial and c) caudal aspect: Test 15-1L, Point Blank

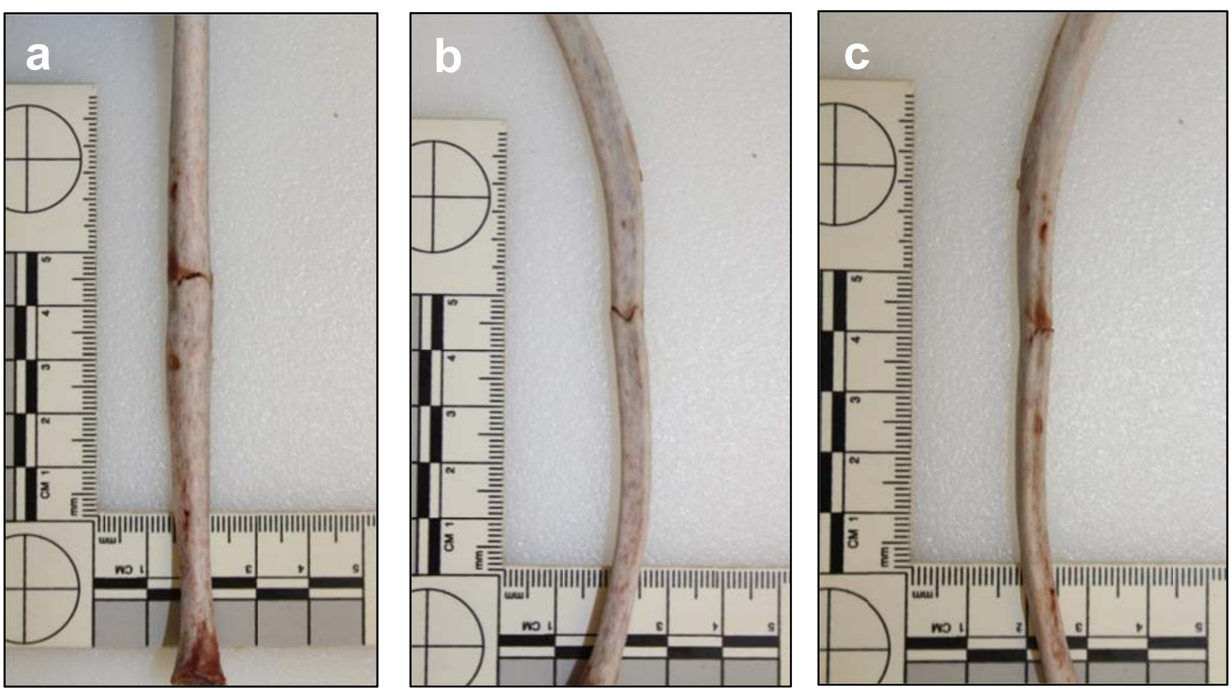

Figure D25: Rib fracture a) medial, b) caudal and c) cranial aspect: Test 15-2R, Point Blank

Figure D26: Rib fracture a) medial, b) cranial and c) caudal aspect: Test 16-1L, Point Blank

FigureD27: No rib fracture, medial aspect: Test 16-2R, Point Blank

APPENDIX E
End User Handler Evaluation

K-9 Armor User Evaluation Questionnaire

HANDLER INFORMATION			
Name		Phone	
Agency		Email	
K-9 INFORMATION			
Name		Duties	#####
Breed		Time Served	#####
Weight			
Type of K-9 Vest Currently In Use: (Manufacturer, Model, Threat):			

ASSESSMENT OF CANINE'S ABILITY DURING AGILITY TRAINING WITH AND WITHOUT ARMOR. PLEASE RATE THE FOLLOWING:

WITH ARMOR

	1 = Poor (hard to do)	2 = Fair	3 = Satisfactory	4 = Good	5 = Excellent (easy to do)
Hurdles	☐	☐	☐	☐	☐
Crawl	☐	☐	☐	☐	☐
Jump	☐	☐	☐	☐	☐
Catwalk	☐	☐	☐	☐	☐
A Frame	☐	☐	☐	☐	☐
Overall Obedience	☐	☐	☐	☐	☐
General Mobility	☐	☐	☐	☐	☐
General Comfort Observed	☐	☐	☐	☐	☐
	Yes	No			
Does the Armor Distract the Dog	☐	☐			
Comments					

WITHOUT ARMOR

	1 = Poor (hard to do)	2 = Fair	3 = Satisfactory	4 = Good	5 = Excellent (easy to do)
Hurdles	☐	☐	☐	☐	☐
Crawl	☐	☐	☐	☐	☐
Jump	☐	☐	☐	☐	☐
Catwalk	☐	☐	☐	☐	☐
A Frame	☐	☐	☐	☐	☐
Overall Obedience	☐	☐	☐	☐	☐
General Mobility	☐	☐	☐	☐	☐

ASSESSMENT OF CANINE'S ABILITY TO COMPLETE SUSPECT SEARCH WITH AND WITHOUT ARMOR. PLEASE RATE THE FOLLOWING:

WITH ARMOR

	1 = Poor (hard to do)	2 = Fair	3 = Satisfactory	4 = Good	5 = Excellent (easy to do)
Concentration	☐	☐	☐	☐	☐
Ability to find suspect	☐	☐	☐	☐	☐
Overall Obedience	☐	☐	☐	☐	☐
General Mobility	☐	☐	☐	☐	☐
General Comfort Observed	☐	☐	☐	☐	☐
	Yes	No			
Does the Armor Distract the Dog	☐	☐			
Comments					

K-9 Armor User Evaluation Questionnaire

WITHOUT ARMOR					
	1 = Poor (hard to do)	2 = Fair	3 = Satisfactory	4 = Good	5 = Excellent (easy to do)
Concentration	☐	☐	☐	☐	☐
Ability to find suspect	☐	☐	☐	☐	☐
Overall Obedience	☐	☐	☐	☐	☐
General Mobility	☐	☐	☐	☐	☐
ASSESSMENT OF CANINE'S ABILITY TO APPREHEND SUSPECT WITH AND WITHOUT ARMOR. PLEASE RANK THE FOLLOWING:					
WITH ARMOR					
	1 = Poor (hard to do)	2 = Fair	3 = Satisfactory	4 = Good	5 = Excellent (easy to do)
Speed while running	☐	☐	☐	☐	☐
Ability to jump	☐	☐	☐	☐	☐
Overall Obedience	☐	☐	☐	☐	☐
General Mobility	☐	☐	☐	☐	☐
General Comfort Observed	☐	☐	☐	☐	☐
	Yes	No			
Does the Armor Distract the Dog	☐	☐			
Comments					
WITHOUT ARMOR					
	1 = Poor (hard to do)	2 = Fair	3 = Satisfactory	4 = Good	5 = Excellent (easy to do)
Speed while running	☐	☐	☐	☐	☐
Ability to jump	☐	☐	☐	☐	☐
Overall Obedience	☐	☐	☐	☐	☐
General Mobility	☐	☐	☐	☐	☐

REFERENCES

Alms, M, 1961. Fracture mechanics. The Journal of Bone and Joint Surgery, 43, 162-166.

Angle, CT and Gillette, RL, 2011. Telemetric measurement of body core temperture in exercising unconditioned labrador retrievers. Canadian Journal of Veterinary Research, 2, 157-159.

Baker, JL, Havas, KA, et al., 2013. Gunshot wounds in military working dogs in Operation Enduring Freedom and Operation Iraqi Freedom: 29 cases (2003-2009). Journal of Veterinary Emergency and Critical Care, 23(1), 47-52.

Baker, JL and Miller, L, 2013. The effects of environmental extremes on working dogs: a collaborative initiative. The United States Army Medical Department Journal, Jan-Mar, 22-27.

Bass, C, Salzar, R, et al., 2006. Injury risk in behind armor blunt thoracic trauma. International Journal of Occupational Safety and Ergonomics, 12(4), 429-442.

Bir, C, 2000. The evaluation of blunt ballistic impacts of the thorax. PhD Dissertation, Wayne State University, Detroit, MI.

Bir, C and Viano, D, 2004. Design and injury assessment criteria for blunt ballistic impacts. Journal of Trauma, 56(6), 1218-1224.

Bir, C, Viano, D, et al., 2004. Development of biomechanical response corridors of the thorax to blunt ballistic impacts. Journal of Biomechanics, 37, 73-79.

Birch, E and Lesniak, K, 2013. Effect of fence height on joint angles of agility dogs. The Veterinary Journal, 198, e99-e102.

Brockman, DJ, Washabau, RJ, et al., 1995. Canine gastric dilatation/volvulus syndrome in a veterinary critical care unit: 295 cases (1986-1992). Journal of American Veterinary Medical Association, 207(4), 460-464.

Cannon, L, 2001. Behind Armor Blunt Trauma - an emerging problem. Journal of the Royal Army Medical Corps, 147, 87-96.

Carroll, A and Soderstrom, C, 1978. A new nonpenetrating ballistic injury. Annals of Surgery, 753-757.

Cavanaugh, J, Zhu, Y, et al., 1993. Injury and response of the thorax in side impact cadaveric tests. In Proceedings of the 37th Stapp Car Crash Conference, SAE Paper No. 933127.

Christensen, A and Smith, V, 2013. Rib butterfly fractures as a possible indicator of blast trauma. Journal of Forensic Sciences, 58, S15-S19.

Chung, J, Cavanaugh, J, et al., 1999. Thoracic injury mechanisms and biomechanical responses in lateral velocity pulse impact. In Proceedings of the 43rd Stapp Car Crash Conference, SAE Paper No. 99SC04.

CPWDA. 1991. Connecticut Police Work Dog Association website. K-9's That Died While Still In Service. Retrieved May 20, 2013, from http://www.cpwda.com/k9_kilod.htm.

Daegling, D, Warren, M, et al., 2008. Structural analysis of human rib fracture and implications for forensic interpretation Journal of Forensic Sciences, 53, 1301-1307.

Dawson, T, Marchand, E , et al., 2001. Military working dogs. Military Police, 28-30.

DeMuth, W, 1968. High velocity bullet wounds of the thorax. American Journal of Surgery, 115, 616-625.

Driehuys, S, Van Winkle, TJ, et al., 1998. Myocardial infarction in dogs and cats: 37 cases (1985-1994). Journal of American Veterinary Medical Association, 213(10), 1444-1448.

DuPont. 2013. IACP/DuPont Kevlar Survivors' Club. Retrieved July 29, 2013, from http://www.dupont.com/products-and-services/personal-protective-equipment/body-armor/articles/kevlar-survivors-club.html.

Dutton, RE and Moore, GE, 1987. Clinical review of death/euthanasia in 123 military working dog necropsies. Military Medicine, 152, 489-493.

Eastridge, BJ, Costanzo, G, et al., 2009. Impact of joint theater trauma system initiatives on battlefield injury outcomes. The American Journal of Surgery, 198, 852-857.

Eck, J, 2006. Biomechanical response and abdominal injury due to blunt ballistic impacts. PhD Dissertation, Wayne State University, Detroit, MI.

Eppinger, R, 1989. On the development of a deformation measurement system and its application toward developing mechanically based injury indices. In Proceedings of the 33rd Stapp Car Crash Conference SAE Paper No. 892426.

Evans, H, 1993. The digestive apparatus and abdomen. Evans, H. (Ed.). Miller's Anatomy of the Dog. Saunders, Philadelphia, 385-462.

Evans, H, 2013. The Respiratory System. Evans, H. and de Lahunta, A. (Ed.). Miller's Anatomy of the Dog. Saunders, Philadelphia, 338-359.

Evans, H, 2013. The Skeleton. Evans, H. and de Lahunta, A. (Ed.). Miller's Anatomy of the Dog. Saunders, Philadelphia, 80-151.

Evans, RI, Herbold, JR, et al., 2007. Causes for discharge of military working dogs from service: 268 cases (2000-2004). Journal of American Veterinary Medical Association, 231, 1215-1220.

FBI-LEOKA. Law enforcement officers killed and assaulted 2013. Retrieved December 2014, from http://www.fbi.gov/about-us/cjis/ucr/leoka/2013.

Fleming, JM, Creevy, KE, et al., 2011. Mortality in North American dogs from 1984 to 2004: an investigation into age-, size-, and breed-Related causes of death. Journal of Veterinary Internal Medicine, 25, 187-198.

Fregin, GF, Luginbuhl, H, et al., 1972. Myocardial infarctionin a dog with bacterial endocarditis. Journal of American Veterinary Medical Association, 160, 956-963.

Frost, D, 1990. A centralized source of information for the military working dog program. Master's Thesis, U.S. Army Command and General Staff College, Fort Leavenworth, KS.

Glickman, LT, Lantz, GC, et al., 1998. A prospective study of survival and recurrence following the acute gastric dilatation-volvulus syndrome in 136 dogs. Journal of the American Animal Hospital Association, 34, 253-259.

Goldfarb, M, Ciurej, T, et al., 1975. A method for soft body armor evaluation: medical assessment. Technical Report EB-TR-74073 Edgewood Arsenal, Aberdeen Proving Ground, MD.

Hanlon, E and Gillich, P, 2012. Origin of the 44-mm behind armor blunt trauma standard. Military Medicine, 177, 333-339.

Hermanson, J, 2013. The Muscular System. Evans, H. and de Lahunta, A. (Ed.). Miller's Anatomy of the Dog. Saunders, Philadelphia, 185-280.

Huelke, DF, Nusholtz, GS, et al., 1987. Use of quadruped models in thoraco-abdominal biomechanics research. Journal of Biomechanics, 19(12), 969-977.

Jennings, PB and Butzin, CA, 1992. Epidemiology of gastric dilatation-volvulus in the military working dog program. Military Medicine, 157, 369-371.

Kolata, RJ and Johnston, DE, 1975. Motor vehicle accidents in urban dogs: A study of 600 cases. Journal of American Veterinary Medical Association, 167(10), 938-941.

Kolata, RJ, Kraut, NH, et al., 1974. Patterns of trauma in urban dogs and cats: a study of 1,000 cases. Journal of American Veterinary Medical Association, 164(5), 499-502.

Kosashvili, Y, Hiss, J, et al., 2005. Influence of personal armor on distribution of entry wounds: lessons learned from urban-setting warfare fatalities. Journal of Trauma, 58, 1236-1240.

Kotwal, RS, Montgomery, HR, et al., 2011. Eliminating preventable death on the battlefield. Archives of Surgery, 146(12), 1350-1358.

Kuppa, S and Eppinger, R, 1998. Development of an improved thoracic injury criterion. In Proceedings of the 42nd Stapp Car Crash Conference, SAE Paper No. 983153.

Kuppa, S, Eppinger, R, et al., 2003. Development of side impact thoracic injury criteria and their application to the modified ES-2 dummy with rib extensions (ES-2re). Stapp Car Crash Journal, 47, 189-210.

LaTourrette, T, 2010. The life-saving effectiveness of body armor for police officers. Journal of Occupational and Environmental Hygiene, 7, 557-562.

Linden, E, Berlin, R, et al., 1988. Some observations relating to behind-body armour blunt trauma effects caused by ballistic impact. Journal of Trauma, 27, S145-148.

Liu, SK, Tilley, LP, et al., 1986. Clinical and pathologic findings in dogs with atherosclerosis: 21 cases (1970-1983). Journal of American Veterinary Medical Association, 189, 227-232.

Love, J and Symes, S, 2004. Understanding rib fracture patterns: incomplete and buckle fractures. Journal of Forensic Sciences, 49, 1153-1158.

Mabry, RL, Holcomb, JB, et al., 2000. United States Army Rangers in Somalia: An analysis of combat casualties on an urban battlefield. Journal of Trauma 49, 515-529.

Maltese, M, Eppinger, R, et al., 2002. Response corridors of human surrogates in lateral impacts. Stapp Car Crash Journal, 46, 321-351.

Mann, NC and Mullins, RJ, 1999. Research recommendations and proposed action items to facilitate trauma system implementation and evaluation. Journal of Trauma, 47(3 Suppl), S75-78.

Merkle, A, Ward, E, et al., 2008. Assessing behind armor blunt trauma (BABT) under NIJ Stadnard - 0101.04 conditions using human torso models. Journal of Trauma, 64, 1555-1561.

Metker, L, Prather, R, et al., 1975. A method for determining backface signatures of soft armors. Technical Report EB-TR-75029. Aberdeen Proving Ground, MD: U.S. Army Armament Research and Development Command.

Montanarelli, N, Hawkins, C, et al., 1973. Protective garments for public officers. LWL-TR-30B73. U.S. Army Land Warfare Laboratory, Aberdeen Proving Ground, MD.

Moore, GE, Burkman, KD, et al., 2001. Causes of death or reasons for euthanasia in military working dogs: 927 cases (1993-1996). Journal of American Veterinary Medical Association, 219(2), 209-214.

Moseley, R, Vernick, J, et al., 1970. Response to blunt chest injury: an experimental model. Journal of Trauma, 10(8), 673-683.

NIJ-0101.06, 2008. Ballistic resistance of body armor U.S. Department of Justice, Office of Justice Programs, Washington, DC.

NLEOMF. 2012. 127 Law Enforcement Officers Killed Nationwide 2012. National Law Enforcement Officers Memorial Fund. Retrieved May 20, 2013, from http://www.nleomf.org/newsroom/news-releases/127-law-enforcement-officers.html.

ODMP. 2012. Officer Down Memorial Page website. K9s. Retrieved May 20, 2013, from http://www.odmp.org/k9.

Olson, CJ, Arthur, M, et al., 2001. Influence of trauma system implementation on process of care delivered to seriously injured patients in rural trauma centers. Surgery, 132, 273-279.

Parr, JR and Otto, CM, 2013. Emergency visits and occupational hazards in Germand Shepherd police dogs (2008-2010). Journal of Veterinary Emergency and Critical Care, 23(6), 591-597.

Peleg, K, Rivkind, A, et al., 2006. Does body armor protect from firearm injury? Journal of American College of Surgeons, 202, 643-648.

Peterson, MR, Frommelt, A, et al., 2000. A study of the lifetime occurrence of neoplasia and breed differences in a cohort of German Shepherd Dogs and Belgian

Malinois Military Workig Dogs that died in 1992. Journal of Veterinary Internal Medicine, 14, 140-145.

Prather, R, Swann, C, et al., 1977. Backface signature of soft body armors and the associated trauma effects. Technical Report ARCSL-TR-77055. Chemical Systems Laboratory, Aberdeen Proving Ground, MD.

Raymond, D, Van Ee, C, et al., 2009. Tolerance of the skull to blunt ballistic temporo-parietal impact. Journal of Biomechanics, 42, 2479-2485.

Roberts, J, O'Connor, J, et al., 2005. Modeling the effect of nonpenetrating ballisitc impact as a means of detecting behind-armor blunt trauma. Journal of Trauma, 58, 1241-1251.

Roberts, J, Ward, E, et al., 2007. Assessing behind armor blunt trauma in accordance with the National Institute of Justice Standard for Personal Body Armor protection using finite element modeling. Journal of Trauma, 62, 1127-1133.

Rose, RJ and Bloomberg, MS, 1989. Responses to sprint exercise in the greyhound: Effects on haematology, serum biochemistry and muscle metabolites. Research in Veterinary Science, 47, 212-218.

SAE-J211-1, 1995. Instrumentation for impact tests, Part 1, electronic instrumentation. Society of Automotive Engineers, Warrendale, PA,

Simpson, SA, Syring, R, et al., 2009. Severe blunt trauma in dogs: 235 cases (1997-2003). Journal of Veterinary Emergency and Critical Care, 19(6), 588-602.

Steiss, J, Ahmad, HA, et al., 2004. Physiologic responses in healthy labrador retrievers during field trial training competition. Journal of Veterinary Internal Medicine, 18, 147-151.

Taylor, WM, 2009. Canine tactical field care: Part two - Massive hemorrhage control and physiologic stabilization of the volume depleted, shock-affected, or heatstroke-affected canine. Journal of Special Operations Medicine, 9(2), 13-21.

USPCA. 2010. Police dog certification: Governing rules and regulations for certification. United States Police Canine Association Retrieved 9/1/2011, from http://uspcak9.com/certification/USPCARulebook2010.pdf.

Viano, D, King, A, et al., 1989. Injury biomechanics research: an essential element in the prevention of trauma. Journal of Biomechanics, 22(5), 403-417.

Viano, D and Lau, I, 1988. A viscous criterion for soft tissue injury assessment. Journal of Biomechanics, 21(5), 387-399.

Weirich, WE, Bisgard, GE, et al., 1971. Myocardial infarction and pulmonic stenosis in a dog. Journal of American Veterinary Medical Association, 159, 315-319.

Wilhelm, M and Bir, C, 2007. Injuries to law enforcement officers: The backface signature injury. Forensic Science International, 174, 6-11.

Wilkinson, DM, Carter, JM, et al., 2008. The effect of cool water ingestion on gastrointestinal pill temperature. Medicine and Science in Sports and Exercise, 40(3), 523-528.

Yoganandan, N, Humm, J, et al., 2013. Oblique lateral impact biofidelity deflection corridors from Post Mortem Human Surrogates. Stapp Car Crash Journal, 57, 427-440.

Yoganandan, N, Pintar, F, et al., 2008. Chest deflections and injuries in oblique lateral impacts. Traffic Injury Prevention, 9, 162-167.

Zehtabchi, S, Nishijima, DK, et al., 2011. Trauma registries: history, logistics, limitations, and contributions to emergency medicine research. Academic Emergency Medicine, 18, 637-643.

ABSTRACT

A BIOMECHANICAL ASSESSMENT OF CANINE BODY ARMOR

by

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August 2015

Advisor: Cynthia Bir, Ph.D.

Major: Biomedical Engineering

Degree: Doctor of Philosophy

The purpose of this research was to establish a biomechanical assessment of canine body armor with a primary focus on civilian law enforcement canines. The specific aims included: 1) the compilation of canine casualty data to determine commonly reported causes of death/euthanasia while in service for civilian law enforcement canines, 2) the evaluation of the biomechanical response of the canine related to a behind armor blunt impact, 3) the identification of an injury criterion that will best predict canine thoracic injury as a result of behind armor blunt trauma, 4) correlation of the behind armor blunt trauma response to the standard backface testing medium (clay), and 5) the evaluation of commercially available canine body armor to determine if the armor inhibits or distracts the canine from performing tasks.

The three leading causes of traumatic death in civilian law enforcement canines were as a result of being struck by a vehicle, heat injury, and ballistic penetrating trauma. The biomedical response of the canine thoracic cavity was determined for three armor conditions: 8-ply packet, 15-ply packet, and commercially available Point Blank

canine armor. Fracture of the impacted rib occurred as a result of behind armor blunt trauma in the majority cases. Measured and calculated engineering parameters were not identified as significant predictors of rib fracture. Testing the backface signature (BFS) in clay of the armor packets did prove to predict rib fractures in the post-mortem canine specimens. Both depth in clay and volume of indentation were significant predictors. The Point Blank armor did prove to increase the time it took canines to complete certain training tasks and also increased their core body temperature. The results of this research provide an initial biomechanical assessment of canine body armor and the response of the canine thorax during behind armor blunt impact. The data from this study could help future research better evaluate and protect law enforcement canines.

AUTOBIOGRAPHICAL STATEMENT

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Stojsih, S, Baker, J, and Bir, C. (2014). *Effects of a ballistic vest on field performance of law enforcement canines.* Canine Science & Technology Workshop. Raleigh NC.

Hewins, K, Anctil, B, **Stojsih, S**, Bir, C. (2012). Ballistic blunt trauma assessment methodology validation. Personal Armour Systems Symposium. Nuremberg, Germany.

Stojsih, S, Longhurst, D, and Bir, C. (2010). *Behind Armor Blunt Trauma: Comparison of Field and Experimental Data*. Personal Armour Systems Symposium. Quebec City.

Stojsih, S, Bir, C. (2009). *Behind Armor Blunt Trauma: Case Study*. 4th European Conference on Protective Clothing. Arnhem, Netherlands.

Stojsih, S, Bir, C. (2008). *Behind Armor Blunt Trauma Injuries in Law Enforcement from Ballistic Impact: Body Armor Assessment*. American Academy of Forensic Sciences Conference. Washington DC.