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# **Comparative Projectile Trauma**

An Examination of the Differences in Skeletal  
Trauma Inflicted by Firearms and Archery  
Weapons

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# Abstract

In recent years, the defining characteristics of cranial projectile trauma have been reported extensively in experimental studies as well as forensic case reports. The existing literature, however, focuses on trauma inflicted by firearms, primarily handguns and rifles. Though firearms are the most common form of projectile weapon used in a forensic context, there are several types of projectile weapons which have not been examined through experimental research. This gap in the literature not only limits the examination of forensic cases, but also inhibits the examination of trauma found within an archaeological context.

This study sought to differentiate the skeletal trauma caused by different projectile weapons that are classified as either firearms (handgun, rifle, and shotgun) or archery weapons (recurve hand bow with field tip arrows, compound hand bow with fixed broadhead arrows, and compound crossbow with field tip bolts, fixed broadhead bolts, and mechanical broadhead bolts). Using polyurethane spheres as proxies for human cranial vaults, samples were shot by one of the specified weapons ( $n=5$ ) and 35 features resulting from projectile impact (both qualitative and quantitative) of the entrance and exit defects were recorded.

Using principal component analysis, it was found that the features of trauma which accounted for the highest proportion of variance observed in the subset which included both entry and exit defects were the maximum fracture length on the external table of the entrance site, the minimum fracture length on the external table of the entrance site, the entrance defect diameter, the minimum fragment length of the fragments that originated from the entrance defect, the width of the reconstructed exit defect, the maximum fracture length on the external table of the entrance defect, and the width of the reconstructed entrance defect. These accounted for 96.74% of the variance within this dataset. When only examining the entrance defects, the most distinguishing variables were the maximum fracture length on the external

table of the entrance defect, the width of the entrance defect, the minimum fracture length on the external table of the entrance defect, and the width of the reconstructed entrance defect, accounting for 95.89% of the variance within this dataset.

Machine learning (linear discriminant analysis) was applied to test the predictive strength of these variables. In testing the accuracy of these predictions, it was found that the program could correctly predict the weapon used for 74.19% of the samples when examining both the entrance and exit defects and 60.87% of the samples when only examining the features of the entrance defect.

The findings of this research exhibit the indiscernible qualitative features between trauma inflicted by different projectile weapons, calling to attention the need to change the current methods of weapon identification. This study has established new quantitative methods for projectile trauma analysis which are simple to perform, require minimal equipment, and are easily applied to forensic and archaeological remains.

# Lay Summary

In a criminal investigation, determining the cause of death often includes deducing what weapon a person was killed with based on the damage caused to the body. When considering the damage caused to the skeleton by projectile weapons (weapons which shoot the ammunition in order to strike a target from a distance) forensic investigators tend to only take firearms into consideration. This study sought to examine the damage which other types of projectile weapons, specifically archery weapons, can cause to the bone which encases the brain (cranial vault) and whether or not the weapon used could be correctly identified based on the features of the damage to the cranial vault. The weapons in this study included: handgun, rifle, shotgun, recurve bow, compound bow, and crossbow.

Some of the key features of damage to the cranial vault caused by firearms typically include two circular holes, one where the bullet enters and one where the bullet exits. Both of these holes also typically have two types of break in the bone (fracture): one which extends from the hole itself and another which spreads in a circular pattern around the hole. Finally, the hole in which the bullet enters has a larger area of damage on the internal surface than on the external surface while the opposite is true for the hole from which the bullet exits the cranial vault.

In this study, synthetic spherical bone (Synbone®) filled with ballistic gelatine was used to replicate the human head. Each sphere was shot from a distance of 10 metres with one of the previously mentioned weapons. 35 features of the damage at both the entrance and exit holes of each sphere were measured and recorded. These features included the features discussed in the previous paragraph, but also included numerical features, such as fracture lengths, fragment dimensions, and the sizes of the entrance and exit holes. A statistical program was then used to determine which of these features could most accurately identify the weapon which was used.

There were three main findings of this study. The first is that archery weapons are capable of damaging bone in the same way that firearms do. Second, even though the current methods of weapon identification typically only focus on what types of features are present, this study showed that weapons can more accurately be identified by measuring numerical features. Finally, it was found that the weapon used could most accurately be identified by measuring seven features when an exit hole is present:

1. The length of the longest fracture on the outer surface of the entrance hole.
2. The length of the shortest fracture on the outer surface of the entrance hole.
3. The size of the entrance hole.
4. The length of the shortest fragment from where the projectile entered the cranial vault.
5. The size of the entrance hole when the fragments are pieced together.
6. The length of the longest fracture on the outer surface of the exit hole.
7. The size of the entrance hole when the fragments are pieced together.

and four features when an exit hole is not present:

1. The length of the longest fracture on the outer surface of the entrance hole.
2. The size of the entrance hole.
3. The length of the shortest fracture on the outer surface of the entrance hole.
4. The size of the entrance hole when the fragments are pieced together.

The findings of this study call to attention the flaws and exclusivity of the current methods of weapon identification. There is a need to change these methods to put more emphasis on numerical features of the damage caused by projectile weapons. The use of these new methods has the potential to substantially enhance the anthropological aspect of forensic investigation.

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# List of Abbreviations

**cm:** centimetre

**g:** gram

**gr:** grain

**in.:** inch

**J:** joule

**kg:** kilogram

**L:** litre

**lb:** pound

**m:** metre

**mm:** millimetre

**PC:** principal component

**s:** second

# 1. Introduction

Projectile weapons have been used by hominids for millennia, potentially dating back as far as the Palaeolithic period, when early projectile weapons consisted of wooden or bone shafts sharpened to a point (Knecht, 1997; Shea, 2006). While handheld lithic tools could be associated with both hunting and scavenging for meat acquisition, lithic points attached to a shaft are some of the earliest forms of tools that can explicitly be linked to hunting (Shea, 1993; Knecht, 1997; Rots, 2016; O'Driscoll and Thompson, 2018; Milks *et al.*, 2019). These early projectile weapons gave early modern humans a distinct advantage with animal hunting as they allow the user to cause lethal damage from a safe distance (Shea, 2006; Milks *et al.*, 2019).

While many modern societies have surpassed the need to hunt for food, they still utilise and develop projectile weapons as a part of a complex system of international affairs, rituals, and interpersonal violence. The concept of violence is a multifaceted discussion across a wide array of fields including, but not limited to, anthropology, psychology, and sociology, with multiple scopes of definitions. Wide definitions of violence include many social injustices and inequalities as a means for individuals to justify meeting widespread violence with direct physical violence (Coady, 1986; Lawrence, 2013). Contrarily, restricted definitions focus on these direct acts of physical violence: acts of force which typically result in physical injury or even death. Between these two ends lies a type of definition which Coady (1986) describes as 'legitimist,' in which violence is specifically the illegal or illegitimate use of force. Not only can acts of physical violence be acknowledged in this type of definition, but acts of emotional, psychological, and sexual violence can be acknowledged as well (Mazza *et al.*, 2001; Montminy, 2005; Khalifeh *et al.*, 2015; Smith *et al.*, 2020). While there are many types of legitimate violence, the current study focuses on the direct infliction of physical force resulting in bodily injuries, i.e., acts of physical violence.

The regularity of violence today is also greatly debated. Some hold the belief that the general level of violence in the world has declined and we are currently in a state of relative peace. Pinker (2011) argues that this is due to factors such as the establishment and refinement of governed civilisations, with judiciary consequences to discourage acts of violence, and, more recently, the presence of mass media, which can prompt people to be more sympathetic to people who are not in their direct social circle. Others believe that the opposite is true, and that violence is just as frequent today as it was amongst early humans. These scholars emphasise that the incomplete datasets for time periods in the past, such as the wider European Mesolithic, prevent us from knowing how reflective the observed levels of violence can be on a global scale (Ferguson, 2013; Fibiger, 2018). Yet it is difficult to discuss changes in violence patterns over time on a global scale when the concept of “violence” is relative to each culture. Such is observable in the Spanish conquest of the New World, for instance, where the conquistadors believed the sacrificial rituals of the native Aztecs to be violent and barbaric while to the Aztec, these sacrifices were not acts of violence, but a foundational aspect of their religious beliefs (Carrasco, 1999).

Ian Morris (2014) presents the idea that over time, war has produced a safer and more prosperous world. Through countless wars over millennia, more defined societies have emerged, establishing governmental power over large societies. Larger groups of people are more easily governed while smaller groups are more likely to exhibit frequent acts of violent anarchy. Morris furthers his argument through his examination of evidence of trauma between skeletal remains of the Stone Age and violent fatality rates of a more modern context. He observes that though the wars fought in the 20th century had death tolls which humanity had never seen before: between 100 million and 200 million of the nearly 10 billion people who lived throughout the 20th century. While these numbers seem staggering, these numbers only equated to 1-2% of the world's population. Violence during the Stone Age, however, manifested in more regular small-scale acts of violence, such as vendettas and raids, yet it is estimated that 10-20% of all the people who

lived in the Stone Age died violent deaths. Morris argues that the practice of partaking in wars is what has reduced the violent death rates over the millennia. Wars establish governmental power over large societies, such as countries seen today. Throughout history, it has been that those vanquished in war were assimilated into the victorious society. Once in power, the governing bodies would need to suppress smaller acts of violence within the society as peaceful subjects were easier to govern than murderous ones. It was then easier to maintain peace in the newly formed larger society as smaller groups of people have less constraints and are more prone to violent acts. Individual acts of violence have become comparatively non-existent as a result of the necessary evil of highly concentrated periods of violence being war (Morris, 2014).

All parties in this debate, however, agree that violence is still present today to some degree and that power is frequently maintained through the threat of violence (Pinker, 2011; Ferguson, 2013; Morris, 2014; Fibiger, 2018). Because of this, the means of violence have modernised. Though the hand-propelled projectiles used in the Palaeolithic period, such as spears, may not be used today, the principles behind the functionality of the weapon are still regularly incorporated into modern weapon design (Churchill, 1993; Shea, 2006; Shea and Sisk, 2010; Adelman and Kieran, 2018; Milks *et al.*, 2019). And as technology has progressed throughout history, the mechanisms and diversity of projectile weapons have advanced to meet the ever-changing needs of people within society.

The development of weapon design has resulted in a wide array of weapons which are produced and extensively used today, not uncommonly in acts of violence which cause harm to other individuals or even oneself. In England and Wales, there were a total of 6,759 firearm offences between 1 April 2018 and 13 March 2019, of which 31 cases involved injuries which were fatal (Allen and Audickas, 2020). During the year of 2019, the United States saw 39,533 gun-related deaths, 15,433 of which were homicides and 24,090 of which were suicides (Gun Violence Archive, 2021). These firearm homicides

accounted for 73.70% of the total homicides committed in the United States that year, but this did not account for non-firearm projectile weapons, such as archery weapons (Uniform Crime Reporting, 2020). Such weapons were classified as “others”, but this classification, which accounted for 11.40% of homicides in 2019, includes all weapons which were not firearms, knives/cutting instruments, or personal weapons (hands, fists, feet, etc.). If the current weapon classification system identified subcategories of firearms and archery weapons within the overarching classification of projectile weaponry, the specificity of the statistics would improve, more accurately reflect the trends of weapon use, and the rate of projectile weapon use would increase. The projectiles involved in such cases often damage skeletal material due to the application of an external force or multiple external forces. This failure of skeletal material as a result of the application of force(s) (trauma) (Blau, 2016) is often vital in understanding both the experiences of the individual during life and the circumstances around their death (Simmons and Haglund, 2005; Kimmerle and Baraybar 2008).

## 1.1. Forensic Anthropology

The field of forensic anthropology represents the multitude of applications of anthropological methods and knowledge to forensic investigations (investigations which involve death(s) in a medicolegal context) (Simmons and Haglund, 2005; Cunha and Cattaneo, 2006; Klepinger, 2006; Ubelaker, 2006; Márquez-Grant and Johnson, 2016). First and foremost, the forensic anthropologist aids the investigative team through identification of significantly decomposed or skeletal remains, including the estimation of sex, age, stature, and ancestry (Buikstra and Ubelaker, 1994; Komar and Buikstra, 2008; Márquez-Grant and Johnson, 2016). Additional roles of the forensic anthropologist include the estimation of the postmortem interval (PMI) based on the level of decomposition, the identification of human and non-human skeletal remains, and the estimation of the minimum number of

individuals (MNI) (Buikstra and Ubelaker, 1994; Cunha and Cattaneo, 2006; Klepinger, 2006; Pinheiro, 2006; Kimmerle and Baraybar, 2008; Komar and Buikstra, 2008; Márquez-Grant and Johnson, 2016; Giles *et al.*, 2020).

Other specialties, such as facial reconstruction and age assessment of the living (in cases of undocumented immigrants, human trafficking, etc) may also require the forensic application of osteological methods (Klepinger, 2006; Introna and Campobasso, 2006; Márquez-Grant and Johnson, 2016; Doyle, *et al.*, 2019). Further roles also include assisting with the identification of remains found in mass graves as well as assisting in disaster victim identification in cases of mass fatalities (e.g., the terrorist attack in New York City on 11th of September 2001) (Klepinger, 2006; Márquez-Grant and Johnson, 2016). In addition to all of these roles, the forensic anthropologist may be required to provide testimony on their analysis of skeletal remains as an expert witness in court (Klepinger, 2006; Hiss *et al.*, 2007; Simmons and Hunter, 2010; Márquez-Grant and Johnson, 2016).

It is also standard practice for an anthropological examination to assess any trauma found on the skeletal remains, being able to determine what type of trauma it is (typically blunt force, sharp force, or projectile) and when the trauma occurred in relation to the individual's death (antemortem, perimortem, or postmortem) (Buikstra and Ubelaker, 1994; Di Maio and Di Maio, 2001; Klepinger, 2006; Komar and Buikstra, 2008; Blau, 2016; Cunha and Pinheiro, 2016; Márquez-Grant and Johnson, 2016; Obertová *et al.*, 2019). Antemortem trauma are injuries which are produced before death, typically showing some level of healing at the trauma site (Moraitis and Spiliopoulou, 2006; de Boer *et al.*, 2012; Cunha and Pinheiro, 2016). Perimortem trauma is inflicted around the time of death, but the perimortem interval is a bit ambiguous and can vary between cases (Moraitis and Spiliopoulou, 2006; Wheatley, 2007; de Boer *et al.*, 2012). In such cases of trauma, the bone will react to the applied forces in a similar way to how it would during the antemortem period, but the damaged bone will lack signs of healing (Appleby *et al.*, 2015; Loe, 2016; Obertová *et al.*, 2019). Postmortem



change to skeletal material is the alteration of the bone after death (Quatrehomme and İşcan 1997b; de Boer *et al.*, 2012; Hart, 2015). Damage to the bone during the postmortem period can include breakage, but it can also include animal activity, human activity, and environmental factors.

In osteological analytical praxis, the trauma inflicted by weapons in instances of violence are generally classified into one of three categories: sharp force trauma, blunt force trauma, and projectile trauma (Buikstra and Ubelaker, 1994; Di Maio and Di Maio, 2001; Smith and Symes, 2001; Klepinger, 2006; Blau, 2016; Loe, 2016; Quatrehomme and Alunni, 2019). Each of these forms of traumatic injury could also be classified as penetrating trauma if the weapon broke through the skin, creating an open wound (Stewart, 2005). Skeletal trauma is categorised as sharp force when a force is applied by an instrument with a fine-pointed surface (e.g. an incised cut from a knife or a chopping impact from a cleaver) (Bartelink *et al.*, 2001; Lovell, 2008; Crowder *et al.*, 2013; Love, 2019), whereas in cases of blunt force trauma, the force is applied to a large surface area of bone (such as a blow from a cricket bat) (Moraitis and Spiliopoulou, 2006; Passalacqua and Fenton, 2012; Galloway *et al.*, 2013).

Projectile trauma, however, is used to denote trauma which is caused by an object which has been propelled toward the body (for example, a bullet or an arrow) (Berryman and Gunther, 2000; Churchill and Rhodes, 2009; Sano *et al.*, 2019). This propulsion allows the assailant to be a distance away from the target, providing a tactical security to the user which blunt force and sharp force weapons do not have (Churchill, 1993; Shea and Sisk, 2010; Adelman and Kieran, 2018). At the same time, this tactical advantage has a psychological disadvantage in that it dehumanises the target in the eyes of the assailant, encouraging indiscriminate lethality. But in times of war, for instance, this impact on the empathy of a soldier could also be viewed as an advantage in making it psychologically easier to kill other people (Bandura, 2002; Cummings, 2006; Miller, 2012; Petras *et al.*, 2016; Adelman and Kieran, 2018).

More specific classifications of trauma, such as blast trauma and sharp-blunt trauma, are also sometimes observed on skeletal remains. The former is a result of trauma caused by either the blast of an explosion or the shrapnel that is propelled from the explosive device, similar to the mechanism of projectile weaponry (Kimmerle and Baraybar, 2008; Christensen *et al.*, 2011; Singleton *et al.*, 2014). While the shrapnel from explosions act as projectiles and exhibit characteristics of projectile trauma, studies have found that the skeletal trauma which they cause can be differentiated from true projectile trauma due to the shrapnel's lower impact force and irregular shape (Christensen and Smith, 2015; Willits *et al.*, 2015). Sharp-blunt trauma is caused by chopping weapons which contain elements of both blunt and sharp force weapons, being both relatively bulky while having at least one fine point edge (Kimmerle and Baraybar, 2008). Sharp-blunt weapons, such as axes and hatchets, will produce trauma which exhibits features of both blunt force and sharp force injuries, typically the large area of fragmentation seen in blunt force trauma and the angular surfaces of cut marks (Kimmerle and Baraybar, 2008).

Each of these categorisations is determined by the characteristics of the instrument which created the trauma and there are vast variations between the weapons of each of the three main categories. Even considering this, projectile trauma in a current forensic context has become nearly synonymous with the phrase "gunshot trauma," which completely neglects the recognition of any other form of projectile weapon, such as archery weapons (see Section 2.8.). As such, there have been very few comparative studies examining the differences between these weapons, none of which focus on comparing modern firearms to archery weapons. Because of this lack of research, archaeological cases of projectile trauma, especially in earlier periods, are not always identified unless the defect corresponds to the outline of the projectile that inflicted it.

Beyond the exclusivity of terminology, the methods used to identify projectile trauma are also relatively limited. The identification of projectile trauma

primarily focuses on morphological features, such as the presence of fractures and bevelling at both the entrance and exit defects (when present) (Smith *et al.*, 1987; Quatrehomme and İşcan; 1998; Berryman and Symes, 1999; Bailey and Mitchell, 2007; Humphrey *et al.*, 2017; Berryman, 2019). Yet, no attempt has been made to quantify any of these features in order to differentiate the types of projectile weapons used. Such is a limitation in the current osteological methods, particularly with the application of these methods in a context which physical anthropological methods are used to assist in legal investigations (i.e., forensic anthropology) (Reichs, 1998; Simmons and Haglund, 2005; Komar and Buikstra, 2008; Márquez-Grant and Johnson, 2016). Komar and Buikstra (2008) emphasise the importance of accurate and precise methods in forensic investigations as flawed methods could result in the false imprisonment of innocent parties. The purpose of the current study is to refine anthropological methods of projectile weapon identification to increase the precision of said methods.

The current study examines the gaps in the currently existing literature which have just been described, proposing a new methodology for identifying trauma origins and substantially enhancing forensic work, and sought to answer the following questions:

1. Can the current osteological methods of analysing projectile trauma accurately identify the weapon used?
2. Which macroscopic characteristics of projectile trauma are most indicative of the weapon used?

In examining these questions, avenues into the investigation of archaeological projectile trauma were also explored. The weapons examined in this study included modern models of handgun, rifle, shotgun, modern recurve bow, compound bow, and compound crossbow (using three different tips: field tip, fixed broadhead, and mechanical broadhead), making the application of these findings primarily relevant in a forensic context. However, the results also have important implications for archaeological trauma

research, shedding light on weapon identification in cases of trauma which are from pre-firearm periods.

## 1.2. Aims and Objectives

This study aimed to:

- Elucidate the impact of projectile weapon trauma on skeletal material.
- Determine if the class of weapon can be identified based on macroscopic trauma features.
- Identify which features of trauma are more indicative of the type of weapon used to cause the trauma.
- Develop a weapon class identification system based on the observed features of this data set.

The objectives to achieve these aims were:

- Designing a suite of experiments to simulate traumatic injuries to bone using a synthetic proxy (polyurethane sphere) for human crania.
- Defining a range of key observable characteristics to permit recording and comparison of data amongst and between samples impacted by different forms of ballistic weaponry.
- Making macroscopic observations on the trauma characteristics regarding residue left by the weapon, fractures, and dislodged fragments. Observations were made on both qualitative and quantitative features of trauma.
- Devising a strategy of inferential testing to add statistical power to quantitative observations.
- Using the quantitative and qualitative results to investigate the extent to which it is possible to create a weapon identification system based on which features of the trauma were found to be more indicative of the weapon of origin.

This thesis is divided into five main chapters. The background chapter (Chapter 2) examines the existing literature regarding projectiles, the skeletal trauma they cause, and the factors that influence the ballistic properties of a projectile. Following this, the methods chapter (Chapter 3) explains the experimental procedure used to obtain the samples in this study, as well as which features of trauma were examined, and how they were quantified. The two results chapters (Chapters 4 and 5) examine the data collected from these experiments: the first results chapter (Chapter 4) describes the data collected from the experiments and the second results chapter (Chapter 5) presents the statistical analysis of the data. The discussion chapter (Chapter 6) then puts these results into a wider forensic and archaeological context as well as highlighting limitations and avenues for future research. The conclusion (Chapter 7) focuses on the main achievements of this study.

## 2. Background

In this chapter, the literature concerning the physics behind projectile weapons, mechanical properties of bone, fracture patterns of bone, projectile weapons, and projectile trauma are examined in order to place the current project in context and clarify the rationale for conducting this study. Previous experimental work, forensic case reports, and archaeological case studies are also examined to understand the modern culture context of projectile weapons and their use and to identify gaps in current knowledge.

### 2.1. The Evolution of Projectile Weapon Design

The earliest evidence of projectile weapons come from the Early Palaeolithic period (Thieme, 1997; Shea, 2006; Schoch *et al.*, 2015), with spears being the earliest known form of true projectile weapons (Knecht, 1997; Rots, 2016; O'Driscoll and Thompson, 2018; Milks *et al.*, 2019). The initial forms of these weapons consisted of a length of wood shaft which had one end sharpened to a point (Thieme, 1997; Schoch *et al.*, 2015). Nine spears of this design, which were found mostly preserved, were excavated between 1994 and 1998 at the Palaeolithic site in Schöningen, Germany (Schöningen 13 II-4) (Figure 2.1) (Schoch *et al.*, 2015). These spears, combined with butchered faunal remains also found at the site, provided the first evidence for large animal hunting with wooden spears in Europe (Schoch *et al.*, 2015). Later spear design included a stone or bone tip attached to a shaft made of organic material such as wood (Shea, 2006; Wilkins *et al.*, 2012; Rots, 2016; O'Driscoll and Thompson, 2018), examples of which have been found at the Klasies River main site in the Eastern Cape Province, South Africa (Bradfield *et al.*, 2020). The development of spears allowed ancient humans to be able to hunt with less risk to the hunter, attacking prey by throwing the spear while remaining at a safe distance (Churchill, 1993; Shea, 2006; Shea and Sisk, 2010; Milks *et al.*, 2019).



*Figure 2.1 Palaeolithic spears from the Schöningen site (Schoch et al., 2015: 215).*

The power of the throwing spear is limited by the strength of its user, a limitation which is lessened with the introduction of the atlatl. The atlatl, or spear thrower, consists of a short board with a spur at one end, to hold the dart (spear) in place and a handle at the other end (Raymond, 1986; Arp, 2016) (Figure 2.2). Stones were commonly attached to the atlatl to increase the efficiency of the weapon. The darts were similar in design to throwing

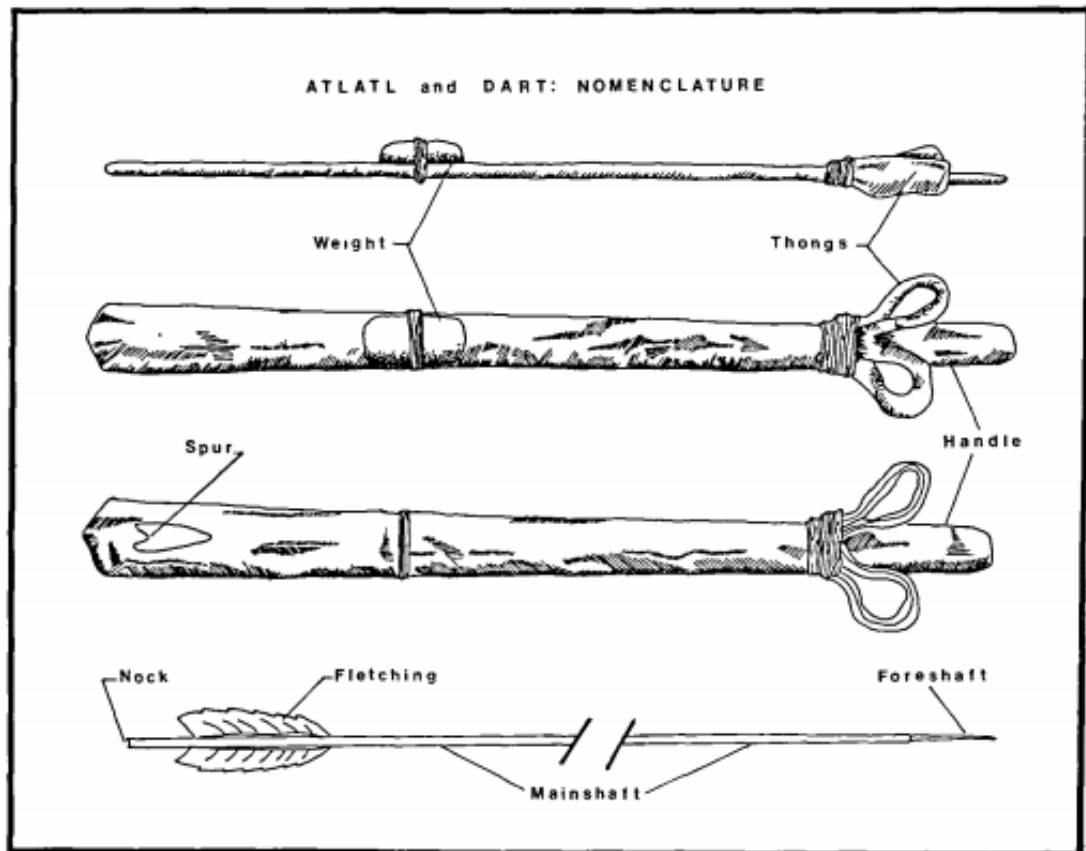


Figure 2.2 Structure of an atlatl (source: Raymond, 1986: 154).

spears: they consisted of a long shaft made of organic material, commonly wood, and were either sharpened to a tip or had a stone tip attached to the shaft. Atlatl darts, however, were made with a nock to fit with the spur on the atlatl as well as were fitted with feather fletching near the nock to stabilise the dart along its flight path (Raymond, 1986; Frison, 1989; Arp, 2016). This seemingly simple design gave hunters the advantage because it provides a greater thrust than one could achieve in throwing by hand due to the prolonged period of contact with the projectile (Howard, 1974) (Figure 2.3). The higher thrust gave more power to the projectile, allowing a hunter to hunt bigger game.

The bow and arrow further improved the power of a projectile by increasing the amount of force behind it. A bow would apply more force to an arrow than an atlatl would to a dart due to the tension in the limbs of the bow itself (Raymond, 1986; Verma, 2020). An arrow is, in design, a small version of a throwing spear and atlatl dart. Early arrows consisted of a small stone tip



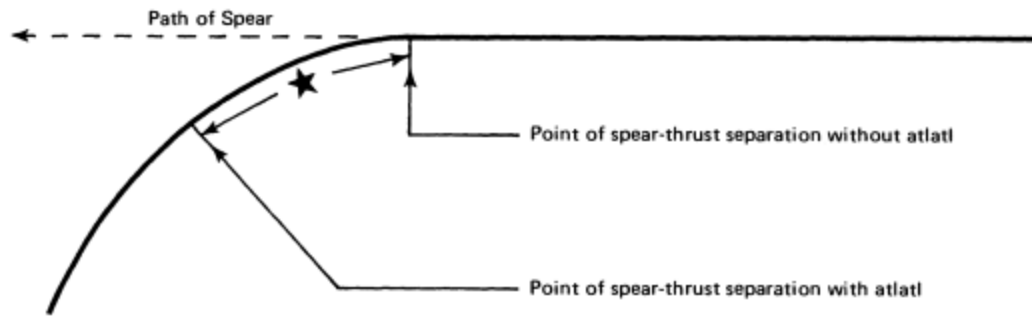


*Figure 2.3 Comparison of length of user contact with a spear/dart with and without an atlatl. Star signifies the amount of contact with the spear/dart along its path which is gained when using an atlatl (source: Howard, 1974: 103).*

attached to a relatively short (when compared to the throwing spear and atlatl dart) shaft made of organic material (Bradbury, 1997; Barton *et al.*, 2009; Gärdenfors and Lombard, 2018). Rather than being manually thrust forward, the bow propels the arrow with a great amount of force, significantly increasing the velocity of the projectile (Figure 2.4). When a bow is drawn, the limbs are pulled back by the drawstring, creating a significant amount of



*Figure 2.4 Fifteenth-century depiction of longbow archers at the battle of Crécy (1346) (source: Loades, 2013: 5).*

potential energy. As the drawstring is released, the limbs will return to their original position, also bringing the drawstring to its original position. This rapid and powerful movement applies force to the arrow, propelling it forward when the bow itself has finished its movement (Wolfson and Pasachoff, 1995). This mechanism was also able to produce a generally more consistent and more accurate shot than the throwing spear (Whittaker, 2013).

The development of archery-type projectile weapons remained relatively static for millennia, not seeing any great change until the development of early forms of the crossbow (Figure 2.5), though it is worth noting that projectile weapons which followed the principles of sling design (such as trebuchets) developed during this time (Hill, 2006; Vega and Craig, 2009). Early crossbow designs emerged as early as 400 BC from both Greece and

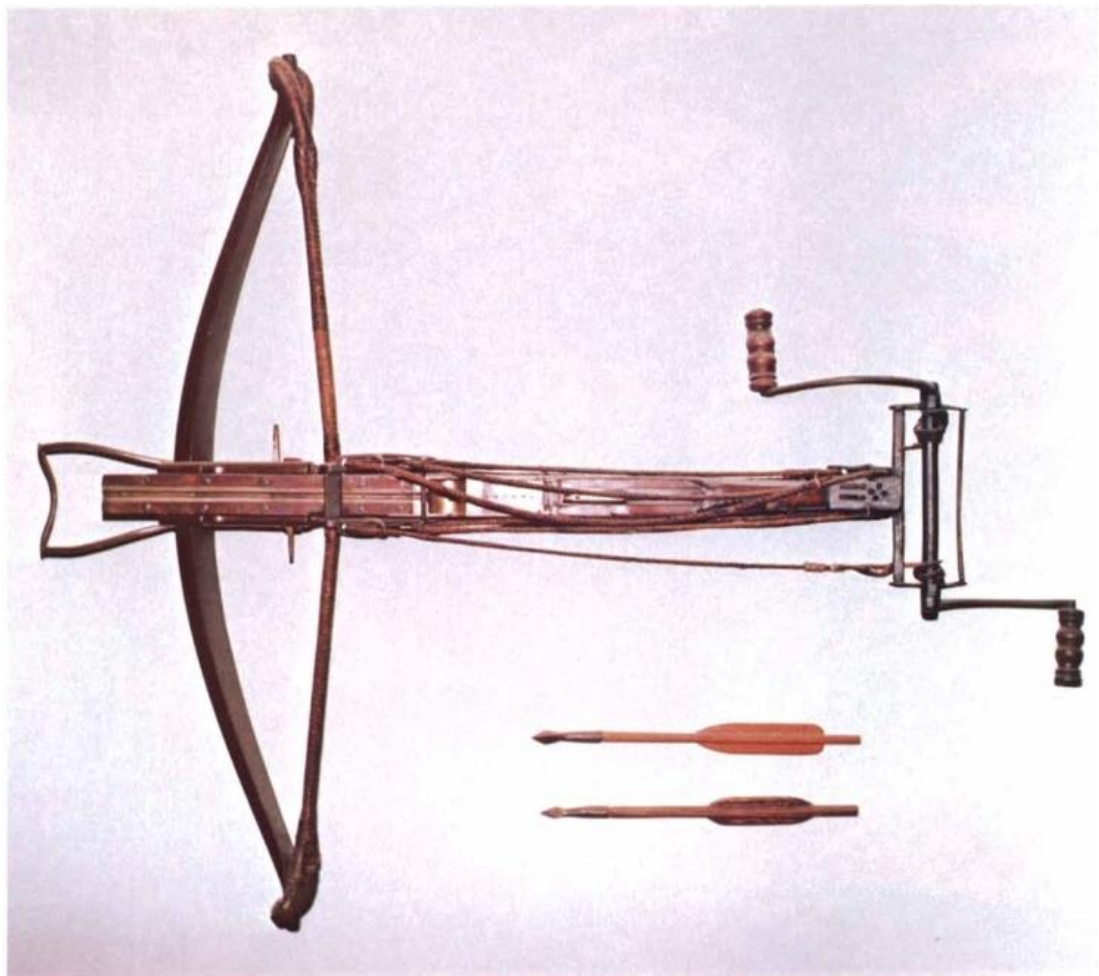


*Figure 2.5 Fourteenth-century crossbow (above) with two of its bolts (below) (source: Foley et al., 1985: 106).*

China (Foley *et al.*, 1985; Loades, 2018). The crossbow was a clear influence on the design seen in more modern projectile weaponry, exhibiting characteristics of both archery weapons and firearms. The main mechanism maintains the mechanism of the bow and arrow, with a drawstring which propels its projectile (bolt) forward when loosed. The key innovation, however, was the addition of a trigger mechanism, a feature which is present on all modern firearms, to release the drawstring (Foley *et al.*, 1985). The development of the crossbow did not render the traditional bow and arrow obsolete; both weapons continued to be used and were gradually replaced by firearms between the 14<sup>th</sup> and 17<sup>th</sup> centuries (Thordeman, 1939; Carman 2015).

At the peak of their popularity in Europe, between the high Middle Ages and the Renaissance (15<sup>th</sup>-17<sup>th</sup> centuries), archery weapons were regularly used in military battles. One notable battle in which archery weapons were utilised was the battle between Danish and Gutnish forces at Visby in AD1361 on the island of Gotland, Sweden. The skeletal remains from the Battle of Visby exhibit many instances of peri-mortem trauma caused by archery weapons. Of the estimated minimum 1,185 individuals excavated from three of the common graves of the battle, at least 586 individuals exhibit skeletal trauma (Thordeman, 1939). These include 456 individuals with sharp force trauma, 126 individuals with trauma caused by arrows (60 of which also exhibited cuts), and four individuals with unspecified trauma (Thordeman, 1939). Trauma caused by arrows has been estimated to have been caused by both longbows and crossbows. It is worth noting that a more modern analysis of these remains might yield different numbers.

Historical records also the overwhelming number of archers involved in the battle of Agincourt, France on the 25<sup>th</sup> of October AD1415. It is estimated that the number of archers (primarily longbowmen, some crossbowmen) in the English campaign was about 5,000 men which fought in wedge formations between the smaller battles and 4,000 men which participated in the larger battles (Clements and Hughes, 2004; Hardy, 2006). The men-at-arms

involved in the smaller battles only amounted to 990 men while the larger battles included 8,000 men. While the French campaign did have some longbowmen and crossbowmen, but they predominately had men-at-arms. The large proportion of archers thus gave the English a distinct advantage in that they could take down enemy melee fighters before they could even reach the English line while the French had minimal distance attacks themselves.

During the reign of Henry VIII (AD1491-1547), longbow ownership was mandated in the name of the crown: all males between the ages of 18 and 60 years were required to own their own longbow (Phillips, 1997; Ascham, 2011). Individuals who failed to abide by this law were fined for every month in which they did not obtain a new bow. Boys between the ages of seven and 17 years were also required to own a longbow, but it was the responsibility of the parents to supply them with a bow and arrows (Ascham, 2011). In addition to ownership, individuals were required to practise using a longbow regularly so that all adult and adolescent males would be well equipped for battle (Davies, 2002; Rogers, 2011), should the need arise (Gunn, 2010). The only individuals who could own and use crossbows were archers who achieved at least 200 marks (i.e. targets hit with a longbow) per year (Ascham 2011).

Archery weapons, however, became redundant in Europe between the 16<sup>th</sup> and 17<sup>th</sup> centuries, following the increased popularity of the musket (Figure 2.6) (Johnes, 2004; Maxson, 2013; Thornton, 2020). While archery weapons are no longer used for military purposes, they have remained popular in recreational activities such as sport or hunting. By the end of the 16<sup>th</sup> century, firearms (both small arms and artillery) had become standard weapons



*Figure 2.6 Nineteenth-century Minié musket (source: Smithurst, 2007: 124).*

among European armies (Johnes, 2004; Ágoston, 2014). The smoothbore muskets of the late 16<sup>th</sup> to early 19<sup>th</sup> centuries were powerful enough to penetrate armour, but these muskets were still fairly limited in range and accuracy, only being effective from a distance of at most 100 m (Moorehead, 2004). In the late 18<sup>th</sup> century, musket barrels with rifling (grooves which spiral along the internal surface of the barrel, causing the bullet to spin as it moves forward) were introduced, increasing the range of firearms to over 500 m as well as increasing the stability of the projectile and accuracy of each shot (Moorehead, 2004; Hanna *et al.*, 2015; Kajal *et al.*, 2017). Rifling in firearms has since become a standard feature of firearms (see Section 2.4.1.).

Following the development of rifling in the barrel of firearms, the most recent significant development of projectile weaponry is the invention of the integrated cartridge. Early firearms required manual loading of ammunition between each shot (Magee, 1995; Smithurst, 2007). Gunpowder was poured down the barrel of the gun, followed by the projectile itself, which was rammed down from the muzzle so the entire load was compacted to the back of the barrel (Magee, 1995; Beckenbaugh, 2009; Perdekamp *et al.*, 2013). Modern firearms, however, have this entire load contained in one pre-packaged round, contained within an integrated cartridge, which was itself a combination of two previous innovations, the percussion cap and the minié ball (this will be discussed in Section 2.4.2.) (Byers *et al.*, 2011). This allowed for loading via the breech rather than the muzzle, although rifles such as the Winchester (1860s) or the Martini-Henry (1870s-1880s) initially remained capable of being loaded only with a single round at a time. This innovation significantly reduced reloading time, with the later improvement of clips capable of holding multiple cartridges coming at the close of the 19<sup>th</sup> century. This development in weapon design introduced the concepts of semi-automatic and fully automatic weapons. In semi-automatic weapons, the shooter must release the trigger of the weapon and re-pull the trigger to fire multiple bullets (Hemenway and Richardson, 1997; Libby and Corzine, 2007). A fully automatic weapon, however, can fire multiple bullets in one

trigger pull and will continue to fire bullets until the trigger is either released or there are no more rounds left in the chamber (Hemenway and Richardson, 1997; Libby and Corzine, 2007; Perdekamp *et al.*, 2008).

Since the introduction of the round during the mid-19<sup>th</sup> century, firearm mechanics have not greatly changed, but weapon design has been continually changing to improve the power and speed of these weapons as well as the destructive ability of the bullets. These physical properties will be discussed in the following section.

## 2.2. The Physics of Projectiles and Terminal Ballistics

Regarding the use of archery weapons, Knudsen (2005) makes the claim that, “the velocity of arrows is nothing like that of firearm bullets” (Knudsen, 2005: 417). This framework of thought has inhibited potential comparative research in trauma analysis. While the initial velocity of a bolt may differ from that of a bullet, there are additional factors that may alter the power of each projectile, such as mass and kinetic energy. Differences in the physical attributes of archery projectiles can compensate for the lower velocity of archery weapons, producing a wounding potential that is comparable to that of firearms. In this section, the physics of terminal ballistics (motion, force, and energy) are examined to explain how projectiles from differing weapon types alter bone in different ways upon impact.

### 2.2.1. Motion

There are many ways to observe the motion of a given object, such as speed, velocity, and acceleration. The first, speed, is a simple relationship between distance and time and unrelated to direction (Serway, 1996; Walker, 2014). Velocity is similar to speed, but it incorporates directionality and can be used to predict the location of an object given its speed and vector, the

path on which it travels (Figure 2.7) (Beiser, 1982; Cutnell and Johnson, 2009; Walker, 2014). An object in motion has two different velocities: its initial velocity and its terminal velocity. Initial velocity is the velocity of the object when it starts to move. Forces acting on the object can cause the velocity to increase; the rate of change in velocity is known as acceleration (the opposite being deceleration). The terminal velocity of the object is the velocity at which the acceleration of the object is zero, or the maximum velocity that an object in motion achieves (Beiser, 1982; Herbert and Toepker, 1999; Shankar, 2014).

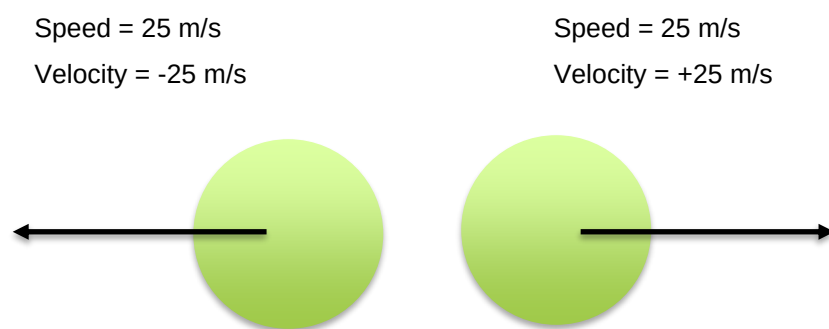


*Figure 2.7 Speed and velocity of two spheres. Both are moving at 25 m/s, but because the ball on the left is travelling in the opposite direction of the right sphere, the left sphere has a negative velocity even though the speed between both spheres is the same.*

### 2.2.2. Force

The concept of force is directly related to velocity. Newton's first law of motion states that, without external forces, objects that are in motion will remain in motion at a constant velocity, but when two objects, at least one of which is in motion, physically interact with each other, the velocity of the object or objects in motion is changed (Beiser, 1982; Wolfson and Pasachoff, 1995). This physical interaction that changes the velocity of an object is known as force (Wolfson and Pasachoff, 1995; Walker, 2014).

Force is a direct relationship between the mass ( $m$ ) and acceleration ( $\vec{a}$ ) of a moving object. While mass can be measured using scales, acceleration is calculated as the change in velocity ( $\Delta v$ ; measured in m/s) over a given time

interval ( $\Delta t$ ; measured in seconds) (Beiser, 1982; Radi and Rasmussen, 2013). That is:

$$\vec{a} = \frac{\Delta v}{\Delta t} = \frac{v_f - v_i}{t_f - t_i}$$

The force of an object can then be measured using the equation  $\sum F = m\vec{a}$ , where the acceleration of the object ( $\vec{a}$ ) is notated in metres per second squared and its mass ( $m$ ) is measured in kilograms (Cutnell and Johnson, 2009; Radi and Rasmussen, 2013). The resulting force is measured in Newtons ( $N$ ), where one Newton is the amount of force required to accelerate one kilogram of mass at the rate of one metre per second squared ( $1 N = 1 \frac{kg \times m}{s^2}$ ).

### 2.2.3. Energy

There are two forms of energy involved in motion: potential energy and kinetic energy (Beiser, 1982; Serway; 1996; Shankar, 2014; Radi and Rasmussen, 2013). Potential energy is the energy that an object holds based on its relative position to other objects and their forces (Bergman *et al.*, 1988; Serway, 1996). For example, a drawn arrow holds potential energy from the bowstring behind the arrow. When the bowstring is released, the potential energy is converted into kinetic energy, that is the energy gained from being in motion. The amount of kinetic energy that an object possesses is the amount of work that is needed to accelerate the body from rest to the given velocity with direct regards to the mass of the object. The kinetic energy of an object's is measured using the formula  $K = \frac{1}{2} mv^2$ , where  $K$  represents the kinetic energy measured in joules (J),  $m$  represents the mass of the object measured in kilograms (kg), and  $v$  represents the velocity of the object measured in metres per second (m/s) (Wolfson and Pasachoff, 1995; Shankar, 2014). This energy remains constant unless external forces are applied to the object. The initial kinetic energy produced by each of the weapons examined in this study are described in Table 2.1.



Table 2.1. Calculations of the kinetic energy of each projectile ( $\frac{1}{2} mv^2$ ).

| Weapon                              | Velocity (m/s) | Projectile Mass (g) | Kinetic Energy (J) |
|-------------------------------------|----------------|---------------------|--------------------|
| Handgun                             | 362.80         | 7.45                | 493.35             |
| Subsonic rifle                      | 376.43         | 2.59                | 183.50             |
| Shotgun*                            | 441.96         | 32.00/250*          | 12.50*             |
| Recurve bow                         | 36.58          | 16.00               | 10.70              |
| Compound bow                        | 101.80         | 38.84               | 201.25             |
| Crossbow (field tip)                | 129.54         | 27.00               | 226.54             |
| Crossbow (fixed broadhead tip)      | 129.54         | 26.48               | 222.18             |
| Crossbow (mechanical broadhead tip) | 129.54         | 28.10               | 235.77             |

\*Energy per pellet; approximately 250 pellets per 32 g load.

When an object in motion collides with another object and the kinetic energy remains constant, the energy is expelled upon impact and thus the energy is not lost but transferred to the object that is hit. Because there is no loss of energy, this type of collision is known as an elastic collision or if the kinetic energy of the object is altered, it is known as an inelastic collision (Fishbane *et al.*, 1993; Serway, 1996; Radi and Rasmussen, 2013). For example, when a bullet collides with bone, some of the energy of the bullet is transferred to the bone and converted to different types of energy, such as thermal and

internal elastic potential energy (Beiser, 1982; Wolfson and Pasachoff, 1995; Serway, 1996), classifying it as an inelastic collision.

## 2.3. Biomechanical Properties of Bone

Any given object has specific mechanical properties which dictate how it interacts with other physical objects and forces and each property results in a strength or weakness when force is applied (Serway, 1996; Cutnell and Johnson, 2009; Walker, 2014; Breithaupt, 2015). An object with a low compression strength, for instance, will readily give in when downward pressure is applied. The mechanical properties of bone, like any object, are highly complex and are influenced by the physical makeup of the bone in relation to the forces put upon it.

### 2.3.1. The Structure of Bone

On a microscopic level, compact mature bone consists of densely arranged haversian systems (osteons) (Figure 2.8) (Cohen and Harris, 1958; Kim *et al.*, 2015; Ahmed *et al.*, 2017). The general structure of each haversian

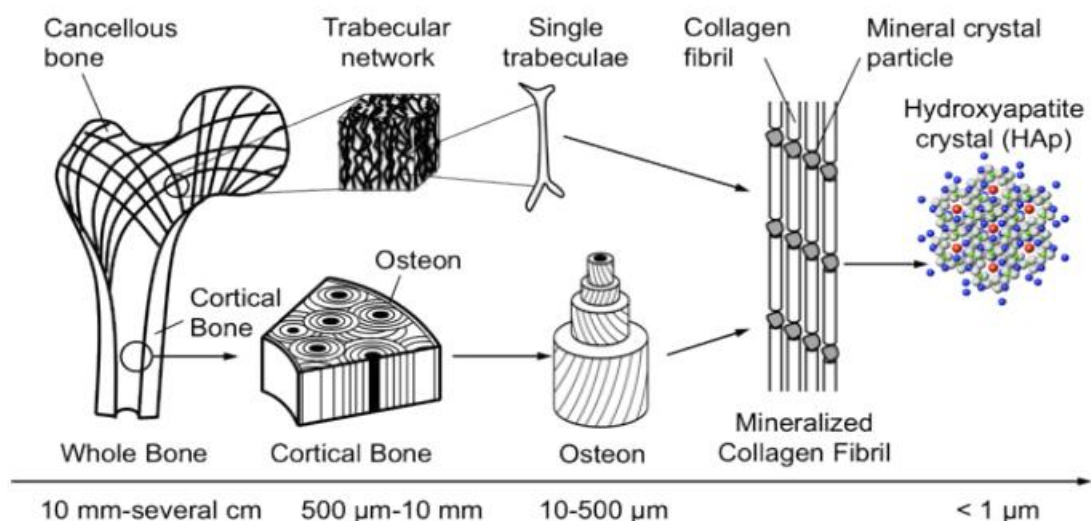


Figure 2.8 Hierarchical structure of trabecular (cancellous) and compact (cortical) bone (source: Gamagedara and Ziana, 2018: 2).

system is similar in appearance to that of a tree trunk, with a hollow canal in the centre (haversian canal) with several concentric rings (haversian lamellae) surrounding the canal. As compact bone cannot gain nutrients from diffusion, blood, lymph, and nerve fibres pass through both the haversian canals and the canals which pass through the bone obliquely, originating from the haversian canal (Volkmann's canals), passing nutrients through even smaller fluid-filled channels (canaliculi) which connect to the living bone cells (osteocytes) found in small cavities in the lamella (lacunae).

Each of the haversian lamellae contains of a bed of collagen, with each successive lamella alternating the orientation of the collagen fibres in order to provide additional strength to the structure (Viguet-Carrin *et al.*, 2005). When new bone tissue is being formed, crystals of hydroxyapatite, the inorganic component of bone, are worked into the collagen beds. On a molecular level, bone is made up of both organic (collagen matrix) and inorganic (hydroxyapatite crystals and calcium salts) components (Nordin and Frankel, 2001; Smith *et al.*, 2001). Organic materials are more elastic, while inorganic materials are more structurally rigid (Smith *et al.*, 2001; Buehler, 2006; Ritchie *et al.*, 2009). When hit with a given force, an elastic material, which has a higher resistance to force, is more likely to return to its original shape (elastic deformity) while plastic inorganic materials are more likely to permanently deform (plastic deformity) (Currey, 1991; Pfeifer, 2009; Banerjee *et al.*, 2018). If increasing force is applied, the object will eventually reach a failure point and break (Harkess *et al.*, 1991; Ritchie *et al.*, 2005; Wolfram and Schwiedrzik, 2016).

Bone which is saturated with fluids during the antemortem and perimortem periods (wet bone) is neither completely elastic nor completely viscous, but a viscoelastic material due to the combination of its organic and inorganic components (Johnson *et al.*, 1980; Smith *et al.*, 2001; Cardoso, *et al.*, 2015). This visco-elasticity provides enough rigidity to support weight bearing while not being brittle enough to fracture with forces associated with movement, such as compression and torsion (Smith *et al.*, 2001; Ritchie *et al.*, 2009). Skeletal material in which the organic material has completely decomposed

from the skeletal material during the post-mortem period (dry bone) is much more brittle and fractures more easily as it lacks the elasticity given from the organic collagen matrix (Cardoso *et al.*, 2015; de Boer and Maat, 2018). The balance of organic and inorganic material within the structure of bone influences the way that the bone itself reacts when a given force, such as a bullet or a bolt, acts upon it. It accounts for the varying levels of damage given different magnitudes of force.

In addition to the composition of the bone, the architecture of the bone also impacts the way in which it reacts to an applied force. There are four classifications of bone shape: long, short, flat, and irregular (Roberts and Gardiner, 1993; Xu *et al.*, 1993; Lovell, 1997; Collins *et al.*, 2017). Forces applied to each of these bones will produce different fractures due to the differences in shape. For instance, tubular bone frequently exhibits localised fractures as a reaction to blow from a blunt force weapon, while blunt force trauma tends to span over a relatively wide surface area in flat bones as well as flatten the cranial vault (Lovell, 1997; Passalacqua and Fenton, 2012; Galloway *et al.*, 2013). Bony features also impact the spread of fractures as the changing thickness in the bone provides more or less resistance in thicker and thinner bone, respectively. As the cranial vault is roughly uniform in shape and bone thickness, fractures are likely to spread over a greater surface area due to the lack of increased resistance (Lovell, 1997; Galloway *et al.*, 2013).

### 2.3.2. Fractures

As previously discussed, the combination of organic and inorganic components gives bone its ability to return to its original shape after a stress has been removed. A bone will, however, inevitably yield under an unusually large force when it surpasses the strength of the bone itself (Nahum, 1975; Galloway, 1999; Cullinane and Einhorn, 2002) (Figure 2.9). When the strength of the bone does fail, it fractures. The way in which this fracture manifests depends on the type of force that is applied to the bone, but bones tend to break in specific patterns. Bone fractures include transverse, oblique,

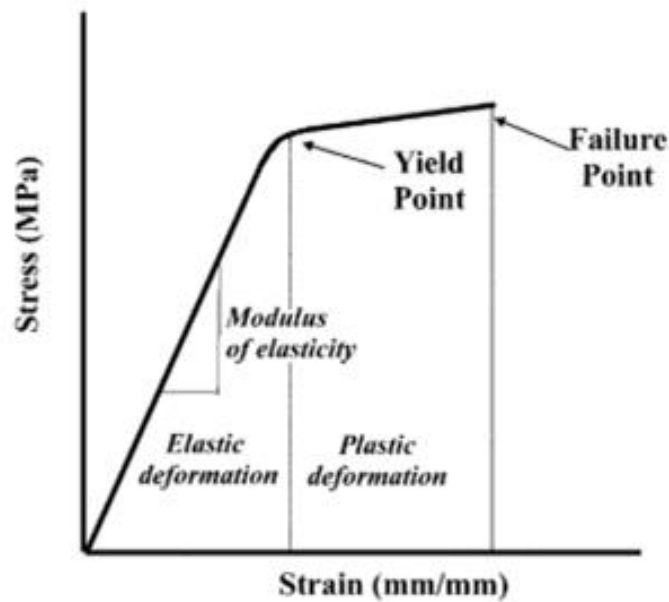


Figure 2.9. Relationship between stress and strain in bone (source: Galloway, 1999: 38).

linear, comminuted, and greenstick fractures (Galloway, 1999) (Figure 2.10) (Table 2.2). Each of these fractures are a direct result of a specific type of force being applied to the bone.

The forces named in Table 2.2 each act upon the bone in different ways, producing distinct fractures. Tension is a force exerted by pulling and therefore elongating the bone (de Albuquerque Taddei *et al.*, 2012; Breithaupt, 2015; Takimoto *et al.*, 2015). Conversely, compression presses material together, decreasing the area of the bone (Fishbane *et al.*, 1993; de Albuquerque Taddei *et al.*, 2012). Shearing force, however, is not a singular force. Instead, it is the combination of two parts of an object being pushed in opposite directions (Fishbane *et al.*, 1993; Megson, 2019) (Figure 2.11).

Flat areas of bone such as the cranial vault exhibit fracture patterns that differ to fracture patterns found in long bones due to the difference in architecture between the two. In regards to projectile trauma, Smith *et al.* (1987) describe a sequence of fracturing as a response to an impact from a bullet. The entrance wound itself is the primary fracture, followed by secondary radial/radiating fractures, and then sometimes (but not always) tertiary concentric heaving fractures (Figure 2.12). The primary fractures are the

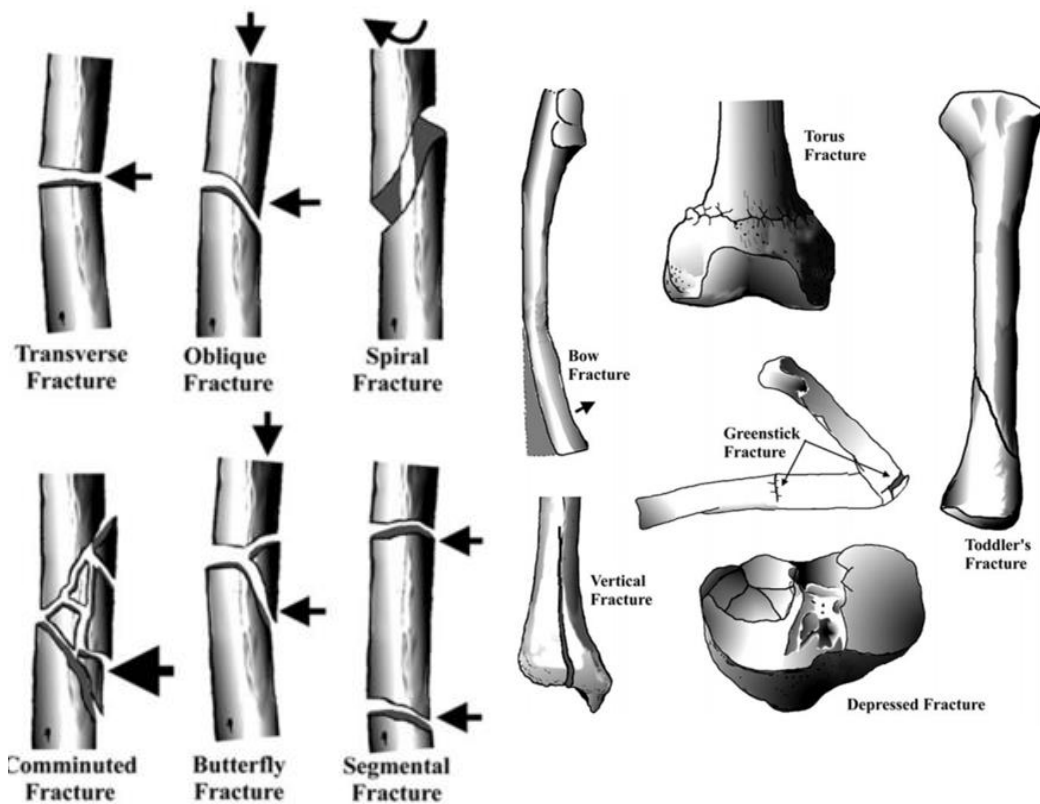


Figure 2.10. Common fracture patterns (source: Galloway, 1999: 50-52). Transverse, oblique, linear, comminuted, and greenstick fractures are commonly observed when the force of a projectile is applied to long bones.

Table 2.2. Description of common long bone fractures and the forces involved in their formation as described by Galloway (1999).

| Fracture   | Description                                                                           | Force                                                  |
|------------|---------------------------------------------------------------------------------------|--------------------------------------------------------|
| Transverse | Runs perpendicular to the long axis of the bone                                       | Tension                                                |
| Oblique    | Runs diagonally across the diaphysis of the bone                                      | Shearing and compression                               |
| Linear     | Runs along the long axis of the bone                                                  | Compression                                            |
| Spiral     | Runs in a winding pattern around the diaphysis of the bone                            | Torque                                                 |
| Comminuted | More than two fragments are produced                                                  | Type of force varies, but must be high levels of force |
| Greenstick | Incomplete fracture where the non-fractured portion of the bone remains bent or bowed | Tension and compression                                |

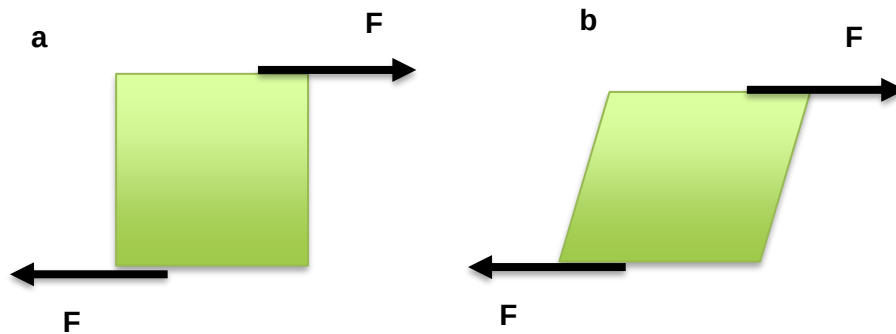


Figure 2.11. Two forces ( $F$ ) acting upon an object in opposite directions (shear force). a) Before shear force. b) After shear force.

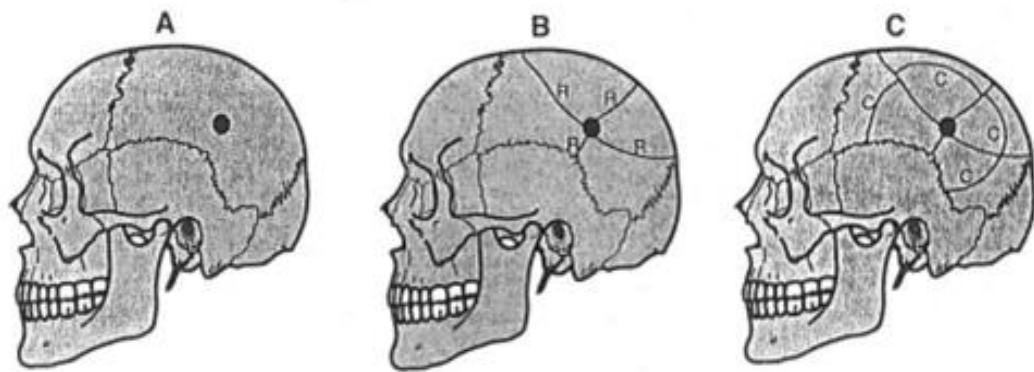


Figure 2.12. Progression of fractures at an entrance defect (A) primary defect (B) secondary (radiating) fractures (C) tertiary (concentric) fractures (source: Berryman and Symes, 1999: 346).

direct effect of the impact of the bullet and consist of an opening which the bullet passed through and bevelling on the internal or external table of the cranial vault (found at the entrance and exit wounds, respectively). This is due to the fact that the tensile strength of bone is weaker than its compressive strength and the force impacted by a travelling bullet compresses the outer table while expanding the inner table (Smith *et al.*, 1987; Berryman and Gunther, 2000) (Figure 2.13). The opposite is true for the exit wound, with bevelling of the external table and a relatively smooth internal table (Quatrehomme and Işcan, 1997a; Berryman and Gunther, 2000; Viel *et al.*, 2009; Delannoy *et al.*, 2013).

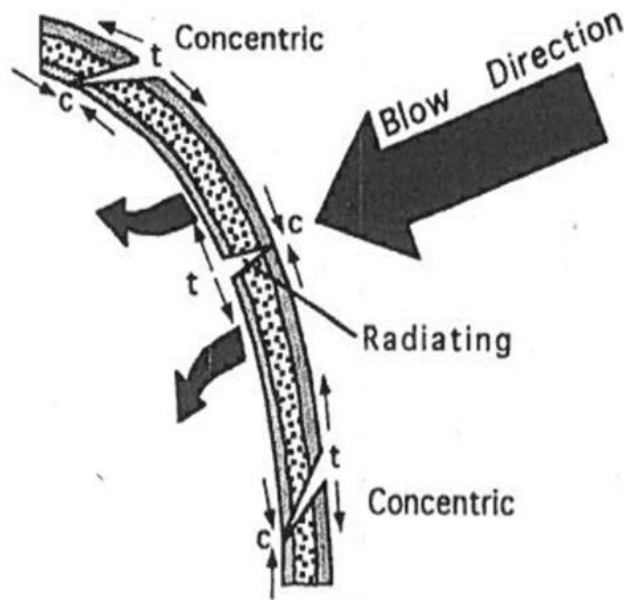


Figure 2.13 Bevel mechanics in gunshot trauma (*t*=tensile stress; *c*=compressive stress) (source: Berryman and Symes, 1999: 347).

Following the initial entrance fracture, the secondary fracture(s) which will originate from the entry point and travel away from the entrance wound (Smith *et al.*, 1987; Berryman and Haun, 1996). If the force of the impact is great enough, concentric heaving fractures will occur after the radiating fractures (Smith *et al.*, 1987; Bird and Fleischman, 2015; Symes *et al.*, 2019). Whereas radiating fractures are a transfer of energy from the bullet to the bone itself, concentric heaving fractures result from the transfer of energy to the soft tissue in the cranial vault (Berryman and Haun, 1996; Hart, 2005). The resulting increased intracranial pressure puts outward pressure on the bone, causing fractures that are perpendicular to the radiating fractures. Such fractures will not manifest without the presence of primary and secondary fractures (Smith *et al.*, 1987; Berryman and Haun, 1996; Bird and Fleischman, 2015; Symes *et al.*, 2019).

These fractures can also be used for sequencing entrance and exit wounds as well as cases of multiple projectile injuries. If a fracture path crosses another fracture that has already formed (as well as cranial sutures), the forming fracture will be halted by completed fracture (Dixon, 1984b; Kimmerle and Baraybar, 2008; Bird and Fleischman, 2015). The fractures from the



entrance wound travel faster than the bullet itself, meaning that the fractures will be completely formed before the bullet exits (Betz *et al.*, 1996; Berryman and Symes, 1999; Tartaglione *et al.*, 2012). Fractures can therefore be affiliated with an entrance or exit defect and entries can be sequenced based on their fractures.

Bullets inflict different fracture patterns when they strike bone tangentially. While a bullet that strikes cranial bone perpendicularly creates a circular hole, bullets that enter on a tangential trajectory produce a more oblong, irregular hole with bevelling on both tables of the cranial vault (Dixon, 1982; Harada *et al.*, 2012; Delannoy *et al.*, 2016; Özsoy and Tugcu, 2016; Quatrehomme and Alunni, 2019). The bone in front of the path of the projectile will also fragment, producing a “keyhole defect” (Spitz, 1980: 254-255) (Figure 2.14). This defect can occur with both entrance and exit defects (Dixon, 1984a; Nayak *et al.*, 2010). Coe (1982), however, notes that the presence of bevelling is sometimes observed on both tables when the cranial vault is hit perpendicularly and it is unknown why this occurs.

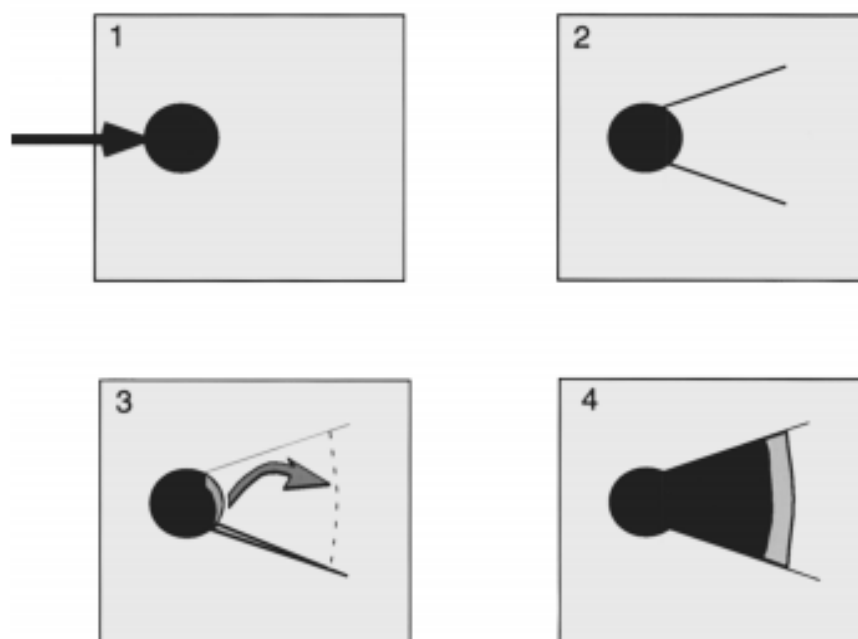


Figure 2.14. Formation of a keyhole defect (source: Berryman and Gunther, 2000: 486).

## 2.4. Firearms

The use of guns as weapons in forensic cases has become common in more recent years with most injuries within the civilian population involving firearms trauma inflicted by handguns, rifles, or shotguns (Bangalore and Messerli, 2013; Stefanopoulos *et al.*, 2014; Legault *et al.*, 2019). As a result, there have been an extensive number of studies examining the trauma which bullets inflict on both soft and hard tissue (Dodd and Budzik, 1990; Berryman and Symes, 1999; Smith *et al.*, 2001). The damage inflicted by a firearm is dependent on the specifications and components of the gun itself and is also greatly impacted by the interaction of the physical concepts described previously and the specifications of the rounds being fired. This section explains the general mechanisms of firearms, provides an overview of types of ammunition commonly used with firearms, discusses what is currently known about the trauma that these projectiles create, and describes a sample of published case reports (both forensic and archaeological).

### 2.4.1. Mechanisms

The basic principle of firearms has remained relatively unchanged for several centuries: a projectile is shot forward through the barrel by a propellant that has been ignited in an otherwise enclosed space (Byers *et al.*, 2011; Powers and Delo, 2013). In modern firearms, the explosive powder is contained within the casing of the round (Wrobel *et al.*, 1998; Hanna *et al.*, 2015; Carlucci and Jacobson, 2019) (Figure 2.15). When the trigger is pulled, the firing pin strikes the primer on the base of the round casing, igniting the explosive powder. The breechblock of the gun prevents the escape of gases from the rear (breech) portion of the barrel, forcing the gases produced by the combustion forward and thus propelling the bullet through the cylindrical passage of the barrel (bore) (Byers *et al.*, 2011). The spent casing is then ejected from the chamber (the cavity that contains the round prior to firing). Firearms can be single-barrelled with a single chamber, multi-barrelled each

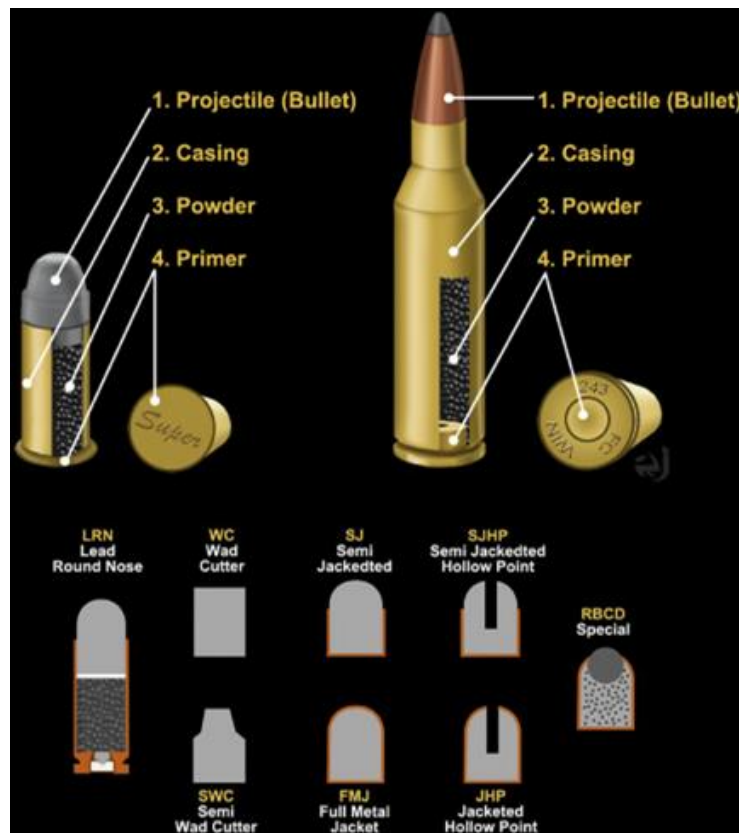


Figure 2.15. Components of a cartridge and common bullet types (source: Hanna *et al.*, 2015: 1187).

with their own chambers, or single-barrelled with multiple chambers (Gunther and Gunther, 1935; Heard, 2008).

The bores of modern handguns and rifles contain internal rifling grooves, a design adaptation which makes the weapon more accurate (Knudsen, 2005; Kajal *et al.*, 2017). These circular grooves lining the bore allow the projectile to spin as it travels forward, providing stability to the projectile during flight (Hanna *et al.*, 2015; Kajal *et al.*, 2017). A bullet that does not spin in flight is less stable due to the greater resistance force exerted over the tail end of the bullet by the discharge gasses (Hopkinson and Marshall, 1967; Kajal *et al.*, 2017).

Shotgun barrels, however, are smooth bore long-barrelled (commonly 66-76 cm in length) (DeMuth, 1971; Lew *et al.*, 2005; Maloney, 2017). Shotgun specifications are notated differently from those of rifle and handguns. The term “gauge” is used to designate the bore calibre of a shotgun. Rather than being defined by the diameter of the bore, the gauge of a shotgun is based

on the “number of spherical lead balls per pound which fit the gun bore” (DeMuth, 1971; pp. 219). As an example, 12 spherical lead balls (each with the same diameter as the bore of a 12-gauge shotgun) would weigh 1 lb (454 g).

The choke of a shotgun is a constriction at the muzzle end of the barrel which can control the spread of the pellets when they leave the barrel (DeMuth, 1971; Arslan *et al.*, 2011; Meric *et al.*, 2020). A constricted barrel will concentrate the pellets, decreasing the area in which the pellets spread and causing a more concentrated impact defect (Figure 2.16). There are three main types of choke: full choke (maximum constriction), modified choke (intermediate constriction), and cylinder bore (no constriction) (DeMuth, 1971; Arslan *et al.*, 2011).

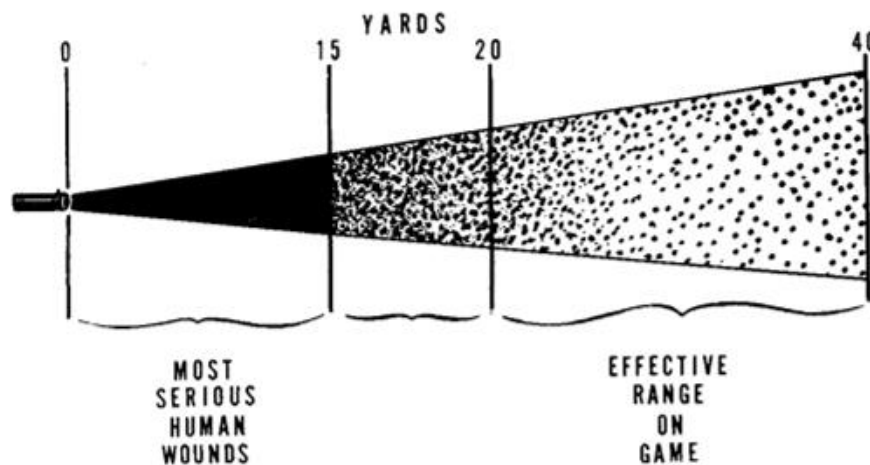


Figure 2.16. Spread pattern of a shotgun blast (source: DeMuth, 1971: 222). Narrowing the bore diameter would decrease the spread area.

Beyond simple functional mechanisms, firearms are also typically categorised into one of two classifications based on initial velocity: high-velocity and low-velocity weapons. While the division between these two classifications is based on the weapon’s initial velocity, the threshold is generally debated. American researchers claim the cut-off between the two classifications to be anywhere between 610 m/s and 914 m/s (Dodd and Budzik, 1990; Young *et al.*, 2015; Blau *et al.*, 2017; Manley *et al.*, 2019), British researchers consider a much lower threshold at 335 m/s (Young *et al.*, 2015), while others argue for a third classification falling in the middle

(typically between 450 and 1000 m/s) (Cohen *et al.*, 1986; Nowotarski and Brumback, 1994; Rhee *et al.*, 2016).

#### 2.4.2. Ammunition

The bullet is the tip of a round which separates from the casing when the explosive powder combusts (Hanna *et al.*, 2015; Rhee *et al.*, 2016). It contains a lead core, coated in a jacket (a harder metal, such as copper) in order to protect the bullet against the friction of the barrel (Dodd and Budzik, 1990; Stefanopoulos *et al.*, 2014). This jacket can either completely cover the bullet, known as a “full metal jacket” (FMJ) bullet, or the nose of the bullet can be left exposed, known as a “semi-jacketed” (Stefanopoulos *et al.*, 2014; Penn-Barwell and Helliker, 2017). Alternatively, the lead core can be plated rather than jacketed. Plated bullets are similar to full metal jacket bullets in that there is a coating of harder metal over the lead core, but the coating of a plated bullet is thinner than the coating of a jacketed bullet (Prahlow *et al.*, 2003; Prahlow *et al.*, 2021).

The calibre of the bullet is measured using the internal diameter of the barrel of the gun, in either hundredths of an inch or in millimetres (Dodd and Budzik, 1990; Hanna *et al.*, 2015; Berryman, 2019). A larger calibre equates to a wider bullet, which results in a larger mass and, therefore, affects the force and energy of the projectile. The potential energy of a fired bullet is also determined by the influence of the barrel length of a firearm on velocity: long barrel rifles are high-velocity firearms while short barrel handguns are low-velocity firearms (Seng and Masquelet, 2013; Hanna *et al.*, 2015; Murphy *et al.*, 2018; Manley *et al.*, 2019).

Shotgun ammunition, however, differs greatly from that of other firearm classifications (Figure 2.17). Each cartridge consists of a paper or plastic casing with a metallic base (this base contains the primer) (DeMuth, 1971; Ravikumar *et al.*, 2004). Within the cartridge, there is a pocket of explosive powder laying on the primer with a wad (typically plastic, felt, paper, or cork)

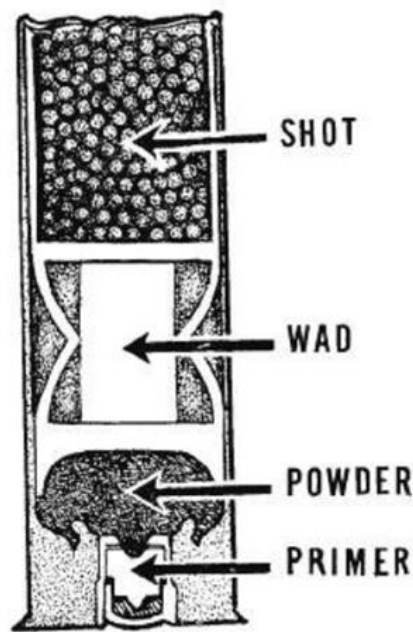


Figure 2.17. Diagram of a shotgun cartridge (source: DeMuth, 1971: 221).

between the powder and the pellets (shot) (Nelson and Winston, 2007; Meric *et al.*, 2020). This wad ensures that the shot is pushed forward when the powder combusts and prevents the gasses from simply passing between the pellets of the shot. “Shot” is used to refer to the collective spheres of the ammunition (Brewer *et al.*, 2003; Nelson and Winston, 2007). “Shot” also refers to the size of the spheres themselves: buckshot are spheres of a larger size (typically used for killing large animals like deer) while birdshot are spheres of a smaller size (typically used for killing birds or other small animals) (DeMuth, 1971; Nelson and Winston, 2007). Single projectiles (slugs) can also be used in shotguns and are typically made of lead alloys or steel (DeMuth, 1971; Nelson and Winston, 2007; Hejna, 2010; Hlavaty *et al.*, 2019).

#### 2.4.3. Soft Tissue Trauma

In addition to the skeletal trauma patterns described in Section 2.3.2., firearm ammunition damages soft tissue in consistent ways. As a high-velocity bullet penetrates soft tissue, it begins to rotate on its flight trajectory, reversing its orientation (Figure 2.18). This rotation, known as tumbling, separates and

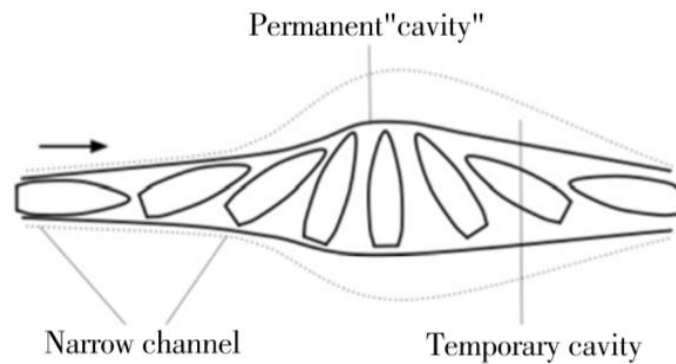


Figure 2.18. Progression of a tumbling bullet in soft tissue (source: Stefanopoulos et al., 2014: 182).

stretches the soft tissue, creating a temporary and a permanent cavity (cavitation) (Maiden, 2009; Oehmichen et al., 2009; Oberlin and Rantissi, 2011; Hanna et al., 2015) (Figure 2.19). Temporary cavities are produced as a result of the bullet stretching the soft tissue while the permanent cavities are produced by the bullet boring through the soft tissue (Karger, 1995; Hanna et al., 2015; Stefanopoulos et al., 2017). Low-velocity projectiles, contrarily, do not typically tumble and simply create narrow channels as they pass through the tissue (Endara et al., 2001; Kaynaroglu and Kiliç, 2012; Hanna et al., 2015; Omura et al., 2017). Because cavitation causes more

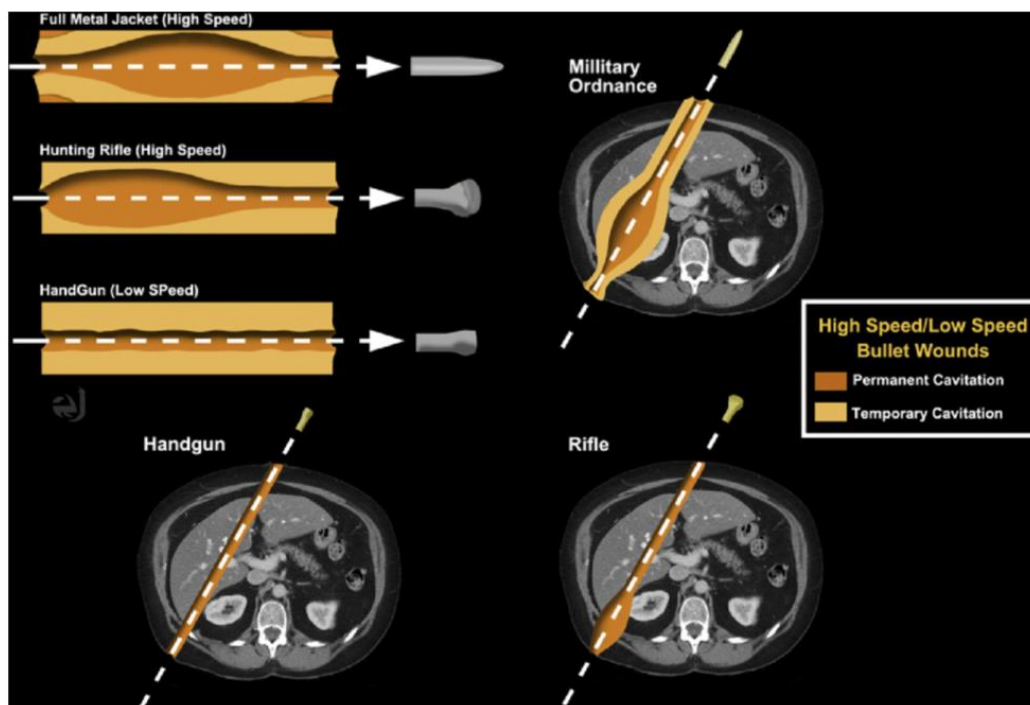


Figure 2.19 Cavitation of high- and low-velocity bullets (source: Hanna et al., 2015: 1188).

destruction to soft tissue than the penetration of the bullet itself, high-velocity bullets cause more soft tissue damage than a low-velocity bullet (Cohen *et al.*, 1986; Stefanopolous *et al.*, 2014).

#### 2.4.4. Postcranial Trauma

While the characteristics of cranial projectile trauma (radiating fractures, concentric heaving fractures, and bevelled entrance and exit defects) tend to be the defining features of projectile trauma, there have also been some studies conducted on the trauma characteristics seen on postcranial bones. Nowotarski and Brumback (1994) conducted a medical research project on treatment methods of femur fractures (caused by handguns) in living patients. While the primary focus of this study was the treatment of the wound itself, they did note that most diaphyseal gunshot wounds are comminuted (Nowotarski and Brumback, 1994). Langley (2007) examined 54 forensic cases of handgun or rifle trauma to bones of the thorax (including clavicles, scapulae, sterna, vertebrae, and ribs). It was found that tubular bones (clavicles and ribs) tended to manifest as a comminuted fracture with a demarcated entrance wound but no exit wound. More recently, Fragkouli (2013) and Terris (2013) examined fracture patterns of postcranial flat bones and long bones, respectively, when shot using a .243 Winchester hunting rifle at short and long-range. These studies show that postcranial bones hit by high-velocity bullets exhibit either comminuted fractures when shot from short range distances or radiating fractures when shot from long-range distances (Figure 2.20) (Fragkouli, 2013; Terris, 2013).

#### 2.4.5. Forensic Case Reports

The following reports describe instances of forensic cases which involve the use of firearms. These cases were selected to be representative of real cases which exhibit the characteristic features of projectile trauma (such as



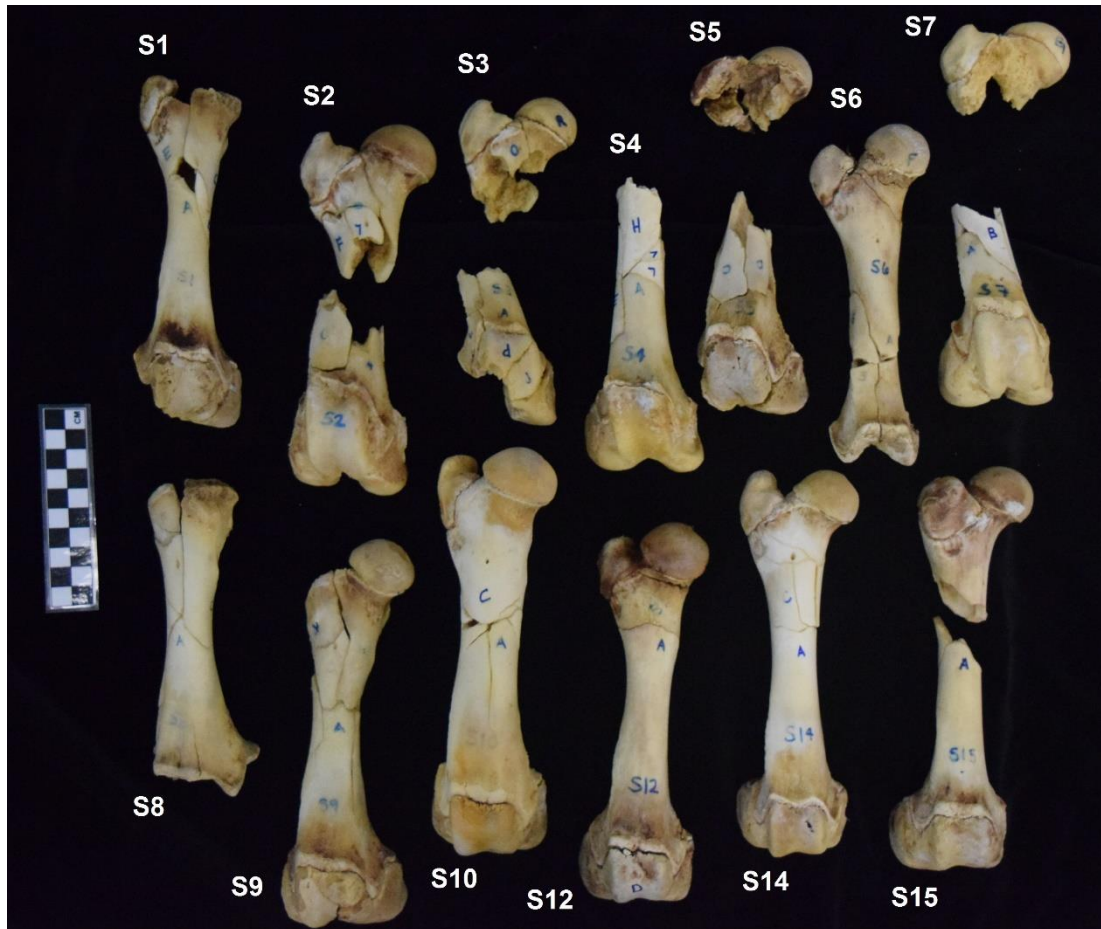


Figure 2.20 Domestic pig femora shot with a .243 rifle which exhibited comminuted fracturing. (source: Astrom, 2016; 32)

entrance/exit shapes, bevelling, and keyhole defects) as well as examples of deviants of the trends of projectile trauma. Emphasis was placed on trauma which was inflicted to the cranial vault, but one case which depicts a case of abdominal trauma (Tsuboi *et al.*, 2014) is discussed to call to attention the use of non-traditional firearms (in this case, a homemade shotgun).

Cases of gunshot wounds are commonly reported in the forensic and medical literature. These include cases using the different classifications of firearms, fatal and non-fatal cases, as well as suicides and homicides. Viel *et al.* (2009) report a case of a 76-year-old male who committed suicide using a Walther Manurhin PPK 7.65 pistol to the head. The deceased was found lying on the back with the pistol still in his hand. The bullet entered through the hard palate and exited through the left parietal bone (Figure 2.21). The entry of the bullet caused high levels of fragmentation of the facial bones and

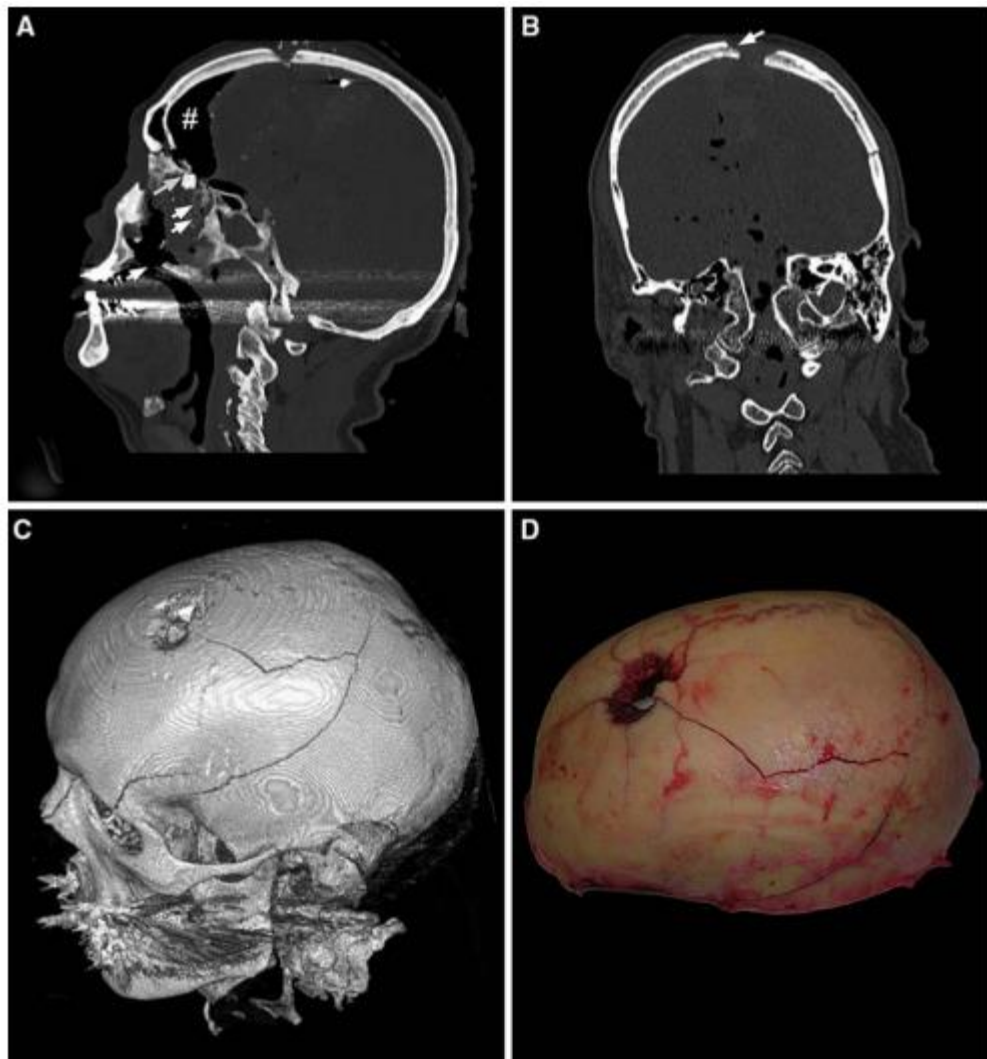


*Figure 2.21 Suicide victim (source: Viel et al., 2009: 25) A) Sagittal cross section; white arrows indicate entry and directionality of bullet. B) Coronal cross section; white arrow indicates exit defect. C) 3D-CT reconstruction of the skull. Exit defect and associated radiating fractures visible on the superior portion of the cranial vault. D) Autopsy picture of the cranial vault.*

also produced a fracture which radiated to the cranial vault, spreading from the left front-temporal bone and crossing to the left parietal bone. The exit defect exhibited bevelling on the external table of the bone as well as six radiating fractures originating from the circular-shaped exit. The internal table of the exit defect measured 1.20 cm in diameter while the external table measured 2.30 cm.

Verhoff and Karger (2003) describe a case of suicide in which the directionality of the projectile was not initially apparent. A 40-year-old male had shot himself in the head using a Sig-Sauer P6 pistol and a 9×19 mm

Quick Defense hollow-point bullet. As the trauma on the right temple (16×6 cm) was larger than the trauma on the left temple (7×12 mm), the police officers at the scene assumed that the bullet entered on the left side of the head and exited through the right. In the autopsy, however, an imprint of the muzzle of the gun was found on the skin of the defect on the right side after the hair had been shaved. Additionally, the left temporal bone exhibited bevelling on the external table, a feature typically associated with an exit defect. These two findings in the autopsy indicated that the bullet had actually entered from the right side of the head and exited from the left side. The bullet had not been found on the right side of the body at the scene, but following the change of directionality of the bullet, investigators were then able to find the bullet 2.30 m to the left of the body, confirming the atypical sizes of the entrance and exit defects. Verhoff and Karger theorise that these irregularities are most likely caused a combination of expanding muzzle gases from the combustion within the barrel and increased intracranial pressure (caused by temporary cavitation).

Austin *et al.* (2013) review three cases which were at first unclear as to if they were homicides or suicides. One of the cases involved a 19-year-old female who was found lying fully clothed on a bed with a .22 calibre automatic rifle on her lap. The autopsy revealed three separated but closely spaced entry wounds, all of which were contact wounds. Each wound was internally bevelled with characteristic fractures of projectile trauma. While the multiple fatal injuries were cause for suspicion of homicide at first, the injuries were concluded to be self-inflicted since the rifle found on the lap of the decedent was capable of rapid fire (Austin *et al.*, 2013).

Dixon (1982) describes a case where a 26-year-old man had been shot in the head with a shotgun at a range of 30.50 cm. The ammunition was a #6 shot (birdshot) fired from a 12-gauge shotgun and struck tangentially. The keyhole defect of the cranium measured 6.40 cm in length and 2.50 cm in width (Figure 2.22) while the soft tissue damage expands over a wider area than the bony defect (10.20 cm length and 5.00 cm width). The circular portion of

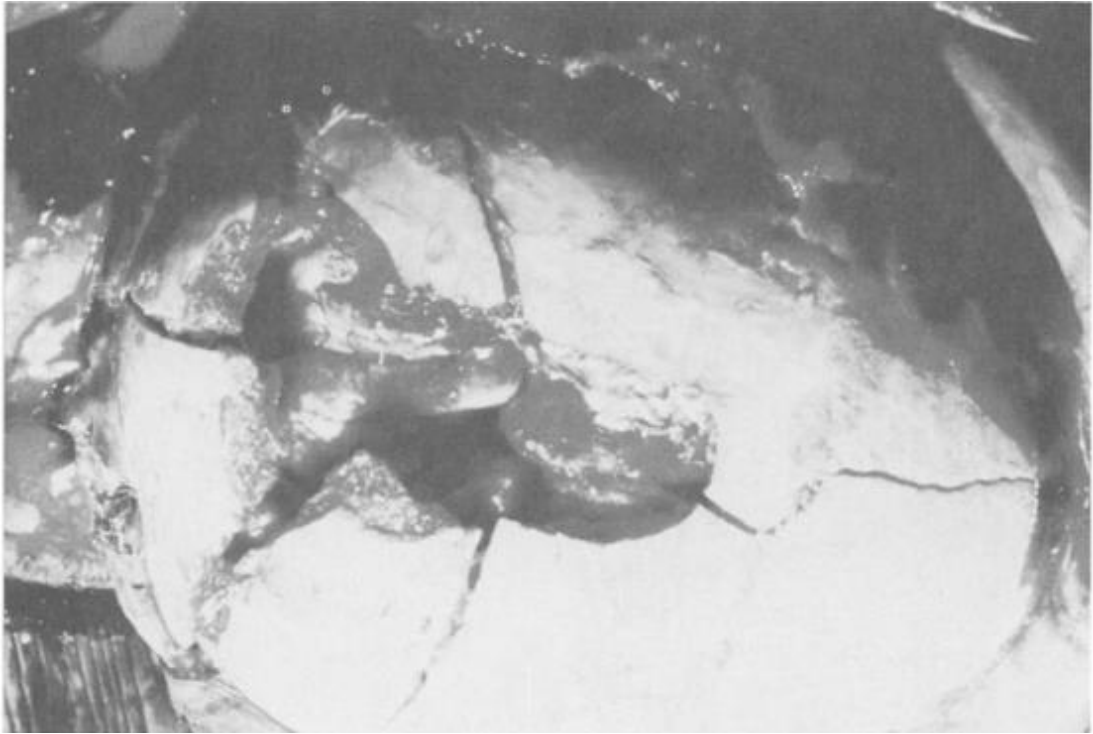


*Figure 2.22 Keyhole fracture observed in homicide victim (source: Dixon, 1982: 558).*

the keyhole was the point of initial contact and bevelled internally while the triangular portion (the exit) bevelled externally. Radiating fractures were also present (Dixon, 1982).

Tsuboi *et al.* (2014) describe a suicide case where the deceased (a male in his late 50s) used a homemade shotgun. The weapon was constructed using a larger tube (27.70 cm in length; 23.00 mm internal diameter) with a short narrower tube (13.90 cm in length; 21.10 mm internal diameter) inserted in it to act as the barrel of the weapon. The deceased used live ammunition, presumably he had kept live ammunition from when he had owned a shotgun which he had surrendered to the authorities five years prior. The firing mechanism consisted of a hand-made firing pin which included a nail, screwdriver, and hammer (which was used for firing by hitting the tip of the screwdriver). The load was shot into his upper abdomen, producing a 2.30 x 2.50 cm open lesion. Due to the lack of powder burn and soot imprint as well as the state of advanced decomposition upon discovery, the cause of death was not initially apparent. It was not until the autopsy when 149 pellets were

removed from the abdomen that the pipe found next to the body was recognised as the weapon used in the self-inflicted fatal injury.

#### 2.4.6. Archaeological Case Reports

While cases of trauma inflicted by firearms are arguably the most common type of trauma reported in a forensic context, they are relatively uncommon in archaeological contexts. With the popularisation of the musket in the 16<sup>th</sup> and 17<sup>th</sup> centuries, firearms would have been a part of the archaeological record for three or four centuries. Even with this consideration, there are still some reports which describe cases of skeletal trauma which had most likely been caused by a firearm.

Gill *et al.* (1984) described the trauma observed on the skeletal remains of a male frontiersman (estimated to have been between the ages of 31 and 37) found at the Korell-Bordeaux site (48GO054) near Lingle, Wyoming, United States. This burial (Burial 15) contained the remains of the only individual of estimated European descent at this grave site, whereas the other nine adult skeletons were estimated to have been Native Americans and five subadults of unknown ancestry. The individual had been buried in a mostly standard anatomical position, with the right forearm placed across the chest and the left forearm across the abdomen. Boots were still on the feet, a hat had been placed over his head, and remains of what were once leather pants were found near the legs. Based on the wear of three copper nickels found with the remains, it is estimated that the burial most likely took place in 1869 or 1870.

The skeletal remains of Burial 15 exhibited multiple perimortem projectile wounds (estimated to be a .44 or .45 calibre weapon), most likely the cause of death (Gill *et al.*, 1984). One of the projectiles entered the cranial vault through the frontal bone (Figure 2.23), 4 cm above the supraorbital margin of the left orbit. The entrance defect was circular in shape with sharp edges,

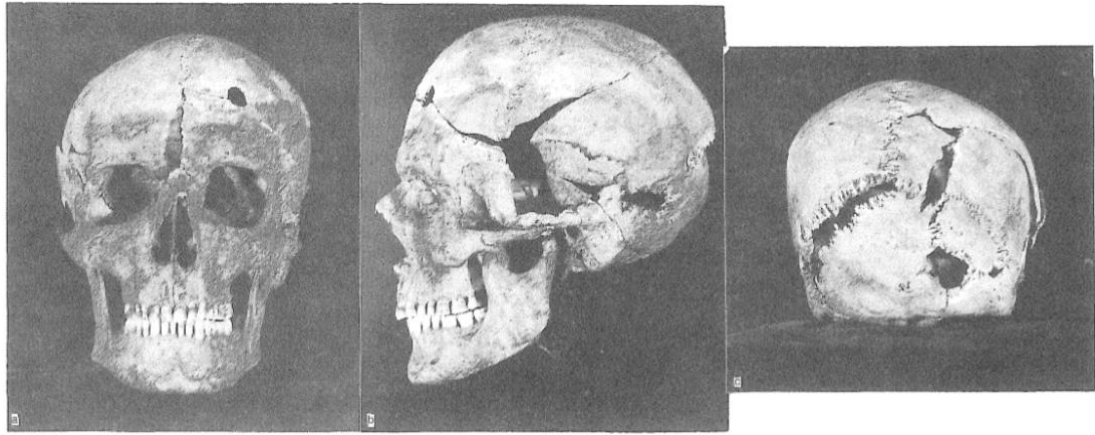


*Figure 2.23 Skull of individual in Burial 15 (source: Gill et al., 1984: 233). Left: projectile's entrance defect on the left frontal. Middle: lateral view of radiating fractures originating from the entrance defect. Right: exit defect of the projectile on the right occipital.*

exhibited bevelling on the internal table of the cranial vault, and measured 12 mm in diameter. The projectile travelled through the length of the cranial vault, exiting on the low right side of the occipital. The exit defect was approximately circular in shape, exhibited bevelling on the external table of the cranial vault, and measured 4 cm in diameter. Radiating fractures originated from both the entrance and exit defects, but no concentric heaving fractures were present.

While the height of the individual was estimated to be about 6 ft 1 in (185.42 cm), the trajectory of this projectile suggests he was shot from above. While this initially seems unusual, it could be explained by a second projectile wound to the proximal epiphysis of the left femur. The large calibre projectile caused extensive fragmentation between the femoral metaphysis and femoral neck. The most likely sequence of events is that the shot to the femur came first, causing the individual to fall to the ground, where he was then shot in the head from overhead.

When examining the skeletal remains from a mass grave in a 17<sup>th</sup> century battle site (part of the Polish-Swedish war of 1655-1660) located in Golańcz, Poland, Łukasik *et al.* (2018) analysed the trauma found on the skeletal remains excavated from the mass grave of the site. Of the 25 individuals excavated, 22 individuals exhibited trauma, with 90 total injuries between



them. While most skeletons exhibited sharp force (80.00%) and/or blunt force trauma (8.00%), there was one individual (4.00%) which showed evidence of projectile trauma on the right os coxae. While an osteoarchaeological analysis could not be conducted on the trauma itself due to excavation damage, the authors were able to hypothesise that the trauma was inflicted by a musket based on historic registers of the belongings of military commanders. Based on these registers, most Swedish commanders carried bladed instruments, but subordinate officers carried firearms such as muskets. Combined with the discovery of a musket bullet near one of the individuals in this mass grave, it is a logical conclusion that this individual had been shot in the hip with a musket.

## 2.5. Archery Ammunition

Both hand bows and crossbows use similar ammunition, arrows for the former and bolts for the latter. Arrows and bolts consist of a shaft which in modern ammunition is commonly metallic or fiberglass, a metallic tip on the target side of the shaft, a plastic nock on the bowstring end of the shaft, and three plastic or feather fletchings positioned in a Y-formation around the shaft near the nock which improve stability in flight (Bergman *et al.*, 1988; Park, 2011b; Merlin Archery, 2019a; Lepers and Rots, 2020). The differences between arrows and bolts are primarily in dimensions: bolts are shorter and thicker than arrows (Mukaiyama *et al.*, 2011). These dimensional differences alter the mass of the constructed arrows and bolts as well as the rigidity, meaning that bolts tend to have a greater mass (though this can vary based on shaft material and tip type) and be stiffer than arrows, limiting the oscillation that is typically seen in arrows (Mukaiyama *et al.*, 2011; Miyazaki *et al.*, 2013).

There are two main types of tip for bolts and arrows: the broadhead and the field tip (Hain, 1989; Chang and Hsee, 2010; Germerott *et al.*, 2010; Salem and Churchill, 2016). There are also two subsections of broadhead tip: fixed

broadhead and mechanical broadhead, both of which are preferentially used for hunting (Pedersen *et al.*, 2014; Sung *et al.*, 2017b). Fixed broadheads have multiple blades attached to the tip with no moving parts while mechanical (sometimes referred to as expandable) broadhead tips have blades that expand upon impact in order to cut more soft tissue (Pedersen *et al.*, 2014; Smith-Blackmore and Robinson, 2018). Both designs of broadhead are made (commonly in two- or three-blade formations) to ensure that the arrow or bolt lodges in the target, causing it to bleed and leave a blood trail as it runs away (Grellner *et al.*, 2004; Pedersen *et al.*, 2008). While bowhunting is illegal in the United Kingdom (Wildlife and Countryside Act, 1981), broadhead tips are still available for sale, purchase, and use. The field tip is more conical shaped and is used more in sports and for target practice (Chang and Hsee, 2010; Grellner *et al.*, 2004) (Figure 2.24).

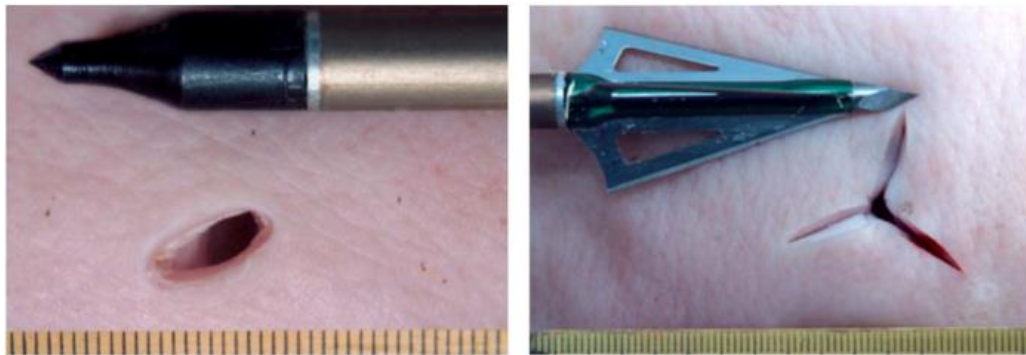


Figure 2.24. Two types of arrow/bolt tips and associated soft tissue damage. Left: field tip. Right: fixed broadhead tip (source: Karger *et al.*, 2004: 335).

## 2.6. Hand Bows

This section explains the general mechanisms of hand bows, discusses what is currently known about the trauma that arrows create, and describes a sample of published forensic and archaeological case reports.



### 2.6.1. Mechanisms

Modern hand bows are typically categorised as either recurve or compound bows. Recurve bows consist of two elastic limbs connected by a rigid middle part which the archer uses to hold the weapon (grip) (Figure 2.25) (Bergman *et al.*, 1988; Kooi, 1991). The limbs are oriented so that they are above and below the grip while a bowstring is attached to the upper extremity of the upper limb and the lower extremity of the lower limb (Kooi, 1991). When an archer sets an arrow on the string and pulls the bowstring back into a full draw, the limbs are retracted back, causing an increase in potential energy behind the nocked arrow (Bergman *et al.*, 1988; Kooi, 1991; Park, 2012).

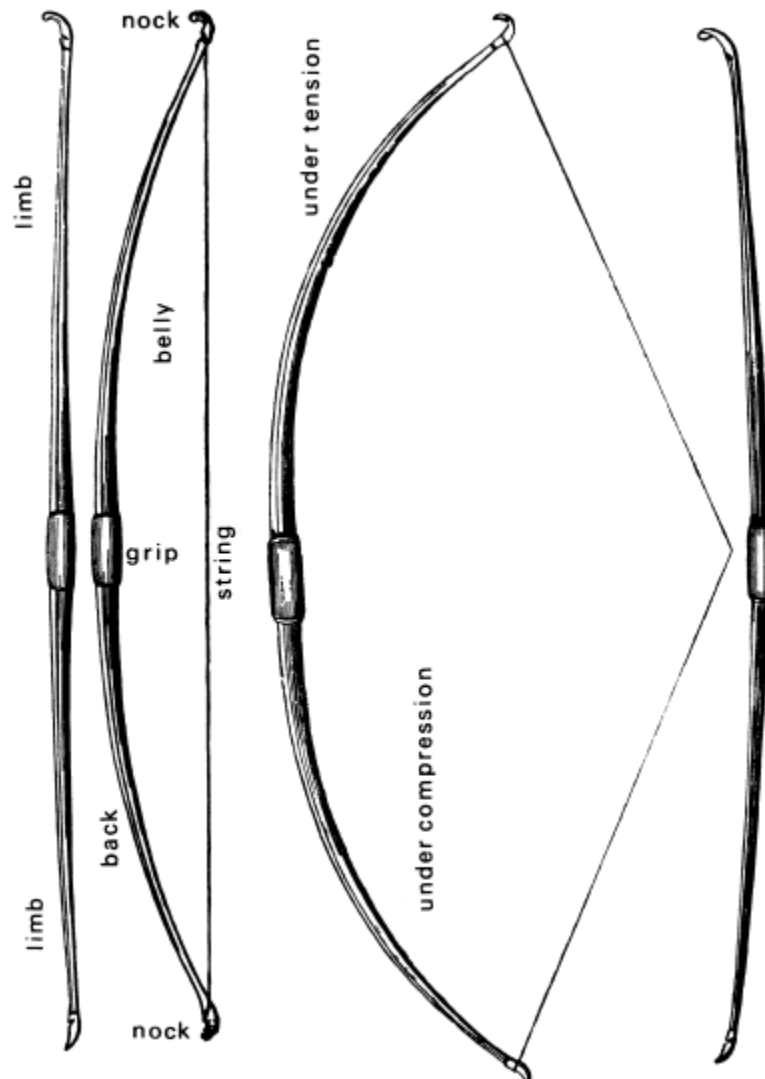


Figure 2.25 Basic hand bow design (source: Bergman *et al.*, 1988: 659).

Upon release, the energy is transferred to the arrow, which is then propelled forward (Kooi, 1991; Park, 2012).

Compound bows use a much more complex mechanism to propel an arrow forward. Where a recurve bow has one bowstring, a compound bow uses multiple strings and cables which connect with and rotate eccentric cams (discs with an off-centre rotational point) on the end of each limb (Figure 2.26) (Park, 2011a; Sung *et al.*, 2017a). A compound bow can either be a single or dual cam system where single cam bows will have a simple wheel on the second limb (Park, 2009; Park, 2011a; Merlin Archery, 2019b). These cams will modify the force-characteristics of the bowstring and provide a more powerful draw weight (Park, 2011a; Maidin and Jaafar, 2015).

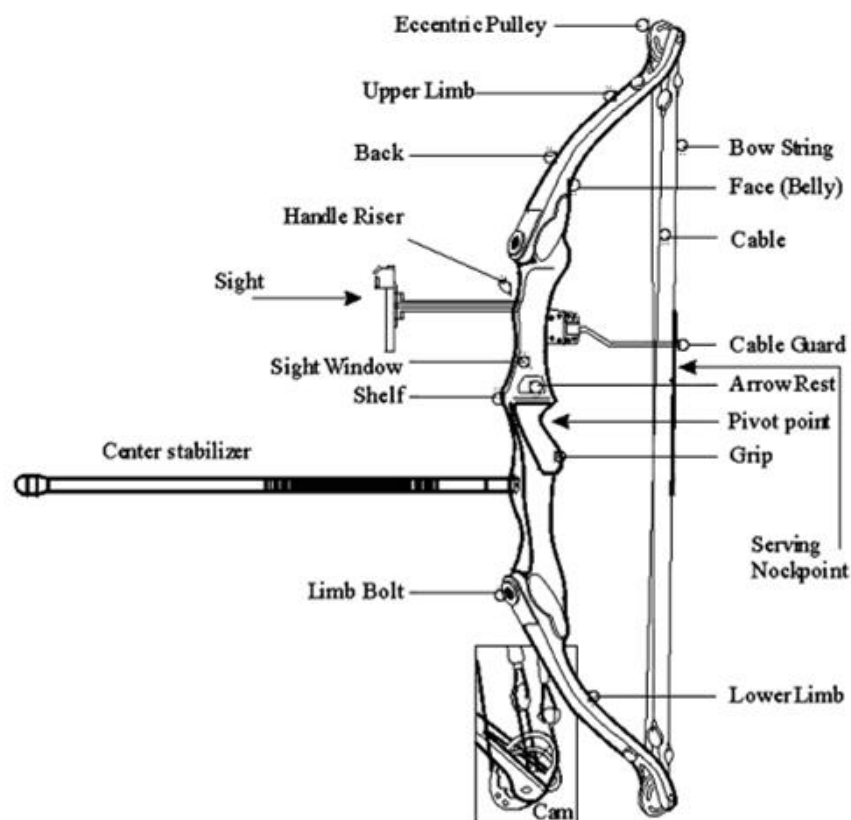


Figure 2.26. Compound hand bow (source: Zanevskyy, 2012: 169).

The off-centre rotational point of the cam(s) also produces a fluctuating force necessary to draw the bowstring (Figure 2.27). As the archer pulls the bowstring back, a significant amount of force is needed at the beginning of the pull, but the necessary force drops near the maximum draw length,

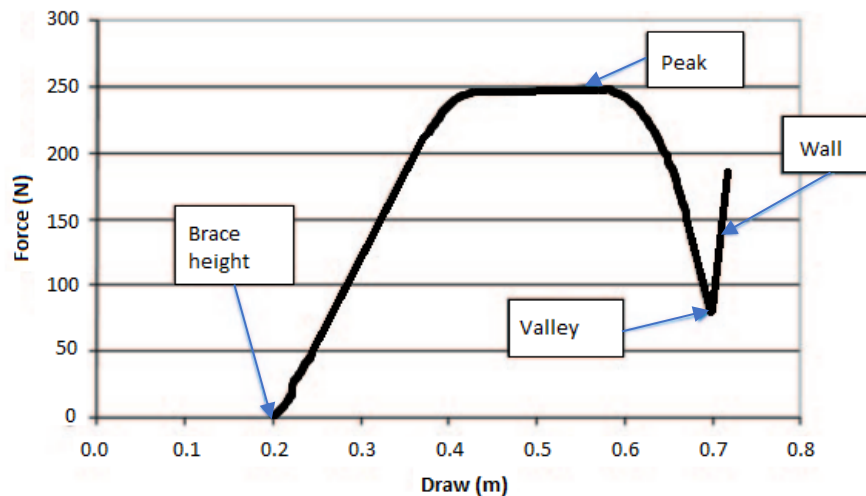


Figure 2.27. Typical force-draw curve for a compound bow (source: Park, 2011a: 9).

making it easier for the archer to hold the draw while aiming. Additionally, archers using a compound bow will pull and release the bowstring using a mechanical release device which uses a trigger release of the bowstring (Park, 2011a). This device makes consistent release technique easier for archers compared to manually pulling and releasing the bowstring of a recurve bow with their fingers.

The measure (notated in pounds) of the amount of force necessary to pull the bowstring back (for all archery weapons) is the draw weight of a bow (Cabela's, 2016; Pontzer *et al.*, 2017). This force is then transferred to propel the arrow (or bolt) forward (Cabela's, 2016). The amount of force that a bow can put behind a bolt affects the velocity and kinetic energy of the arrow/bolt, affecting the damage that the projectile inflicts on its target. The draw weight of bows varies between make models, but on average, recurve bows have the lowest draw weights, followed by compound bows, then recurve crossbows have the second highest draw weights, followed by compound crossbows (Cabela's, 2016; Verma, 2020).

### 2.6.2. Trauma

Smith *et al.* (2007) note that cases of projectile trauma in the archaeological record are typically only identified when projectile points are embedded in the bone or sometimes when penetrating injuries are present. This study sought to identify methods of identifying trauma caused by stone-tipped arrows when the projectile is not embedded in the bone by observing skeletal damage itself. Two sets of experiments were conducted. The first used a longbow (single stave made from yew) and replica arrows with flint arrowheads to shoot cattle and pig scapulae as well as cattle ribs, all with small amounts (up to 5 mm thickness) of soft tissue still attached. Modern arrows were also used to assess if the two types of arrow produced comparable damage. All arrows were fired at close range (3-5 m).

The second experiment used a Charpy impact-testing machine instead of a bow, allowing the examiners to control all variables of the shooting itself, such as the angle and velocity of the flight path. This firing mechanism was used to shoot cattle scapulae. The results of this study showed three main findings. First was that flint arrowheads were capable not only of completely perforating both sides of the flat bone, but also produced internal bevelling. The second finding was that the flint arrowheads frequently left small tips embedded in the bone, with 43.75% of impacts in this study leaving fragments in the bone. Finally, when microscopically examining the bone, the flint arrowheads commonly left striations on wounds which did not have full thickness punctures (19/25; 76.00%). These findings show that it is possible to identify cases of projectile trauma within the archaeological record even when the projectile is not present.

### 2.6.3. Forensic Case Reports

The following reports describe investigative and medical cases of trauma inflicted by hand bows. These cases were selected to include both compound and recurve bows as well as fixed broadhead tips and field tips. While one

case of cranial trauma inflicted by hand bow is examined in this section (O'Neill *et al.*, 1994), cases of postcranial trauma are more frequently reported in the literature. The cases of hand bow trauma featured in this section include homicides, suicides, and accidental injury.

O'Neill *et al.* (1994) describe a case where a 25-year-old male survived being shot with a compound bow after having a friend attempt to shoot a can off the top of his head. The aluminium shaft arrow with a fixed broadhead entered through the right eye orbit, crossed through the brain material in the cranial vault, and then lodged itself in the occipital bone with a small portion of the tip protruding through the scalp (Figure 2.28). Following major surgery to remove the arrow, the patient recovered with no complications and left the hospital after eight days (O'Neill *et al.*, 1994).

Additional cases reports describe suicides and homicides in which a compound bow had been used, but in most cases, the victims had been shot

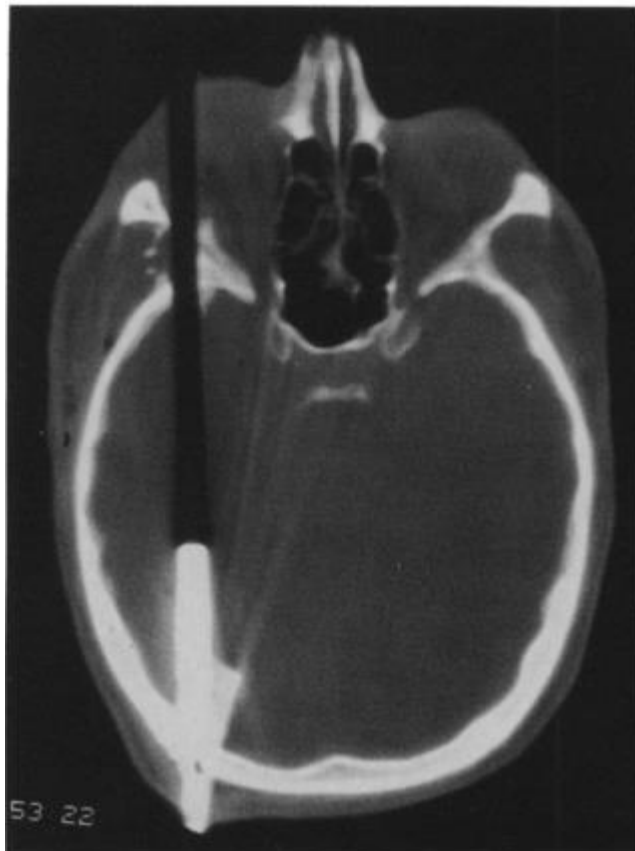


*Figure 2.28 CT image along the transverse plane (source: O'Neill *et al.*, 1994: 495). The arrow travelled posteriorly from the eye orbit and lodged in the occipital.*

in the chest. Cina *et al.* (1998) describe a case where a 17-year-old male committed suicide using a model Whitetail II compound bow with a 60 lb draw weight. The victim had used his feet to draw the bow and released the arrow at his chest at point-blank range. The arrow, fitted with a broadhead tip in a three-blade configuration, passed through the chest and embedded into the ninth thoracic vertebra. The victim died at the scene.

Wilson *et al.* (2004) examine a case in which a 46-year-old male committed suicide using a compound bow. The victim had used a Whitetail Hunter compound bow with a draw weight between 50 and 70 lb and a 34-inch aluminium arrow equipped with a broadhead tip in a four-blade configuration. The arrow was shot at point-blank range, entering through the abdomen and exiting through the ninth intercostal space. The body was found with the arrow in situ and the bow at the feet. No skeletal trauma was noted.

Eriksson *et al.* (2000) describe a homicide case in which a 59-year-old male had been shot using a compound bow. The body of the victim was found with three arrows in situ: one broadhead-tipped arrow in the chest, one in the abdomen, and an arrow equipped with a field tip arrow in his arm. The arrow which struck the chest passed through the sternal body and penetrated 28 cm into the body, while the arrow in the abdomen hit the 10th rib and the arrow in the arm caused no skeletal damage. The shooter had used a 45-60 lb draw weight compound bow from a distance of approximately 5 m.

Hain (1989) briefly examines a case where a 32-year-old male was shot with a compound bow following an altercation. The arrow, equipped with a fixed broadhead tip in a four-blade configuration, entered through the right bicep and then the right side of the chest, exiting through the left side of the chest. The entrance and exit lesions (as well as the damaged muscle tissue in between) reflected the x-shape of the broadhead tip.

#### 2.6.4. Archaeological Case Reports

The following reports describe archaeological cases of trauma in which the original examiners of the skeletal remains concluded that the trauma was inflicted by hand bows. Nearly all of the cases described in this section were identified based on the presence of lithic points which had embedded in the bone, including both cranial and postcranial elements.

Jurmain (2001) analyses the trauma found on the skeletal remains of 162 individuals from the Yukisma site (SCI-038), a prehistoric site located in the northern Santa Clara Valley, California (United States). While most of these cases are either blunt or sharp force trauma, obsidian projectiles, most likely tips of arrows, were found embedded in the skeletal remains of four individuals (Figure 2.29). Three of these individuals were estimated to have been male and one was of indeterminate sex. The estimated age range for these four individuals was reported as 16-35 years with an average age of

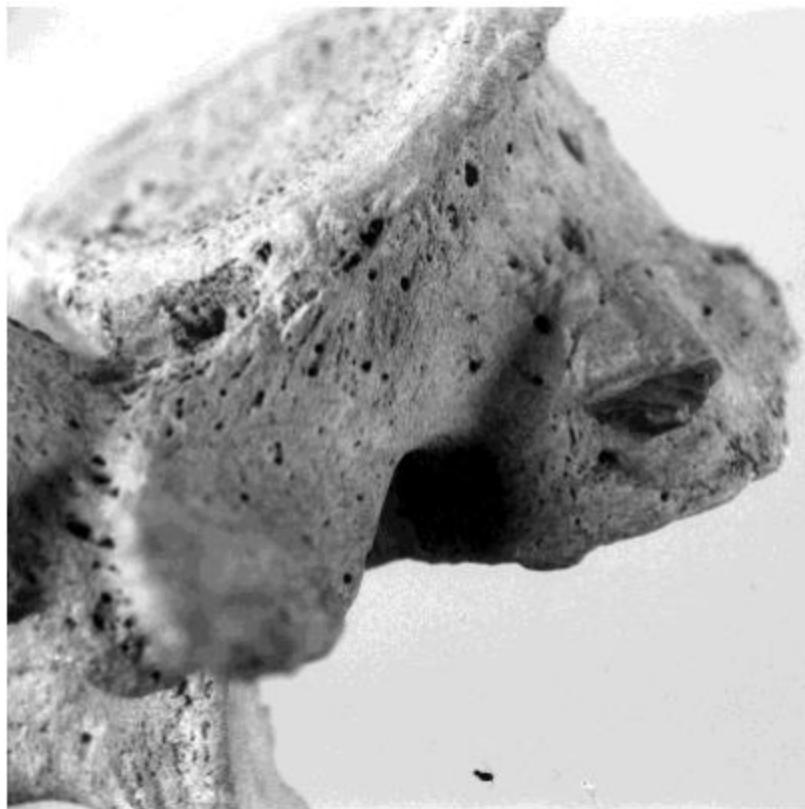


*Figure 2.29 Embedded obsidian projectile on the body of a fifth lumbar vertebra. Significant healing is present. (source: Jurmain, 2001: 17).*

23.80 years. All four projectiles were embedded in postcranial skeletal elements, specifically a lumbar vertebra, a rib, a hand phalanx, each found separately on the four separate individuals. Bony reaction and healing were present on the vertebra, rib, and phalanx, indicating that these were antemortem injuries, but there was no evidence of healing on the femur, indicating that it was most likely a perimortem injury.

In their study of patterns of interpersonal violence within a prehistoric central Californian population, Jurmain *et al.* (2009) examined the craniofacial fractures, projectile injuries, forearm fractures, and perimortem bone modification found on the skeletal remains from the CA-ALA-329 site (San Francisco, USA). Of the estimated 503 individuals examined in this study, 393 individuals were used for analysis of projectile trauma. This subset consisted of 158 males, 154 females, and 81 individuals of indeterminate sex (51 of which were adolescents). Amongst these individuals, it was concluded that only 15 showed evidence of projectile trauma. The only evidence for presence of projectile trauma which was noted was that there were 17 projectile points found embedded in the bones of 15 individuals. Nine of these individuals were males, five were female, and three were of indeterminate sex, showing no significant difference in prevalence of trauma between the sexes. The age distribution, however, showed a significantly higher prevalence of trauma in young adults (16-34 years). Three of the individuals (average age: 35.20 years; sex unspecified) wounds which had completely healed. The location of the projectiles showed no distinct patterns: points were found in cranial and postcranial elements, elements of both the axial and appendicular skeletons, as well as were equally distributed anteriorly and posteriorly, and medially and laterally. Overall, the prevalence of projectile injury was significantly higher at this site than at most North American sites but did not stand on both a more local and global scale. It is worth noting, however, that the methods of projectile trauma identification are severely limited, relying on the projectile embedding in the bone, which is not guaranteed. In both this study and the previous study (Jurmain, 2001), the



frequency of projectile injury is likely underrepresented due to limited methods of projectile trauma identification.

Creighton *et al.* (2020), however, were able to identify arrow trauma on skeletal remains without any part of the projectile embedded in the bone. The remains were excavated from a burial site (EPH06 8849) affiliated with a medieval Dominican friary in Exeter, England. Of the 30 bone fragments from the skeletal material excavated at this site which exhibited traumatic injury, only one cranial vault (sex and age unspecified) showed evidence of trauma. Superior to the right orbit, two sides of a right-angled puncture were still observable (Figure 2.30). Upon microscopic examination, a small area (~1 mm) of spalling and a small (3.20 mm) radiating fracture originating from the superior corner of the defect were observed on the external surface of this defect. It was hypothesised that the shape and size of the entrance defect (5.80 mm medio-laterally; 5.20 mm supero-inferiorly) of this puncture defect

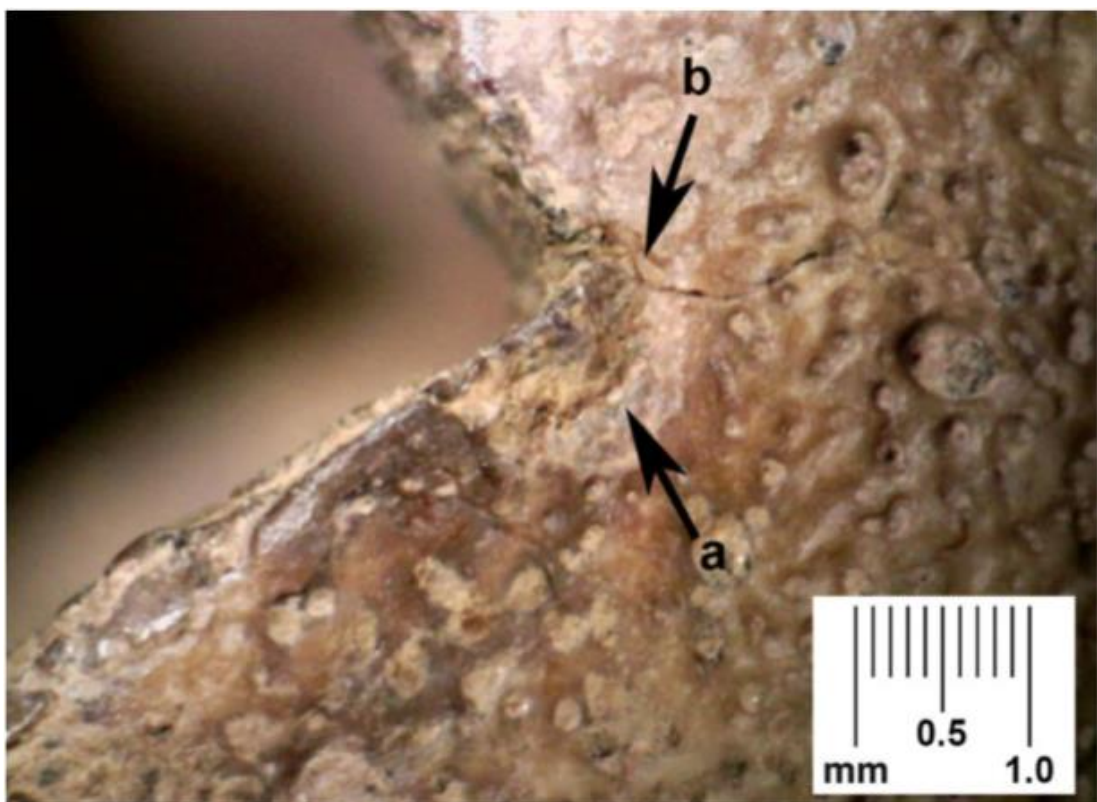


Figure 2.30 External view of a right-angled cranial injury found on remains from a medieval burial site (EPH06 8849). a) spalling on the ectocranial surface b) radiating fracture originating from the corner of the puncture wound (source: Creighton *et al.*, 2020: 10)

represent the cross-section of the impacting implement. Based on this hypothesis, it was concluded that this injury was most likely caused by a bodkin-type arrowhead. Furthermore, the examiners state the unlikelihood that this arrow was shot using a crossbow as crossbow bolts tended to be larger in size.

A second injury was noted on the occipital of the same cranium, assumed to be an exit defect affiliated with the previous injury (Creighton *et al.*, 2020). This defect measured 24.60 mm medio-laterally, but the height could not be ascertained due to fragmentation. Spalling was, again, noted on the external surface of the defect, as well as multiple radiating fractures, expanding laterally on both sides. An unexpected observation was the presence of bevelling on the internal surface of the exit defect instead of the external surface. This is most likely a result of the retraction of the penetrating object as no arrowheads were found in the cranial vault.

## 2.7. Crossbows

This section explains the general mechanisms of crossbows, discusses what is currently known about the trauma that these projectiles create, and describes a sample of published case reports (both forensic and archaeological).

### 2.7.1. Mechanisms

Downs *et al.* (1994) describes a crossbow as “a derivative of the longbow and a predecessor of the rifle” (Downs *et al.*, 1994: 428), that is to say a crossbow has components and functionality of both its predecessor (the longbow) and its successor (the rifle) (Figure 2.31). The bowstring is pulled back manually or with a crank and latched onto the trigger mechanism.

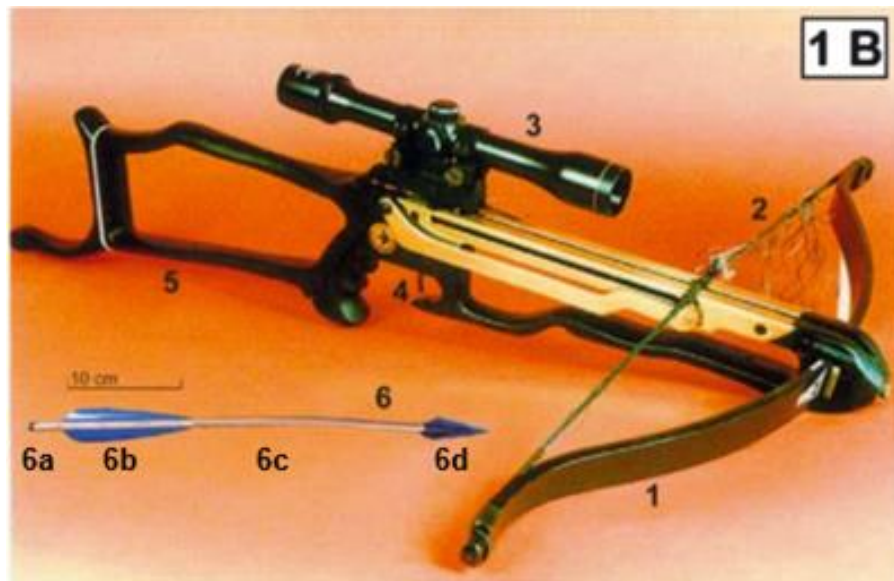


Figure 2.31. Components of a recurve crossbow 1) limbs, 2) bowstring, 3) sight, 4) trigger, 5) stock, 6) bolt, 6a) nock, 6b) fletching, 6c) shaft, 6d) tip (source: Grellner et al., 2004: 19).

Crossbows can be either recurve or compound, both of which reflect the same mechanism as their hand bow counterparts.

A bolt is loaded into the weapon by placing the nock end of the bolt against the bowstring. When the trigger is pulled, the bowstring is released, propelling the bolt forward with the force built up in the bending of the bow limbs (Grellner et al., 2004). Because the bolt does not tumble like a bullet or oscillate like a longbow arrow (Mukaiyama et al., 2011; Miyazaki et al., 2013), injuries caused by crossbow bolts have been found to simply separate the soft tissue, creating a channel rather than cavities (Endara et al., 2001; Kaynaroglu and Kiliç, 2012; Omura et al., 2017).

### 2.7.2. Trauma

Most of the literature surrounding crossbow trauma consists of case reports describing accidental discharge (Salam et al., 1990; Chang and Hsee, 2010), suicides and suicide attempts (Hain, 1989; Endara et al., 2001; Preiss et al., 2003; Byard et al., 1999; Smyk, 2009; Xiao et al., 2016), and homicides (Grellner et al., 2004; Karger et al., 2004). Throughout these cases, the most common wound locations are in the thorax and skull. Yet in forensic cases

involving crossbows where the weapon was not found at the scene, it is not uncommon for the trauma on the body to be confused with gunshot trauma (Randall and Newby, 1989; Zátopková and Hejna, 2011).

There is, however, one study of note (Randall and Newby, 1989) which examined through experimental means the soft tissue damage inflicted by crossbow. Randall and Newby describe a case where a deer had been killed using a 12- or 20-gauge shotgun slug during archery-only season and the hunter claimed to have killed the deer using a field-tip crossbow bolt.

Comparing the soft tissue damage of crossbow bolts and various bullets on mostly roadkill samples, it was found that bullets tend to leave a more regular circle-shaped entrance wound with prominent abrasion rings while field-tipped crossbow bolts produce an irregular entrance wound without abrasion rings (Randall and Newby, 1989). Additionally, nearly all the samples shot using guns showed a presence of metallic deposits whereas the samples shot using a field-tip bolt contained no residue from the projectile (Randall and Newby, 1989).

While Randall and Newby (1989) provide beneficial insights into the features of damage inflicted by crossbows, the knowledge of this trauma is still greatly limited. This publication is one of the first studies to observe the destructive features of field-tip bolts on soft tissue through experimental means, but they did not examine the damage field-tips would inflict upon skeletal elements.

### 2.7.3. Forensic Case Reports

The following reports describe cases of homicides and suicides which were inflicted by crossbows, including recurve and compound crossbows as well as field tip and broadhead tips. These cases were selected to be representative of real cases with emphasis on trauma caused to both cranial and postcranial skeletal elements and a secondary focus on trauma patterns which reflect the shapes of broadhead tips. One case (Pomara *et al.*, 2007) also exemplifies a case in which the observed trauma was initially mistaken

to have been inflicted by a firearm. Three news articles which involve the use of a crossbow are also discussed to exemplify the relevance of crossbows in a forensic context. While these publications do not examine the trauma inflicted to the body of each victim, they demonstrate the current use of crossbows in acts of violence.

Panata *et al.* (2017) report a case where a 40-year-old man committed suicide using a Barnett Commando II compound crossbow. The bolt, tipped with a three-blade fixed broadhead, entered through the suprahyoid region and travelled superiorly and posteriorly through the cranial vault where the tip embedded into the left parietal region. The soft tissue along the path of the bolt (including skin, tongue, and dura mater) reflected the Y-shape of the blade configuration. The exit defect exhibited bevelling on the external table, radiating fractures, and fragmentation between the intruding blades of the broadhead tip.

Pomara *et al.* (2007) describe a homicide where a 52-year-old male had been shot with an initially unknown weapon. It was later discovered that the weapon used had been a recurve crossbow with a field-tipped bolt. Since the perpetrator had removed the bolt and both the entry and exit defects had characteristics which mimicked the typical aspects of gun trauma, it could have easily been confused with a firearm wound. The circular entry defect (measuring 1 cm in diameter) on the occipital bone exhibited bevelling on the inner table of the bone while the irregularly shaped exit defect on the frontal bone exhibited bevelling on the outer table of the bone (measuring 1.30 cm × 1.00 cm). Experimental tests were run to try to replicate the observed trauma in this case using a crossbow with a field-tipped bolt and a captive bolt gun with cranial models made of plaster. The results of these experiments showed that the crossbow was the more likely murder weapon of the two. Upon searching the property of the suspect, a recurve crossbow was found which the investigators confirmed was the murder weapon.

Downs *et al.* (1994) describe two cases of homicide and one case of suicide which involved the use of a crossbow. In the first case, a man attacked his

ex-wife with a knife, but shot himself in the head with a Thunderbolt-2 compound crossbow (150 lb draw weight) after she called the police. He was brought to the hospital by the police but died approximately two hours later and the bolt was still in situ. The fixed broadhead-tipped bolt entered through the right orbital plate, exiting through the right occipital. The exit defect bevelled externally and reflected the shape of the three-bladed configuration of the tip, with three radiating fractures.

The second case involved a 27-year-old woman shot by her estranged husband following a domestic argument. The husband claimed that his loaded crossbow accidentally fired, and the bolt struck the woman in the back and the woman then begged for him to end her life as the pain was unbearable. He then shot her in the back again with the crossbow. The crossbow was a Barnett crossbow with a 100-125 lb draw weight and both bolts were equipped with fixed broadhead tips in a three-blade configuration with a diameter of 2.40 cm. The first bolt entered between the second and third cervical vertebrae, lodging in the spinal cord while the second bolt entered in the ninth intercostal space and exited through the second intercostal space. The tip of the second bolt was blunted, suggesting that the victim had been lying down when shot for a second time and the bolt blunted when it struck the floor (Downs et al., 1994).

In the final case, an 18-year-old man shot a 28-year-old homeless man with a crossbow (model unknown) after having grown bored with shooting targets that did not move. The bolt was equipped with a fixed broadhead tip in a four-blade configuration measuring approximately 2.40 cm in diameter. The bolt had entered the thoracic cavity between the fourth and fifth ribs (anterior to posterior), penetrating the right lung and heart (Downs et al., 1994).

Smyk (2009) summarises a case in which a 49-year-old male committed suicide using a recurve crossbow (model unspecified). The crossbow had been equipped with a fixed broadhead-tipped bolt in a three-blade configuration. The bolt entered anteriorly through the left chest just superior to the nipple, passed through the fourth intercostal space, and lodged in the

left lung at the level of the fifth intercostal space. The wound tract was about 20.00 cm long, reflected the triple-blade shape and size (1.50-2.00 cm per blade) of the broadhead tip, and did not produce an exit wound.

Taupin (1998) examined specifically the damage to textiles of two cases involving crossbow homicides. In the first case, a human torso wrapped in a tarpaulin was discovered on a beach. The following day, another bundle, containing two severed hands, two severed feet, a severed head, a tie, a shirt, and a pair of underpants, was discovered nearby. The legs and remaining clothing were never recovered. A crossbow bolt equipped with a fixed broadhead tip in a three-blade configuration was still lodged in the torso with the shaft broken off. As the bolt passed through the shirt and thoracic cavity, where it pierced the right ventricle of the heart, it produced a cut to the shirt which reflected the three-blade configuration of the fixed broadhead tip.

The second case involved a middle age man who went missing. Ten years later, the son boasted to a friend that he had shot his father in the stomach with a crossbow, buried the body, and burned the remains 18 months later, disposing of what remained into a local river while the crossbow was never found. A previous girlfriend of the son alleged that he had shot her bed with a crossbow during a recent altercation, leaving Y-shaped cut marks. The bedding was examined and used as evidence during the trial, using the findings of the first case as a reference. Based on the distinct marks left by the fixed broadhead bolt, the son of the deceased was found guilty even without the body or weapon (Taupin, 1998).

The distinctive shape of the broadhead tips, in these instances a three-blade Y-shaped configuration, left corresponding tear marks in the fabric, aiding in both the correct identification of the weapons used and the conviction of the guilty parties (Taupin, 1998). It was concluded that damage to textiles may more clearly indicate the geometry of the weapon than the damage to the underlying soft tissue.

Three news stories of crossbow use occurring in the past five years are also worth noting. In June of 2016 in the city of Philadelphia (United States), a

man shot his wife with a crossbow (model and tip unspecified), believing her to be Satan (Anonymous, 2016). She later died in the hospital and in 2017, he was found guilty of non-premeditated murder (Slobodzian, 2017). In April of 2019 in the town of Holyhead (Wales), a man was shot with a crossbow (model unspecified) while fixing his satellite dish (Anonymous, 2019a). The arrow, equipped with a broadhead tip, punctured his stomach and he died from the injury three weeks later. A man was later found guilty of the murder in early 2020 (Anonymous, 2020). The final news story occurred in 2019 in both Passau, Bavaria, and Wittingen, Germany (Anonymous, 2019b). Three bodies (one male and two female) were found in a hotel room in Passau, each with multiple crossbow bolts in the head and chest. Shortly after, two more bodies (both female) were found at their home in Wittingen, both also had crossbow bolts in their heads and chests. It was, however, estimated that the Wittingen victims had died days before and that the two cases were linked to each other. It was believed that the male victim in Passau had led a cult devoted to medieval folklore and that the deaths involved in this case were most likely the result of a murder-suicide pact, but no crossbows were recovered at either scene.

#### 2.7.4. Archaeological Case Reports

The following reports describe instances of trauma found on archaeological remains that were likely caused by crossbow bolts. These cases were selected to be representative of real cases which exhibit the current methods of identifying crossbow use in an archaeological context, which primarily relies on matching the shape of the trauma on skeletal remains to the shapes of known arrowheads. Even so, it is not always clear whether the arrows were shot with a crossbow or long bow. All three cases described the remains of individuals who fought in the battle of Towton (1461).

Novak (2007) describes the trauma found on the skeletal remains from the battle of Towton (1461). Three of these individuals were hypothesised to



have been struck by either crossbows or longbows. The first of these individuals (Towton 17) was a male whose age was estimated to have been between 26 and 35 years. Two injuries were found on the cranial vault, both roughly square perforations. One was on the right parietal and measured 15 mm in width and 16 mm in length while the other was on the left parietal and measured 10.00 mm in width and 11.00 mm in length. Both injuries had radiating fractures extending from the primary defect and as the fractures from the left injury intersected the fractures of the right injury, it was determined that the right injury was inflicted first. The injury on the left parietal exhibited ectocranial and endocranial bevelling, but bevelling was only present on the external table of the injury on the right parietal. These injuries were created by either a crossbow bolt or the beak of a war hammer, but they were both most likely created by the same weapon.

The second burial (Towton 21) was that of an adult male between the ages of 20 and 25 (Novak, 2007). An irregular puncture wound which was oblong in shape and measured 8.00 mm long and 2.70 mm wide was noted on the occipital. This projectile perforated a small portion of the cranial vault and produced bevelling on the external table along the inferior left margin of the opening. It was concluded that this lesion was created by a bodkin arrowhead as the shape of the lesion matched the profile of this arrowhead. The features of this injury match the description of a keyhole defect where the arrow travelled in a right to left direction on the occipital, producing external bevelling in the direction of the flight path of the arrow (along the left margin).

The third individual from the battle of Towton mass grave was an adult male between the ages of 36 and 45 (Novak, 2007). One of the injuries noted on the remains of the individual was an oval-shaped perforation on the left frontal bone. The lesion, which measured 14.50 mm long and 11.00 mm wide, had perforated the internal table of the cranial vault. There was also one radiating fracture that originated from the perforation and extended posteriorly. This fracture, however, was halted by the radiating fractures that

originated from another perimortem injury caused by a blunt force weapon. This indicates that the perforated injury occurred after the blunt force trauma. The shape and size of the perforation injury matched the profile of an armour piercing war arrowhead used in this battle, but it is unknown if this arrow was shot using a crossbow or a longbow.

## 2.8. Terminology Use in the Literature Describing Projectile Trauma (1980s-2010s)

The terminology used in the literature on projectile trauma analysis exemplifies the narrow scope of weapons which have been possible projectile weapons. Beginning with the 1980s, there is an overall trend of using terms like “gunshot trauma” and “bullets” exclusively, with very little use of terms like “projectile trauma” or “projectiles.” Researchers such as Spitz (1980) and Coe (1982) used “bullet” almost exclusively, without acknowledging that the trauma in which they described could be caused by other types of projectile weapons. Dixon (1982) did use the broader term “projectile” in his analysis of keyhole fractures, but the term is used interchangeably with “bullet.” This implies that “projectile” is simply synonymous with “bullet” and while all bullets may be projectiles, not all projectiles are bullets. Two years later, however, Dixon (1984a; 1984b) reverted to using “gunshot” and “bullet” almost exclusively when discussing trauma analysis methods.

The interchangeability of “projectile” and “bullet,” however, does bring to attention more complex semantics involved in describing trauma analysis. As previously stated, all bullets are projectiles, so describing a bullet as a projectile is not incorrect or misleading. The issue arises when researchers such as Dixon (1982), use over-specific terms (“bullet”) and more inclusive terms (“projectile”) interchangeably when describing methods which are applicable to more than just one projectile classification. The

interchangeability of the two terms is more acceptable and concise when discussing cases of trauma where the classification of the projectile is known and has been specified.

During the 1990s, there was a cementing of using over-specific terminology in forensic anthropology and osteoarchaeology with core texts, such as Berryman and Symes (1999), designating “gunshot trauma” as one of the three categories of trauma. Generally, the literature describing projectile trauma during this period hardly ever used terms like “projectile,” with researchers mainly opting for “gunshot trauma,” “gunshot wound,” and “bullets.” In their examination of archaeological remains, Berryman and Haun (1996) exclusively use the terms “gunshot” and “bullet” without acknowledging the consideration of other projectile weapons. Yet in the field of orthopaedics, McAndrew and Johnson (1991) use the phrase “airborne projectile” prior to specifying that the cases in which they examined were known to be specifically gunshot injuries. The few times during this time period in which “projectile” is used in forensic anthropology and osteoarchaeology, however, are when “projectile” is used as a synonym for “bullet,” such as is used by Smith *et al.* (1991). As seen in the previous decade, this gives the impression that all projectiles are bullets and “projectile” can mainly be used to lower the number of times “bullet” is used when describing trauma caused by firearms.

It was not until the 2000s that a shift in terminology was noticeable. The beginning of the decade still shows the remnants of the 1990s, with Berryman and Gunther (2000) still clinging to the exclusive use of “gunshot” and “bullet.” While this article (Berryman and Gunther, 2000) does examine known gunshot cases, using “bullet” to describe the methods of projectile trauma analysis, as previously discussed, implies that these methods are not applicable to other forms of projectile. It is not long after when a distinct change in terminology is apparent. In their description of the methods used in trauma analysis, Smith *et al.* (2001) are some of the first to use the more-inclusive phrase “ballistic trauma” rather than simply “gunshot trauma.” While

they do mirror Dixon's (1982) tendency to use "bullet" and "projectile" interchangeably, this article (Smith *et al.*, 2001) is still a pivotal point in terminology used as "projectile" is clearly used more than it had been by Dixon (1982) as well as it is important to see that these methods of trauma analysis are being described using the term "projectile." This shift even goes as far as researchers such as Knudsen (2005) actively acknowledging the possibility that "the wounding effect of bullets is not in principle different from that of other missiles used by people to injure each other: stones, javelins, spears, and arrows, be they from the longbow or the crossbow" (Knudsen, 2005: 413). These types of notes in the literature and the shift from "gunshot trauma" to "ballistic trauma" show how osteological methods were beginning to be adjusted in order to consider a wider range of weapons which are used in instances of trauma.

More recent literature has proved to be more consciously aware of non-firearm projectile weapons and concise with the terminology which is used. Most of the literature from the 2010s, however, focuses on case reports (Zátópková and Hejna, 2011; Austin *et al.*, 2013; Tsuboi *et al.*, 2014; Xiao *et al.*, 2015; Panata *et al.*, 2017) with little examination of analytical methods. Hanna *et al.* (2015), however, preface their study by specifying that they would focus on firearms and gunshot wounds, yet they continue to use inclusive terms such as "wound ballistics" and "projectile." Meanwhile, Stefanopoulos *et al.* (2014) examine the tissue damage caused by specifically handgun and rifle bullets, appropriately using the term "bullet" throughout their analysis. When discussing the physics of general terminal ballistics, however, they switch from using "bullet" to using the all-inclusive term "projectile," showing the acknowledgment that these concepts could be applied to non-bullet projectiles. Similarly, Smith *et al.* (2015) uses general terms like "projectiles" and "weapons," only using specific terms like "bullet" when referring to firearms. This study also shows the beginnings of weapon-inclusive studies, testing the applicability of polyurethane bone substitutes to the analysis of trauma inflicted by a wide range of projectile weapons.

The most beneficial way for the field of anthropology to advance is to abandon the use of misleading specific descriptors, such as “gunshot trauma”, when referring to instances of trauma where the weapon used is not confirmed. While all firearms are projectile weapons, not all projectile weapons are firearms. Such an assumption could lead to the misclassification of weapons involved in cases of trauma. For instance, Spatola (2015) presents a case where a child was killed by the end of an umbrella. Another child was spinning an umbrella when the point at the end detached, the centrifugal force turning the detached part into a projectile which struck the victim’s head. Spatola notes that the characteristics of the skeletal trauma reflected those typically observed in cases of “gunshot trauma”, and that an examiner may have incorrectly identified this trauma had the details of the victim’s death not been known. These findings are then used to make the argument that trauma should not be classified according to weapon to avoid such misclassifications. But had more inclusive terminology been used when assessing the skeletal trauma, chiefly “projectile trauma” instead of “gunshot trauma”, this case would have been correctly classified as the part of the umbrella which struck the victim did, in fact, meet the criteria of a projectile. The findings of the current study are to be used in such a way that future examiners will consider more weapon classifications as projectile weaponry. Such a shift would prevent misclassifications of trauma while still preserving the vital trauma categorisation system in anthropology which Spatola erroneously argues against.

## 2.9. Weapons Legislations

As the methods used in this study were conducted in both the United Kingdom and the United States, the legislation regarding weapon ownership and weapon use established by both governments need to be examined.

### 2.9.1. United Kingdom

Law in the United Kingdom defines the term “firearms” as “a lethal barrelled weapon of any description from which any shot, bullet, or other missile can be discharged” (*Firearms Act*, 1968: 22). Certain firearms are legal to own and use in the United Kingdom following specific regulations. The *Firearms Act of 1968* mandates that individuals must obtain a certificate in order to purchase and own a firearm. Individuals must be at least 17 years of age in order to obtain this certificate. Individuals with a criminal record are not eligible for a firearm certificate. Certification is required for all firearms except air weapons and shotguns with a barrel length of greater than 24 inches. The 1997 amendment of this act prohibits the use or ownership of firearms which have a barrel length of less than 30.00 cm (or overall length of the weapon is less than 60.00 cm) (*Firearms Act* 1997). All fully automatic weapons are prohibited, and individuals are not permitted to carry firearms or ammunition in a public place (*Firearms Act* 1968).

This certificate is also required to purchase ammunition, with the exceptions of cartridges with five or more shots (none of which exceeds 0.36 in. diameter), air weapon ammunition, and blank cartridges (not greater than a 1 inch diameter along the base) (*Firearms Act* 1968). The 1997 amendment of the *Firearms Act* prohibits the use, sale, or ownership of ammunition that is designed to expand upon impact (*Firearms Act* 1997). All restrictions specified in the *Firearms Acts* also apply to imitation firearms (*Firearms Act* 1982).

As archery weapons are not barrelled weapons, they do not fall under the jurisdiction of the *Firearms Act of 1968*. Crossbows are legal for civilians to own, but the purchaser and owner need to be at least 17 years of age. If a seller sells a crossbow to an underage individual, both parties are guilty of an offence. It is also not permitted for an underage individual to have in their possession parts that could be assembled to make a crossbow (*Crossbows Act* 1987).

While both hand bows and crossbows are legal to own in the United Kingdom without special permissions, these weapons are only to be used in sport. The *Wildlife and Countryside Act* (1981) prohibits the use of bows or crossbows to hunt birds, mammals, and other animals. Hand bows are commonly used in competitive contemporary sport in the United Kingdom. Crossbows, however, are typically not allowed in competition and are frequently not permitted in archery ranges (Archery GB, 2020).

### 2.9.2. United States

Gun laws in the United States date back to the founding of the country, after the American Revolution in 1783. With the signing of the American Constitution in 1787, American citizens were given the right to keep and bear arms, a right which remains true to this day (U.S. Const., amend. II). Since then, gun laws have been regulated on both federal and state levels. While there are no federal regulations regarding whether or not a permit is a requirement for gun ownership (as laws regarding gun permits are state regulated), the *Federal Firearms Act* (1938) mandates that sellers and manufacturers are required to obtain a special licence (Federal Firearms License [sic]) to distribute firearms. The *Omnibus Crime Control and Safe Streets Act* (1968) then prohibits interstate trade of handguns between these licenced sellers/manufacturers. Interstate gun commerce was further regulated that same year with the *Gun Control Act* (1968). This act prohibits interstate transfers of firearms except between licenced manufacturers, sellers, and importers, criminalising the sales and purchases of mail-order firearms (*Gun Control Act* 1968). More recent federal legislation has protected licenced firearms sellers, proclaiming that sellers are not liable/negligent when crimes have been committed with their products (*Protection of Lawful Commerce in Arms Act* 2005).

Though federal regulations do not require individual gun owners to have a permit, there are federal regulations on who can purchase firearms. The *Brady Handgun Violence Prevention Act* (1993) requires background checks

on all firearm purchasers while the *Federal Firearms Act* (1938) prohibits convicted felons from purchasing or owning firearms. The minimum age in which an individual is legally allowed to purchase long guns (rifles and shotguns) and correlating ammunition varies between states, but an individual must be at least 21 years of age in order to purchase a handgun and correlating ammunition (*Omnibus Crime Control and Safe Streets Act* 1968). Automatic firearms are strictly prohibited to all civilians (*Firearm Owners Protection Act* 1986). Concealed carry, that is, concealing a carried weapon, is generally legal within the United States though laws regarding concealed firearms vary between states. The *Gun-Free School Zones Act* (1990), however, prohibits unauthorised individuals from possessing a firearm while in a school zone.

Archery weapons are significantly less regulated in the state of New Jersey, where the crossbow samples of this study were obtained. A permit or license is not required to either purchase or own archery weapons (both hand bows and crossbows). Individuals who wish to use these weapons for hunting, however, must obtain a “Bow and Arrow Hunting License” New Jersey Division of Environmental Protection, 2019). In order to obtain a New Jersey hunting licence (for both firearm and bow hunting), an individual must be of at least ten years of age and must have completed a hunter education course. Such licenses are valid for a calendar year and must be renewed at the end of each year (New Jersey Division of Environmental Protection, 2019). Should an individual intend to use any archery weapons not for hunting but for sport, a hunting licence would not be required. No legal distinction is made between hand bows and crossbows.

## 2.10. Use of Synbone® in Experimental Research

Animal substitutes (most commonly domestic pig (*Sus s. domesticus*)) are commonly used in anthropology as an analogue to humans in both taphonomy and trauma studies due to the similarities in aspects of



postcranial skeletal morphology, skin structure, and muscle-to-fat ratio between the two species (Anderson and VanLaerhoven, 1996; Pearce et al., 2007; Schoenly *et al.*, 2007; Miles *et al.*, 2020). However, the use of animal tissue raises some ethical concerns and, in the United Kingdom, requires a review by the Animal Welfare and Ethical Review Body (AWERB) to promote animal welfare and reduction of superfluous use of animal material.

Additionally, more recent studies have shown that while human anatomy is structurally similar to pig anatomy, the differences, mainly in size, shape, bone thickness, and biomechanical properties, can be significant enough that any results from experimental studies using pig would not be applicable to human remains (Zephro *et al.*, 2013; Smith et al., 2015; Brown et al., 2019). This is especially true when attempting to replicate the cranium as no other species has a cranium that is architecturally comparable to that of a human (Smith et al., 2015; Mahoney *et al.*, 2017a; Mahoney *et al.*, 2017b).

In recent years, Synbone® synthetic bone material products have been gaining popularity in skeletal trauma studies (blunt force, sharp force, and ballistic), replacing the use of animal substitutes (Bowyer et al., 1996; Bolliger et al., 2014; Taylor and Kranioti, 2018; Downing and Fibiger, 2017; Ruchonnet *et al.*, 2019). Previous studies (Dyer and Fibiger, 2017; Smith et al., 2015; Thali et al., 2002) have examined the replicability of projectile and blunt force trauma to the cranium using a non-biological Synbone® sphere and found that the spheres were able to produce fracture patterns (as well as entrance/exit wounds) similar to those seen in real forensic and archaeological cases.

Synbone® ballistic proxies are polymer (polyurethane) replicas of human bones used as a substitute for biological material in destructive experiments. Each Synbone® sphere consists of two hemispheres glued together to create one continuous sphere with the contact point of the hemispheres acting as a circumventing suture. Additionally, one of the hemispheres contains a hole with a diameter of 4 cm to replicate the foramen magnum. Synbone® replicas are most commonly used to simulate either the cranial vault or long bones of the human skeleton, but the long bone replicates have been found to not be

entirely applicable proxies for organic long bones (Bir et al., 2016; Henwood and Appleby-Thomas, 2020). Henwood and Appleby-Thomas note that while Synbone® generic cylinders may be comparable to trauma inflicted to porcine bone, this was found to not be true for anatomical models. The fractures observed on the anatomical models were only similar to fractures on porcine bone when described in overly broad generalisations.

Synbone® spheres, however, are more commonly accepted as proxies for human cranial vaults due to the presence of an inner and outer table with the porous polyurethane acting as a representation of the middle diploë layer between the two tables (Brown et al., 2019; Pullen et al., 2021). Also, a key aspect of the latter is that such spheres replicate the cranial vault in that they present a closed sphere, which can be filled with a medium simulating brain tissue (such as ballistic gelatine) whilst also constituting homogenous samples which eliminates the individual variations in form and thickness that are inherent in real human crania (Faulkner-Jones, 2016; Liebscher and Salziger, 2019; Euteneuer and Courts, 2021).

## 2.11. Previous Experimental Research

As previously discussed, animal proxies are frequently used in taphonomic and traumatic experimental studies due to comparable muscle-to-fat ratio and skin structure. Forsom and Smith (2017) note that skeletal material is also acceptable to use as it can react to trauma in the same manner as human bone. Specifically, their study examined the wound morphology of bony lesions left by medieval arrowheads using domestic cattle (*Bos taurus*) scapulae as proxies for human cranial vaults. In this study, three types of replica arrowheads were shot using a longbow which was made using a design used throughout prehistory and the Middle Ages: a bow made from a single piece of wood (yew) with a D-shaped profile. The arrowheads included a bladed broadhead (often used in hunting and warfare), a bodkin (an armour-piercing arrowhead; exclusively used for warfare), and a barbed

broadhead (mainly used for hunting). It is worth noting that the bovine scapulae were defleshed before shooting due to practical constraints, but since there is not a thick layer of flesh on the human skull, the potential effect of soft tissue was considered negligible.

The results of this study showed that the skeletal trauma inflicted by the medieval arrowheads were typically similar to puncture wounds with 85.11% of the samples being classified as punctures (Forsom and Smith, 2017). Furthermore, there was roughly an even split between arrows which partially punctured the bone (47.50%) and arrows which completely perforated the bone (52.50%). The bodkin arrowheads were found to have penetrated the bone more easily than either broadhead, most likely due to the smaller surface area of the bodkin arrowhead. Additionally, the shape and size of the puncture wounds generally reflected the cross-section of the arrowhead used. On nearly all of the samples, bevelling was observed on the side opposite from the impact, a feature which is typically associated with an entrance defect of trauma inflicted by firearms (Berryman and Gunther, 2000; Delannoy *et al.*, 2013; Gascho *et al.*, 2020; Mittal, 2021).

In order to understand the trauma found on the os coxae of an individual from the battle of Stoney Creek (War of 1812, United States), Lockau *et al.* (2016) conducted experiments to reproduce the trauma with a smoothbore flintlock musket, using porcine scapulae as proxies for the human ilium. The scapulae were wrapped in porcine meat to create a proxy buttocks which was then covered with fabrics which replicated the British military uniform in order to account for textile-related ballistic resistance. The ammunition used in these experiments (“buck and ball” cartridges loaded with one 0.65 inch (16.51 mm) diameter lead ball and three 0.31 inch (7.87 mm) diameter lead buckshot pellets and “buckshot only” cartridges) mirrored the type of ammunition issued to the American troops at the battle of Stoney Creek. In order to produce enough data points and replicate the close-range conditions of this particular battle, shots were taken from 10.00 and 25.00 yards (9.14 and 18.29 m). The trauma found on the archaeological remains consisted of

two circular depression lesions found on the posterior surface of the ilium, measuring 8.60 and 9.70 cm in diameter, with damage to the bone between the two lesions (forming a “horseshoe” shaped pattern). The trauma observed on the porcine scapulae mimics the size and shape of the trauma on the archaeological material, but the experimental projectiles broke through both sides of the bone. The close proximity of the two lesions on the archaeological remains (1.50 cm) suggests that these projectiles were fired at close range (allowing for minimal spread), but the low penetration suggests that the projectiles were moving at a lower velocity. It is likely that there was an external factor which interfered with the flight path/velocity of the bullets.

While animal proxies have frequently been used in anthropological studies, Karger *et al.* (1998) sought to examine the suitability of ballistic gelatine and ballistic soap for experimental arrow wounds as potential alternatives to biological samples. In this study, four adult pigs, blocks of gelatine (10.00% solution), and blocks of Swiss ballistic soap were each shot using a longbow (draw weight: 33.40 kg), a compound bow (draw weight: 26.80 kg), and a recurve crossbow (draw weight: 33.40 kg) from a distance of eight metres. While Karger *et al.* noted a significant difference in the penetration depths between the biological, ballistic soap, and ballistic gelatine samples and concluded that ballistic gelatine and ballistic soap are not suitable simulant medias for experimental arrow wounds, this study did not take into account the effect of skeletal material on the penetrative power of a projectile. Neither the gelatine nor the soap blocks contained bone proxies and only non-bone shots on the pigs were compared to the shots on the gelatine and soap blocks. While these results may show the unsuitability of ballistic gelatine and ballistic soap to act as a representative of soft tissue damage, no conclusions can be made on if a combination of non-biological soft and hard tissue proxies would exhibit more comparable results to biological samples.

Thali *et al.* (2002), however, sought to examine the applicability of both hard and soft tissue proxies in experimental studies, providing one of the first

significant ballistic tests of polyurethane. The purpose of this study was to develop a synthetic skin-skull-brain model which can replicate projectile trauma. Polyurethane spheres with thicknesses of 5 mm, 6 mm, and 7 mm and a 19 cm diameter were filled with a 10.00% gelatine solution (widely used in ballistic tests as it is approximately the density of human brain material), coated with a thin latex layer to represent the periosteum, and covered with a silicon cap to represent the scalp. These spheres were shot from a distance of 10 m with a variety of weapons including 9 mm Luger (full metal jacket bullets), 22 LR, .38 special, 44 Remington Magnum, 7.62 mm NATO (7.62 x 39 full metal jacket bullets), and 12 gauge shotgun (12/70 slug).

The results of this study showed that realistic wound morphology was present on the polyurethane spheres and that wound patterns inflicted to the spheres are comparable to gunshot injuries in human cranial remains. Regarding bevelling patterns, the synthetic bone material was able to produce bevelling on the internal table at the entrance defect and externally at the exit defect. Both radiating and concentric fractures were observable and in the case of multiple entries, fractures were arrested by already present fractures, allowing for sequencing of the shots.

Smith *et al.* (2015) expanded upon this study, bringing to attention that the ballistic research done by Thali *et al.* (2002) only focused on a small range of projectile weapons. Smith and his colleagues examined the impact of a larger range of weapons, including low, medium, and high velocity weapons, on polyurethane flat plates and spheres. The weapons used in this study included a 7.62 mm Parker Hale T4 target rifle (7.62 x 51 NATO full metal jacket bullet; high velocity), a Tikka model 550 rifle (.243 in. 100 gr soft point bullet; high velocity), a replica 1861 model .58 calibre carbine black powder musket (solid 13.50 mm lead minié balls; medium velocity), and a Jaguar 175 lb recurve crossbow (17.25 in. Perfectline alloy bolts with conical field tip heads; low velocity). As part of health and safety requirements, each sphere (both 5 mm and 7 mm thicknesses; filled with 10.00% ballistic gelatine) and flat plate (5 mm thick) were placed in a pit that was 1.50 m deep where the

bottom 0.80 m of fill was sieved sand (to reduce the risk of ricochet). The weapons were fired from a distance of 2.00 m at an angle of 65°.

The samples were assessed based on gross morphological features of both entrance and exit wounds and any additional fractures on a macroscopic level, any microscopic characteristics (using light microscopy) of the defects, and the form of the bevelling at both the entrance and exit wounds. Their results are consistent with those of Thali *et al.* (2002) showing that when hit with the examined projectiles, the synthetic bone material generally mimicked true bone on a macroscopic level, but significant differences between the two were noted on a finer level. Smith and his colleagues note that the synthetic bones still provide a decent approximation of trauma found on real bone. This is especially true when using the spheres to examine cranial trauma as animal proxies are too structurally dissimilar to provide useful data.

Synthetic bone has also been used in experiments examining blunt force and sharp force trauma. Downing and Fibiger (2017) examined European Bronze Age sharp force weapons, using Synbone® spheres filled with a 10.00% ballistic gelatine solution as proxies for human cranial vaults and brain material, respectively. The weapons used in these experiments (a Middle Bronze Age dirk, flanged axe, and an early phase Late Bronze Age sword) were modern replicas. The spheres were struck with these weapons at either a 90° angle or approximately a 45° angle. The resulting trauma was then assessed on both a macroscopic and microscopic level. In regards to the use of synthetic bone material in experimental sharp force trauma studies, Downing and Fibiger found the Synbone® spheres to be an adequate substitute for true bone material and stress the need for continued experimental studies to understand patterns of violence in the European Bronze Age.

Dyer and Fibiger (2017) also used Synbone® spheres filled with a 10.00% ballistic gelatine solution, but this study focused on a Neolithic blunt force weapon. A replica of the “Thames Beater” (a Neolithic wooden club) was used to strike the prepared spheres in one of two ways: a pommel strike (with

the back end of the handle) or a double-handed strike (downward swing with both hands on the handle). The findings of this study show that while observations of trauma on Synbone® spheres are not comparable to true bone observations on a microscopic level, the macroscopic observations of trauma are virtually identical to archaeological trauma cases (Dyer and Fibiger, 2017).

Furthermore, other methods of trauma analysis, such as the use of microscopy and computerised tomography (CT), are frequently used in the examination of skeletal remains and in experimental studies. While traditional light microscopy is capable of magnifying x1000 through light and lenses (Vernon-Parry, 2000; Murphy 2002), scanning electron microscopes (SEM) fire a focused beam of electrons against the specimen to record the interactions of the electrons with the external topography of the specimen, producing a magnified image of the external surface of the specimen itself (McMullan, 1995; Goldstein *et al.*, 2018). Radiography, however, is an imaging technique capable of capturing two dimensional images of internal regions in a non-invasive way through the use of low-level radiation (X-rays) (Whaites and Drage, 2013; Menk, 2018). Similar to X-ray imaging, CT scans are images of cross-sections of the body obtained using X-rays as a means of non-invasive examination (Hu, 1999; Herman, 2009; Sarma *et al.*, 2012). With CT scanning, however, the two-dimensional images are then used to create a three-dimensional rendition of the body for a more extensive non-invasive analysis of trauma. Similarly, magnetic resonance imaging (MRI) is an imaging technique capable of non-invasively producing three-dimensional renditions of the body but using magnetic fields instead of radiation (Khoo *et al.*, 1997; Hashemi *et al.*, 2012).

These computerised tools provide the anthropologist with the added benefit of utilising machine-precise measurements, allowing for not only microscopic measurements, but also highly accurate measurements of macroscopic features. While microscopy (Galloway and Zephro, 2005; Rickman and Smith, 2014; Smith *et al.*, 2015), two-dimensional radiography (X-ray) (Davidson *et al.*, 2011; Spies *et al.*, 2020; Spies *et al.*, 2021), three-

dimensional radiography (CT technology) (Schyma *et al.*, 2012; Blau, 2016; Christensen *et al.*, 2018; Obertová *et al.*, 2019; Spies *et al.*, 2020), and MRI technology (Thali *et al.*, 2003; Aghayev *et al.*, 2005; Buck *et al.*, 2007; Obertová *et al.*, 2019) are all used in anthropological trauma analysis, they require the use of expensive equipment which are not always accessible to examiners. As such, it was decided to conduct this study using easily accessible and/or non-expensive tools to measure the macroscopic features of trauma.

Prior to the initiation of the current research, a preliminary experimental study (Astrom, 2016) was conducted which examined skeletal trauma inflicted by rifle (.22 and .243) and crossbow (field tip bolts). In this study, the crania, scapulae, seventh rib, and femora of domestic pigs were shot with either a crossbow or .22 rifle while the .243 samples utilised had been collected from previous studies (Fragkouli, 2013; Terris, 2013).

The methods used in the current research are similar to the methodology of this preliminary study (Astrom, 2016), but the latter used pig rather than synthetic bone. In the 2016 study, ten pigs were obtained from local farms (Lancashire, England) and humanely dispatched (using a captive bolt gun) on site, after which they were eviscerated and bisected in order to use skeletal elements from both halves of each pig. Each half-carcass was then hung on a steel A-frame by the hind limb to be shot (Figure 2.32).

Each of the examined skeletal elements were shot once with either a Ruger .22 long rifle or a recurve crossbow (model unknown) with a draw weight of 175 lb. Additionally, the samples were shot both at point-blank range and from a distance of 5 m. The bullets used with the rifle were .22 long rifle copper-plated round nose rounds while the bolts used with the crossbow were field-tipped with a diameter of approximately 10 mm. Following the shooting, the samples were macerated in detergent and water in order to remove all of the soft tissue from the bone, dried, and reconstructed. In order to compare the characteristics of trauma between the weapons, both quantitative and qualitative features were examined. These features included





Figure 2.32. Experimental setup: half-car carcass hung from hind limb on steel A-frame and marksman positioned 5 m away from target (source: Astrom, 2016: 17).

the presence of residue, presence of bevelling, presence of a complete fracture (in rib and femur samples), number of fractures, fracture length, fracture width, number of dislodged fragments, and presence of different types of fractures (transverse, oblique, comminuted, greenstick, radiating, and concentric heaving).

The findings of this preliminary study were twofold: the skeletal trauma inflicted by rifle and crossbow were broadly comparable to each other and the most differentiating features of the trauma were quantitative rather than qualitative variables. The trauma inflicted by both rifles and crossbow exhibited similar qualitative characteristics, such as bevelling and fracture patterns (Figure 2.33). This is problematic as commonly used methods of identifying projectile trauma are primarily focused on qualitative variables, such as fracture patterns and the presence of bevelling (Smith *et al.*, 1987; Quatrehomme and İşcan; 1998; Berryman and Symes, 1999; Bailey and Mitchell, 2007; Humphrey *et al.*, 2017; Berryman, 2019). While this may be useful in identifying generic projectile trauma, the preliminary study shows



*Figure 2.33. Two samples which exhibit similar fracturing. Top: shot with crossbow (field tip); bottom: shot with .22 rifle (source: Astrom, 2016: 50).*

that it is not as useful in the identification of the specific projectile weapon. Because of these findings, a more extensive study is warranted to examine not only rifle and crossbow, but a broad spectrum of common projectile weapons in use today to better categorise observed skeletal trauma and correlate it with the proper weapon. While this preliminary study was fundamental in the justification of conducting the current study, the data collected in the preliminary study was not used in the current study. As the methods had been altered to improve the applicability of the findings to real cases (mainly, using synthetic bone instead of animal proxies; see Chapter 3), it was decided that the samples collected using the two different methods would not be mixed in order to maintain consistency amongst the samples.

The topics discussed in this chapter were all crucial in both the design of the methods conducted in this research (discussed in Chapter 3) and the interpretation of the measured results (discussed in Chapters 4, 5, and 6). These concepts formed the foundation of the experimental design of this study.

### 3. Methods

While the results of this study are applicable to human remains in forensic cases as well as archaeological remains, these experiments could not be conducted on human samples for legal (*Human Tissue Act* 2004; NJ Rev Stat § 2C:22-1, 2019), ethical, and biosafety concerns (Smith *et al.*, 2015; Mole and Heyns, 2019; Pullen *et al.*, 2021). Due to these restrictions, it was necessary to use artificial bone material. The following methods were applied to Synbone® spheres, which acted as a human bone replicate (see Section 2.10.). All variables were controlled as much as possible so that it was assured that the different weapons examined in the current study caused the differences in the observed features of trauma.

#### 3.1. Ethical Approval

This study and these methods were approved by the Research Ethics Committee of the School of History, Classics, and Archaeology at the University of Edinburgh on 28th November 2018. These methods follow the school's ethical framework of dignity, respect, and care in obtaining the data for this study (School of History, Classics, and Archaeology, 2015).

#### 3.2. Use of Synbone® Spheres

As discussed in the previous chapter, there are many ethical issues which stem from using biological material, both human and animal, in experimental studies. Given these issues, it was decided to use synthetic bone replicas in this project. These spheres are commonly accepted and have been used in many experimental studies (see Section 2.10.) as proxies for human cranial vaults. This is due to the presence of an internal and external table with the porous polyurethane acting as a diploë between the two tables (Brown *et al.*,

2019; Pullen *et al.*, 2021). Additionally, these spheres are ideal as cranial replicates as they present a mostly closed sphere, which can be filled with a medium simulating brain tissue (10.00% ballistic gelatine in this study) whilst also constituting homogenous samples which eliminates the individual variations in form and thickness that are inherent in real human crania.

Each Synbone® sphere consists of two hemispheres glued together to create one continuous sphere with the contact point of the hemispheres acting as a circumventing suture. Additionally, one of the hemispheres contains a hole with a diameter of 4 cm to replicate the foramen magnum (Figure 3.1). Due to the availability of resources, two types of spheres were used: spheres with a thickness of 5 mm (39 spheres) while the remaining spheres (7) had a thickness of 7 mm. These thicknesses replicate a realistic cranial vault thickness: the average thickness of an adult cranial vault is approximately 6 mm (de Boer *et al.*, 2016). The spheres were also filled with 10.00% ballistic gelatine to represent the brain within the cranial vault.



Figure 3.1 Generic 5 mm Synbone® sphere (source: Synbone, 2020).

While the use of Synbone® spheres as cranial vault proxies has been generally accepted to approximate the features observed in real instances of skeletal trauma (Thali *et al.*, 2002; Smith *et al.*, 2015; Downing and Fibiger, 2016; Taylor and Kranioti, 2018; Ruchonnet *et al.*, 2019), some argue that the damage done to the spheres does not adequately reflect realistic characteristics of trauma. Appleby-Thomas and colleagues (2017) examined the suitability of Synbone® material as proxies for real bone in ballistic experiments. Their conclusions in this study were that Synbone® did not behave similarly to real bone and that a multi-simulant model should be

utilised in ballistic experimentation. Walters (2018) agrees with these findings, noting that Synbone® material shows isotropic behaviour while other synthetic bone products, such as Boneism, better reflect the anisotropic behaviour of real bone.

Mahoney and colleagues (2019) make the further observation that Synbone® spheres tend to produce more comminuted fracturing than what is observed in real instances of military grade projectile trauma. Earlier studies (Mahoney, et al. 2017a; Mahoney et al., 2017b), however, showed that synthetic skulls were capable of producing more realistic fracturing when shot with more civilian grade ammunition and when the architecture of the crania proxies are more intricately designed, mainly due to the synthetic bone being anatomically correct and internal and external soft tissue simulants are used. These studies claim that the complex nature of biological materials is inadequately represented by Synbone® material alone and call for each layer of organic tissue to be represented by its own adequate simulant. Yet it is important to note that the findings of the current study are meant to be used as approximations and future studies should compare these results to real cases of trauma to be appropriately extrapolated to reflect the reaction of living tissue (Jussila, 2004).

Pullen and colleagues (2021) conducted a study to examine the suitability of Synbone® plates as proxies for domestic pig ribs in ballistic experimentation. In these experiments, domestic pig ribs and Synbone® plates were embedded in 10% ballistic gelatine then shot with 5.56 mm open tip match ammunition. While they did conclude that there was no significant difference between the two materials in nearly all of the measured quantitative features, it was found that the depth of tissue damage (represented by 10% ballistic gelatine) significantly differed between the synthetic bone and the real bone. Though the current study does not examine the soft tissue damage which projectiles cause, the flight path of the projectiles included passing through one plate of the sphere, passing through the 10% ballistic gelatine, then potentially passing through a second plate of the sphere. If the synthetic

bone significantly affects the depth of travel in the gelatine, it would also affect the amount of energy expelled upon impact with the second plate (exit point) of synthetic bone. This difference could impact the trauma observed at the exit defect, particularly the quantitative features. Future studies should further examine whether the quantitative features of projectile exit defects significantly differ from trauma observed on real bone.

### 3.3. Weapons

#### 3.3.1. Selection

This study focused on nine different sample sets (Table 3.1), each defined by

*Table 3.1. Weapons, firing distance, and marksmen involved in this study.*

| Weapon                                         | Distance | Marksman                                  | Qualifications/ Experience                                               |
|------------------------------------------------|----------|-------------------------------------------|--------------------------------------------------------------------------|
| Handgun (mixed calibre)                        | 0.50 m   | Not specified (Taylor and Kranioti, 2018) | n/a                                                                      |
| Compound bow (broadhead arrows)                | 10 m     | Helen Woodcock                            | Archery Coach Level 2; Co-founder of NFP Archery (Huddersfield, England) |
| Shotgun                                        |          | Wilfred Dolman                            | Firearm certificate number: 04/A/009345/2013                             |
| Rifle                                          |          |                                           |                                                                          |
| Recurve bow (field tip arrows)                 |          | Amy Cole                                  | Archery Coach Level 1                                                    |
| Handgun (9mm)                                  |          | Cody Yates                                | Recreational hunter                                                      |
| Compound crossbow (field tip bolts)            |          |                                           |                                                                          |
| Compound crossbow (fixed broadhead bolts)      |          |                                           |                                                                          |
| Compound crossbow (mechanical broadhead bolts) |          |                                           |                                                                          |

the weapons examined in this study. Weapons were selected based on two main characteristics: presence in forensic cases (as well as archaeological remains) and ease of access. While firearms such as handguns and the generic “firearm” are extensively examined in the existing literature on projectile trauma, rifles, shotguns and archery weapons are commonly overlooked despite their appearance in real cases as well as ease of access for use in violent attacks. Very few studies (e.g. Thali *et al.*, 2002; Smith *et al.*, 2015) have examined the trauma inflicted by these weapons through an experimental approach. Without experimentation, much of what we think we know about the injuries these weapons (both modern and archaeological) leave on bone is largely speculation.

The weapons which were examined in this study were each specifically chosen to be representative of projectile weapons which are involved in forensic cases of trauma, consisting of three classifications of firearm weaponry and five classifications of archery weaponry. Handgun ownership and handgun crime are particularly present in modern America, where ownership is primarily claimed for defensive purposes (Stroud, 2012; Kleck, 2017; Legault *et al.*, 2019; Stroebe *et al.*, 2020). While both rifles and shotguns are commonly owned and used for hunting, the ammunition between the two weapons are completely different and warranted separate examination (Bangalore and Messerli, 2013; Khalil, 2017; Kleck, 2017).

Projectile trauma in cases of both fatal and non-fatal injuries is most inflicted by guns. The shotgun and rifle were chosen due to their common use in hunting, which makes them easily accessible to the public. While handguns are not legal to be owned by civilians in the United Kingdom (*Firearms Act* 1968), they are legal to be owned and carried by civilians in other regions of the world (such as the United States), meriting their involvement in this study.

Today, archery weapons are primarily used for hunting (Zanevskyy, 2008; Carpenter, 2016; Tomka, 2013) while the recurve bow is also commonly used in sporting events (Zanevskyy, 2008; Fritzsche *et al.*, 2012; Reichart,



2016). It was decided to place more emphasis on the design of the arrow/bolt tip as opposed to focusing on the bow design as the different shapes in arrow design would more directly alter the trauma they inflict. As such, it was decided to not duplicate the tips on both recurve and compound hand bows/crossbows. In the final weapon selection, field-tip arrows were shot using a recurve hand bow, fixed broadhead arrows were shot using a compound hand bow, and field-tip, fixed broadhead, and mechanical broadhead bolts were shot using a compound crossbow. The decision to use these combinations of bow and tips was made based on the accessibility of the weapons: the recurve hand bow marksman (Amy Cole, Table 3.1) had only worked exclusively with field-tips and had no experience with fixed broadheads while the marksman (Helen Woodcock, Table 3.1) which had experience with broadhead arrows owned a compound hand bow. The crossbow marksman (Cody Yates, Table 3.1) had extensive experience with all three tips examined in this study, but only owned a compound crossbow. The weapons/tips which were excluded from this study should be examined in future studies.

Archery weapons are also commonly used in target sports in the United Kingdom and in hunting elsewhere and are significantly easier for the general population to obtain than firearms. Rifles and shotguns are legal to own and use in the United Kingdom but require that the owner be certified to own such weapons (*Firearms Act 1968*).

Archery weapons, however, do not require this certification. While archery weapons may not be as prevalent in forensic cases as guns, there are still numerous cases involving hand bows and crossbows described in the literature (Downs *et al.*, 1994; Cina *et al.*, 1998; Eriksson *et al.*, 2000; Anonymous, 2019a; Anonymous, 2019b). Yet there has been significantly less research conducted on the trauma they inflict on skeletal material and the research that has been carried out tends to focus on ancient weapons (Smith *et al.*, 2007; O'Driscoll and Thompson, 2014; Forsom and Smith, 2017).



In this study, the specific model for all weaponry was not considered important as long as the same weapon was used for all relative samples and the weapon was not a unique, custom-made weapon.

The preliminary study (2016) showed that distance between point-blank range and 10 m did not significantly affect trauma characteristics for rifle and crossbow. Given this as well as to maintain consistency, subjects were all shot from an equal distance. Forensic cases involving projectile weapons are mostly incidents where the weapon has been fired at close range, typically 10 m or less (Dixon, 1982; Downs *et al.*, 1994; Eriksson *et al.*, 2000; Karger *et al.*, 2004). For safety reasons, all samples were shot from a distance of 10 m to ensure that no one involved in the experimentation was hit with either a ricocheting projectile or fragments of the spheres. All weapons used in this study were shot by qualified and experienced individuals, either certified instructors or recreational shooters (Table 3.1).

### 3.3.2. Specifications

The following weapons were used in the sample collection of this study (see previous chapter for details on the firearms which Taylor and Kranioti (2018) used to obtain additional handgun samples). All weapons and ammunition were selected based on prevalence within projectile weapon ownership (i.e., no rare or one-of-a-kind weapons were used). The specific models used in this study were primarily intended to be standard models which are commonly owned and used. Following this requirement, each model was selected based on which model each marksman owned. Ammunition was selected first based on the compatibility of the ammunition with the weapon, then based on the experienced recommendation of each marksman.

### 3.3.3. Handgun (9 mm)

The handgun marksman (Cody Yates; Table 3.1) used a semi-automatic Glock (Figure 3.2). Glock is one of the United States' leading pistol producers, with most law enforcement agencies using Glock pistols as their standard firearm in the United States (Glock, 2019). The marksman used the Glock handgun which he owned, a Glock 17 9 mm Luger pistol with a barrel length of 4.50 in. The ammunition used with this firearm were Winchester 9 mm Luger 115 gr (approximately 7.45 g) full metal jacket bullets. Each bullet consisted of a lead core, a brass jacket, and a brass casing.



*Figure 3.2. Glock 17 (top) and Winchester 9 mm round (right).*



### 3.3.4. Rifle

The rifle marksman (Wilfred Dolman; Table 3.1) used a Ruger 10/22 model carbine semi-automatic .22 LR calibre rifle with a barrel length of 18.50 in. (Figure 3.3). This rifle was fitted with a scope for increased accuracy. The



*Figure 3.3. .22 Ruger rifle (top) and .22 LR rounds (right).*



bullets used with this firearm were CCI Mini Mag 22 LR bullets which were copper plated and round nosed. Each bullet weighs approximately 2.60 g.

### 3.3.5. Shotgun

The shotgun marksman (Wilfred Dolman; Table 3.1) used a 12-gauge Winchester 101 shotgun (Figure 3.4). This shotgun was 28 in. in length with a dual barrel in an over and under configuration. The ammunition used were 12-gauge Hull High Pheasant High Performance Cartridges with fibre plugs. Each 5 shot cartridge was 67 mm long and contained a 32 g load, typically used for game hunting.



Figure 3.4. Winchester 101 shotgun (top) and Hull High Pheasant cartridges (right).



### 3.3.6. Recurve Bow

The recurve bow marksman (Amy Cole; Table 3.1) used a custom-made Hoyt Recurve Barebow made with Hoyt 840s short 22 lb limbs and a Grizzly Strings 14 strand vantage string for a 22 lb draw weight (Figure 3.5). The arrows used with this bow were made with Easton XX75 platinum shafts,



Figure 3.5. Recurve bow (top) and field tip (right).





“One-Piece Bullet Point” tips, three plastic fletchings on each arrow, and plastic nocks. On average, the total mass of each arrow was 16 g.

### 3.3.7. Compound Bow

The compound bow marksman (Helen Woodcock; Table 3.1) used a Hoyt UltraTec compound bow with a 38 lb peak draw weight (Figure 3.6). The

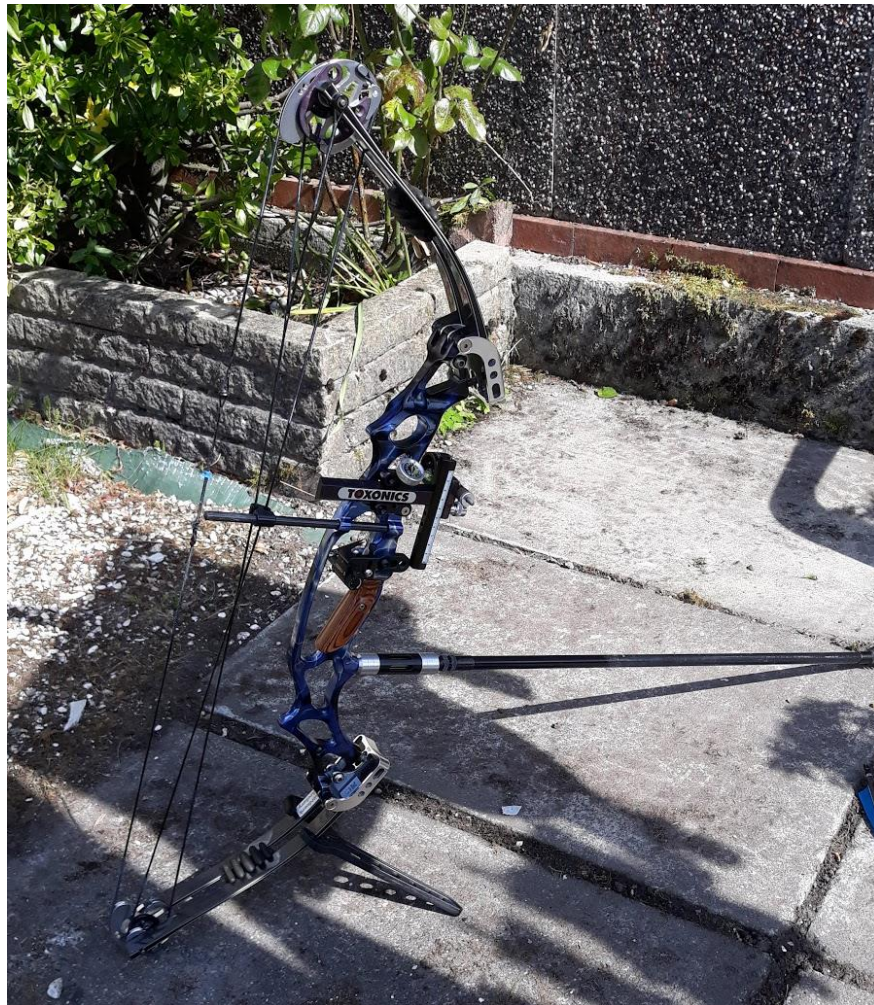


*Figure 3.6. Hoyt UltraTec compound bow (top) and fixed broadhead arrows (right).*



arrows used with this weapon were constructed using an Easton XX75 Platinum Plus full length (32.50 in.) shafts, three feather fletchings for each arrow, and a plastic nock. The broadhead tips were Huntingdoor 125 gr fixed broadheads in a three-blade design with an aluminium shaft and stainless steel blades with a total length of 1.80 in. and width of 1 in. On average, the total mass of each arrow was 39 g.

### 3.3.8. Crossbow

The crossbow marksman (Cody Yates; Table 3.1) used a Ravin R15 compound crossbow which uses a crank draw mechanism and has a draw weight of 195 lb (Figure 3.7). The bolts used with the crossbow consisted of Ravin .003 20-inch carbon construction arrows which included three plastic fletchings and a plastic nock pre-attached, while the tip could be interchangeable. The same crossbow and arrows were used for each type of tip.

The field tips were pointed convex metallic tips, each with a weight of 100 gr (approximately 7.00 g). The fixed broadhead tips were Excalibur 100 gr Boltcutters. Each tip was in a three-blade design with stainless steel blades and shaft and weighed approximately 7.00 g. The mechanical broadhead tips were Rage Crossbow X Broadheads 125 gr (approximately 8.10 g). These stainless steel tips consist of a two-blade design which expand upon impact and a third blade at the apex for a facilitated entry of the target.





Figure 3.7. Top: Ravin R15 crossbow (top view); second row: Ravin R15 crossbow (side view); third row (left to right): fixed broadhead tip, field tips; bottom row (left to right): mechanical broadhead tip; mechanical broadhead tip, expanded.



### 3.4. Samples

Each weapon set collected in this study had a replicate number of five spheres. The spheres shot using the handgun weapons from a distance of 0.50 m were collected as a part of a separate study (Taylor and Kranioti, 2018) and were used as comparative samples in this study. This set of samples had a replicate number of six. While this project would have benefitted from an increased replicate number, the number of replicates for each weapon were kept low due to time and funding restraints. A minimum of five replicates per weapon were produced to obtain a minimal level of statistical relevance in the analysis of the data obtained from the samples of this study. Further replications are recommended in future studies to corroborate the findings of this study with a robust sample size.

#### 3.4.1. Sample Labels

Samples were assigned a label based on the weapon they were shot with (Table 3.2) and replicate number. Replicate numbers were simply assigned

*Table 3.2. Weapon labels.*

| Weapon                              | Label |
|-------------------------------------|-------|
| Handgun                             | Hg    |
| Rifle                               | Ri    |
| Shotgun                             | Sh    |
| Recurve bow (field tip)             | RcFt  |
| Compound bow (broadhead tip)        | CpBh  |
| Crossbow (field tip)                | CbFt  |
| Crossbow (fixed broadhead tip)      | CbBh  |
| Crossbow (mechanical broadhead tip) | CbBhX |



in order of shooting, starting with “1”, and follow the weapon label. Handgun samples were also labelled according to their calibre, reading after the replicate number.

### 3.4.2. Gelatine Preparation

Each sphere contained a mix of 315 g of Honewell Fluka™ gelatine powder (Type 3) to 2.80 L of water. The gelatine for each sphere was prepared in thirds (each third was processed in a 1 L beaker) concurrently to make the process more manageable with the available resources. The water (933 mL per 1 L beaker) was first chilled and brought down to 7-10° C. For each 1 L beaker, 105 g of Honeywell® ballistic gelatine powder from porcine skin was mixed in gently using a stirring rod in a downward motion in order to minimise clumping and therefore ensuring an evenly dispersed solution. This mixture was then refrigerated for two hours to allow the gelatine to absorb the liquid.

Following this period of chilling, the beakers with the gelatine mixture were placed in a hot water bath set at approximately 100° C (Figure 3.8). The

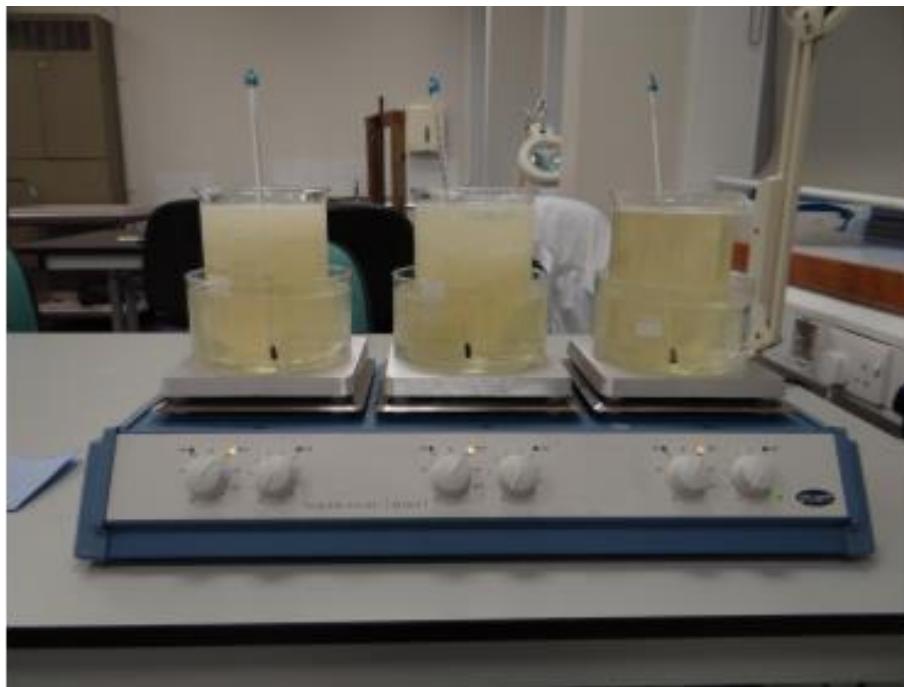


*Figure 3.8. Gelatine mixture (divided into thirds) in hot water baths.*

mixtures were stirred continuously until they became pale yellow in colour and structurally homogeneous throughout. During this step, the mixtures were kept below 50° C. Once the mixtures were brought up to temperature, the three beakers were poured into a sphere.

These spheres were placed in a refrigerator and allowed to set for 24-48 hours, until firm.

### 3.5. Shooting

The shooting of all samples took place at designated facilities approved for the use of projectile weapons. As the *Firearms Act* (1968) prevents the ownership of handguns, not all experimentation could be conducted in the United Kingdom. The outdoor setting of both facilities, while beneficial regarding safety concerns, was slightly problematic in that the irregular terrain (i.e. dips in the ground and tall grass) prevented the collection of 100% of the dislodged fragments amongst the samples. In samples where fragments were clearly missed during collection (Figure 3.9), not all data regarding dislodged fragments could be measured. Features of the fragments which were collected for such samples were still considered in the analysis of the data.

#### 3.5.1. United Kingdom Facilities

The recurve bow, compound bow, shotgun, and rifle samples were shot at the University of Central Lancashire's Taphonomic Research in Anthropology: Centre for Experimental Studies (TRACES) facilities in Lancashire (England) (Figure 3.10). This is the first facility in the United Kingdom dedicated to experimental studies in forensic taphonomy, anthropology, and entomology using animal models (primarily pig) (University



*Figure 3.9. Exit defect of sample Hg 1 (9 mm) after reconstruction using recovered dislodged fragments. Reconstruction incomplete due to missing fragments.*



*Figure 3.10. TRACES facilities.*

of Central Lancashire, 2020). It comprises of 13 acres of land and has been the centre of several anthropological and entomological studies. The land is a combination of open field and wooded areas and is equipped with essential anthropological tools as well as farming tools. It is located in farmland in the Lancashire countryside to prevent accidental injury to surrounding neighbours. The facilities have been approved for the use of biological materials as well as the use of the weapons examined in this study (except handgun).

### 3.5.2. United States Facilities

Due to the previously mentioned legal issues, the handgun samples could not be obtained in the United Kingdom. All crossbow samples (field tip, fixed broadhead, and mechanical broadhead tips) were collected using the same facilities due to the lack of availability of marksmen in the United Kingdom. As such, these samples were obtained at a private shooting range (owned by marksman Cody Yates) in Manchester, New Jersey (USA) (Figure 3.11). The land of these facilities is a combination of open field and wooded area, the former being used for firearm practice and clay pigeon shooting while the



*Figure 3.11. Private shooting range in Manchester, New Jersey (USA).*

latter is set up for archery practice. This shooting range is located in an unpopulated wooded area to prevent accidental injury to surrounding neighbours.

### 3.5.3. Experimental Setup

The spheres were not elevated to a constant height across the samples, but instead were elevated relative to the height of each marksman to account for height differences. Each sphere was elevated to the shooting height of each marksman to ensure that the projectile maintained a consistent angle across all samples ( $90^\circ$  angle). Spheres were elevated in one of two ways, either positioned on structures which were already present at the facilities (such as cages or fence posts) or positioned on a haybale structure which was assembled when no pre-existing structure was present (Figure 3.12). Once at eye level, the sphere was placed on a cork ring and secured with ratchet straps to prevent movement when hit. The marksman was positioned so that the tip of the weapon was 10 m away from the sphere. This distance was chosen to ensure the safety of the participants (as shooting from closer



*Figure 3.12. Experimental setup: sphere is elevated to shooting level for respective marksman who is firing from a distance of 10 m.*

distances could be hazardous due to ricocheting projectiles and/or fragments propelled from the sphere) while still maintaining a close distance to reflect the close-range firing distances observed in forensic cases (Dixon, 1982; Deitch and Grimes, 1984; Salvino *et al.*, 1991; Downs *et al.*, 1994; Cina *et al.*, 1998; Eriksson *et al.*, 2000; Karger *et al.*, 2004; Naik *et al.*, 2011; Castro-Espicalsky *et al.*, 2020). Safety precautions were taken as necessary with each weapon: protective eyewear and ear protection were worn for the shotgun and handgun collections and participants stood a safe distance from the shooting region for all weapons.

The methods used to obtain samples which reflect projectile trauma were designed to control as many extraneous variables as possible so that the examination and analysis would reflect only the effect which the explanatory variable (weapon) had on the response variable (trauma produced). Few researchers argue for the lack of controlling external variables, stating that real-life scenarios would not be so controlled, so overly controlling the experiments are not reflective of reality (Chalmers, 1986; Evans, 2016). In the context of the current study, securing the spheres, for example, restricts the movement which would inevitably occur when a projectile strikes a cranium. This movement could influence the trauma which is observed in real cases of trauma, bringing to question the applicability of the findings from these overly controlled experiments. The experiments conducted as part of the current study were designed to measure the weapon's influence on trauma without the combined effect of other variables. The need to understand the isolated influence of weapon outweighed the disadvantages of unrealistically controlling the aspects of projectile injury.

### 3.6. Post-Shooting

Immediately following shooting, photos were taken of the entrance and (where applicable) exit defects of all samples in situ. The camera used at the United Kingdom facilities was a Nikon D3300, set at an ISO number of 200,

f/9 aperture, and shutter speed of 1/320. The camera used at the United States facilities was a Nikon D750, set at an ISO number of 100, f/7.1 aperture, and a shutter speed of 1/200. All arrows and bolts required extraction from the spheres. All broadhead tips (both fixed and mechanical) were removed from the shafts prior to extraction to prevent experiment unrelated damage to the spheres. The fixed broadhead tips shot with the compound bow were unscrewed from the shaft while remaining in the gelatine inside the sphere and were carefully removed in the process of cleaning the gelatine out of each sphere. Additionally, the presence or absence of residue was noted for each sample prior to cleaning as this could be washed away in the cleaning process.

If the spheres were mostly intact, the gelatine was removed by scooping it out through the hole with a spoon. When spheres had separated along the joint point of the hemispheres, the gelatine could be removed in one piece. Additional fragments were collected from the gelatine for each sample. Following cleaning, additional pictures were taken of all entrance and (where applicable) exit defects using the same respective cameras.

### 3.6.1. Analysis

In order to compare characteristics of projectile trauma found in these samples, both qualitative and quantitative features were examined and categorised by level of measurement. Nominal variables are those that are measured with a finite number of labels (such as presence or absence of features and shapes of entry/exit). Dichotomous nominal variables are nominal variables that have two possible labels (such as presence or absence of features). Interval variables are those that are measured on a continuous numerical scale (such as length and width). All quantitative variables which were not frequency counts were rounded to two decimal places.



All examined features (both qualitative and quantitative) were measured on a macroscopic scale. This decision was made so that the results of the statistical analysis could be applied without the need for specialised equipment (such as is required when using light microscopy, scanning electron microscopy, computerised tomography, etc.; see Section 2.11.), which an examiner might not have access to. The most specialised equipment used to obtain these measurements was a set of sliding calipres, a standard, non-expensive laboratory tool. Future studies should examine these features on a microscopic level.

The following features were examined:

- i. Complete/Incomplete entry defect: measured by the presence of a point where the projectile breaks through both the outer and inner table at the point of initial contact. Dichotomous nominal level of measurement (Figure 3.13).

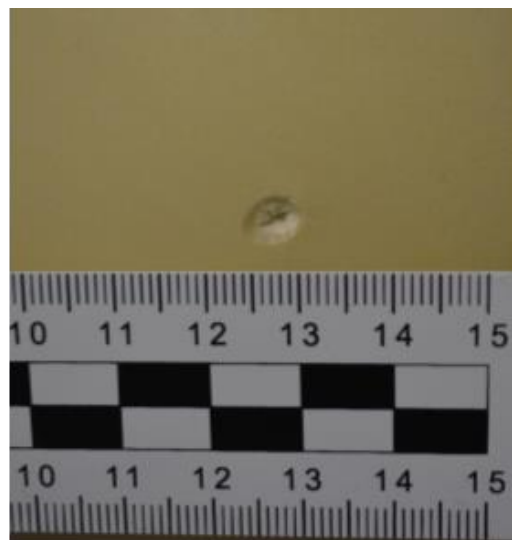


*Figure 3.13. Incomplete entry: projectile broke through the outer table but not the inner table (sample RcFt 3).*



- ii. Presence or absence of an exit defect: measured by the presence of any damage done to the surface opposite to the entrance defect. Dichotomous nominal level of measurement.
- iii. Entrance shape: designated as circular (clear circular shape that breaks through both the inner and outer tables), conical (circular entrance on the outer table that tapers inwards without breaking through the inner table), or irregular (any shape that does not match the description of the previous two categories). Nominal level of measurement (Figure 3.14).

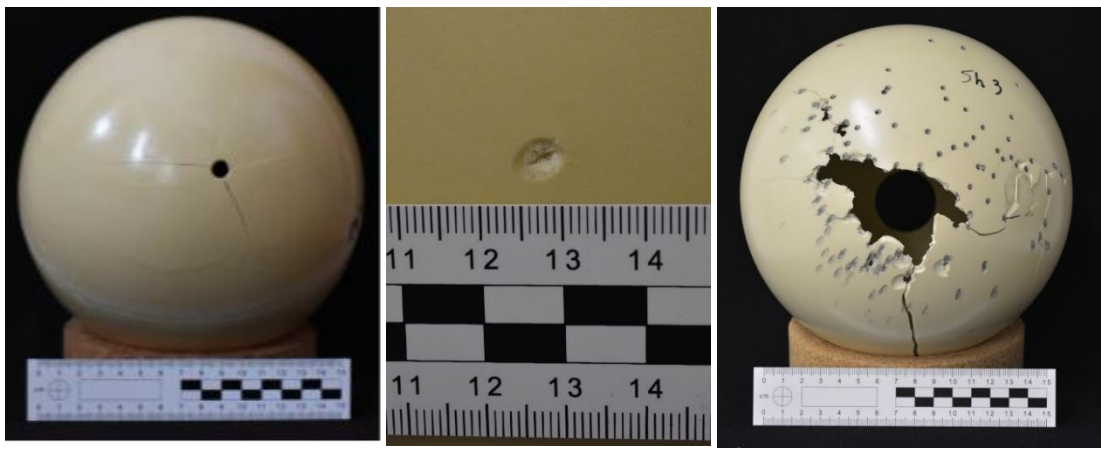


*Figure 3.14. Circular entry (left; sample CbFt5), conical entry (middle; sample RcFt3), irregular entry (right; sample Sh3).*

- iv. Exit shape (if applicable): designated as circular (clear circular pattern that breaks through both the inner and outer tables) or irregular (non-circular). Dichotomous nominal level of measurement (Figure 3.15).
- v. Presence or absence of bevelling at entrance defect: marked as present when more of either the inner or outer table of the entrance defect is broken away than the other table, exposing the inner diploë. Dichotomous nominal level of measurement.
- vi. Location of bevelling at entrance defect (if applicable): categorised as “internal” if the diploë is exposed internally or “external” if the diploë is exposed externally. Dichotomous nominal level of measurement.

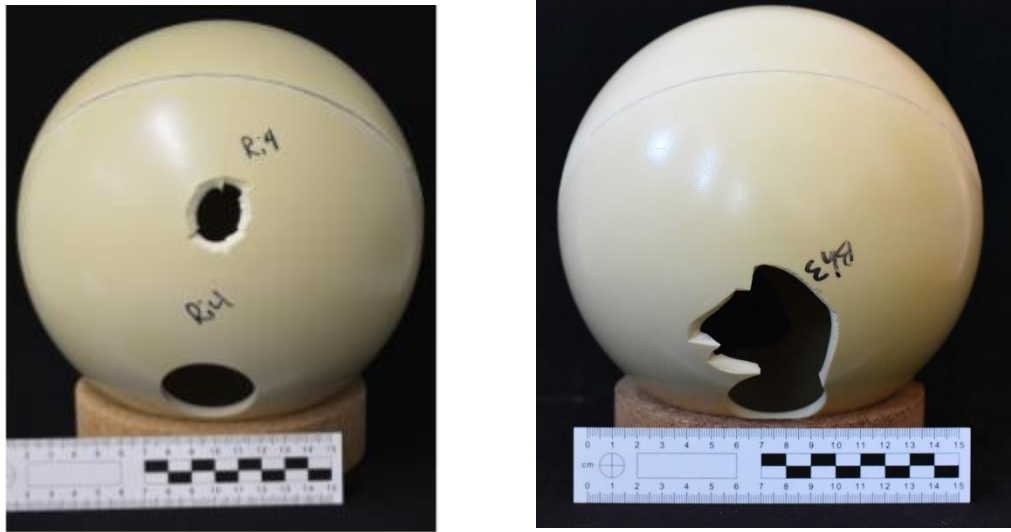


Figure 3.15. Exit shapes: circular (left; sample Ri 4) and irregular (right; sample CbBh 3).

- vii. Presence or absence of bevelling at exit defect (if applicable): marked as present when more of either the inner or outer table of the exit defect is broken away than the other table, exposing the inner diploë. Dichotomous nominal level of measurement (Figure 3.16).
- viii. Location of bevelling at exit defect (if applicable): categorised as “internal” if the diploë is exposed internally or “external” if the diploë is exposed externally. Dichotomous nominal level of measurement.



Figure 3.16. Exit defect with external bevelling (sample Ri4).

- ix. Presence or absence of residue: measured by the presence of any amount of particulates near the impact site (both entrance and exit defects) transferred by the projectile. Dichotomous nominal level of measurement (Figure 3.17).



*Figure 3.17. Residue at impact sites (sample Sh1).*

- x. Entrance maximum diameter (mm): measure of the widest portion of the entry defect opening without reconstructing using recovered fragments. Measured using sliding callipers. Interval level of measurement (Figure 3.18).
- xi. Reconstructed entrance maximum diameter (mm): measure of the widest portion of the entry defect opening (reconstructing using recovered fragments). Measured using sliding callipers. Interval level of measurement (Figure 3.19).
- xii. Exit maximum diameter (mm) (if applicable): measure of the widest portion of the exit defect opening without reconstructing using recovered fragments. Measured using sliding callipers. Interval level of

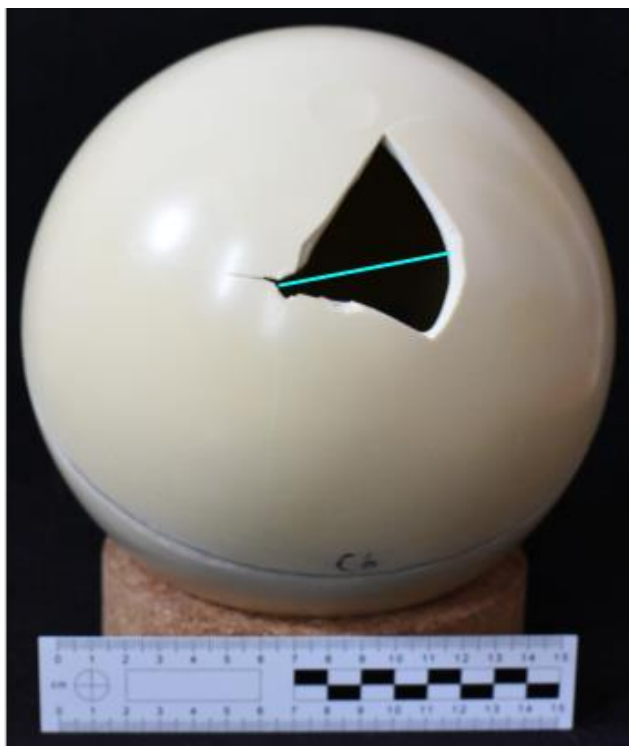


Figure 3.18. Entrance without reconstruction (sample CbBhX 1). Blue line represents maximum opening.

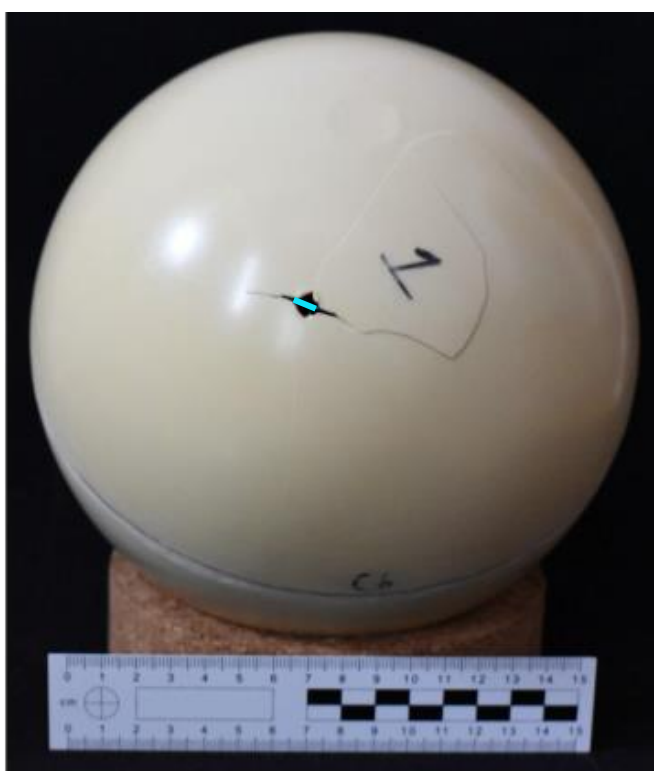


Figure 3.19. Reconstructed entrance (sample CbBhX 1). Blue line represents maximum opening.

measurement (Figure 3.20).



*Figure 3.20. Exit without reconstruction (sample Ri2). Blue line indicates maximum diameter.*

- xiii. Reconstructed exit maximum diameter (mm) (if applicable): measure of the widest portion of the exit defect opening (reconstructing using recovered fragments). Measured using sliding callipers. Interval level of measurement (Figure 3.21).
- xiv. Presence or absence of radiating fractures at the entrance defect: measured by the presence of any length of fracture that radiates from the entrance point of the projectile. Dichotomous nominal level of measurement.
- xv. Presence or absence of radiating fractures at the exit defect (if applicable): measured by the presence of any length of fracture that radiates from the exit point of the projectile. Dichotomous nominal level of measurement.
- xvi. Presence or absence of concentric heaving fractures at the entrance defect: measured by the presence of fractures that form in a circular



*Figure 3.21. Reconstructed exit (sample Ri2). Blue line indicates maximum exit diameter.*

pattern around the entrance defect. Dichotomous nominal level of measurement.

- xvii. Presence or absence of concentric heaving fractures at the exit defect (if applicable): measured by the presence of fractures that form in a circular pattern around the exit defect. Dichotomous nominal level of measurement.
- xviii. Number of entrance fractures (external table): count of any macroscopic fractures (not including the primary fracture) present on the external table which originate from the energy dispersed from the entrance defect produced by the projectile. Interval level of measurement.
- xix. Number of entrance fractures (internal table): count of any macroscopic fractures (not including the primary fracture) present on the internal table which originate from the energy dispersed from the entrance defect produced by the projectile. Interval level of measurement.

- xx. Number of exit fractures (if applicable) (external table): count of any macroscopic fractures (not including the primary fracture) present on the external table which originate from the energy dispersed from the exit defect produced by the projectile. Interval level of measurement.
- xxi. Number of exit fractures (if applicable) (internal table): count of any macroscopic fractures (not including the primary fracture) present on the internal table which originate from the energy dispersed from the exit defect produced by the projectile. Interval level of measurement.
- xxii. Maximum fracture length at the entrance defect (mm) (external table): the length of the longest fracture (not including the primary fracture) on the external table at the entrance defect. In order to account for the curvature of the sphere, this variable was measured by tracing the path of the fracture with twine then measuring the length of this segment with sliding callipers. Interval level of measurement.
- xxiii. Minimum fracture length at the entrance defect (mm) (external table): the length of the shortest fracture (not including the primary fracture) on the external at the entrance defect. In order to account for the curvature of the sphere, this variable was measured by tracing the path of the fracture with twine then measuring the length of this segment with sliding callipers. Interval level of measurement.
- xxiv. Maximum fracture length at the exit defect (mm) (external table): the length (mm) of the longest fracture (not including the primary fracture) on the external table at the exit defect. In order to account for the curvature of the sphere, this variable was measured by tracing the path of the fracture with twine then measuring the length of this segment with sliding callipers. Interval level of measurement.
- xxv. Minimum fracture length at the exit defect (mm) (external table): the length of the shortest fracture (not including the primary fracture) on the external table at the exit defect. In order to account for the curvature of the sphere, this variable was measured by tracing the

path of the fracture with twine then measuring the length of this segment with sliding callipers. Interval level of measurement.

- xxvi. Number of dislodged fragments at the entrance defect: count of any recovered segments of synthetic bone which separated from the entrance defect. This does not include the separation of the two hemispheres. Interval level of measurement.
- xxvii. Maximum entrance fragment length (mm) (if applicable): the longest length of the longest fragment from the entrance defect. In order to account for the curvature of the sphere, this variable was measured by tracing the length with twine then measuring the length of the twine segment with sliding callipers. Interval level of measurement (Figure 3.22).

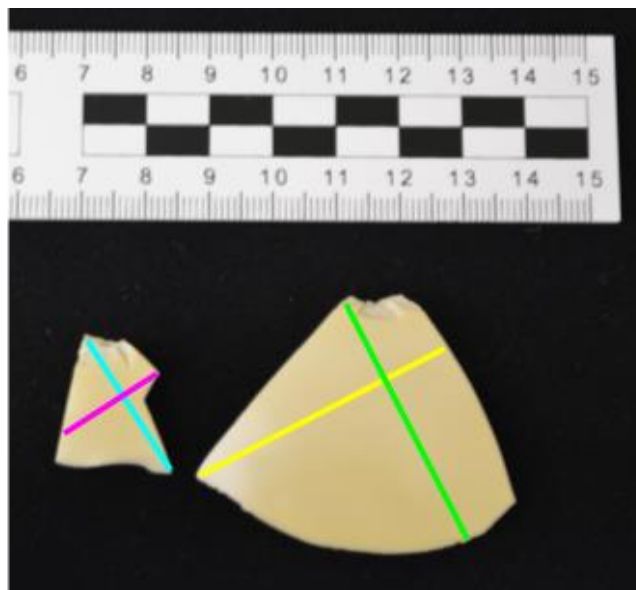


*Figure 3.22. Fragment dimensions: maximum length (yellow), minimum length (blue), maximum width (green), and minimum width (purple).*

- xxviii. Minimum entrance fragment length (mm) (if applicable): the shortest length of the shortest fragment from the entrance defect. In order to account for the curvature of the sphere, this variable was measured by tracing the length with twine then measuring the length of the twine segment with sliding callipers. Interval level of measurement (Figure 3.22).



- xxix. Maximum entrance fragment width (mm) (if applicable): the longest width of the fragments from the entrance defect. Width is defined as the plane which lies perpendicular to the length of the fragment. The widest of the entrance fragments does not inherently coincide with the longest of the entrance fragments. In order to account for the curvature of the sphere, this variable was measured by tracing the length with twine then measuring the length of the twine segment with sliding callipers. Interval level of measurement (Figure 3.22).
- xxx. Minimum entrance fragment width (mm) (if applicable): the shortest width of the fragments from the entrance defect. Width is defined as the plane which lies perpendicular to the length of the fragment. The most narrow of the entrance fragments does not inherently coincide with the shortest of the entrance fragments. In order to account for the curvature of the sphere, this variable was measured by tracing the length with twine then measuring the length of the twine segment with sliding callipers. Interval level of measurement (Figure 3.22).
- xxxi. Number of dislodged fragments at the exit defect: count of any recovered segments of synthetic bone which separated from the exit defect. This does not include the separation of the two hemispheres. Interval level of measurement.
- xxxii. Maximum exit fragment length (mm) (if applicable): the longest length of the longest fragment from the exit defect. In order to account for the curvature of the sphere, this variable was measured by tracing the length with twine then measuring the length of the twine segment with sliding callipers. Interval level of measurement (Figure 3.22).
- xxxiii. Minimum exit fragment length (mm) (if applicable): the shortest length of the shortest fragment from the exit defect. In order to account for the curvature of the sphere, this variable was measured by tracing the length with twine then measuring the length of the twine segment with sliding callipers. Interval level of measurement (Figure 3.22).

- xxxiv. Maximum exit fragment width (mm) (if applicable): the longest width of the fragments from the exit defect. Width is defined as the plane which lies perpendicular to the length of the fragment. The widest of the exit fragments does not inherently coincide with the longest of the exit fragments. In order to account for the curvature of the sphere, this variable was measured by tracing the length with twine then measuring the length of the twine segment with sliding callipers. Interval level of measurement (Figure 3.22).
- xxxv. Minimum exit fragment width (mm) (if applicable): the shortest width of the fragments from the exit defect. Width is defined as the plane which lies perpendicular to the length of the fragment. The most narrow of the exit fragments does not inherently coincide with the shortest of the exit fragments. In order to account for the curvature of the sphere, this variable was measured by tracing the length with twine then measuring the length of the twine segment with sliding callipers. Interval level of measurement (Figure 3.22).

### 3.6.2. Statistical Analysis

The statistical software program Rstudio (version 3.1.1) (R Core Team, 2014) was used to quantifiably analyse the data collected in this study. To better understand the meaning of the data collected in these experiments, principal component analyses (see Appendix A), one-way analysis of variance (ANOVA)/Kruskal-Wallis tests (see Appendix B), Tukey/Dunn post hoc tests, and linear discriminant analyses (see Appendix C) were conducted to isolate the most differentiating features of projectile trauma. Within this data set, the features discussed in Section 3.6.1. act as the explanatory variables while the weapon of origin is the response variable. The results of this study are intended to provide a classification system for cases of skeletal trauma where the weapon of origin is unknown and the observed trauma features would

indicate the most likely weapon of origin. All tests were interpreted with a significance level of  $p \leq 0.05$ .

Principal component analysis is a useful tool for discerning which of the explanatory variables in a given data set are more relevant for predicting the response variable (in this case that of weapon type) of a sample. Principal component analysis, however, can only assess which of the explanatory variables are more differentiating through the clustering of samples, it does not categorise the samples into the categories which are set by the researcher. For example, the principal component analyses run on the data from these experiments were able to distinguish which of the examined features of trauma are able to separate the samples into clusters on a multi-dimensional plane but does not associate those clusters with the weapon which was used to shoot each sample.

One of two tests (either a one-way ANOVA or Kruskal-Wallis test) was run on each of the principal components extracted from the principal component analyses. A one-way ANOVA is best run with parametric data, or data that can be predicted given a couple of parameters. First, the residuals must be normally distributed. The second is that the amount of variance is within each of the groups of the explanatory variable is roughly equal between groups (homoscedasticity). When the data met these assumptions, a one-way ANOVA was used to assess the statistical significance of the relationship between a singular explanatory variable and a singular response variable. The results of this test indicate whether the means of a response variable significantly differ between the groups of the explanatory variable, with the null hypothesis predicting that there is no significant difference.

In the context of this study, this linear model was used to analyse the statistical significance of the relationships between the weapon used (the explanatory variable) and each principal component extracted from the principal component analyses (the response variable) with the null hypothesis for each feature examined stating that there is no statistical difference between the means of each weapon used. An ANOVA test which

resulted in a p-value which is  $\leq 0.05$ , the null hypothesis was rejected, signifying that there was a difference between the means of at least two of the response categories (i.e., weapons used).

When an ANOVA test is run on data which does not meet the assumptions of parametric data, however, it is more like to produce a false positive result. Due to this, any features which did not meet and could not be transformed to meet the assumptions of parametric data were analysed using a Kruskal-Wallis one-way ANOVA. The Kruskal-Wallis test is the nonparametric equivalent of the one-way ANOVA test. The results of this test were interpreted in the same way as the one-way ANOVA results.

For both the one-way ANOVA and the Kruskal-Wallis test, the results only indicate that there is a significant relationship between at least two of the categories of the explanatory variable, it does not specify which categories have significantly different means. An additional post hoc analysis was conducted for each of the features which exhibited a significant relationship to discern which weapons' means differed from each other. A Tukey test was run for features which had been analysed with a one-way ANOVA test and a Dunn test was run for features which had been analysed with a Kruskal-Wallis test. In each of these tests, the results showed the significance (p-values) of the differences between each of the weapons compared against each other. Any p-value which was  $\leq 0.05$  signified a significant difference in mean between the two weapons.

Linear discriminant analysis, however, can use the information of clusters established in the principal component analyses and their most relevant distinguishing features to differentiate between the response categories defined by the researcher. This method of machine learning can then be used to predict the outcome of new samples based on the findings of the established dataset. This process was used to assign each of the clusters established in the principal component analyses from this study to one of the examined weapons. The results of the linear discriminant analysis can then

be used on future samples of cranial projectile trauma to estimate the most likely weapon of origin.

Finally, a tree diagram (see Appendix D) was constructed using the components extracted from the principal component analysis. This diagram illustrates not only which features are more indicative of the weapon used, but also provides defined dividing points between the clusters of data which can be used as a prediction for future cases. From this, a new protocol for projectile weapon identification was created in which the user would follow the most appropriate path in the diagram through answering a series of yes/no questions.

Two separate sets of each of these analyses were conducted: once which examines features of only the entrance defect and one which examines features of both the entrance and exit defects. As principal component analysis cannot process missing data, either samples without an exit defect or the features of the exit defects would have to be removed in order to run the analysis. Instead, samples with an exit defect present were examined separately, removing the samples which had no exit defect. The second analysis examined all samples, but the variables regarding the features of the exit defect were removed to accommodate for the samples which had no exit. This produced two classification systems: one which is to be used for instances where an exit defect is present and one which is to be used for instances where an exit defect is not present. Both systems examine the entrance defect.

When measuring quantitative variables, dimensions of features, such as fracture length, which were not present in a sample were recorded as "0.00 mm." Since zero is a quantifiable amount, this measurement would still be reflective of the trauma that a weapon can produce. This also allowed these samples to be included in the analysis of these variables.

The results of these tests are presented in Chapters 4 and 5 and are further discussed in Chapter 6.

## 4. Results I - Features

This chapter will discuss the observed trauma in the samples of this study, reviewing all measured variables. Samples are discussed according to the weapon of origin. Measurements that are reported as 0.00 mm signifies a sample which has none of the examined features (such as fractures or fragments).

### 4.1. Handgun Features

Each of the 11 handgun samples exhibited the presence of both a complete entrance defect and exit defect. The entrances for all samples were circular in shape. Bevelling was present on 100.00% of the samples, eight of which exhibited this feature internally (72.73%; 8/11) and three both internally and externally (27.27%; 3/11) (Figure 4.1). Within these samples, the widest opening of each entrance defect (without reconstructing with the dislodged fragments) ranged from 6.30 mm to 124.50 mm ( $n=11$ ;  $SD= \pm 47.58$  mm)

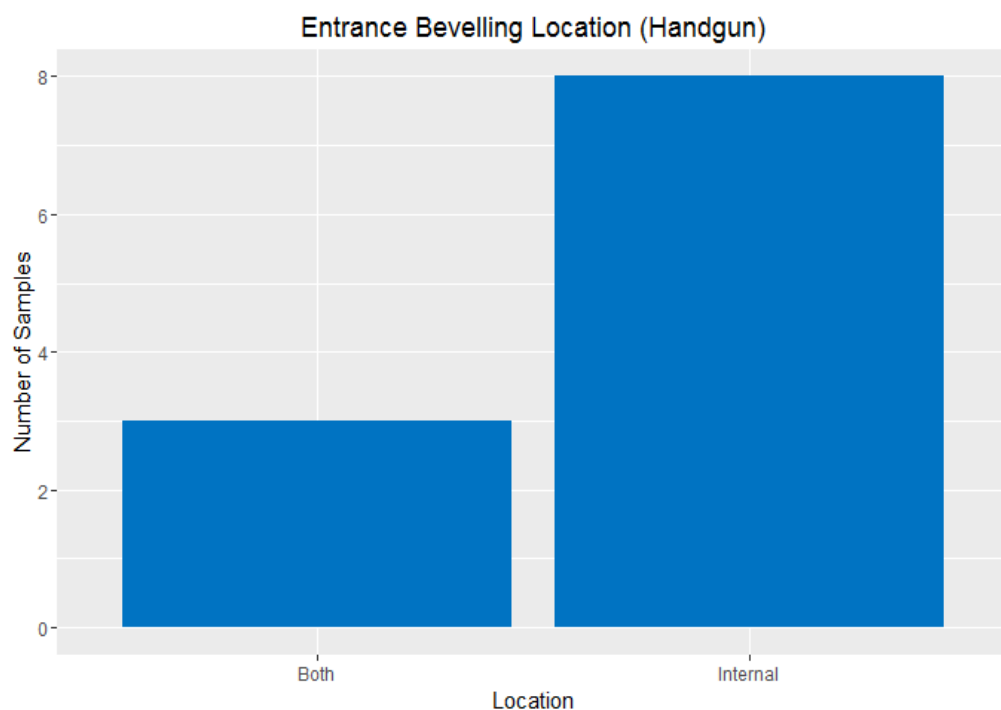


*Figure 4.1 Frequency of bevelling on the internal table only or both the internal and external tables of the entrance defect (handgun samples).*

(Table 4.1). The upper limit of this range nearly halves when the samples are reconstructed with dislodged fragments (where applicable), dropping to 72.00 mm ( $n=11$ ;  $SD= \pm 22.48$  mm). It was more common for samples to require reconstruction of the entrance defect (72.73%; 8/11) whereas only three of the entrance defects (27.27%; 3/11) did not need to be reconstructed due to a lack of dislodged fragments. Of the eight samples with dislodged fragments, the number of fragments ranged from one fragment to seven ( $n=11$ ;  $SD= \pm 2.14$ ), with more samples falling in the lower end of this range (Figure 4.2). Where entrance fragments were present, the dimensions of the fragment were quite large: the maximum lengths of the fragments ranged from 69.50 mm to 138.20 mm ( $n=8$ ;  $SD= \pm 45.34$  mm) while the maximum widths ranged from 43.50 mm to 79.30 mm ( $n=8$ ;  $SD= \pm 28.84$  mm). The minimum lengths (13.20 mm to 138.20 mm;  $n=8$ ;  $SD= \pm 43.20$  mm) and minimum widths (8.40 mm to 79.30 mm;  $n=8$ ;  $SD= \pm 27.12$  mm) of the fragments were noticeably smaller.

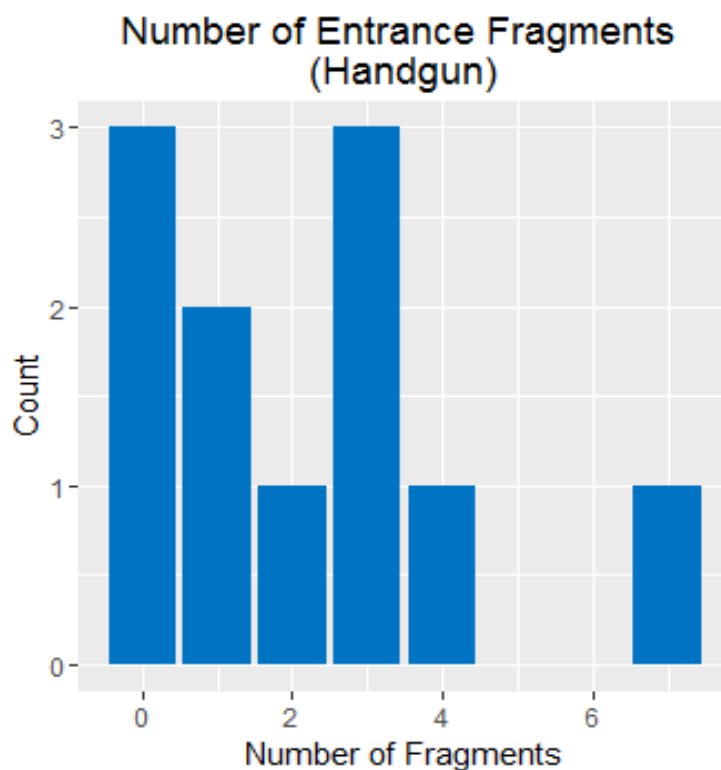


Figure 4.2. Frequency of number of fragments that originated from the entrance defect.

*Table 4.1 Mean and standard deviation of quantitative variables (handgun samples; n=11).*

| <b>Feature</b>                              | <b>Mean</b> | <b>Standard Deviation</b> |
|---------------------------------------------|-------------|---------------------------|
| Entrance defect diameter                    | 69.74 mm    | ± 47.58 mm                |
| Entrance defect diameter (reconstructed)    | 18.22 mm    | ± 22.48 mm                |
| Number of fragments (Entrance)              | 2.18        | ± 2.14                    |
| Entrance fragment maximum length            | 63.35 mm    | ± 45.34 mm                |
| Entrance fragment maximum width             | 42.49 mm    | ± 28.84 mm                |
| Entrance fragment minimum length            | 43.01 mm    | ± 43.20 mm                |
| Entrance fragment minimum width             | 28.75 mm    | ± 27.12 mm                |
| Number of fractures (external entrance)     | 7.55        | ± 4.16                    |
| Number of fractures (internal entrance)     | 8.18        | ± 3.71                    |
| Maximum fracture length (external entrance) | 179.79 mm   | ± 73.35 mm                |
| Minimum fracture length (external entrance) | 59.94 mm    | ± 60.26 mm                |
| Exit defect diameter                        | 69.97 mm    | ± 43.37 mm                |
| Exit defect diameter (reconstructed)        | 43.14 mm    | ± 28.11 mm                |
| Number of fragments (Exit)                  | 2.45        | ± 2.30                    |
| Exit fragment maximum length                | 48.21 mm    | ± 51.96 mm                |
| Exit fragment maximum width                 | 33.35 mm    | ± 39.67 mm                |
| Exit fragment minimum length                | 35.78 mm    | ± 48.10 mm                |
| Exit fragment minimum width                 | 24.71 mm    | ± 35.66 mm                |
| Number of fractures (external exit)         | 9.00        | ± 4.10                    |
| Number of fractures (internal exit)         | 9.18        | ± 3.95                    |
| Maximum fracture length (external exit)     | 95.72 mm    | ± 54.98 mm                |
| Minimum fracture length (external exit)     | 21.87 mm    | ± 12.58 mm                |



Most of the handgun samples had multiple fractures (ranging from 0-12 fractures;  $n=11$ ;  $SD= \pm 4.16$ ) on the external table of the entrance defect (Figure 4.3). Radiating fractures were present on the external table of the entrance site on ten of the 11 samples (90.90%). Concentric heaving fractures, however, were only present on the external table of the entrance defect on seven of the samples (63.64%; 7/11) and absent on four samples (36.36%; 4/11). The maximum length of the fractures (both radiating and concentric heaving) found on the external table of the entrance defect of each sample measured up to 267.10 mm ( $n=11$ ;  $SD= \pm 73.35$  mm). The minimum lengths of these fractures (0.00 mm-215.90 mm;  $n=11$ ;  $SD= \pm 60.26$  mm) are not much shorter than the maximum lengths. Excluding the samples with no fractures at the entrance defect, the maximum length ranges from 136.60 mm to 267.10 mm while the minimum length ranges from 8.40 mm to 215.00 mm.

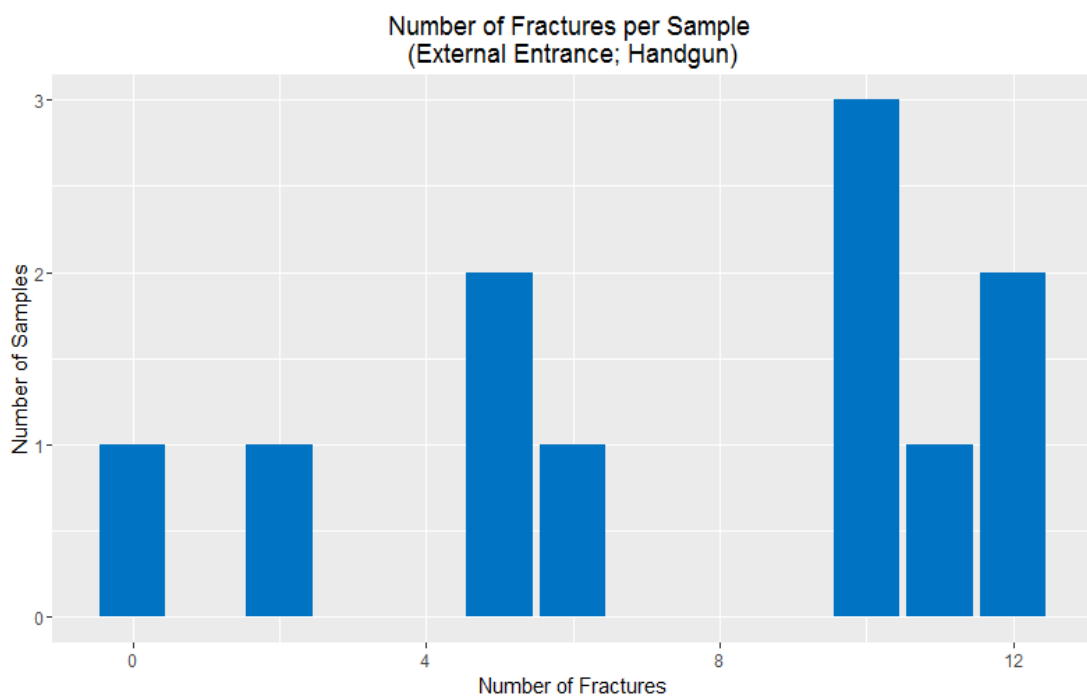


*Figure 4.3. Frequencies of the number of fractures on the external table of the entrance defect (handgun samples).*

The number of fractures on the internal table of the entrance defect of handgun samples mirrors the fractures observed on the external table of the entrance defect, ranging from zero to 12 fractures ( $n=11$ ;  $SD= \pm 3.71$ ) (Figure 4.4). Radiating fractures were present on the internal table of the entrance

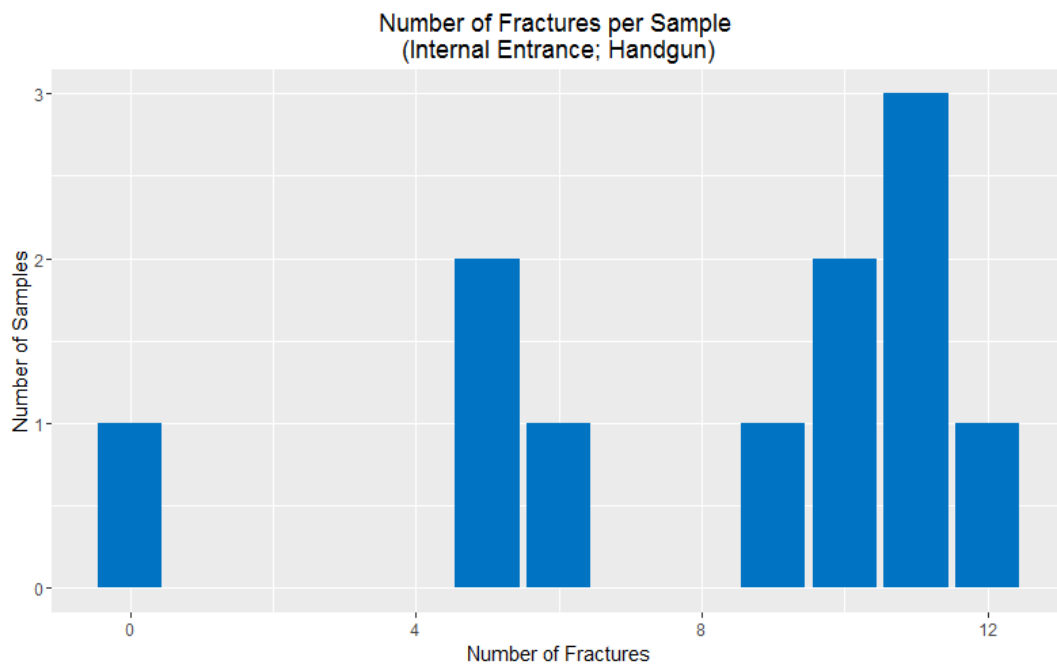


*Figure 4.4. Frequencies of the number of fractures on the internal table of the entrance defect (handgun samples).*

defect on ten samples (90.90%; 10/11) but were absent on one sample (9.10%; 1/11) which had zero fractures. Concentric heaving fractures, however, were only present on the internal table of the entrance defect on eight samples (72.73%; 8/11) and absent on three samples (27.27%; 3/11). While all handgun samples exhibited a circular entrance shape, only five samples' exits (45.45%; 5/11) were circular in shape while the other six (54.55%; 6/11) exhibited an irregular shape (Figure 4.5). Bevelling was present at the exit defect in 100% of the samples and all exit defects bevelled externally. Within these samples, the widest opening of each exit defect (without reconstructing with the dislodged fragments) ranged from 24.70 mm to 118.40 mm ( $n=11$ ;  $SD= \pm 43.37$  mm). Both limits of this range greatly decreased when the samples are reconstructed with dislodged fragments (where applicable) (0.00 mm-73.60 mm;  $n=11$ ;  $SD= \pm 28.11$  mm) (Figure 4.6). Eight samples (72.73%; 8/11) required this reconstruction of the entrance defect whereas three samples (27.27%; 3/11) had no dislodged fragments.

Of the eight samples with dislodged fragments that originated from the exit

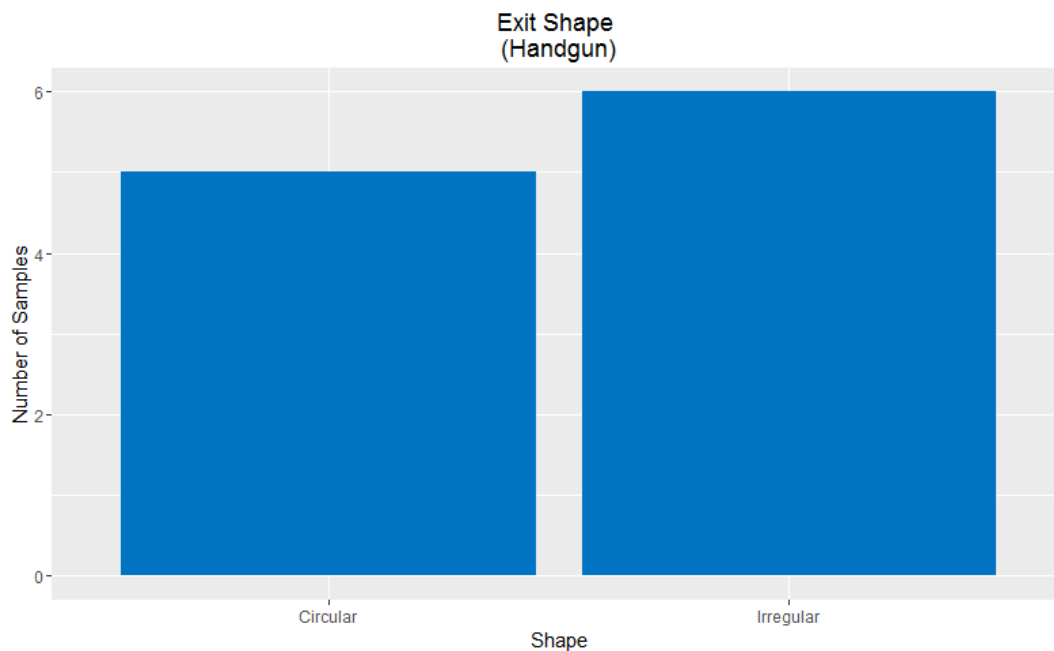


*Figure 4.5 Frequencies of exit shapes (handgun samples).*

defect, the number of fragments ranged from one fragment to seven fragments ( $n=8$ ;  $SD= \pm 2.30$ ) with most samples falling in the lower end of this range (Figure 4.7). Where exit fragments were present, the dimensions of the fragments were generally smaller than the dimensions of the entrance fragments: the maximum lengths of the fragments ranged from 27.60 mm to 153.90 mm ( $n=8$ ;  $SD= \pm 51.96$  mm) while the maximum widths ranged from 16.20 mm to 116.30 mm ( $n=8$ ;  $SD= \pm 39.67$  mm). The minimum lengths (13.80 mm-153.90 mm;  $n=8$ ;  $SD= \pm 48.10$  mm) and widths (6.80 mm-116.30 mm;  $n=8$ ;  $SD= \pm 35.66$  mm) of the fragments were not much smaller than the maximum fragment dimensions.

The number of fractures found on the external table of the exit defect varied between samples, ranging from three to 15 ( $n=11$ ;  $SD= \pm 4.10$ ) with relatively even distribution (Figure 4.8). Radiating fractures were present on the external table of the exit defect on all 11 of the samples. Concentric heaving fractures, however, were only present on the external table of the entrance defect on five samples (45.45%; 5/11) and absent on six samples (54.55%; 6/11). The maximum length of the fractures (both radiating and concentric

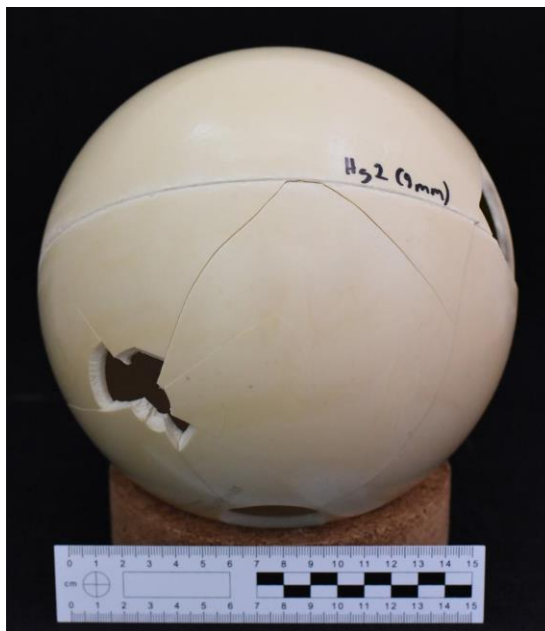
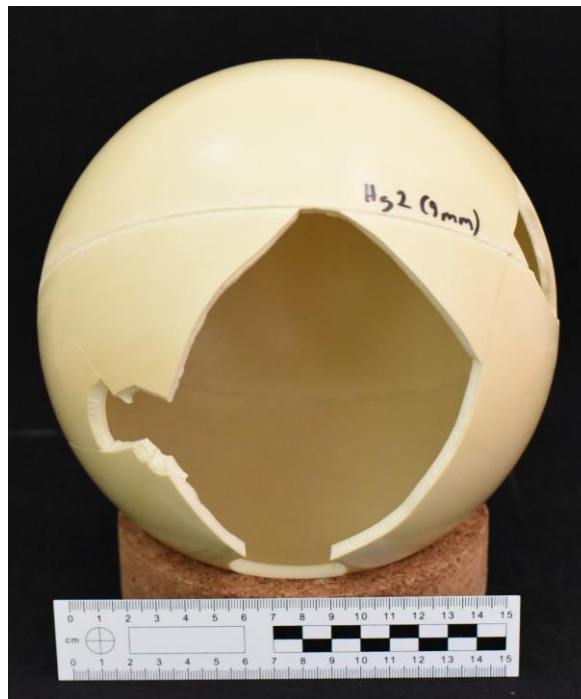


*Figure 4.6. Reconstruction of exit site (sample Hg 2 (9 mm)), which greatly affects the diameter of the defect. Top: exit defect without reconstruction; Bottom: exit site with reconstruction.*

heaving) found on the external table of the exit defect of each sample ranged from 18.40 mm to 183.50 mm ( $n=11$ ;  $SD= \pm 54.98$  mm). The minimum lengths of the fractures were noticeably shorter (5.00 mm-41.40 mm;  $n=11$ ;  $SD= \pm 12.58$  mm) than the shortest fractures found on the external table of the entrance defect.

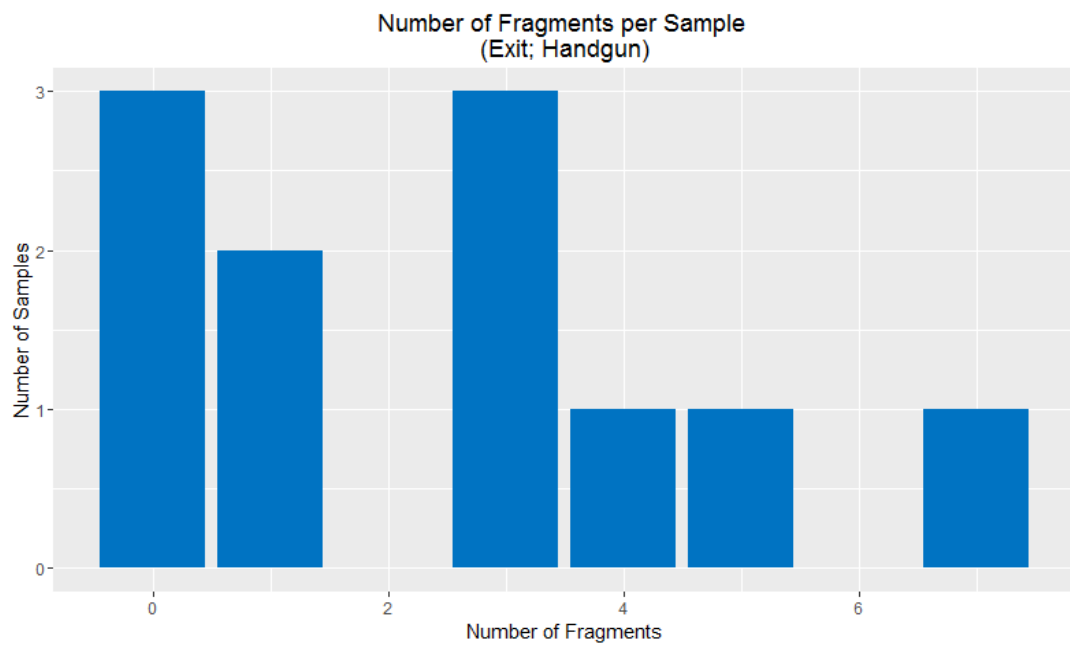


Figure 4.7. Frequencies of the number of fragments that originated from the exit defect (handgun samples).

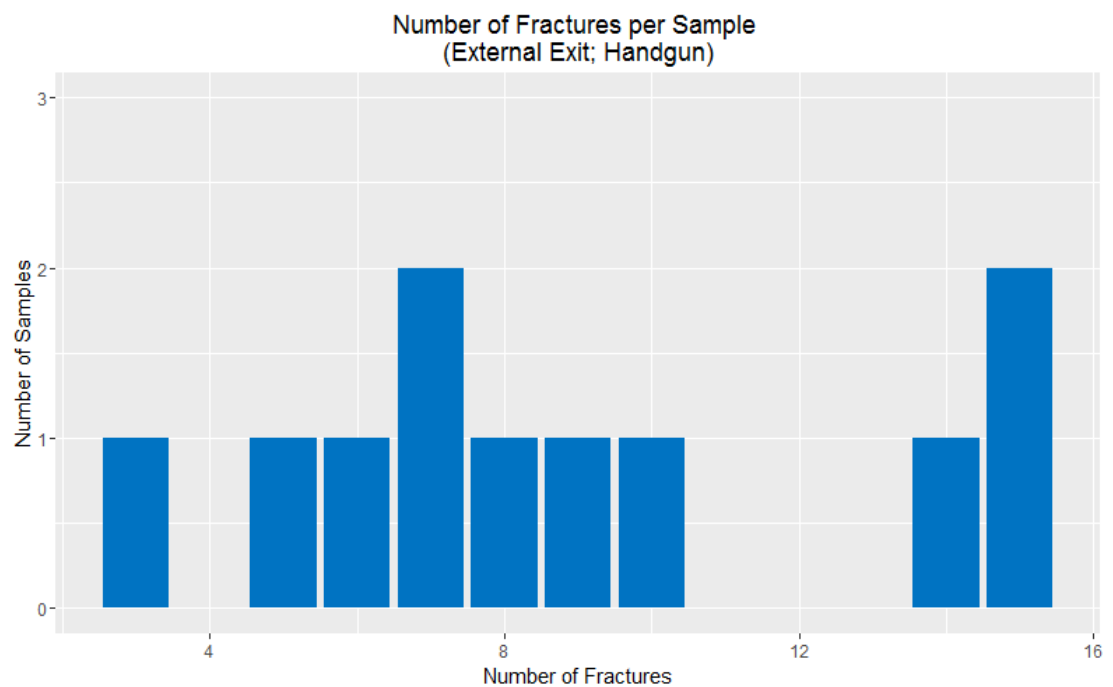


Figure 4.8. Frequencies of the number of fractures on the external table of the exit defect (handgun samples).

The number of fractures found on the internal table of the exit defect of handgun samples had a slightly tighter range (five to 15;  $n=11$ ;  $SD= \pm 3.95$ ) than that of the external table (Figure 4.9). Radiating fractures were present on the internal table of the exit defect on all 11 of the samples. Unlike the external table of the exit defects, concentric heaving fractures were present on the internal table of the exit defect on nine samples (81.82%; 9/11), nearly double the number of samples, and only absent on two samples (18.18%; 2/11).

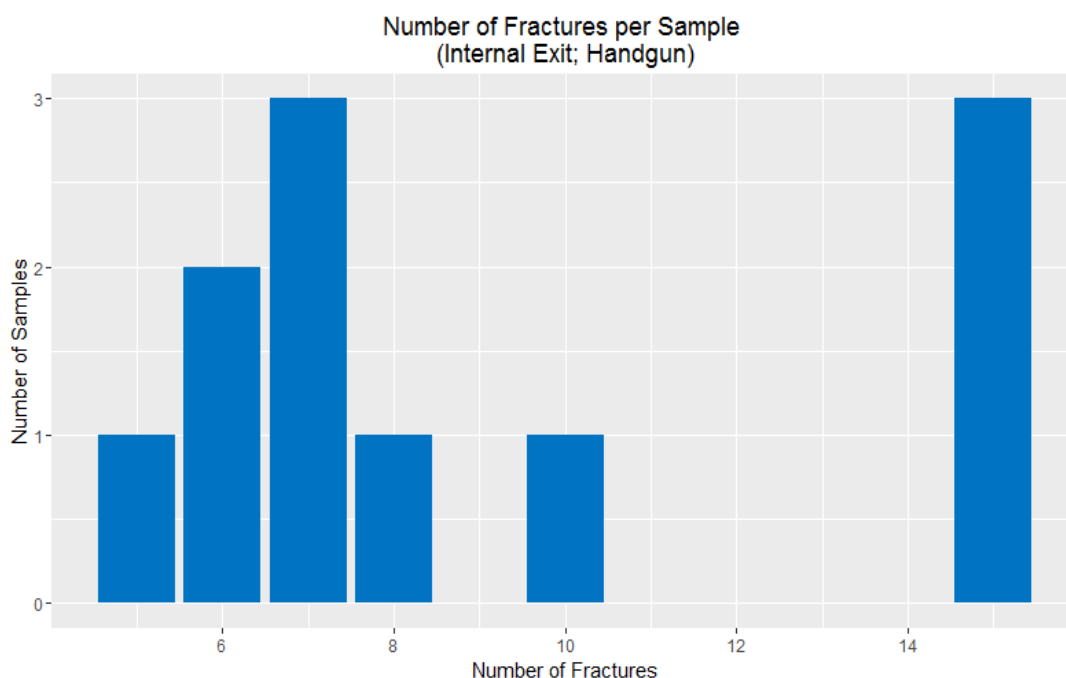


*Figure 4.9. Frequencies of the number of fractures on the internal table of the exit defect (handgun samples).*

All samples retained at least some level of residue left from the projectile.

## 4.2. Rifle Features

The rifle samples exhibited the characteristic qualitative features of projectile trauma. Of the five rifle samples, all had both a complete entrance and an exit wound. The entrance defects of all five samples were circular in shape with bevelling present on the internal table. The largest portion of each entrance opening (without reconstruction using dislodged fragments) ranged

from 3.50 mm to 6.50 mm ( $n=5$ ;  $SD= \pm 1.39$  mm) (Table 4.2). This range did not change after reconstruction as no entrance fragments were directly adjacent to the impact site (Figure 4.10).



*Figure 4.10. Sample where reconstructing the entrance defect does not affect the diameter of the entrance itself (Sample Ri 1).*

The majority of the rifle samples (60.00%; 3/5) had no dislodged fragments originating from the entrance defect while two samples (40.00%; 2/5) had fragments (Figure 4.11). One of the samples with fragments had one entrance fragment while the other had two ( $n=5$ ;  $SD= \pm 0.89$ ). Of the three total fragments originating from the entrance defect, the maximum fragment dimensions were small to medium in size, with lengths ranging from 76.20 mm to 90.00 mm ( $n=5$ ;  $SD= \pm 45.78$  mm) and widths ranging from 11.70 to 65.10 mm ( $n=5$ ;  $SD= \pm 28.26$  mm). The minimum fragment length maintains the upper limit of 90.00 mm ( $n=5$ ;  $SD= \pm 38.98$  mm), but the lower limit drops to 20.80 mm ( $n=5$ ;  $SD= \pm 6.46$  mm). The entrance fragment minimum widths, however, narrow considerably (11.70 mm-11.90 mm;  $n=5$ ;  $SD= \pm 6.46$  mm).

Table 4.2. Mean and standard deviation of quantitative variables (rifle samples; n=5)

| Feature                                     | Mean      | Standard Deviation |
|---------------------------------------------|-----------|--------------------|
| Entrance defect diameter                    | 4.98 mm   | ± 1.39 mm          |
| Entrance defect diameter (reconstructed)    | 4.98 mm   | ± 1.39 mm          |
| Number of fragments (Entrance)              | 0.60      | ± 0.89             |
| Entrance fragment maximum length            | 33.24 mm  | ± 45.78 mm         |
| Entrance fragment maximum width             | 15.36 mm  | ± 28.26 mm         |
| Entrance fragment minimum length            | 22.16 mm  | ± 38.98 mm         |
| Entrance fragment minimum width             | 4.72 mm   | ± 6.46 mm          |
| Number of fractures (external entrance)     | 4.00      | ± 1.22             |
| Number of fractures (internal entrance)     | 3.80      | ± 0.84             |
| Maximum fracture length (external entrance) | 211.91 mm | ± 44.43 mm         |
| Minimum fracture length (external entrance) | 56.74 mm  | ± 37.08 mm         |
| Exit defect diameter                        | 45.78 mm  | ± 21.25 mm         |
| Exit defect diameter (reconstructed)        | 23.90 mm  | ± 3.40 mm          |
| Number of fragments (Exit)                  | 1.80      | ± 2.00             |
| Exit fragment maximum length                | 24.80 mm  | ± 20.10 mm         |
| Exit fragment maximum width                 | 17.42 mm  | ± 16.58 mm         |
| Exit fragment minimum length                | 29.22 mm  | ± 30.37 mm         |
| Exit fragment minimum width                 | 23.44 mm  | ± 28.03 mm         |
| Number of fractures (external exit)         | 5.60      | ± 2.41             |
| Number of fractures (internal exit)         | 5.80      | ± 2.17             |
| Maximum fracture length (external exit)     | 92.14 mm  | ± 18.73 mm         |
| Minimum fracture length (external exit)     | 28.20 mm  | ± 14.34 mm         |



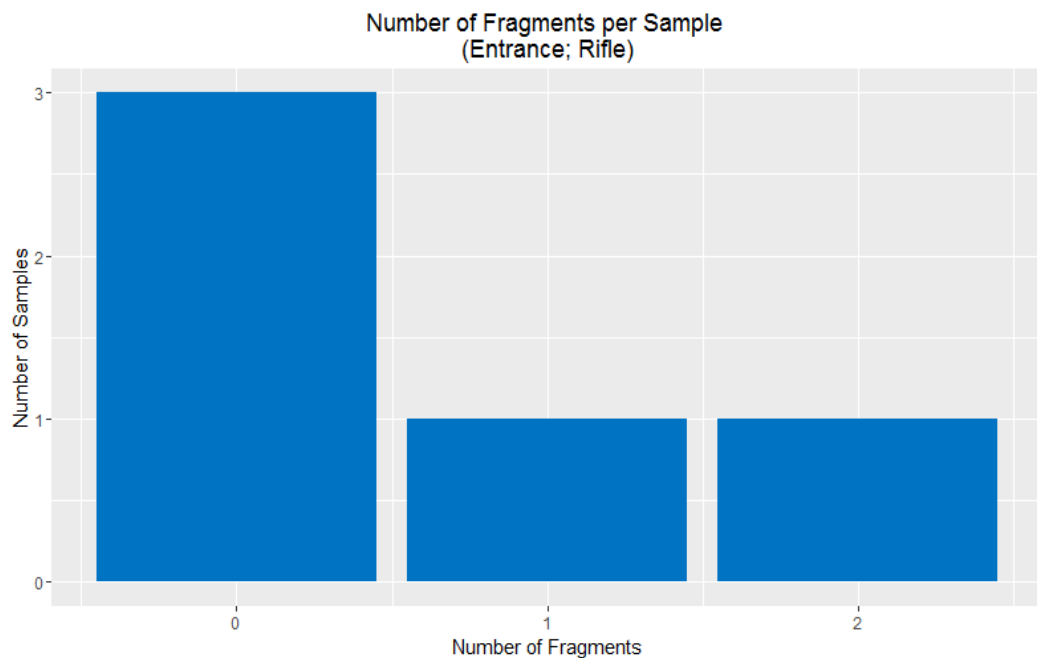


*Figure 4.11. Frequencies of the number of fragments that originated from the entrance defect (Rifle samples).*

All samples had fractures on the external table of the entrance defect. The number of fractures per sample was generally consistent with minimal variation (three to six fractures;  $n=5$ ;  $SD= \pm 1.22$ ) (Figure 4.12). Radiating fractures were present on the external table of the entrance defect for all five samples while concentric heaving fractures were only present on the external table of three samples (60.00%; 3/5). The maximum length of these fractures (both radiating and concentric heaving) ranged from 139.90 mm to 249.10 mm ( $n=5$ ;  $SD= \pm 44.43$  mm) while the minimum lengths of these fractures were less than half of this range (11.80 mm-107.30 mm;  $n=5$ ;  $SD= \pm 37.08$  mm).

All samples also had fractures present on the internal table of the entrance defect. The range of number of fractures per sample was even more narrow (three to five;  $n=5$ ;  $SD= \pm 0.84$ ) than the external table (Figure 4.13). Radiating fractures were present on the internal table of the entrance defect for all five samples, but concentric heaving fractures were present on only three samples (60.00%; 3/5).

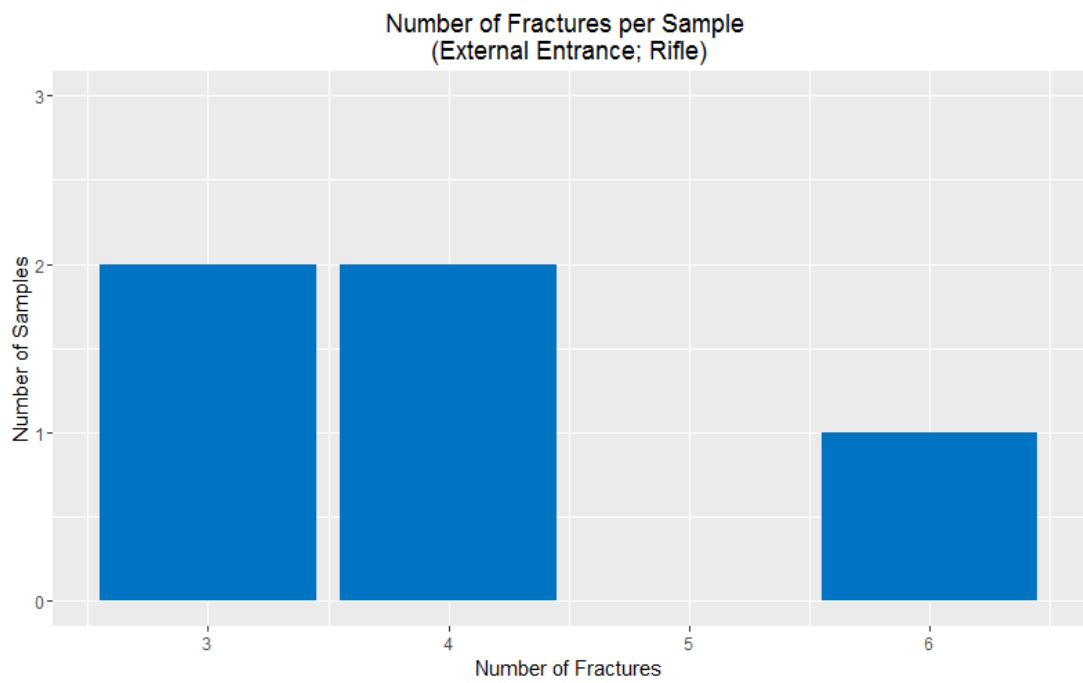


Figure 4.12. Frequencies of the number of fractures on the internal table of the entrance defect (rifle samples).

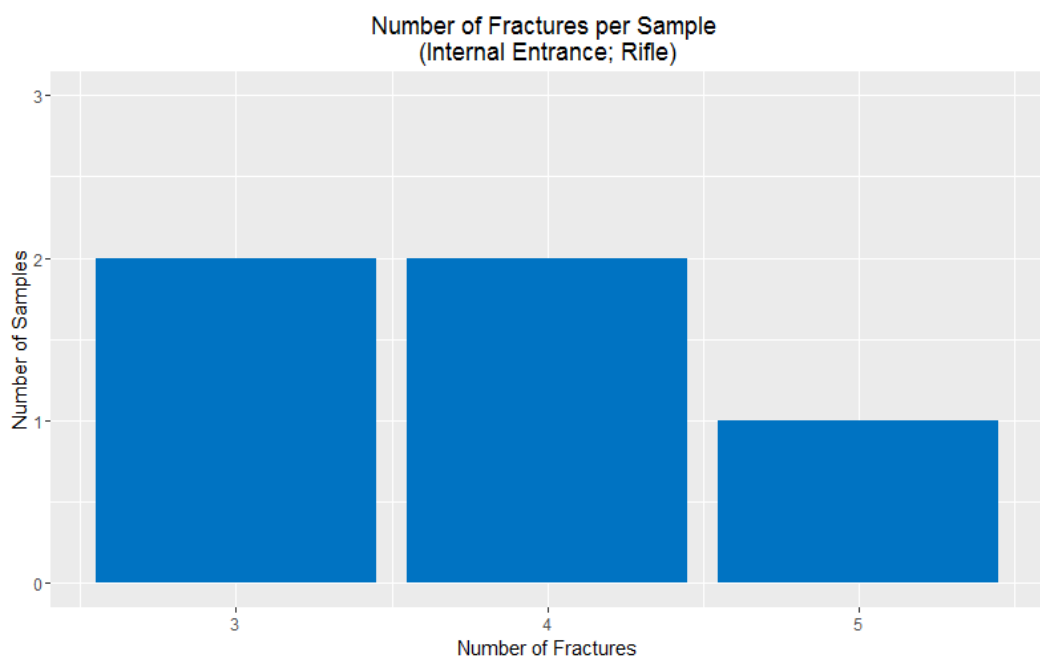


Figure 4.13. Frequencies of the number of fractures on the external table of the entrance defect (rifle samples).

Three of the exit defects within the rifle samples (60.00%; 3/5) were circular in shape while two (40.00%; 2/5) were irregularly shaped (Figure 4.14). Four exit defects (80.00%; 4/5) exhibited bevelling, but one exit defect (20.00%; 1/5) had no bevelling. Of the four samples which had bevelling at the exit defect, all four bevelled externally. The largest portion of each exit opening (without reconstructing using dislodged fragments) was generally small (24.20 mm-76.20 mm;  $n=5$ ;  $SD= \pm 21.25$  mm). When the rifle samples were reconstructed, the exit opening size range did not greatly decrease, but exhibited less variation between the samples (18.90 mm-27.90 mm;  $n=5$ ;  $SD= \pm 3.40$  mm).

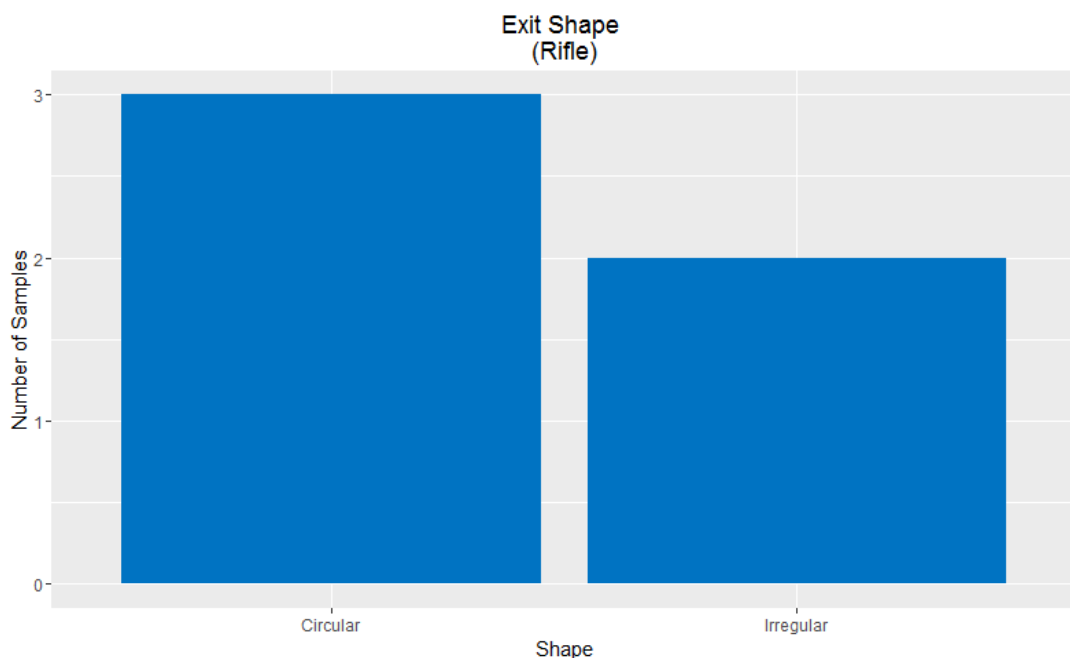


Figure 4.14. Frequencies of exit shapes (rifle samples).

The majority of the rifle samples (60.00%; 3/5) had fragments originating from the exit defect while two of the samples (40.00%; 2/5) had none. Of the three samples with exit fragments, the number ranged from one to five fragments per sample (Figure 4.15). The dimensions of these fragments were relatively similar to each other, with the largest lengths ranging from 17.60 mm to 81.80 mm ( $n=5$ ;  $SD= \pm 20.10$  mm) and smallest lengths ranging from 4.10 mm to 81.80 mm ( $n=5$ ;  $SD= \pm 30.37$  mm). The widths of these fragments showed a parallel pattern of similarity between maximum (10.70

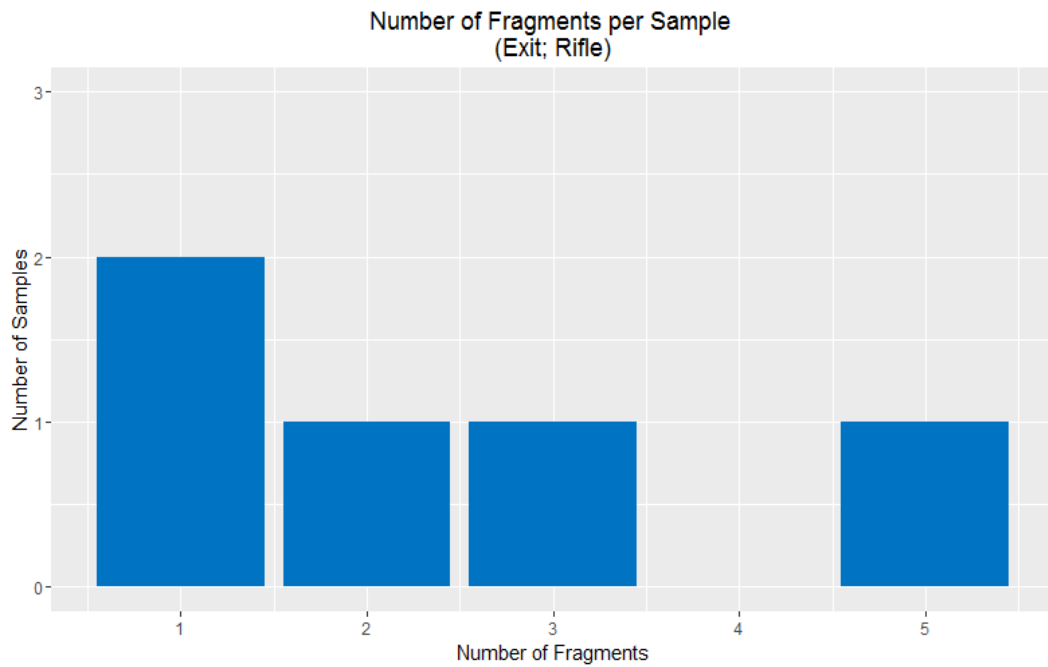


*Figure 4.15. Frequencies of the number of fragments that originated from the exit defect (rifle samples).*

mm-72.60 mm;  $n=5$ ;  $SD= \pm 16.58$  mm) and minimum measurements (2.50 mm-72.60 mm;  $n=5$ ;  $SD= \pm 28.03$  mm).

All samples had fractures on the external table of the exit defect with the number of fractures per sample ranging from three to nine fractures ( $n=5$ ;  $SD= \pm 2.41$ ) with fairly even distribution throughout (Figure 4.16). Radiating fractures were present on the external table of the exit defect for all five samples while concentric heaving fractures were only present on the external table of three samples (60.00%; 3/5). The fractures of the exit defect are generally in the mid-range of fracture lengths observed in this study, with the maximum lengths of the exit fractures (both radiating and concentric heaving) on the external table ranging from 71.10 mm to 115.40 mm ( $n=5$ ;  $SD= \pm 18.73$  mm) while the minimum lengths ranged from 9.90 mm to 46.20 mm ( $n=5$ ;  $SD= \pm 14.34$  mm).

The overview of the internal fractures at the exit defect mirrors the external table in regards to number of fractures (three to nine;  $n=5$ ;  $SD= \pm 2.17$ ) (Figure 4.17) and presence of radiating fractures (100%) and concentric heaving fractures (60.00%; 3/5).

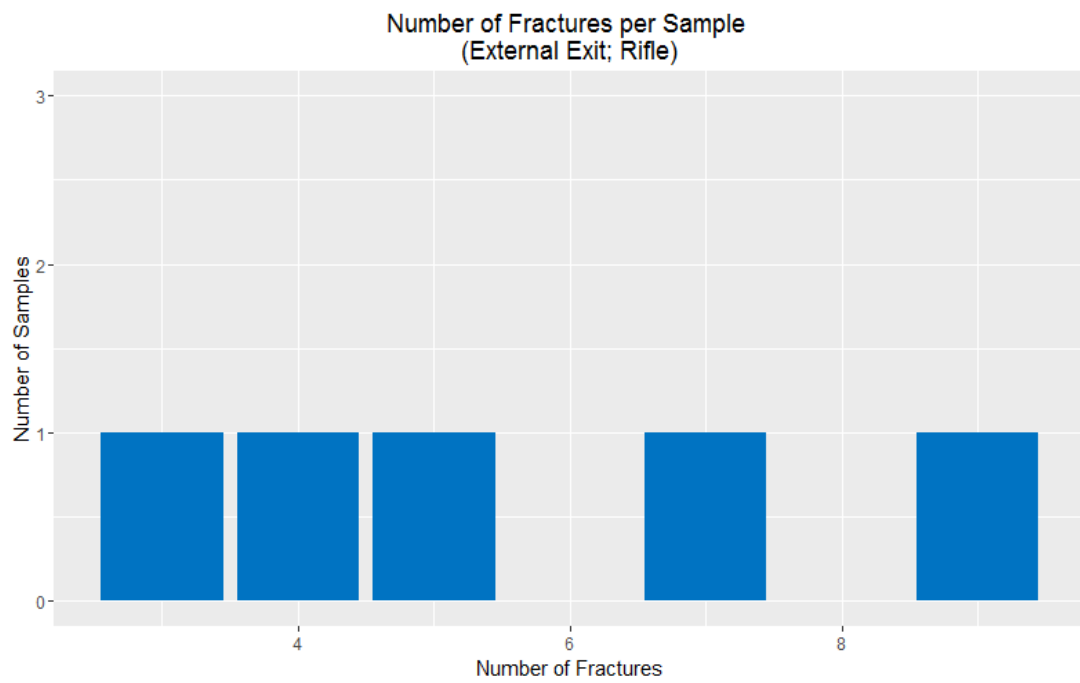


Figure 4.16. Frequencies of the number of fractures on the external table of the exit defect (rifle samples).

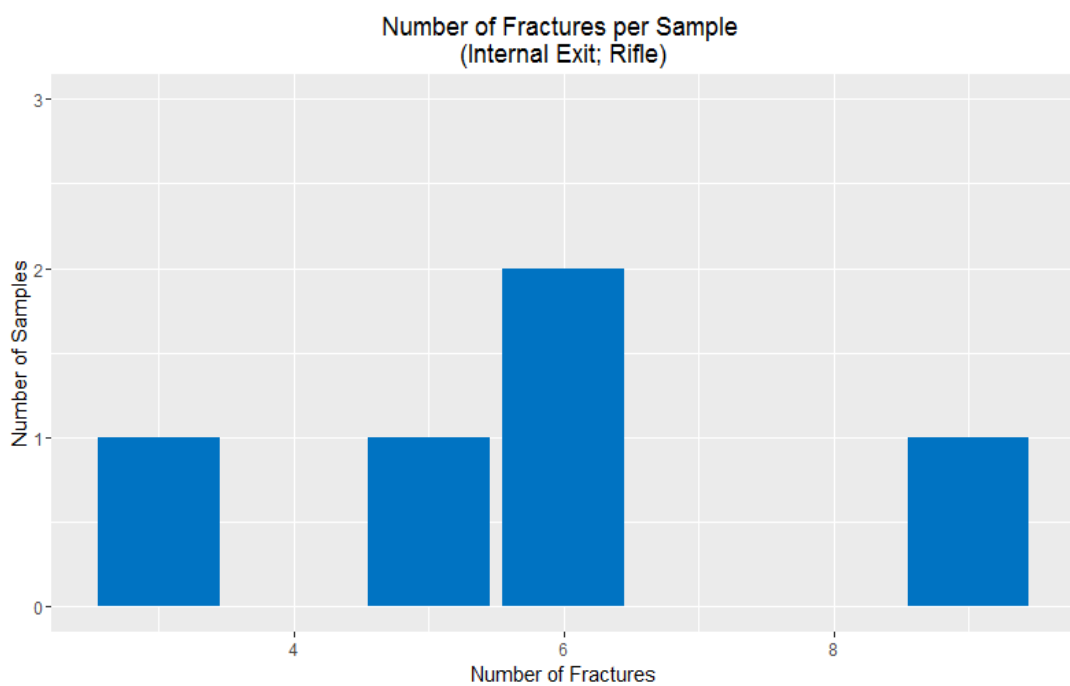


Figure 4.17. Frequencies of the number of fractures on the internal table of the exit defect (rifle samples).

All five samples retained at least some level of residue left from the projectile.

### 4.3. Shotgun Features

Only four of the five shotgun samples (80.00%) had a complete entrance defect. The absence of an exit defect, however, was observed on all five shotgun samples. Of the entrance defects (both complete and incomplete), four were irregular in shape (80.00%; 4/5) while one was circular in shape (20.00%; 1/5) (Figure 4.18). Bevelling was observed at the entrance defect of all five samples. The shotgun samples were the only samples to have multiple impact points with one shot (Figure 4.19) and separate regions of bevelling were present at each impact point in all five samples. The location of the bevelling, however, varied between the samples: three samples (60.00%; 3/5) were bevelled internally, one sample (20.00%; 1/5) was bevelled externally, and one sample (20.00%; 1/5) was bevelled both internally and externally (Figure 4.20). The widest points of the entrance defects measured up to 93.10 mm ( $n=5$ ;  $SD= \pm 43.95$  mm) without reconstructing using any recovered fragments (Table 4.3). When the entrance defects were reconstructed with the dislodged fragments (where applicable), the upper limit of this range decreased to 78.70 mm ( $n=5$ ;  $SD= \pm 31.66$  mm).

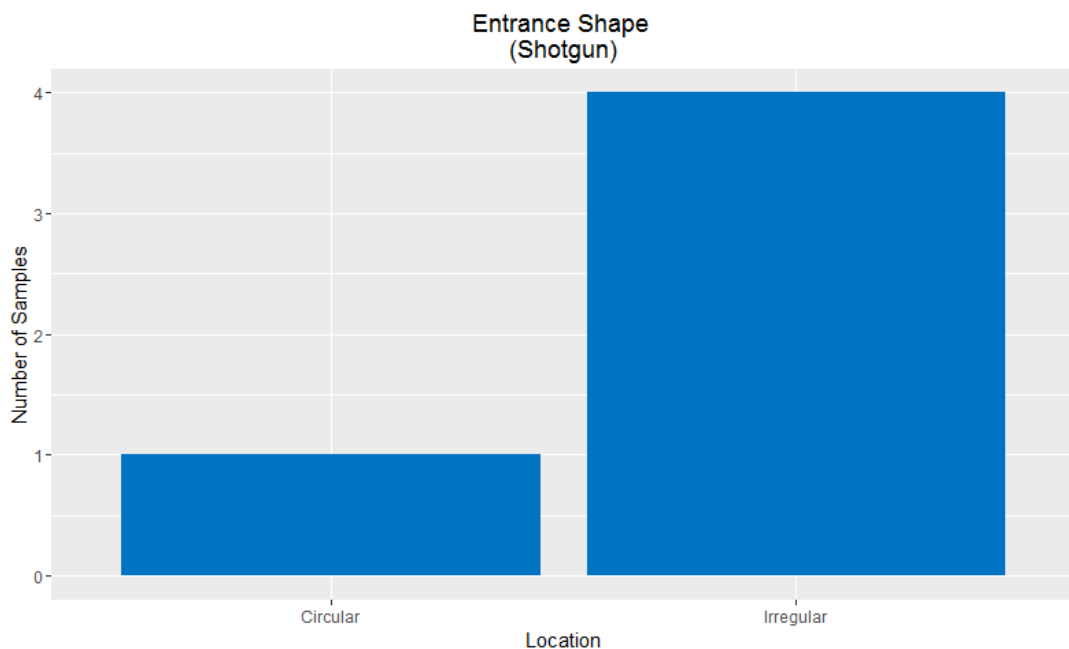


Figure 4.18 Frequencies of entrance shapes (shotgun samples).

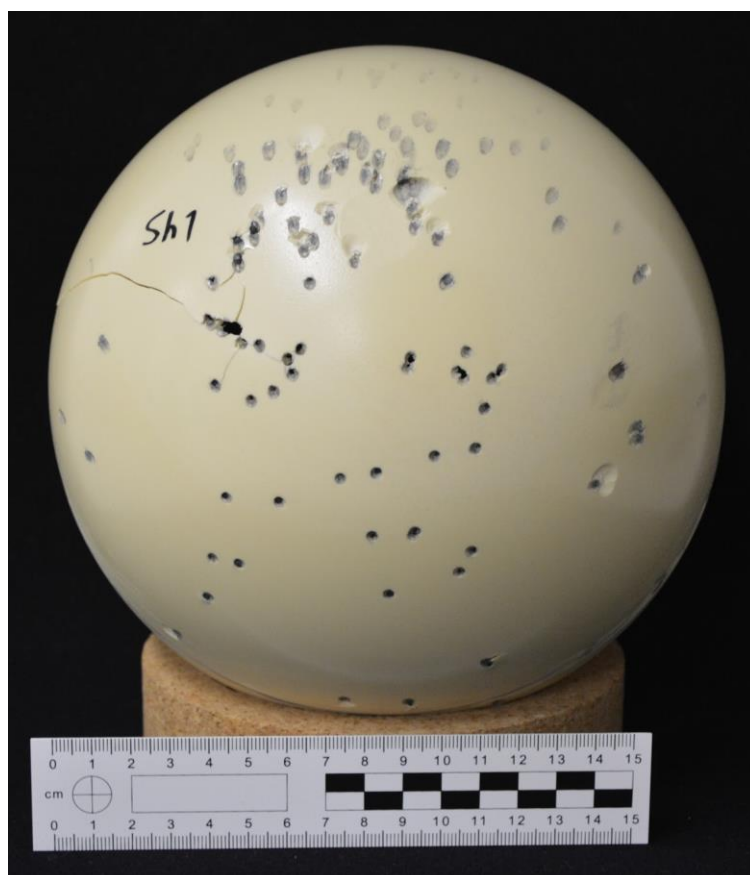


Figure 4.19. Multiple entry points with a single shot from a shotgun. (Sample Sh1).

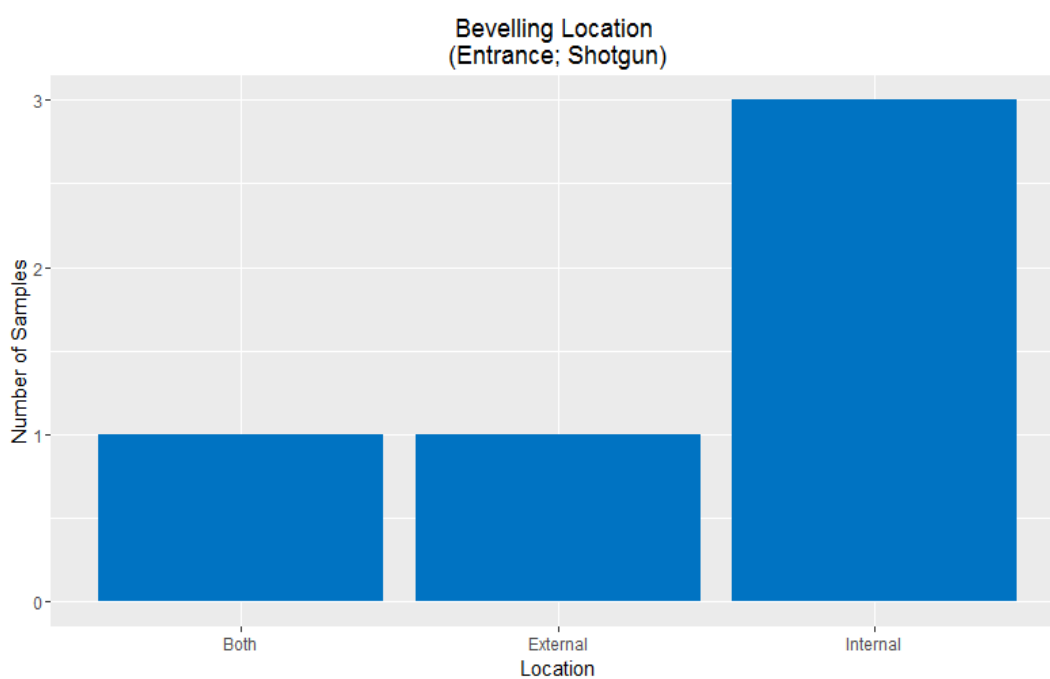


Figure 4.20. Frequency of bevelling on the internal table only, the external table only, or both the internal and external tables of the entrance defect (shotgun samples).

Table 4.3. Mean and standard deviation of quantitative variables (shotgun samples;  $n=5$ ).

| Feature                                     | Mean     | Standard Deviation |
|---------------------------------------------|----------|--------------------|
| Entrance defect diameter                    | 38.40 mm | $\pm 43.95$ mm     |
| Entrance defect diameter (reconstructed)    | 25.74 mm | $\pm 31.66$ mm     |
| Number of fragments (Entrance)              | 34.20    | $\pm 22.98$        |
| Entrance fragment maximum length            | 25.70 mm | $\pm 34.01$ mm     |
| Entrance fragment maximum width             | 15.92 mm | $\pm 18.63$ mm     |
| Entrance fragment minimum length            | 3.14 mm  | $\pm 1.88$ mm      |
| Entrance fragment minimum width             | 1.68 mm  | $\pm 1.06$ mm      |
| Number of fractures (external entrance)     | 13.40    | $\pm 6.99$         |
| Number of fractures (internal entrance)     | 15.80    | $\pm 11.58$        |
| Maximum fracture length (external entrance) | 85.65 mm | $\pm 54.27$ mm     |
| Minimum fracture length (external entrance) | 2.50 mm  | $\pm 0.90$ mm      |

Four samples (80.00%; 4/5) had dislodged fragments while one sample (20.00%; 1/5) presented with no fragments. The number of fragments per sample (23-54;  $n=5$ ;  $SD= \pm 22.98$ ) was noticeably higher in shotgun samples than any other weapon (Figure 4.21). These fragments, however, were generally very small. The largest dimensions of these fragments ranged from 11.10 mm to 85.40 mm in length ( $n=5$ ;  $SD= \pm 34.01$  mm) and 7.80 mm to 48.10 mm in width ( $n=5$ ;  $SD= \pm 18.63$  mm). The smallest fragments are significantly smaller, with lengths between 3.40 mm and 5.10 mm ( $n=5$ ;  $SD= \pm 1.88$  mm) and widths between 1.40 mm and 2.80 mm ( $n=5$ ;  $SD= \pm 1.06$  mm).

All five shotgun samples had fractures on the external table of the entrance defect. Similar to the number of fragments, the number of fractures per shotgun sample was very high (5 to 23;  $n=5$ ;  $SD= \pm 6.99$ ) (Figure 4.22). Though all five samples showed the presence of radiating fractures on the external table, no samples had produced concentric heaving fractures. The



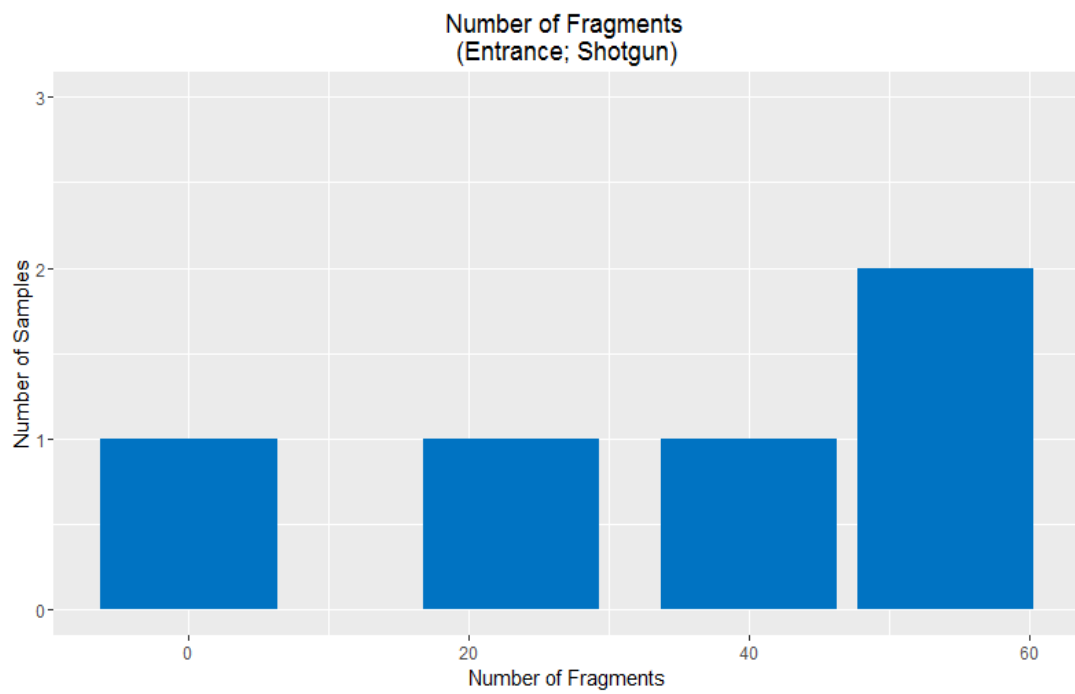


Figure 4.21. Frequencies of the number of fragments that originated from the entrance defect (shotgun samples).

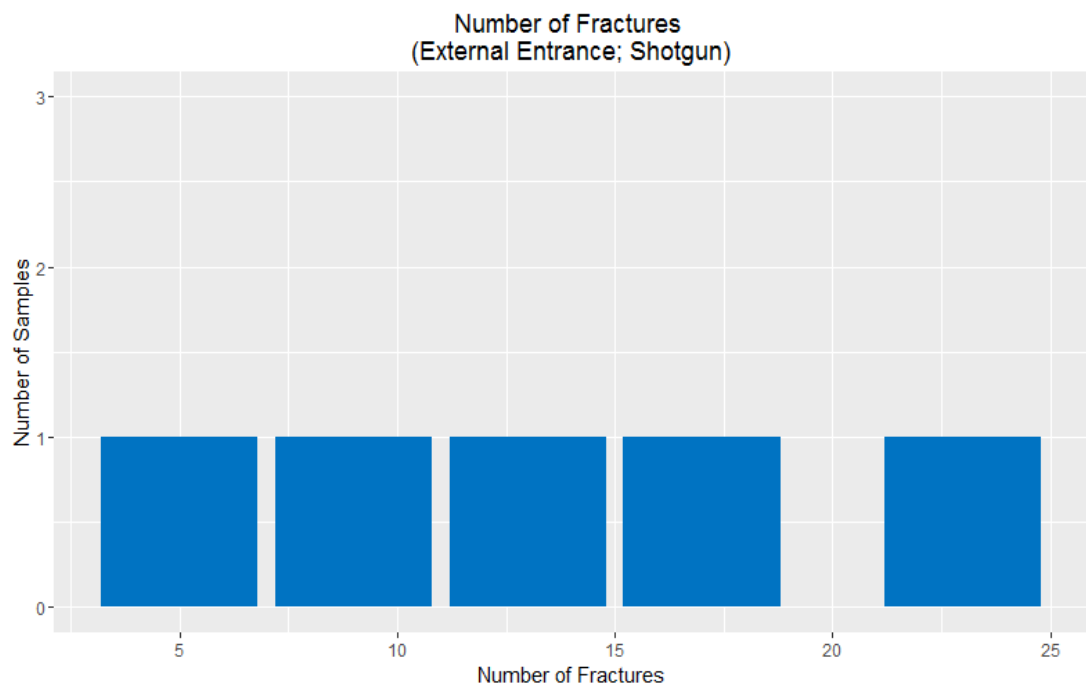


Figure 4.22. Frequencies of the number of fractures on the external table of the entrance defect (shotgun samples).

maximum fracture lengths along the external table varied greatly, ranging from 9.50 mm to 138.30 mm ( $n=5$ ;  $SD= \pm 54.27$  mm). The minimum lengths, however, were very consistent (1.30 mm-3.50 mm;  $n=5$ ;  $SD= \pm 0.90$  mm).

Only four samples (80.00%; 4/5) had fractures on the internal table of the entrance defect and one sample (20.00%; 1/5) had none. The number per sample ranged from 0 to 26 ( $n=5$ ;  $SD= \pm 11.58$ ) (Figure 4.23). When excluding the one sample with no fractures, the lower limit of this range increases to seven, a similar range to the amount on the external table. Though all four samples with fractures (80.00%) showed the presence of radiating fractures on the internal table, no samples had produced concentric heaving fractures.

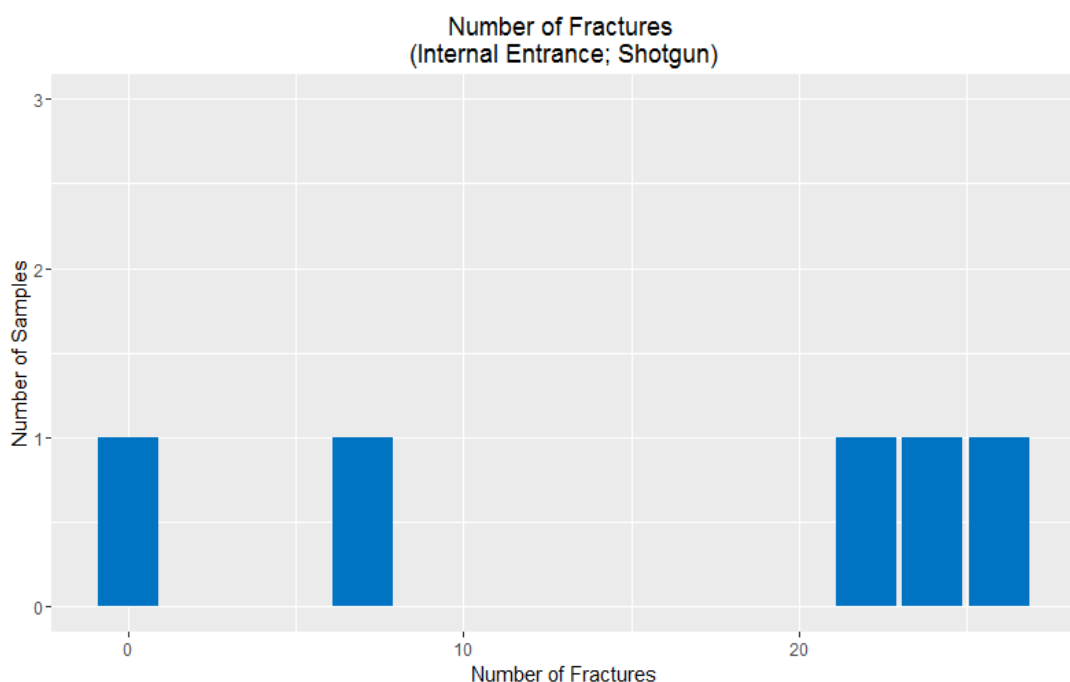


*Figure 4.23 Frequencies of the number of fractures on the internal table of the entrance defect (shotgun samples).*

All five samples retained at least some level of residue left from the projectile.

#### 4.4. Recurve Bow Features

Of the seven samples shot with a recurve bow, only one (14.29%) had a complete entrance defect (Figure 4.24). With the other six samples (85.71%; 6/7), the arrow had damaged the external table, but had not broken through the internal table. None of the samples had an exit defect. Five of the entrance defects (71.43%; 5/7) were conical in shape, one entrance defect (14.29%; 1/7) was circular in shape, and one entrance defect (14.29%; 1/7) was irregularly shaped (Figure 4.25). Bevelling at the entrance defect was present on three (42.86%; 3/7) samples and absent on four samples (57.14%; 4/7). Where bevelling was present, it was located on the internal table of all samples (100%; 3/3). The widest point of the entrance defects (both complete and incomplete) were relatively small (5.30 mm-15.00 mm;  $n=7$ ;  $SD= \pm 3.39$  mm) (Table 4.4), but comparable to the size of the rifle entry defects. None of the samples required reconstruction of the entrance defect.

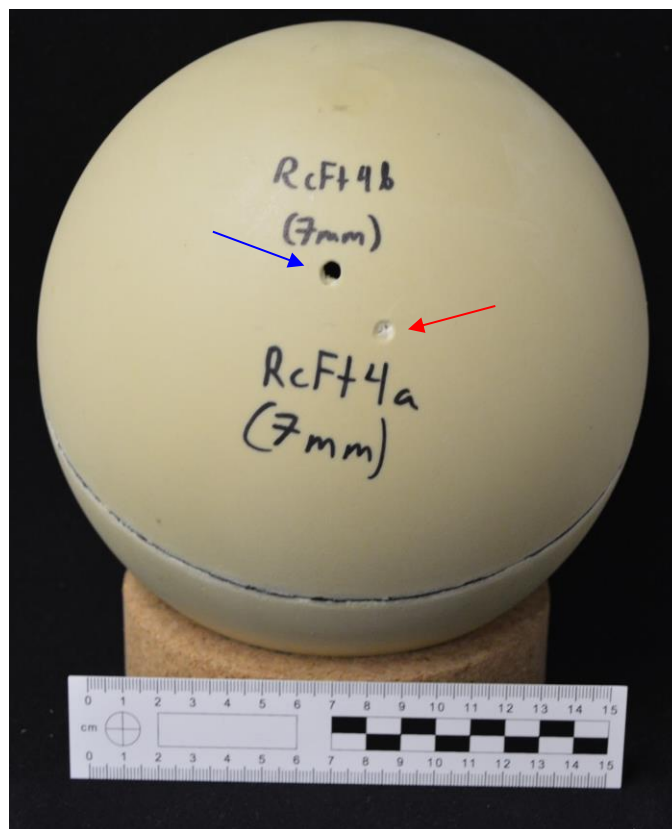


Figure 4.24. Two recurve bow samples: RcFt 4a (red arrow) is an incomplete entrance where only the external table was damaged and RcFt 4b (blue arrow) is a complete entrance where the arrow broke through both the external and internal table.

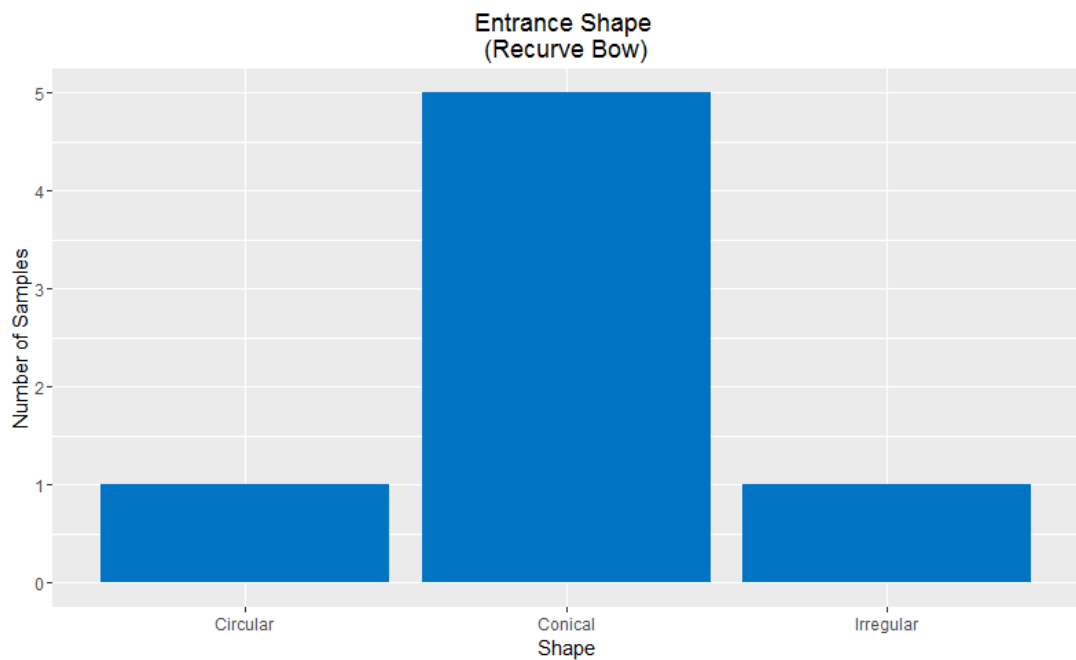


Figure 4.25. Frequencies of entrance shapes (recurve bow samples).

Only one sample (14.29%; 1/7) presented with dislodged fragments. This sample had one fragment, which measured 25.00 mm in length and 17.10 mm in width.

Only two samples (28.57%; 2/7) had fractures on the external table of the entrance defect while five samples (71.43%; 5/7) had no fractures on the external table of the entrance defect. Of the two samples with fractures, the number of fractures per sample ranged from one to four ( $n=7$ ;  $SD= \pm 1.50$ ) (Figure 4.26). Both of these samples showed the presence of radiating fractures on the external table of the entrance defect, but neither had concentric heaving fractures. The maximum fracture lengths between these two samples were small, ranging from 7.20 mm to 8.30 mm ( $n=7$ ;  $SD= \pm 1.06$  mm) while the minimum fracture lengths were not much smaller (2.70 mm-7.20 mm;  $n=7$ ;  $SD= \pm 2.74$  mm).

Two samples (28.57%; 2/7) had fractures on the internal table of the entrance defect while five samples (71.43%; 5/7) had no fractures on the internal table of the entrance defect. Of the two samples with fractures, the number of fractures along the internal table (one to two;  $n=7$ ;  $SD= \pm 0.79$ )

Table 4.4. Mean and standard deviation of quantitative variables (recurve bow samples; n=5).

| Feature                                     | Mean    | Standard Deviation |
|---------------------------------------------|---------|--------------------|
| Entrance defect diameter                    | 7.36 mm | ± 3.39 mm          |
| Entrance defect diameter (reconstructed)    | 7.36 mm | ± 3.39 mm          |
| Number of fragments (Entrance)              | 0.14    | ± 0.38             |
| Entrance fragment maximum length            | 3.57 mm | ± 9.45 mm          |
| Entrance fragment maximum width             | 2.44 mm | ± 6.46 mm          |
| Entrance fragment minimum length            | 3.57 mm | ± 9.45 mm          |
| Entrance fragment minimum width             | 2.44 mm | ± 6.46 mm          |
| Number of fractures (external entrance)     | 0.71    | ± 1.50             |
| Number of fractures (internal entrance)     | 0.43    | ± 0.79             |
| Maximum fracture length (external entrance) | 2.21 mm | ± 3.79 mm          |
| Minimum fracture length (external entrance) | 1.41 mm | ± 2.74 mm          |

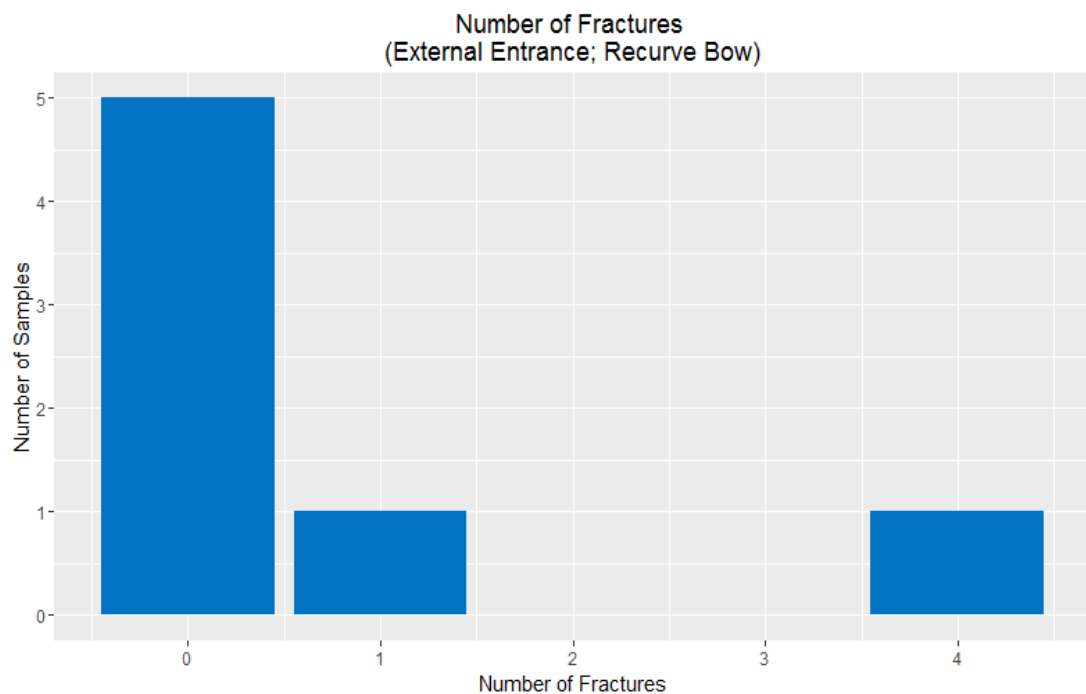


Figure 4.26. Frequencies of the number of fractures on the external table of the entrance defect (recurve bow samples).

was less than the fractures on the external table (Figure 4.27). As with the external table, both of these samples showed the presence of radiating fractures on the internal table of the entrance defect, but neither had concentric heaving fractures.

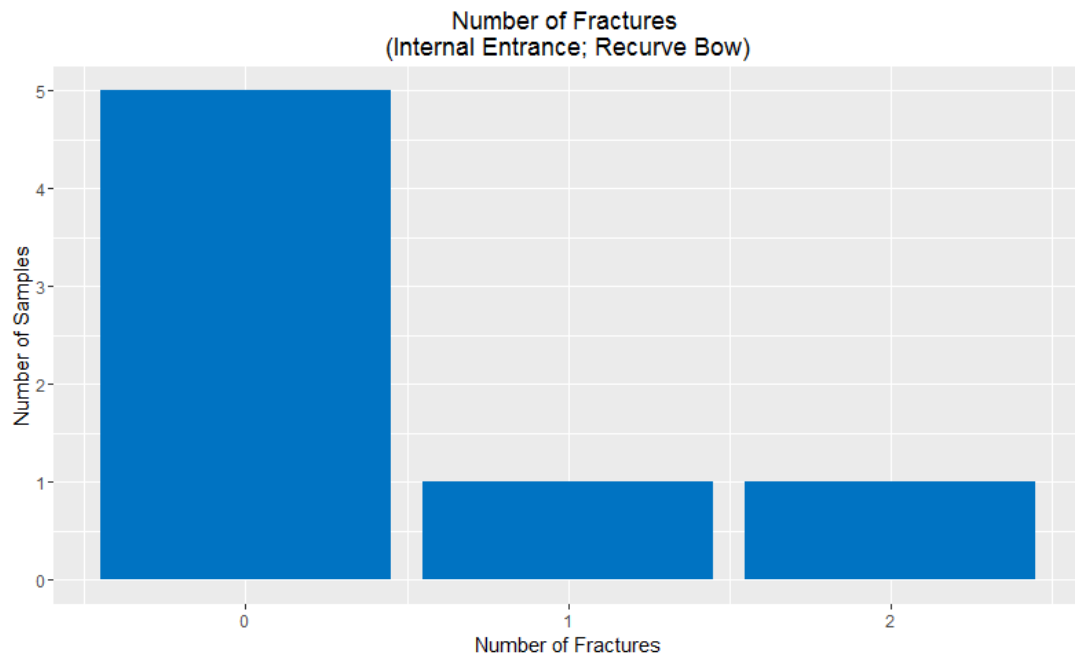


Figure 4.27 Frequencies of the number of fractures on the internal table of the entrance defect (recurve bow samples).

None of the samples retained any level of residue left from the projectile.

## 4.5. Compound Bow Features

All five of the compound bow samples had a complete entrance defect but lacked an exit defect. Three samples (60.00%; 3/5) had entrances were circularly shaped, one (20.00%; 1/5) was irregularly shaped, and one (20.00%; 1/5) exhibited a keyhole defect (Figure 4.28). The keyhole defect (Figure 4.29) was treated as a circular entrance in the analysis as a keyhole defect is made up of a circular portion with a triangular portion following the path of the projectile (Dixon, 1982; Özsoy and Tugcu, 2016; Berryman, 2019). Bevelling was present at the entrance defect in all five samples, but the location of the bevelling varied slightly. In three samples (60.00%; 3/5),

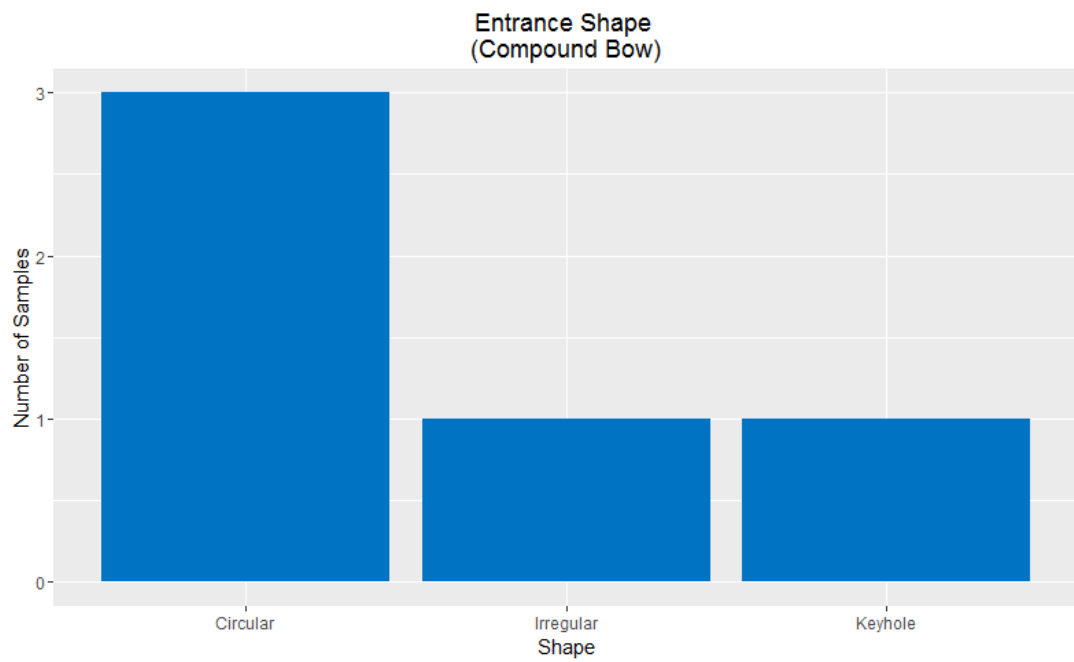


*Figure 4.28. Frequencies of entrance shapes (compound bow samples).*



*Figure 4.29. Keyhole defect at the entrance site (sample CpBh 3).*

beavelling was located internally while in two samples (40.00%; 2/5), beavelling was located on both the internal and external tables (Figure 4.30). The largest portions of the entrance defects without reconstruction using any dislodged fragments (10.20 mm to 35.20 mm;  $n=5$ ;  $SD= \pm 9.44$  mm) were of a small to mid-range size (Table 4.5). Only one sample (20.00%; 1/5) could be reconstructed using dislodged fragments and the entrance defect measured 8.80 mm wide when reconstructed.

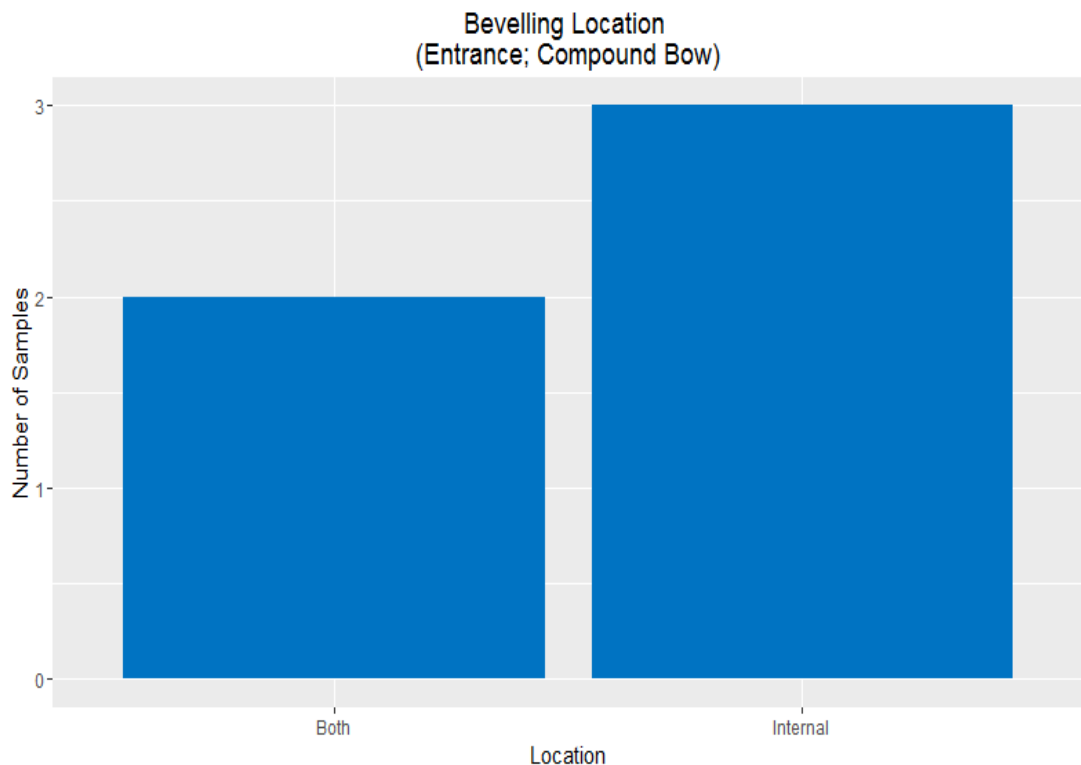


*Figure 4.30. Frequency of beavelling on only the internal table or both the internal and external tables of the entrance site (compound bow samples).*

All five of the compound samples had at least one (one to seven fragments;  $n=5$ ;  $SD= \pm 2.59$ ) dislodged fragment originating from the entrance defect (Figure 4.31). The maximum lengths of these fragments were similar to rifle fragments originating from the exit defect (8.40 mm to 33.40 mm;  $n=5$ ;  $SD= \pm 2.59$  mm). The minimum fragment lengths see a small decrease in the lower limit to 5.70 mm while the upper limit decreases to 8.40 mm ( $n=5$ ;  $SD= \pm 1.12$  mm).



*Table 4.5. Mean and standard deviation of quantitative variables (compound bow samples; n=5).*

| <b>Feature</b>                              | <b>Mean</b> | <b>Standard Deviation</b> |
|---------------------------------------------|-------------|---------------------------|
| Entrance defect diameter                    | 23.06 mm    | ± 9.44 mm                 |
| Entrance defect diameter (reconstructed)    | 17.78 mm    | ± 8.26 mm                 |
| Number of fragments (Entrance)              | 4.20        | ± 2.59                    |
| Entrance fragment maximum length            | 18.50 mm    | ± 11.33 mm                |
| Entrance fragment maximum width             | 11.74 mm    | ± 5.07 mm                 |
| Entrance fragment minimum length            | 7.28 mm     | ± 1.12 mm                 |
| Entrance fragment minimum width             | 3.52 mm     | ± 1.59 mm                 |
| Number of fractures (external entrance)     | 3.80        | ± 1.30                    |
| Number of fractures (internal entrance)     | 3.40        | ± 0.55                    |
| Maximum fracture length (external entrance) | 45.60 mm    | ± 26.31 mm                |
| Minimum fracture length (external entrance) | 11.14 mm    | ± 8.28 mm                 |

The width measurements of these fragments were not much different from the length measurements, with the largest widths ranging from 6.10 mm to 17.60 mm ( $n=5$ ;  $SD= \pm 5.07$  mm) while the smallest widths measured between 1.90 mm and 11.70 mm ( $n=5$ ;  $SD= \pm 1.59$  mm).

All five of the samples had fractures on the external table of the entrance defect. Of these samples, the number of fractures per sample ranged from three to six ( $n=5$ ;  $SD= \pm 1.30$ ), typically reflecting the three-blade configuration of the arrow tip (Figure 4.32). All of these samples showed the presence of radiating fractures on the external table of the entrance defect, but none of the samples had concentric heaving fractures. The maximum fracture lengths (23.30 mm-77.30 mm;  $n=5$ ;  $SD= \pm 26.31$  mm) between these

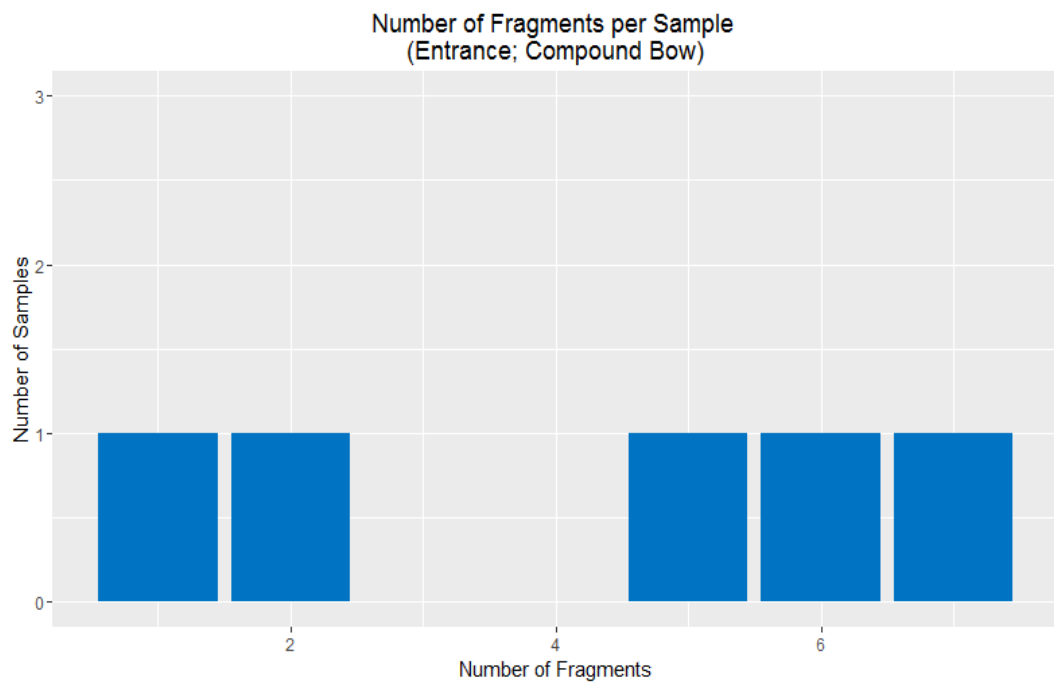


Figure 4.31. Frequencies of the number of fragments that originated from the entrance defect (compound bow samples).

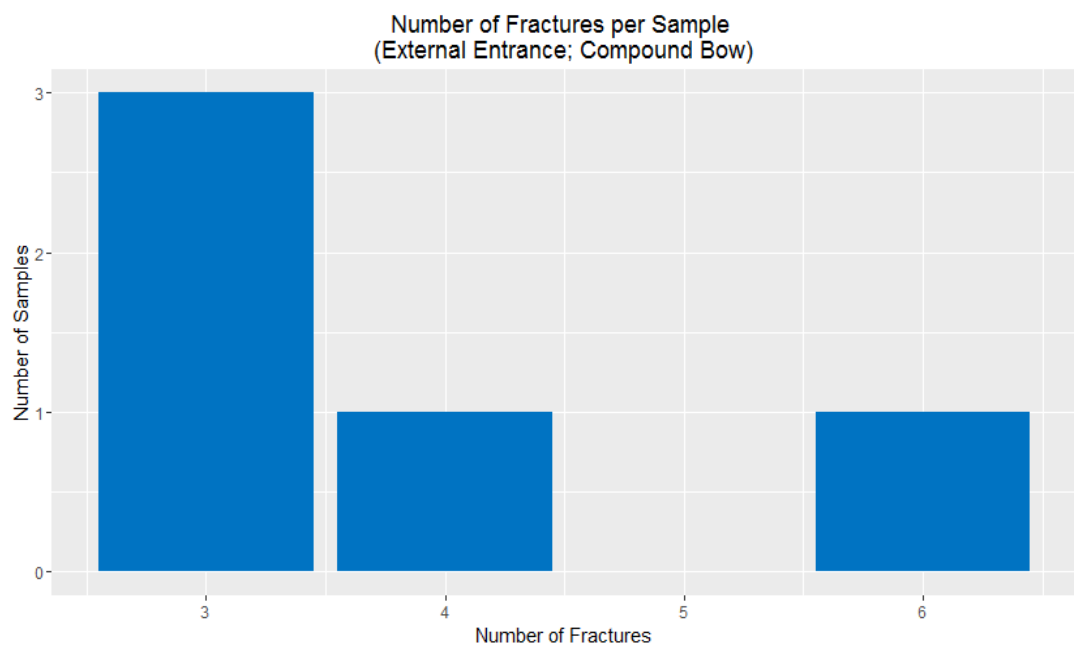


Figure 4.32. Frequencies of the number of fractures on the external table of the entrance defect (compound bow samples).

samples were, again, comparable to fractures in the rifle samples, specifically the minimum fracture lengths. The minimum fracture lengths (4.60 mm-20.40 mm;  $n=5$ ;  $SD= \pm 8.28$  mm), however, were generally very short, with the higher end of this range (20.40 mm) still in the low-range size of fractures observed in this study.

All five of the samples also had fractures on the internal table of the entrance defect. The number of fractures per sample was either three or four ( $n=5$ ;  $SD= \pm 0.55$ ) (Figure 4.33). All of these samples showed the presence of radiating fractures on the internal table of the entrance defect, but none of the samples had concentric heaving fractures.

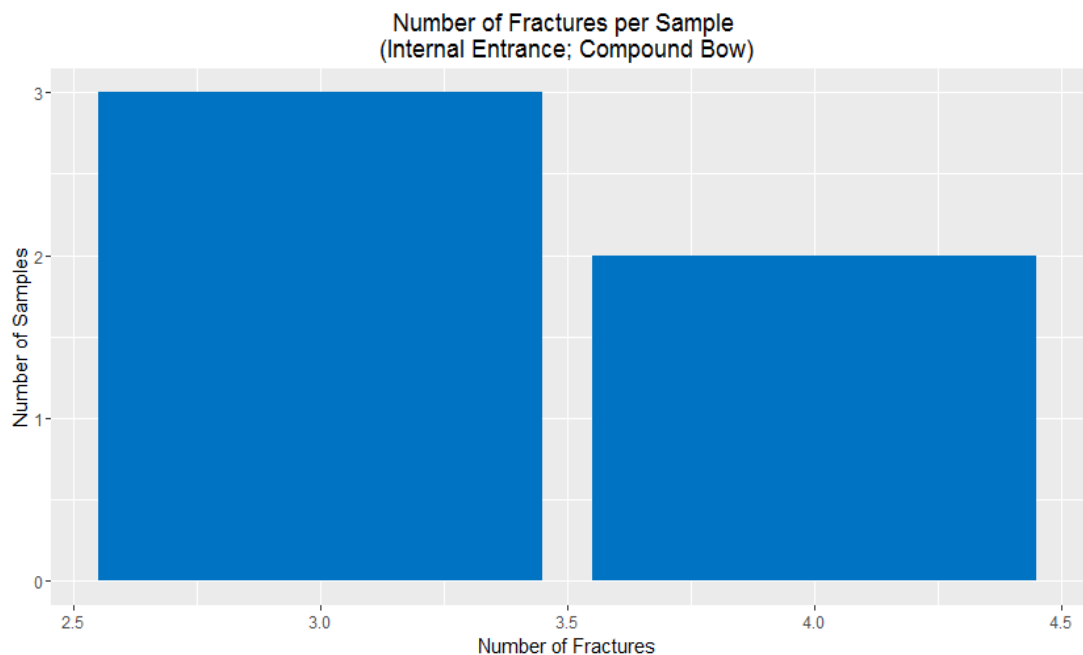


*Figure 4.33. Frequencies of the number of fractures on the internal table of the entrance defect (compound bow samples).*

Three samples (60.00%) retained some level of residue left from the projectile while two samples (40.00%) retained no residue from the projectile. This was the only weapon to not have a uniform “presence” or “absence” of residue within the samples.

## 4.6. Crossbow (Field Tip) Features

Of the samples shot with field tip bolts, all five had complete entrance defects. All five of these entrance defects were circular in shape and were bevelled internally. The largest portion of each entrance opening ranged from 7.50 mm to 10.30 mm ( $n=5$ ;  $SD= \pm 1.21$  mm), reflecting the diameter of the shaft of the bolt (Table 4.6). None of the entrance defects required reconstruction using dislodged fragments. Only one sample (20.00%; 1/5) had dislodged fragments that originated from the entrance defect (Figure 4.34). Between the two entrance fragments from this sample, the maximum length (15.90 mm;  $n=5$ ;  $SD= \pm 7.11$  mm) and minimum length (9.10 mm;  $n=5$ ;  $SD= \pm 4.07$  mm) was similar to, if not smaller than, the entrance fragments in the compound bow samples. A similar pattern was observed in the maximum (10.30 mm;  $n=5$ ;  $SD= \pm 4.61$  mm) and minimum (5.90 mm;  $n=5$ ;  $SD= \pm 2.64$  mm) widths of these fragments.

All five samples had fractures on the external table of the entrance defect. The number of these fractures per sample ranged from two to four ( $n=5$ ;  $SD= \pm 1.10$ ) (Figure 4.35). Radiating fractures were present on the external table of the entrance defect of all five field tip bolt samples. Concentric heaving fractures, however, were absent on the external table of the entrance defect on all five of the field tip bolt samples. The longest fractures along the external table (21.30-108.70 mm;  $n=5$ ;  $SD= \pm 32.11$  mm) were similar to the lengths of the shorter fractures found along the external table of the rifle entrance defects. The minimum fracture lengths (5.90-43.40 mm;  $n=5$ ;  $SD= \pm 16.18$  mm), however, were more similar to the minimum lengths of the fractures found on the compound bow samples.

All five samples shot with field tip bolts also had fractures along the internal table of the entrance defect. The number of these fractures per sample ranged from three to five ( $n=5$ ;  $SD= \pm 0.71$ ), similar to the pattern seen on the external table (Figure 4.36). Radiating fractures were present along the internal table of the entrance defect on all five of the samples. Concentric

*Table 4.6. Mean and standard deviation of quantitative variables (crossbow (field tip) samples; n=5).*

| <b>Feature</b>                              | <b>Mean</b> | <b>Standard Deviation</b> |
|---------------------------------------------|-------------|---------------------------|
| Entrance defect diameter                    | 8.14 mm     | ± 1.21 mm                 |
| Entrance defect diameter (reconstructed)    | 8.14 mm     | ± 1.21 mm                 |
| Number of fragments (Entrance)              | 0.40        | ± 0.89                    |
| Entrance fragment maximum length            | 3.18 mm     | ± 7.11 mm                 |
| Entrance fragment maximum width             | 2.06 mm     | ± 4.61 mm                 |
| Entrance fragment minimum length            | 1.82 mm     | ± 4.07 mm                 |
| Entrance fragment minimum width             | 1.18 mm     | ± 2.64 mm                 |
| Number of fractures (external entrance)     | 3.20        | ± 1.10                    |
| Number of fractures (internal entrance)     | 4.00        | ± 0.71                    |
| Maximum fracture length (external entrance) | 73.56 mm    | ± 32.11 mm                |
| Minimum fracture length (external entrance) | 26.68 mm    | ± 16.18 mm                |
| Exit defect diameter                        | 37.24 mm    | ± 14.65 mm                |
| Exit defect diameter (reconstructed)        | 8.14 mm     | ± 1.21 mm                 |
| Number of fragments (Exit)                  | 4.40        | ± 4.16                    |
| Exit fragment maximum length                | 25.20 mm    | ± 15.69 mm                |
| Exit fragment maximum width                 | 18.86 mm    | ± 11.21 mm                |
| Exit fragment minimum length                | 8.76 mm     | ± 5.85 mm                 |
| Exit fragment minimum width                 | 6.28 mm     | ± 5.15 mm                 |
| Number of fractures (external exit)         | 11.40       | ± 3.13                    |
| Number of fractures (internal exit)         | 10.80       | ± 3.83                    |
| Maximum fracture length (external exit)     | 51.56 mm    | ± 33.41 mm                |
| Minimum fracture length (external exit)     | 10.12 mm    | ± 2.05 mm                 |

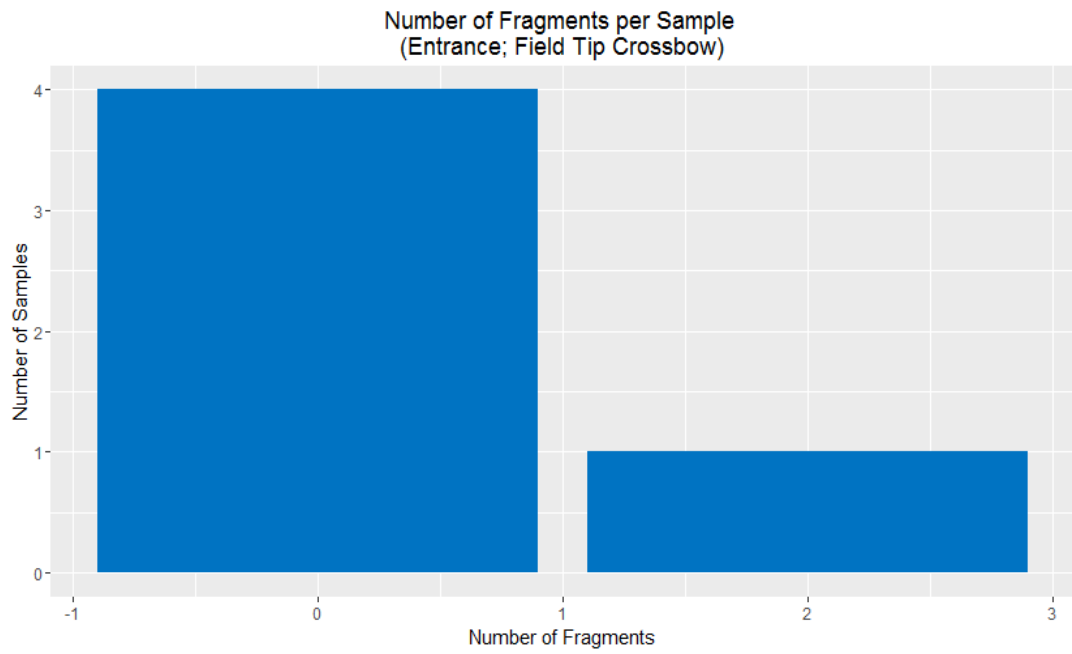


Figure 4.34. Frequencies of the number of fragments that originated from the entrance defect (crossbow (field tip) samples).

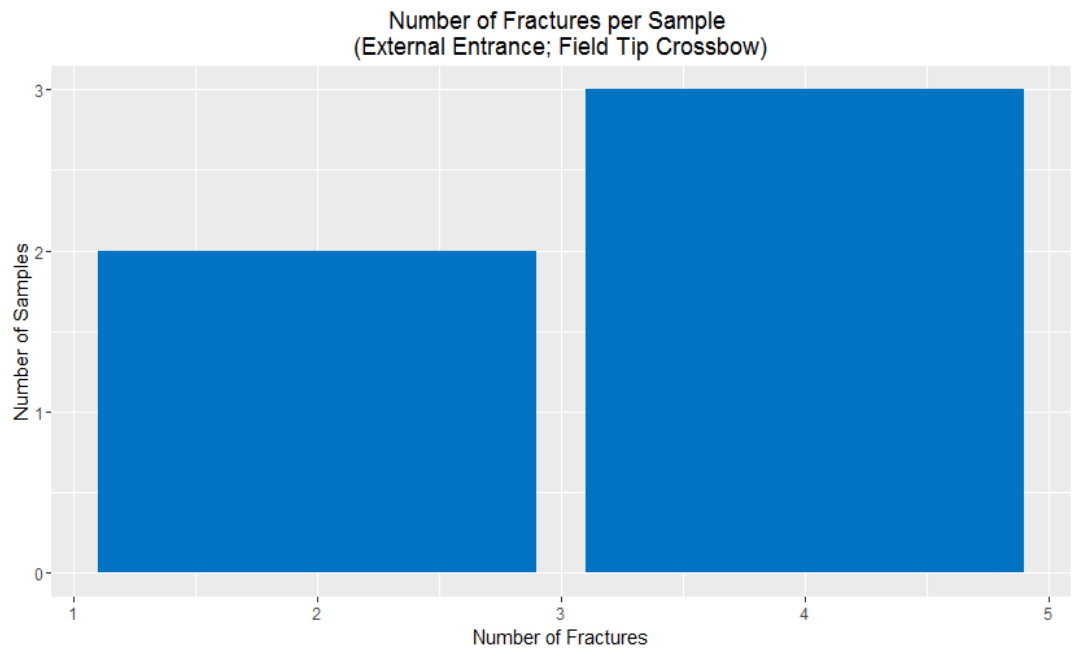


Figure 4.35. Frequencies of the number of fractures on the external table of the entrance defect (crossbow (field tip) samples).

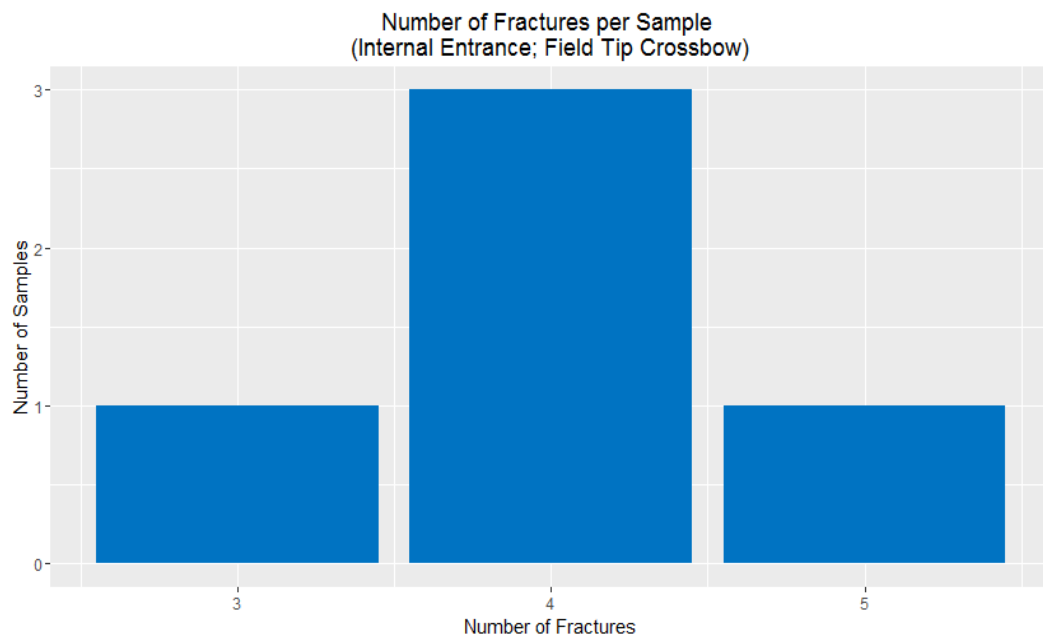


*Figure 4.36. Frequencies of the number of fractures on the internal table of the entrance defect (crossbow (field tip) samples).*

heaving fractures, however, were only present along the internal table of the entrance defect in one sample (20.00%; 1/5).

Of the five samples shot with field tip bolts, all five had the presence of an exit. Three of these exit defects (60.00%; 3/5) were circular in shape, but two (40.00%; 2/5) were irregularly shaped (Figure 4.37). All five exit defects were bevelled externally. The largest portion of each exit opening (without reconstruction) was generally small to mid-range in size (20.90 mm-58.20 mm;  $n=5$ ;  $SD= \pm 14.65$  mm). When reconstructed with any dislodged fragments, the lower limit of this range dropped to 17.60 mm while the upper range dropped to 25.50 mm ( $n=5$ ;  $SD= \pm 1.21$  mm). The general shape and size of the exit defects within the field tip bolt samples were noticeably similar to the exit defects of the rifle samples (Figure 4.38)

Only one sample (20.00%; 1/5) had no dislodged fragments that originated from the exit defect. The other four samples (80.00%; 4/5) had at least one dislodged fragment, varying between one and ten fragments ( $n=5$ ;  $SD= \pm 4.16$ ) (Figure 4.39). The dimensions of these fragments mirror the dimensions of the exit defect fragments from the rifle samples: the maximum

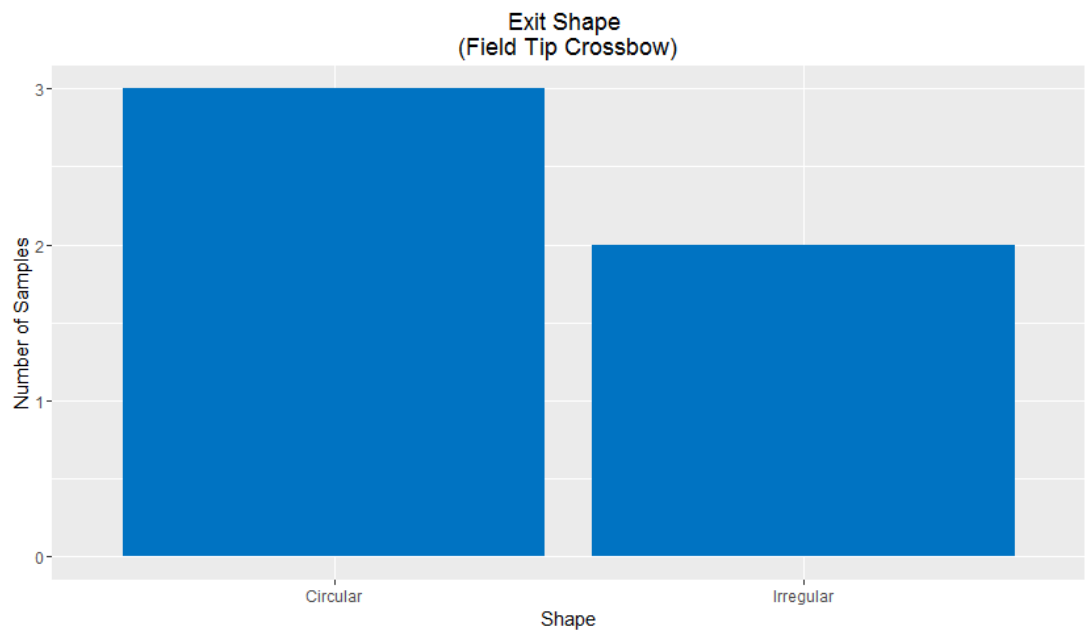


Figure 4.37. Frequencies of exit shapes (crossbow (field tip) samples).

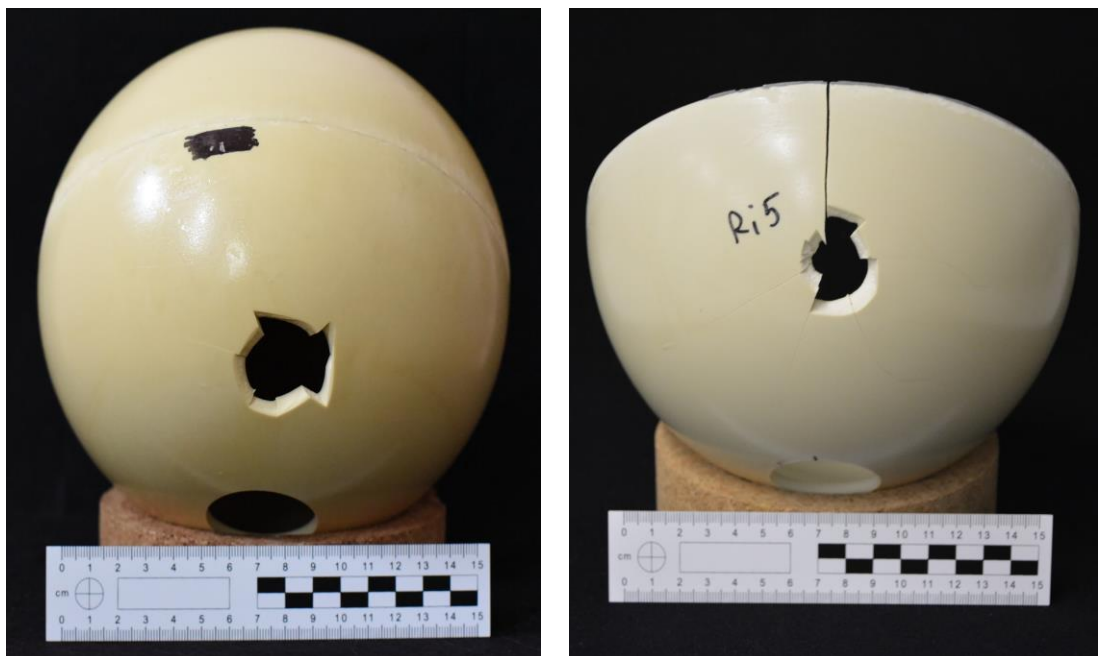


Figure 4.38. Similar exit shapes and sizes between sample CbFt 5 (left) and Ri 5 (right).



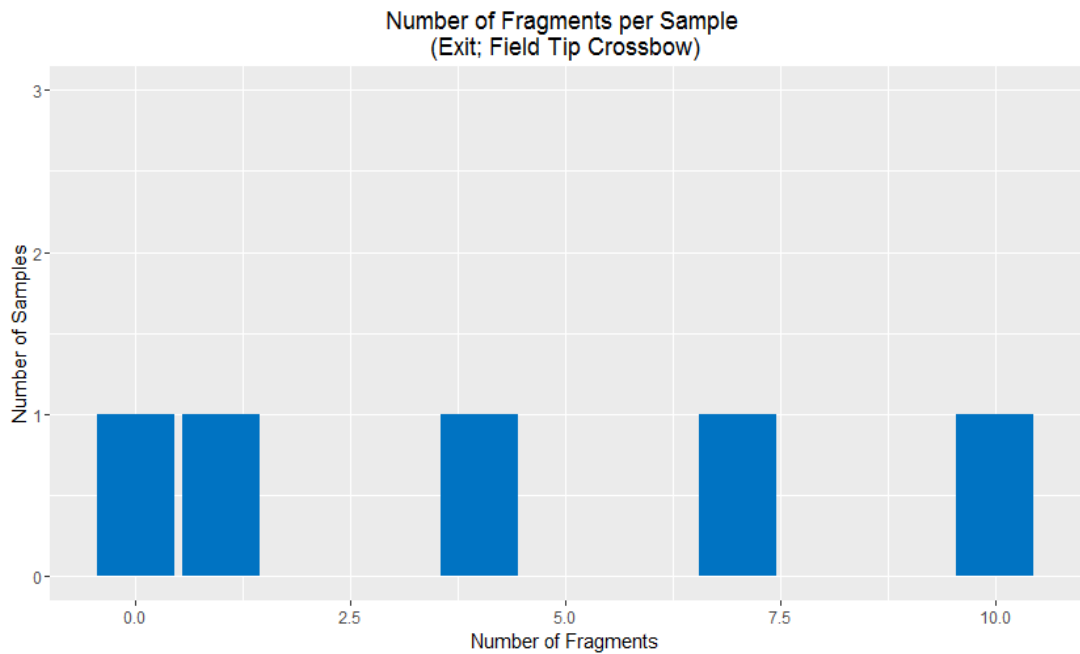


Figure 4.39. Frequencies of the number of fragments that originated from the exit defect (crossbow (field tip) samples).

fragment length per sample ranged from 26.50 mm to 43.30 mm ( $n=5$ ;  $SD= \pm 15.69$  mm), the minimum length ranged from 7.60 mm to 14.40 mm ( $n=5$ ;  $SD= \pm 5.85$  mm), the maximum width ranged from 19.70 mm to 28.60 mm ( $n=5$ ;  $SD= \pm 11.21$  mm), and the minimum width ranged from 2.70 mm to 11.50 mm ( $n=5$ ;  $SD= \pm 5.15$  mm).

All five samples had fractures on the external table of the exit defect, ranging from eight to 16 ( $n=5$ ;  $SD= \pm 3.13$ ) (Figure 4.40). Both radiating and concentric heaving fractures were present on the external table of the exit defect of all five field tip bolt samples. The maximum fracture length along the external table had a fairly wide range (24.10 mm-100.70 mm;  $n=5$ ;  $SD= \pm 33.41$  mm), but range of the minimum fracture lengths was quite narrow (7.00 mm-12.70 mm;  $n=5$ ;  $SD= \pm 2.05$  mm).

All five samples shot with field tip bolts also had fractures along the internal table of the entrance defect. The number of these fractures per sample ranged from seven to 16 ( $n=5$ ;  $SD= \pm 3.83$ ), roughly reflecting the fractures on the external table (Figure 4.41). Both radiating and concentric heaving

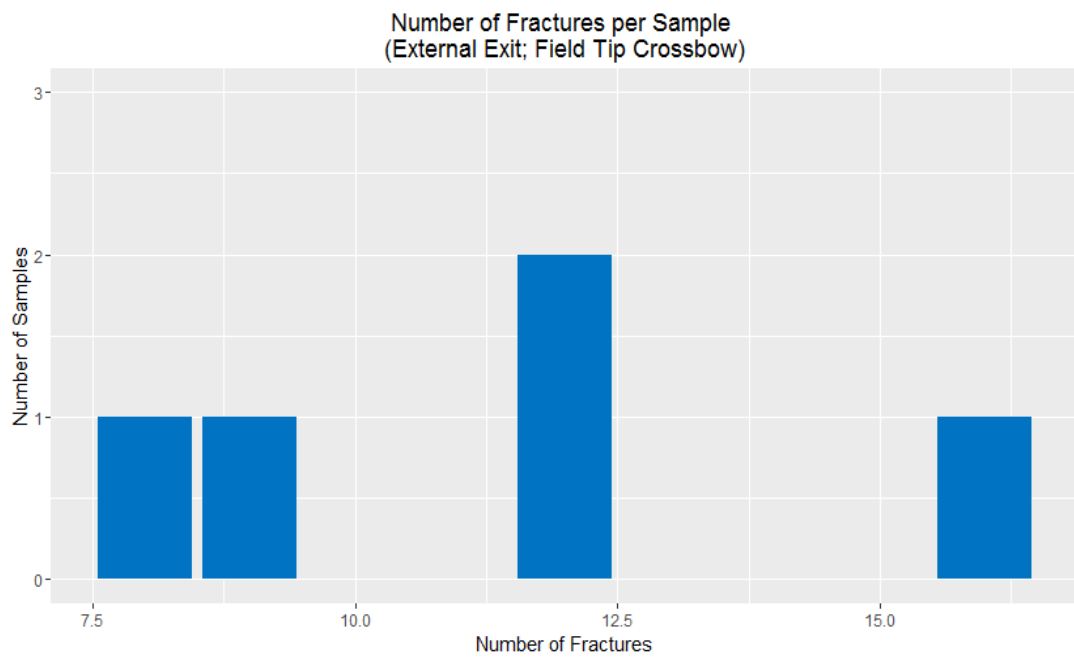


Figure 4.40. Frequencies of the number of fractures on the external table of the exit defect (crossbow (field tip) samples).

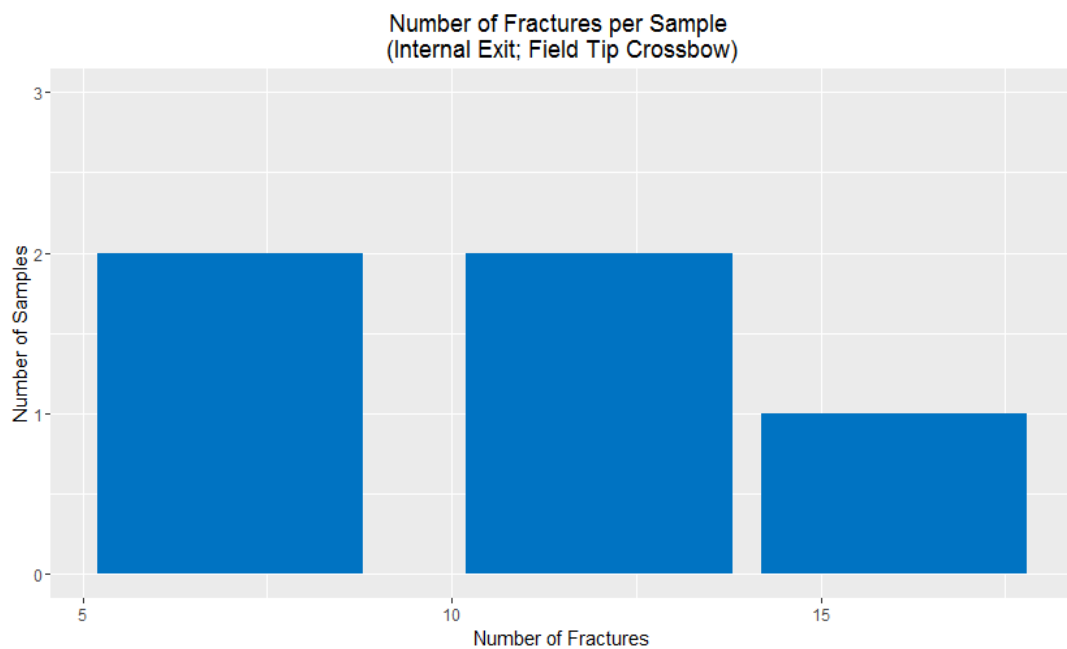


Figure 4.41. Frequencies of the number of fractures on the internal table of the exit defect (crossbow (field tip) samples).

fractures were present along the internal table of the exit defect on all five samples.

All of the samples retained some level of residue left from the projectile.

#### 4.7. Crossbow (Fixed Broadhead) Features

A complete entrance was present in all five samples shot with fixed broadhead bolts. All five of these entrances were circular in shape and had the presence of bevelling, though the bevelling location varied between the samples. Three samples (60.00%; 3/5) bevelled internally while two samples (40.00%; 2/5) had bevelling on both the internal and external table (Figure 4.42). The measurement of the widest portion of each entrance defect (without reconstruction) was inconsistent in size (5.80 mm-70.20 mm;  $n=5$ ;  $SD= \pm 27.93$  mm) (Table 4.7) as two entrance defects (40.00%; 2/5) reflected the diameter of the shaft of the bolt, two (40.00%; 2/5) required reconstruction with dislodged fragments, and one (20.00%; 1/5) could not successfully be reconstructed. When the entrance defect was reconstructed

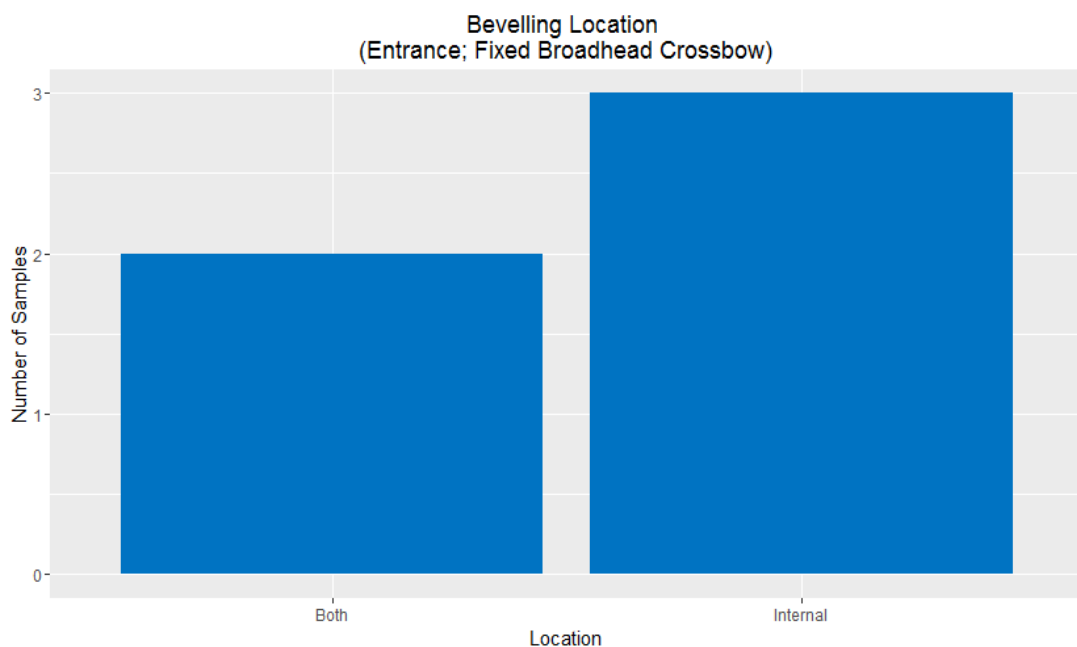


Figure 4.42. Frequency of bevelling on the internal table only or both the internal and external tables of the entrance defect (crossbow (fixed broadhead) samples).

*Table 4.7. Mean and standard deviation of quantitative variables (crossbow (fixed broadhead) samples; n=5).*

| <b>Feature</b>                              | <b>Mean</b> | <b>Standard Deviation</b> |
|---------------------------------------------|-------------|---------------------------|
| Entrance defect diameter                    | 32.40 mm    | ± 27.93 mm                |
| Entrance defect diameter (reconstructed)    | 11.22 mm    | ± 10.34 mm                |
| Number of fragments (Entrance)              | 0.60        | ± 0.89                    |
| Entrance fragment maximum length            | 29.10 mm    | ± 41.49 mm                |
| Entrance fragment maximum width             | 19.18 mm    | ± 31.17 mm                |
| Entrance fragment minimum length            | 22.24 mm    | ± 38.58 mm                |
| Entrance fragment minimum width             | 16.92 mm    | ± 31.13 mm                |
| Number of fractures (external entrance)     | 5.20        | ± 2.59                    |
| Number of fractures (internal entrance)     | 5.00        | ± 2.74                    |
| Maximum fracture length (external entrance) | 150.60 mm   | ± 50.53 mm                |
| Minimum fracture length (external entrance) | 57.78 mm    | ± 10.71 mm                |
| Exit defect diameter                        | 51.42 mm    | ± 2.96 mm                 |
| Exit defect diameter (reconstructed)        | 9.10 mm     | ± 17.79 mm                |
| Number of fragments (Exit)                  | 3.80        | ± 1.10                    |
| Exit fragment maximum length                | 48.92 mm    | ± 4.54 mm                 |
| Exit fragment maximum width                 | 26.64 mm    | ± 4.96 mm                 |
| Exit fragment minimum length                | 29.30 mm    | ± 9.79 mm                 |
| Exit fragment minimum width                 | 16.78 mm    | ± 1.45 mm                 |
| Number of fractures (external exit)         | 7.80        | ± 1.92                    |
| Number of fractures (internal exit)         | 7.80        | ± 1.92                    |
| Maximum fracture length (external exit)     | 57.79 mm    | ± 10.71 mm                |
| Minimum fracture length (external exit)     | 19.68 mm    | ± 7.08 mm                 |

(where applicable), the lower limit of this range decreased slightly to 5.60 mm while the upper limit dropped to 29.60 mm ( $n=5$ ;  $SD= \pm 10.34$  mm).

Of the five samples shot with fixed broadhead bolts, only two (40.00%; 2/5) had dislodged fragments that were associated with the entrance defect. One sample had a total of two entrance fragments while the other had one fragment (Figure 4.43). These fragments were mid-range size fragments within this study, with the maximum length ranged from 56.40 mm to 89.10 mm ( $n=5$ ;  $SD= \pm 41.49$  mm) and the lower limit of this range dropped to 22.10 mm ( $n=5$ ;  $SD= \pm 38.58$  mm) when measuring the minimum fragment lengths. The largest widths of these fragments then measured between 24.20 mm and 71.10 mm ( $n=5$ ;  $SD= \pm 31.17$  mm) while the lower limit of this range dropped to 12.90 mm ( $n=5$ ;  $SD= \pm 31.13$  mm) when measuring the minimum fragment widths.

All five samples had fractures along the external table of the entrance defect. The number of fractures per sample ranged from three to eight ( $n=5$ ;  $SD= \pm 2.59$ ) (Figure 4.44), commonly reflecting the pattern of the three-blade bolt tip

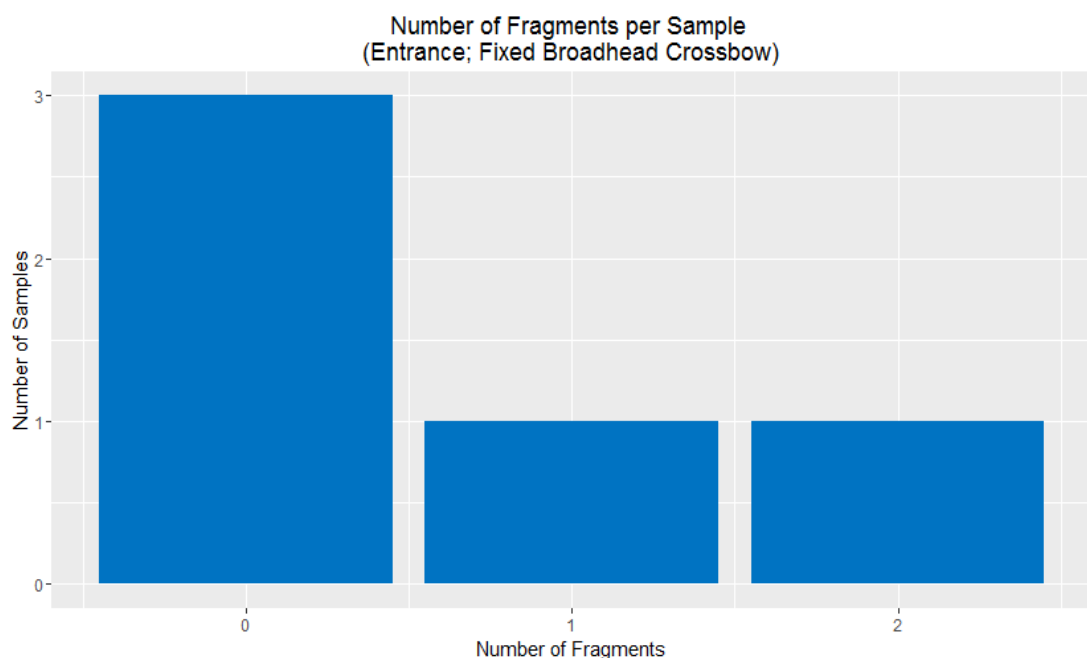


*Figure 4.43. Frequencies of the number of fragments that originated from the entrance defect (crossbow (fixed broadhead) samples).*

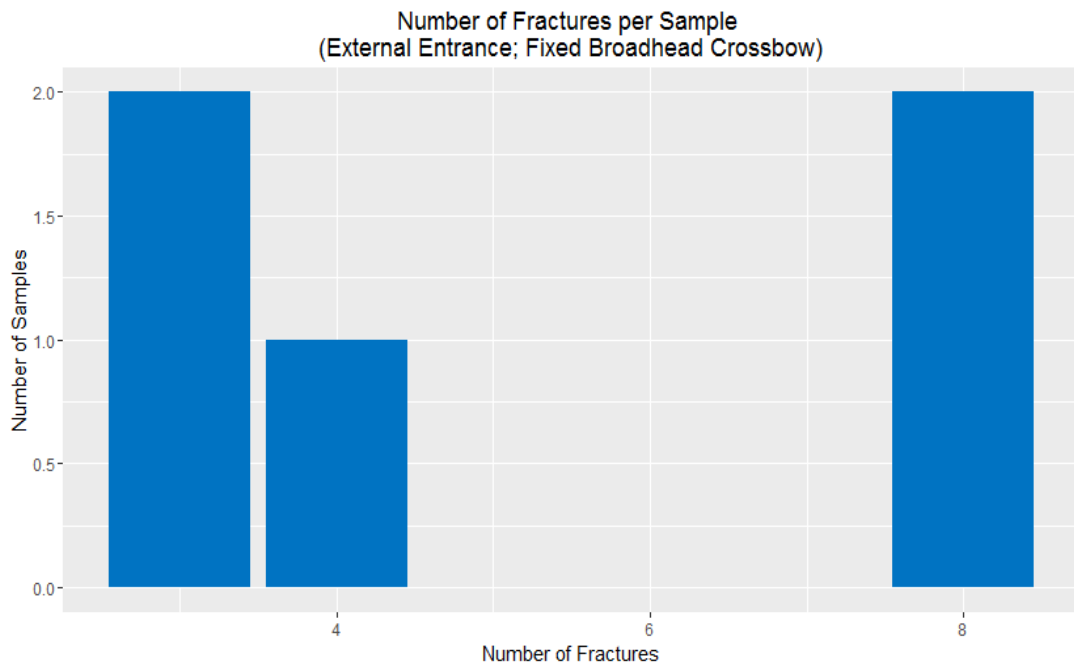


Figure 4.44. Frequencies of the number of fractures on the external table of the entrance site (crossbow (fixed broadhead) samples).

(Figure 4.45). Radiating fractures were present on the external table of the entrance in all samples. Concentric heaving fractures, however, were only present on the external table of the entrance defect in two samples (40.00%; 2/5) and were absent in the other three samples (60.00%; 3/5). The longest fractures (5.90 mm-220.90 mm;  $n=5$ ;  $SD= \pm 50.53$  mm) on the external table of the entrance defect of each sample were generally mid to long- range in size, while the shortest fractures (5.20 mm-126.60 mm;  $n=5$ ;  $SD= \pm 10.71$  mm) were generally low- to mid-range in length.

All five of the samples also had fractures along the internal table of the entrance defect. The range of total number of fractures per sample also ranged from three to eight ( $n=5$ ;  $SD= \pm 2.74$ ) (Figure 4.46). Radiating fractures were present on the internal table of the entrance defect on all five samples. Concentric heaving fractures, however, were only present on the internal table of the entrance defect on two samples (40.00%; 2/5) and were absent on the other three samples (60.00%; 3/5).



Figure 4.45. Entrance defect of fixed broadhead sample (CbBh 5) where the fracture pattern reflects the arrangement of the three-blade tip.

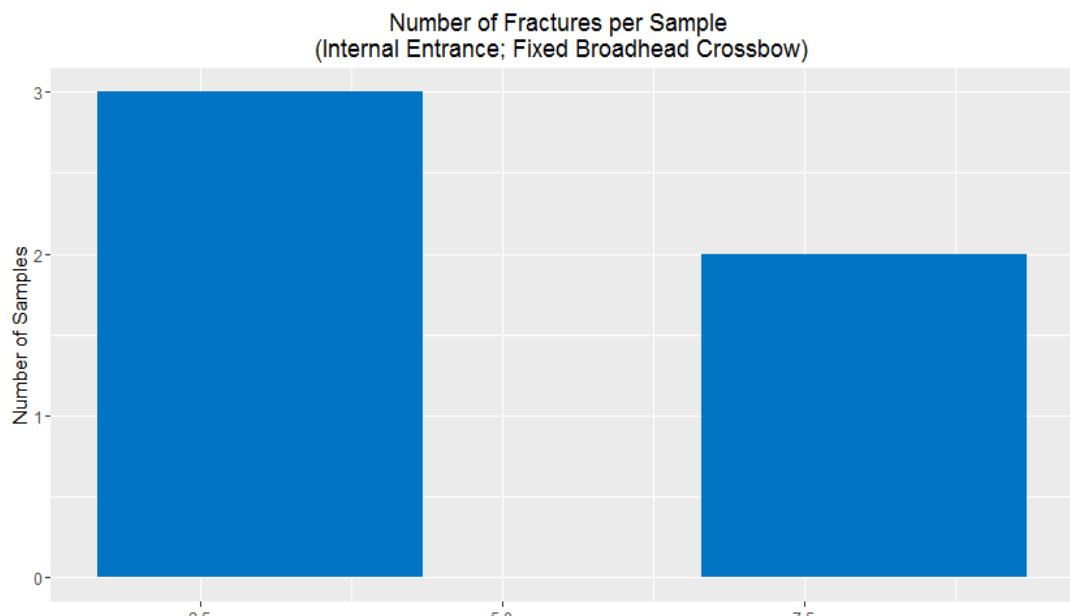


Figure 4.46. Frequencies of the number of fractures on the internal table of the entrance defect (crossbow (fixed broadhead) samples).

An exit was present in all five samples shot with fixed broadhead bolts and four of these exits (80.00%; 4/5) were circular in shape while one (20.00%; 1/5) was irregularly shaped. Bevelling was only present at the exit defect on four samples (80.00%; 4/5) and was absent on one sample (20.00%; 1/5). Of the four samples which had bevelling present, all four exit defects were bevelled externally. The measurements of the largest portion of each exit defect (without reconstruction) (48.50 mm-55.40 mm;  $n=5$ ;  $SD= \pm 2.96$  mm) were not much bigger than the entrance defects. When the entrance defect was reconstructed (where applicable), the lower limit of this range decreased noticeably to 0.00 mm while the upper limit dropped to 40.70 mm ( $n=5$ ;  $SD= \pm 17.79$  mm).

All samples had dislodged fragments that were associated with the exit defect. The number of exit fragments per sample (two to five;  $n=5$ ;  $SD= \pm 1.10$ ) did not vary greatly between the samples (Figure 4.47). The maximum length (45.60 mm-56.70 mm;  $n=5$ ;  $SD= \pm 4.54$  mm) also did not vary greatly. While the minimum fragment length (15.70 mm-39.20 mm;  $n=5$ ;  $SD= \pm 9.79$  mm) had a higher level of variance than the maximum length, there is still a low level of variance between these samples. A similar pattern is seen

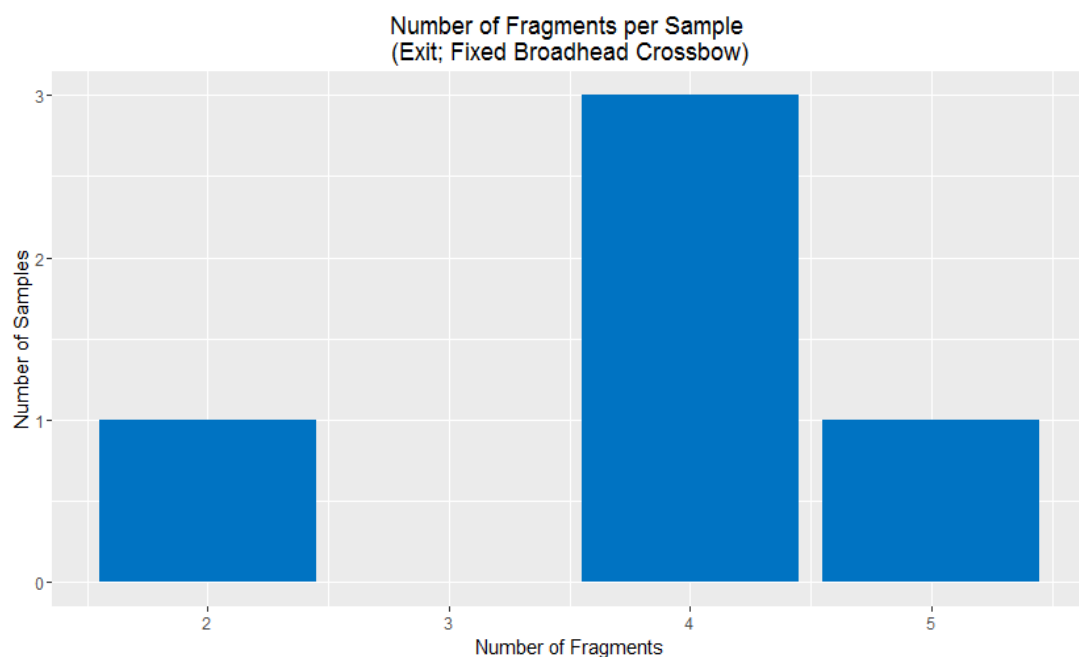


Figure 4.47. Frequencies of the number of fragments that originated from the exit defect (crossbow (fixed broadhead) samples).



between the largest (23.00 mm to 35.20 mm;  $n=5$ ;  $SD= \pm 4.96$  mm) mm and smallest (14.80 mm to 18.40 mm;  $n=5$ ;  $SD= \pm 1.45$  mm) widths of these fragments.

All five samples had fractures along the external table of the exit defect. The number of fractures per sample ranged from six to 11 ( $n=5$ ;  $SD= \pm 1.92$ ), with most of the samples falling in the lower end of this range (Figure 4.48). Both radiating and concentric heaving fractures were present on the external table of the exit in all samples. The longest fractures on the external table of the exit defect (39.30 mm-65.90 mm;  $n=5$ ;  $SD= \pm 10.71$  mm) were generally of a low- to mid-range length while the shortest fractures at the exit defect (8.60 mm-26.70 mm;  $n=5$ ;  $SD= \pm 7.08$  mm) were of a low-range length.

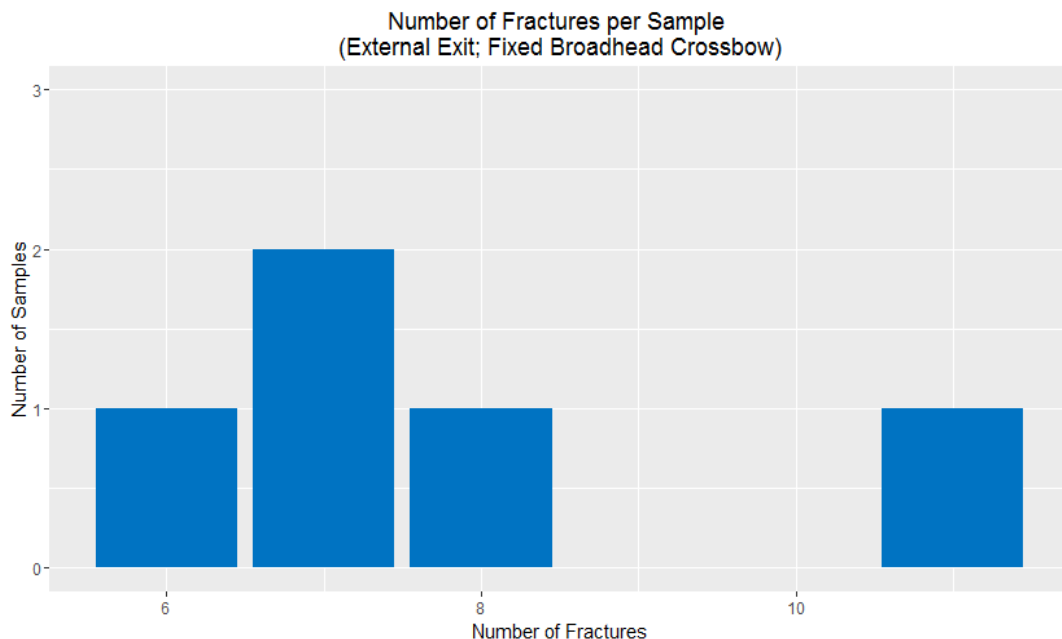


*Figure 4.48. Frequencies of the number of fractures on the external table of the exit defect (crossbow (fixed broadhead) samples).*

All five of the samples also had fractures along the internal table of the exit defect. The range of total number of fractures per sample mirrored the number of fractures on the external table (six to 11;  $n=5$ ;  $SD= \pm 1.92$ ) (Figure 4.49). Both radiating and concentric heaving fractures were present on the internal table of the exit defect on all five samples.

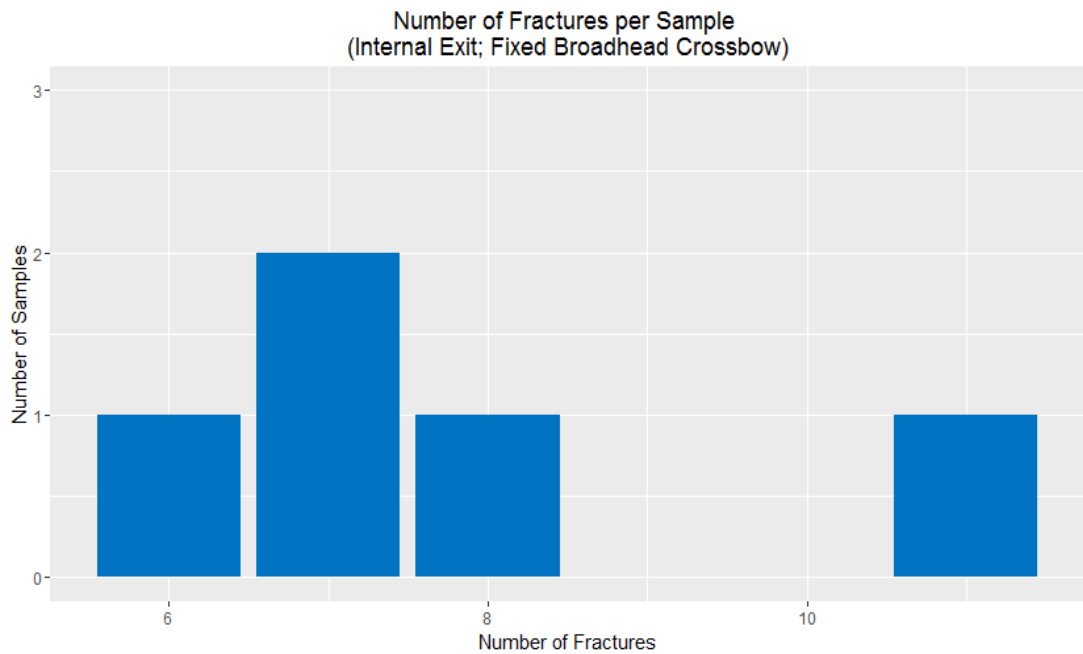


Figure 4.49. Frequencies of the number of fractures on the internal table of the exit defect (crossbow (fixed broadhead) samples).

All samples retained some level of residue left from the projectile.

## 4.8. Crossbow (Mechanical Broadhead) Features

A complete entrance was present on all five of the samples that were shot using mechanical broadhead bolts. Two samples (40.00%; 2/5) had circular in shape entrances while three of the entrances (60.00%; 3/5) were irregularly shaped (Figure 4.50). All five entrance defects had bevelling present, but the location varied between samples. In two samples (40.00%; 2/5), bevelling was located internally, but in three samples (60.00%; 3/5), bevelling was found on both the internal and external tables of the entrance defects (Figures 4.51 and 4.52). The widest point of these entrances (without reconstructing using any dislodged fragments) varied greatly, ranging from 7.80 mm to 132.30 mm ( $n=5$ ;  $SD= \pm 44.67$  mm) (Table 4.8). Four samples (80.00%; 4/5) required reconstruction using dislodged fragments that originated from the entrance defect. When these four samples were reconstructed, the widest portion of each entrance ranged from 6.70 mm to

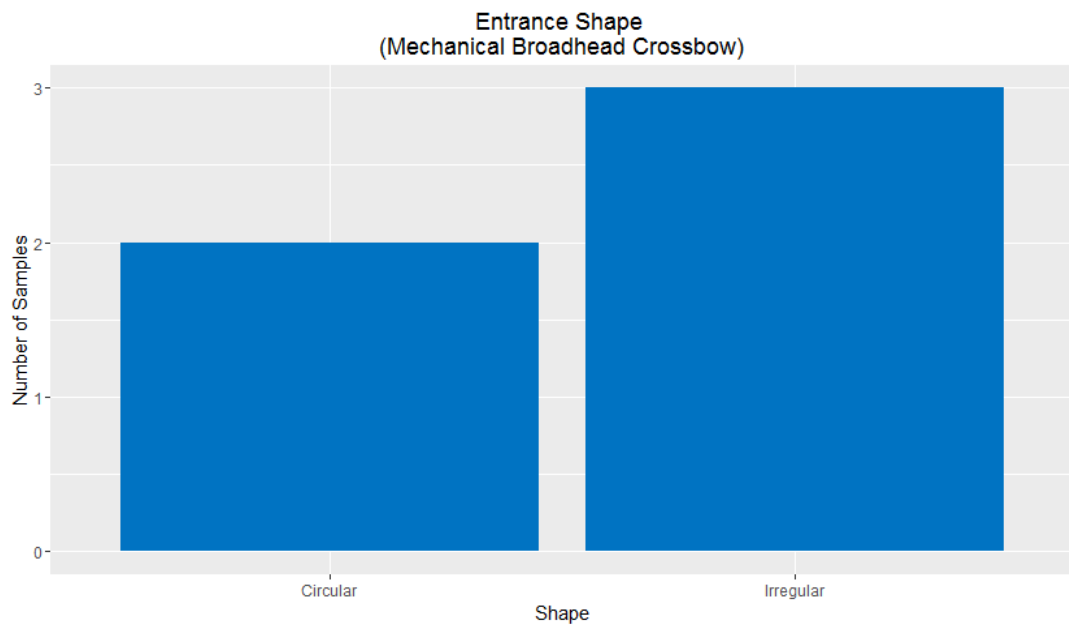


Figure 4.50. Frequencies of entrance shapes (crossbow (mechanical broadhead) samples).

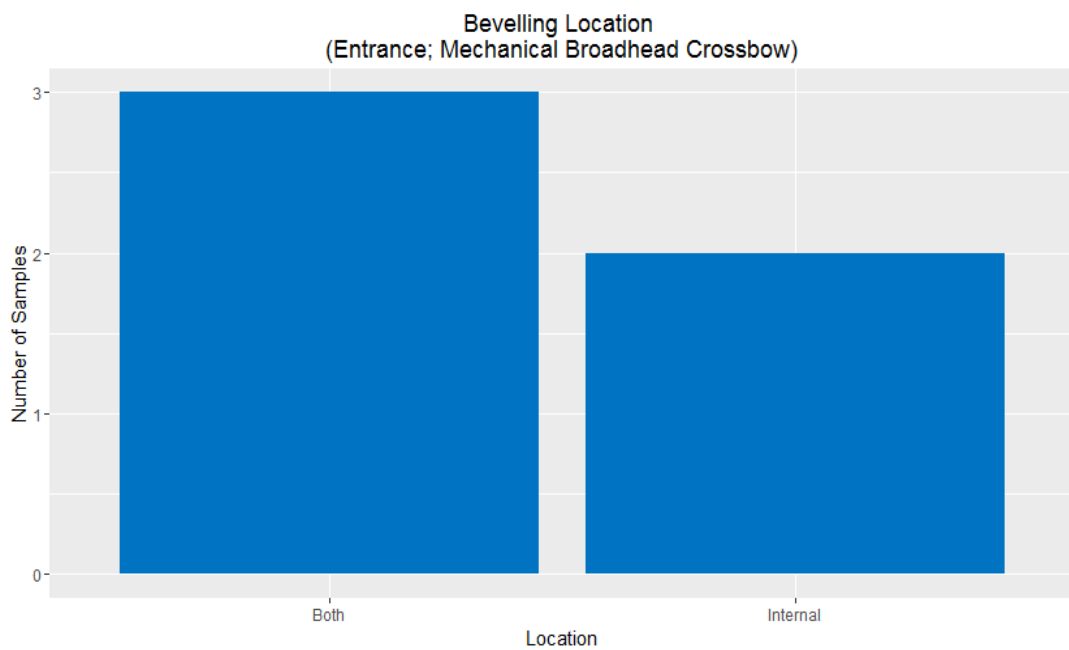


Figure 4.51. Frequency of bevelling on the internal table only or both the internal and external tables of the entrance defect (crossbow (mechanical broadhead) samples).

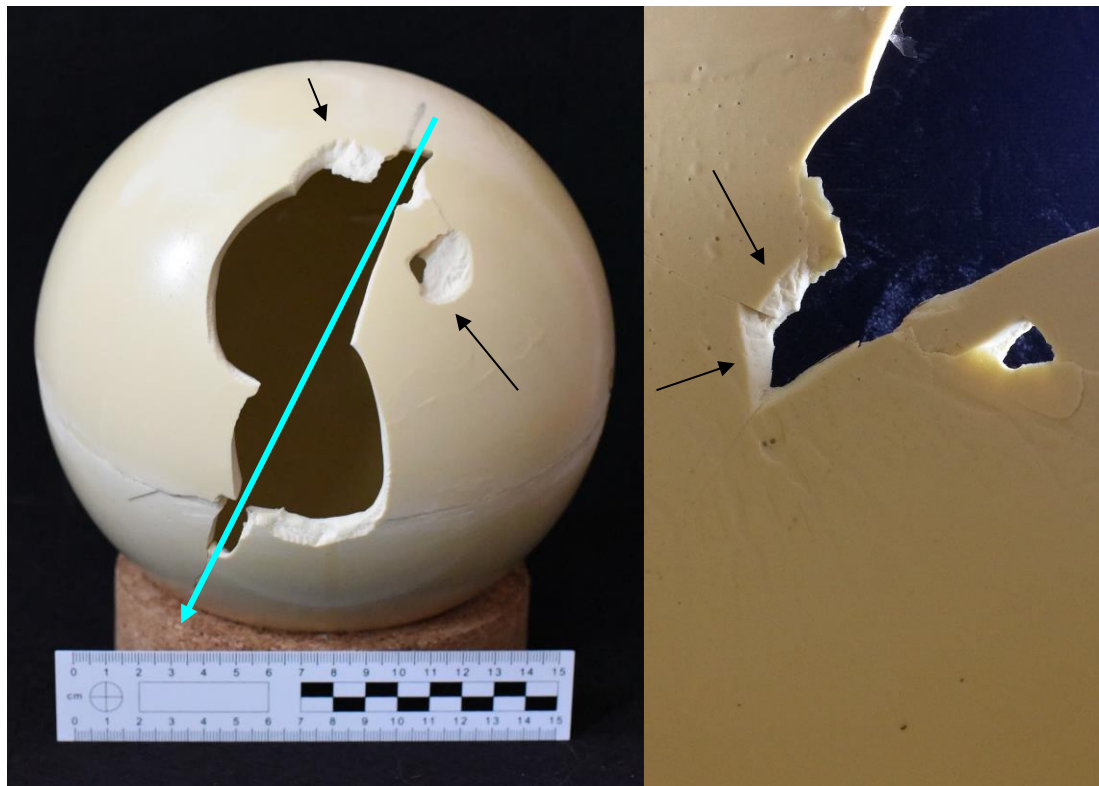


*Figure 4.52. Mechanical broadhead sample (CbBhX 2) joint entrance and exit defect with bevelling on both the external (left) and internal (right) tables (black arrows). (Cyan arrow shows flight path of the bolt.)*

21.00 mm ( $n=5$ ;  $SD= \pm 5.69$  mm), also significantly decreasing the level of variation between the samples.

Four samples shot with mechanical broadhead bolts (80.00%; 4/5) had fragments (one to four;  $n=5$ ;  $SD= \pm 1.82$ ) which had dislodged from the entrance defect (Figure 4.53). When excluding samples which had no fragments, these fragments, similar to the fixed broadhead fragments, were generally mid-range size fragments. The largest lengths of these fragments ranged from 54.10 mm to 65.00 mm ( $n=5$ ;  $SD= \pm 26.95$  mm) while the minimum fragment lengths ranged from 12.60 mm to 59.90 mm ( $n=5$ ;  $SD= \pm 23.03$  mm). The maximum (25.10 mm-46.30 mm;  $n=5$ ;  $SD= \pm 19.27$  mm) and minimum (9.30 mm-46.30 mm;  $n=5$ ;  $SD= \pm 17.74$  mm) fragment widths were similar to the lengths of the fragments.

*Table 4.8. Mean and standard deviation of quantitative variables (crossbow (mechanical broadhead) samples; n=5).*

| <b>Feature</b>                              | <b>Mean</b> | <b>Standard Deviation</b> |
|---------------------------------------------|-------------|---------------------------|
| Entrance defect diameter                    | 66.88 mm    | ± 44.67 mm                |
| Entrance defect diameter (reconstructed)    | 12.02 mm    | ± 5.69 mm                 |
| Number of fragments (Entrance)              | 2.40        | ± 1.82                    |
| Entrance fragment maximum length            | 47.72 mm    | ± 26.95 mm                |
| Entrance fragment maximum width             | 31.20 mm    | ± 19.27 mm                |
| Entrance fragment minimum length            | 24.08 mm    | ± 23.03 mm                |
| Entrance fragment minimum width             | 16.12 mm    | ± 17.74 mm                |
| Number of fractures (external entrance)     | 6.40        | ± 1.52                    |
| Number of fractures (internal entrance)     | 5.40        | ± 0.89                    |
| Maximum fracture length (external entrance) | 156.44 mm   | ± 23.39 mm                |
| Minimum fracture length (external entrance) | 25.16 mm    | ± 13.61 mm                |
| Exit defect diameter                        | 71.94 mm    | ± 43.83 mm                |
| Exit defect diameter (reconstructed)        | 15.04 mm    | ± 15.59 mm                |
| Number of fragments (Exit)                  | 2.80        | ± 1.10                    |
| Exit fragment maximum length                | 47.30 mm    | ± 23.07 mm                |
| Exit fragment maximum width                 | 32.82 mm    | ± 14.25 mm                |
| Exit fragment minimum length                | 26.80 mm    | ± 10.05 mm                |
| Exit fragment minimum width                 | 16.54 mm    | ± 4.49 mm                 |
| Number of fractures (external exit)         | 4.20        | ± 2.68                    |
| Number of fractures (internal exit)         | 3.80        | ± 2.49                    |
| Maximum fracture length (external exit)     | 77.68 mm    | ± 58.45 mm                |
| Minimum fracture length (external exit)     | 21.34 mm    | ± 12.68 mm                |

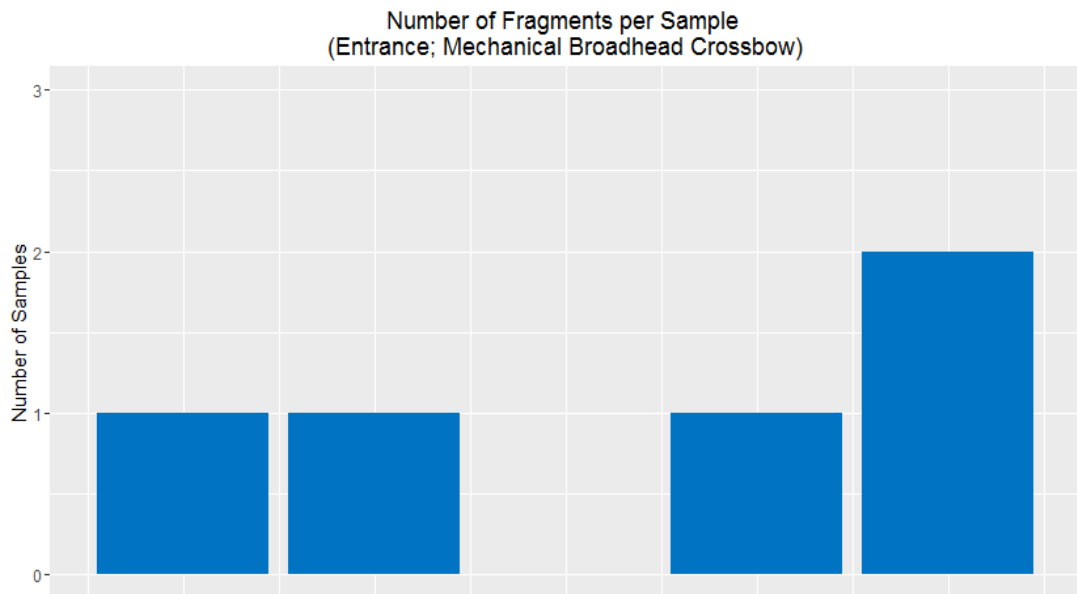


Figure 4.53. Frequencies of the number of fragments that originated from the entrance defect (crossbow (mechanical broadhead) samples).

All five samples shot with the mechanical broadhead bolts had at least one (five to nine;  $n=5$ ;  $SD= \pm 1.52$ ) fracture on the external table of the entrance site (Figure 4.54). Radiating fractures were present on the external table of the entrance defect of all five samples, but concentric heaving fractures were

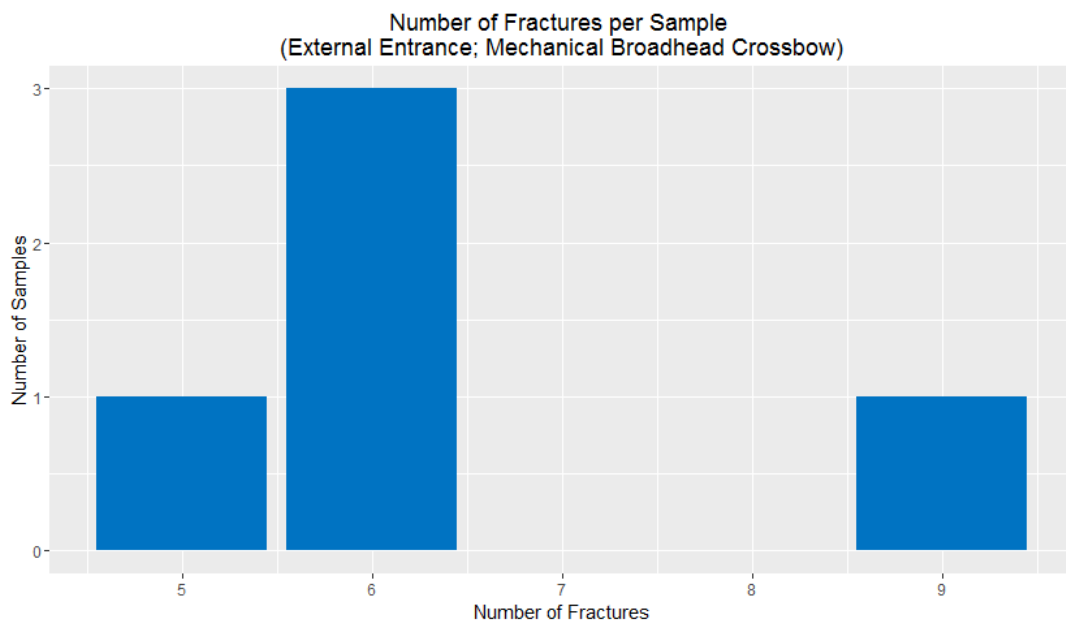


Figure 4.54. Frequencies of the number of fractures on the external table of the entrance defect (crossbow (mechanical broadhead) samples).

only present on three samples (60.00%; 3/5) and absent on two samples (40.00%; 2/5). The longest fractures (131.70 mm-192.70 mm;  $n=5$ ;  $SD= \pm 23.39$  mm) were comparable to fracture lengths observed on the external table of the entrance defect in the handgun samples while the shortest mechanical broadhead fractures (11.30 mm-47.10 mm;  $n=5$ ;  $SD= \pm 13.61$  mm) did still overlap with the shortest handgun fractures.

All five samples also consistently had fractures (four to six;  $n=5$ ;  $SD= \pm 0.89$ ) present along the internal table of the entrance defect (Figure 4.55).

Radiating fractures were present along the internal table of the entrance defect in all five samples, but concentric heaving fractures were only present on three samples (60.00%; 3/5) and absent on two samples (40.00%; 2/5).

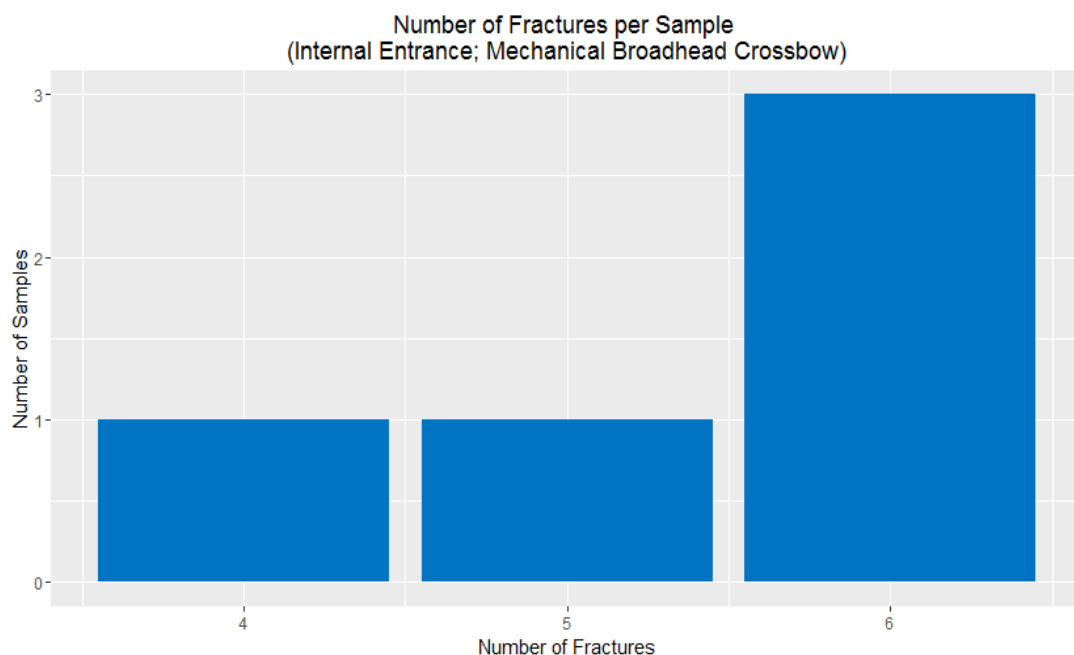


*Figure 4.55. Frequencies of the number of fractures on the internal table of the entrance defect (crossbow (mechanical broadhead) samples).*

An exit was present on all five samples which were shot using mechanical broadhead bolts. Three samples (60.00%; 3/5) had exits which were circular in shape while two (40.00%; 2/5) were irregularly shaped (Figure 4.56). All five exit defects had bevelling on the external table. The widest points of these exits (without reconstructing using any dislodged fragments) (28.20 mm-132.30 mm;  $n=5$ ;  $SD= \pm 43.83$  mm) were generally similar in size to the

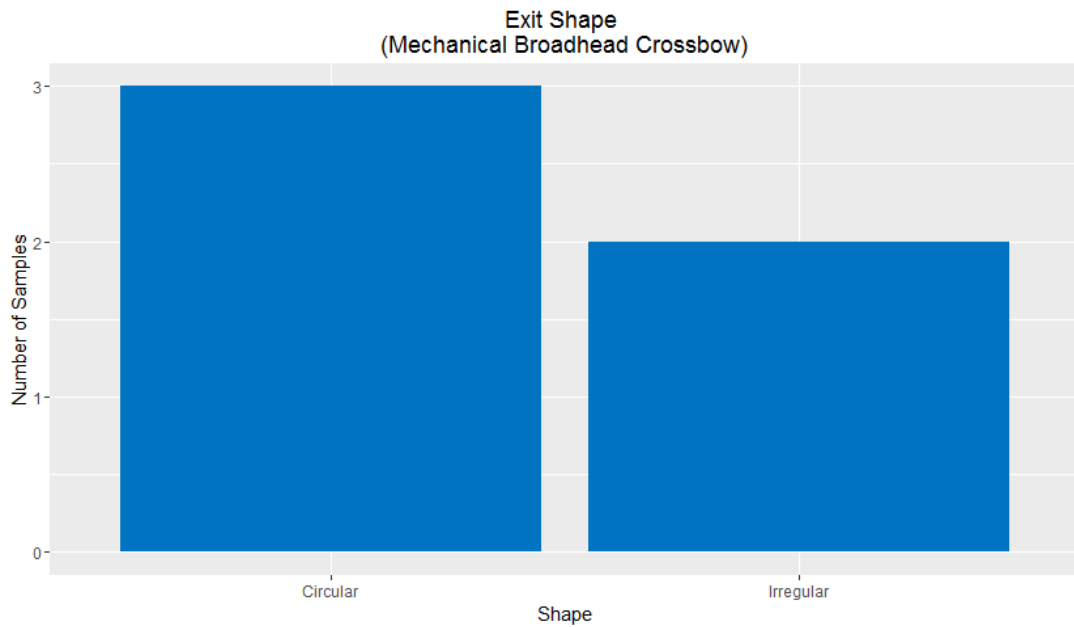


Figure 4.56. Frequencies of exit shapes (crossbow (mechanical broadhead) samples).

entrance defects. All five of the samples required reconstruction using dislodged fragments that originated from the exit defect. When the samples were reconstructed, the widest portion of each exit measured up to 41.10 mm ( $n=5$ ;  $SD= \pm 15.59$  mm).

All samples shot with mechanical broadhead bolts (100%; 5/5) had fragments that had dislodged from the exit defect (two to four;  $n=5$ ;  $SD= \pm 1.10$ ) (Figure 4.57). These fragments were similar in size to the entrance fragments: the maximum fragment length among these samples ranged from 26.60 mm to 82.50 mm ( $n=5$ ;  $SD= \pm 23.07$  mm), the minimum fragment length ranged from 17.10 mm to 43.40 mm ( $n=5$ ;  $SD= \pm 10.05$  mm), the maximum fragment width ranged from 19.60 mm to 49.10 mm ( $n=5$ ;  $SD= \pm 14.25$  mm), and the minimum fragment width ranged from 11.00 mm to 22.30 mm ( $n=5$ ;  $SD= \pm 4.49$  mm).

Four samples which were shot with the mechanical broadhead bolts (80.00%; 4/5) had at least one fracture (three to six;  $n=5$ ;  $SD= \pm 2.68$ ) on the external table of the exit defect, but one (20.00%; 1/5) had no fractures (Figure 4.58). Radiating fractures were present on the external table of the entrance defect of four samples (80.00%; 4/5), but were absent on one sample (20.00%; 1/5). Similar to the fixed broadhead samples, concentric



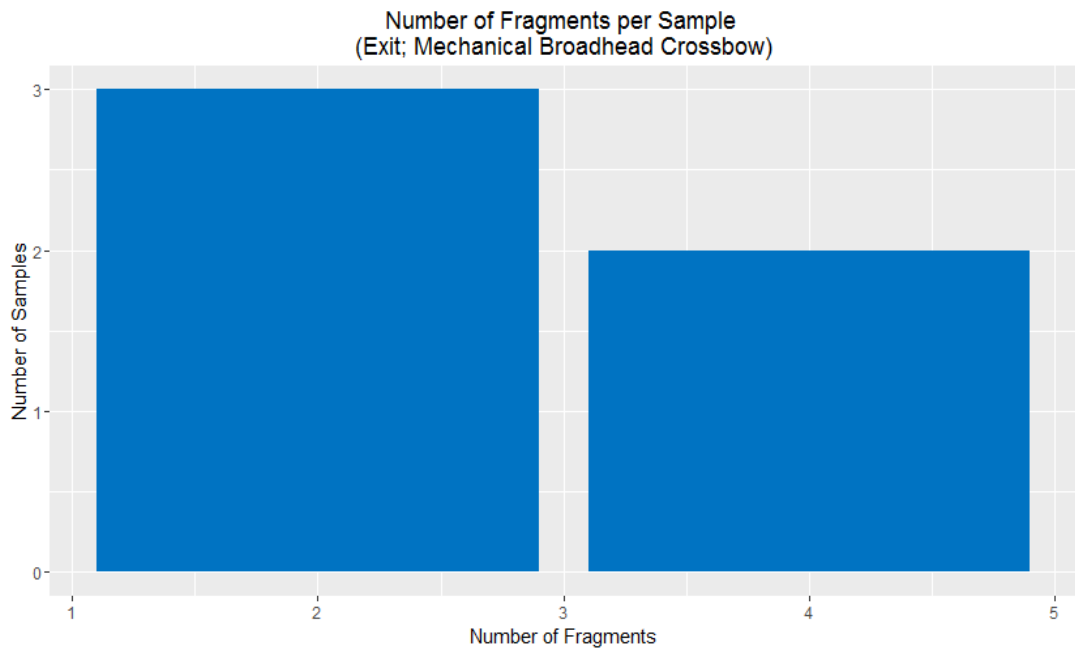


Figure 4.57. Frequencies of the number of fragments that originated from the exit defect (crossbow (mechanical broadhead) samples).

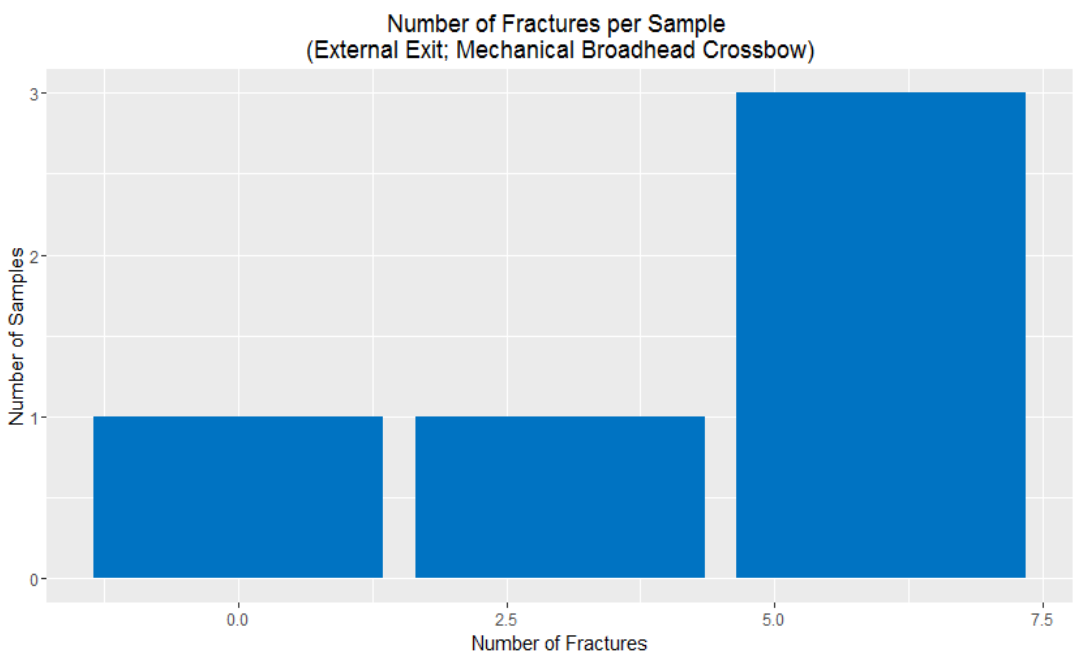


Figure 4.58. Frequencies of the number of fractures on the external table of the exit defect (crossbow (mechanical broadhead) samples).

heaving fractures were present on three samples (60.00%; 3/5) and absent on two samples (40.00%; 2/5). When excluding the sample with no fractures, both the longest (56.40 mm-139.10 mm;  $n=5$ ;  $SD= \pm 58.45$  mm) and shortest fractures (19.50 mm to 30.70 mm;  $n=5$ ;  $SD= \pm 12.68$  mm) per sample were, once again, comparable to the fractures at the exit defects of the handgun samples.

Four samples (80.00%; 4/5) also had fractures present along the internal table of the exit defect and one sample (20.00%; 1/5) had no fractures. The number of fractures per sample (3-6;  $n=5$ ;  $SD= \pm 2.49$ ) on the internal table of the exit defect reflected the number of fractures on the external tables (Figure 4.59). Radiating fractures were present on the internal table of the entrance defect of four samples (80.00%; 4/5), but were absent on the sample with no fractures. As was observed on the external table, concentric heaving fractures were only present on three samples (60.00%; 3/5) and absent on two samples (40.00%; 2/5).

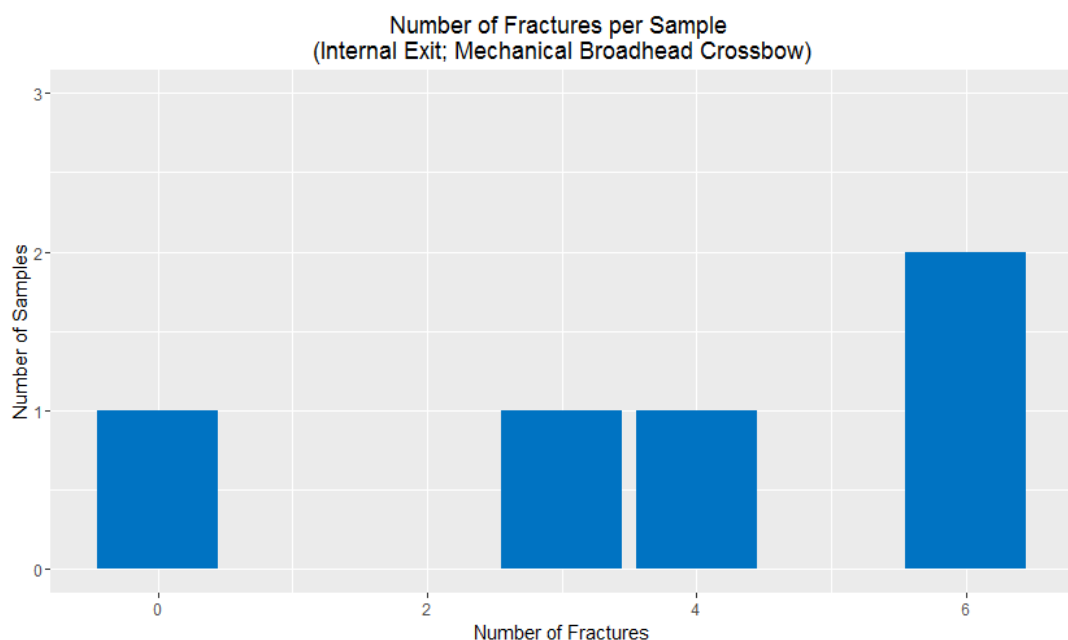


*Figure 4.59. Frequencies of the number of fractures on the internal table of the exit defect (crossbow (mechanical broadhead) samples).*

All samples retained some level of residue left from the projectile.

The following chapter discusses the statistical analysis of the findings presented in this chapter.

## 5. Results II - Statistical Analysis

This chapter discusses the statistical analyses of the observations described in the previous chapter. Each section examines the results of the following statistical tests: principal component analysis, one-way ANOVA/Kruskal-Wallis test, and linear discriminant analysis. The two subsets of the data (one including the exit features and one excluding the exit features) were examined separately for each of these tests.

### 5.1. Principal Component Analysis

The initial principal component analysis was able to extract the most distinguishing variables in the data set by plotting each of the variables against each other, giving each variable its own dimensional plane. When including the features of the exit defect, this study examined 35 variables, so the principal component analysis conducted on the data created a theoretical plot of all the samples with an exit in a 35-dimensional graph. The program is then able to calculate the axis, referred to as a "principal component," on which the data as a whole is the most spread out and contains the most variation. Because the principal component has the highest level of variation, it is the axis which is the most likely to separate and group the data into clusters. If the data were to be laying on top of each other, it could be difficult to distinguish which samples belong to which group. By having the data as spread out as it can possibly be, patterns can begin to emerge based on which samples are grouped together on the plot.

Rather than just use the one variable, represented by the one axis in the first principal component, the program repeats the process for each plane, organising the axes of the variables from the highest variation to the lowest variation. These repetitions then create a hierarchy of the axes starting at PC1 and, in this study, ending with PC35.

Additionally, the program also computes how much of the variation each axis accounts for, known as the proportion of the variance. The first principal component will always account for the highest percentage of the variation, followed by PC2, etc. When observed independently from each other, each principal component accounts for so much of the variation. But when multiple variables are taken into consideration, they will account for the variation of each individual variable. This level of variation, known as the cumulative proportion of the variance, is a simple sum of the proportion of the variance for each principal component.

As discussed in the methods chapter (Chapter 3), two separate sets of statistical analyses were conducted: one for the samples with an exit defect present and another for the samples without an exit defect.

#### 5.1.1. Exit Included

As previously stated, 35 variables were observed in samples which had an exit. This created a 35-dimensional plot with 35 principal components. The most influential feature of the observed trauma was found to be the maximum length on the external table of the entrance defect, with the proportion of the variance at 42.95% (Table 5.1). Examining this variable alone would only account for a small portion of the variation within the data, so it is necessary to use multiple variables from this dataset.

Statistical significance ( $p \leq 0.05$ ) is not achieved within the cumulative proportion of the variance until PC7 (96.74%). That is to say that of the 35 variables observed in the samples with an exit defect, the seven variables with the highest proportions of variance account for 96.74% of the variation in the dataset. These seven variables, in descending order, are: the maximum fracture length on the external table of the entrance defect (PC1), the minimum fracture length on the external table of the entrance defect (PC2), the diameter of the entrance defect (without reconstruction) (PC3), the

*Table 5.1. Principal component analysis summary (principal component values, proportion of variance, and cumulative proportion of variance for PC1-PC7) for the analysis conducted on samples with an exit defect.*

| <b>Feature</b>                                                              | <b>PC Value</b> | <b>Proportion of Variance (%)</b> | <b>Cumulative Proportion (%)</b> |
|-----------------------------------------------------------------------------|-----------------|-----------------------------------|----------------------------------|
| <i>Maximum fracture length on the external table of the entrance defect</i> | 4.15e-01        | 42.95                             | 42.95                            |
| <i>Minimum fracture length on the external table of the entrance defect</i> | -4.32e-01       | 21.41                             | 64.36                            |
| <i>Entrance diameter (without reconstruction)</i>                           | 3.70e-01        | 14.52                             | 78.87                            |
| <i>Minimum fragment length (entrance fragments)</i>                         | -5.32e-01       | 7.29                              | 86.17                            |
| <i>Reconstructed exit diameter</i>                                          | -3.95e-01       | 5.45                              | 91.62                            |
| <i>Maximum fracture length on the external table of the exit defect</i>     | 6.53e-01        | 3.35                              | 94.97                            |
| <i>Reconstructed entrance diameter</i>                                      | 3.36e-01        | 1.77                              | 96.74                            |

minimum fragment length of the entrance defect (PC4), the reconstructed diameter of the exit defect (PC5), the maximum fracture length on the external table of the exit defect (PC6), and the reconstructed diameter of the entrance defect (PC7).

### 5.1.2. Exit Excluded

Within the subset of the data which did not examine the features of an exit defect, only 22 features of trauma were examined. In the principal component analysis, the program was able to construct a theoretical 22-dimensional graph, with a principal component for each axis. The most influential

explanatory variable (PC1) was found to be the maximum fracture length on the external table of the entrance defect, which accounted for 62.83% of the variance within the data (Table 5.2).

*Table 5.2. Principal component analysis summary (principal component values, proportion of variance, and cumulative proportion of variance for PC1-PC4) for the analysis conducted on entrance features only.*

| <b>Feature</b>                                                              | <b>PC Value</b> | <b>Proportion of Variance (%)</b> | <b>Cumulative Proportion (%)</b> |
|-----------------------------------------------------------------------------|-----------------|-----------------------------------|----------------------------------|
| <i>Maximum fracture length on the external table of the entrance defect</i> | -0.85           | 62.83                             | 62.83                            |
| <i>Entrance diameter (without reconstruction)</i>                           | -0.51           | 21.33                             | 84.16                            |
| <i>Minimum fracture length on the external table of the entrance defect</i> | 0.69            | 7.68                              | 91.83                            |
| <i>Reconstructed entrance diameter</i>                                      | 0.35            | 4.05                              | 95.89                            |

While this does account for a simple majority of the variance, the relationship between the maximum fracture length on the external table of the entrance defect and the weapon of origin alone would not be statistically significant. In examining this subset, 95.89% of the variation within the data was accounted for by the four most influential explanatory variables. This number of principal components required to reach statistical significance ( $p \leq 0.05$ ) is a fraction of the number of principal components required for the subset of samples where the exit defect features were examined. Following the maximum fracture length on the external table of the entrance defect, the most distinguishing features of trauma at the entrance defect were found to be the maximum diameter of the entrance defect (without reconstruction) (PC2), the minimum fracture length on the external table of the entrance defect (PC3), and the maximum diameter of the reconstructed entrance defect (PC4) (Table 5.2).

## 5.2. One-Way Analysis of Variance/Kruskal-Wallis

Each of the seven features (when including the features of the exit defect) and four features (when excluding the features of the exit defect) which were found to be most indicative of weapon were further analysed separately.

### 5.2.1. Analysis 1: Maximum Fracture Length on the External Surface of the Entrance Defect

This test compared the means of the length of the longest fracture on the external surface of the entrance defect between each of the five weapons examined in the subsection of this study which included exit defect features. In testing the assumptions for an ANOVA test, it was found that the residuals were normally distributed (Figure 5.1) and exhibited homoscedasticity (Table 5.3). As all the assumptions for an ANOVA test were met, a one-way ANOVA could confidently be conducted on the relationship between these two variables.

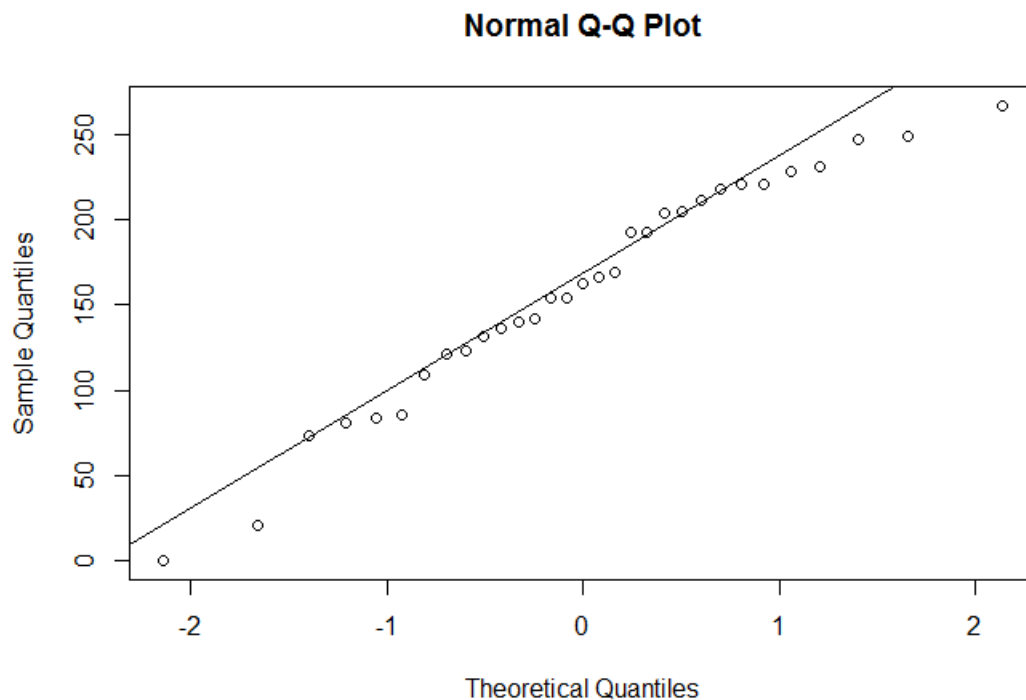


Figure 5.1 Q-Q plot and line of best fit of the residuals of Analysis 1.



Table 5.3 Results of testing the assumptions of an ANOVA (Analysis 1).

| Assumption  | W-value | Df | F-value | P-value |
|-------------|---------|----|---------|---------|
| Normality   | 0.96    | -  | -       | 0.36    |
| Homogeneity | -       | 4  | 0.77    | 0.55    |

After verifying that the assumptions of an ANOVA were met, a one-way ANOVA test was conducted on these two variables. The results of this test (Table 5.4) showed that the two variables were significantly related ( $F_{4,26}=4.62$ ,  $p<0.01$ ) signifying that there were at least two weapons which exhibited significantly different means of this feature.

Table 5.4 Analysis 1 one-way ANOVA results.

|           | Df | Sum Sq | Mean Sq | F value | P value |
|-----------|----|--------|---------|---------|---------|
| Values    | 4  | 55633  | 13908   | 4.62    | <0.01   |
| Residuals | 26 | 78218  | 3008    | -       | -       |

A Tukey post hoc test was then conducted to distinguish which of the weapons had means which significantly differed. Two weapon pairings were found to have significantly different means of the maximum fracture length on the external table of the entrance defect. Handgun strongly differed from field-tipped crossbow bolts ( $p=0.01$ ) as well as rifle showed a strong significant difference from field-tipped crossbow bolts ( $p<0.01$ ).

### 5.2.2. Analysis 2: Minimum Fracture Length on the External Surface of the Entrance Defect

This test compared the means of the length of the shortest fracture on the external surface of the entrance defect between each of the five weapons examined in the subsection of this study which included exit defect features. Though the residuals in this data were found to exhibit homoscedasticity, they were found to not have a normal distribution (Figure 5.2) (Table 5.5). A logarithmic transformation was attempted in order to transform the data to

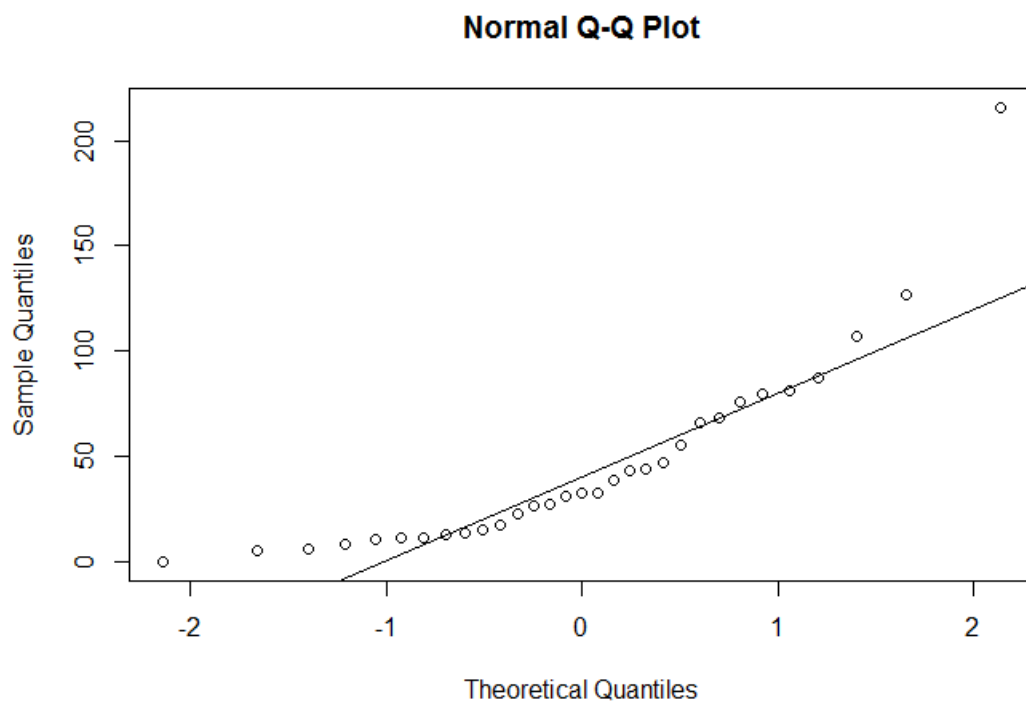


Figure 5.2 Q-Q plot and line of best fit of the residuals of Analysis 2.

Table 5.5 Results of testing the assumptions of an ANOVA (Analysis 2).

| Assumption  | W-value | Df | F-value | P-value |
|-------------|---------|----|---------|---------|
| Normality   | 0.81    | -  | -       | <0.01   |
| Homogeneity | -       | 4  | 1.01    | 0.42    |

better fit a normal distribution and the transformed data exhibited an approximately normal distribution of residuals (Figure 5.3) while still maintaining homoscedasticity (Table 5.6).

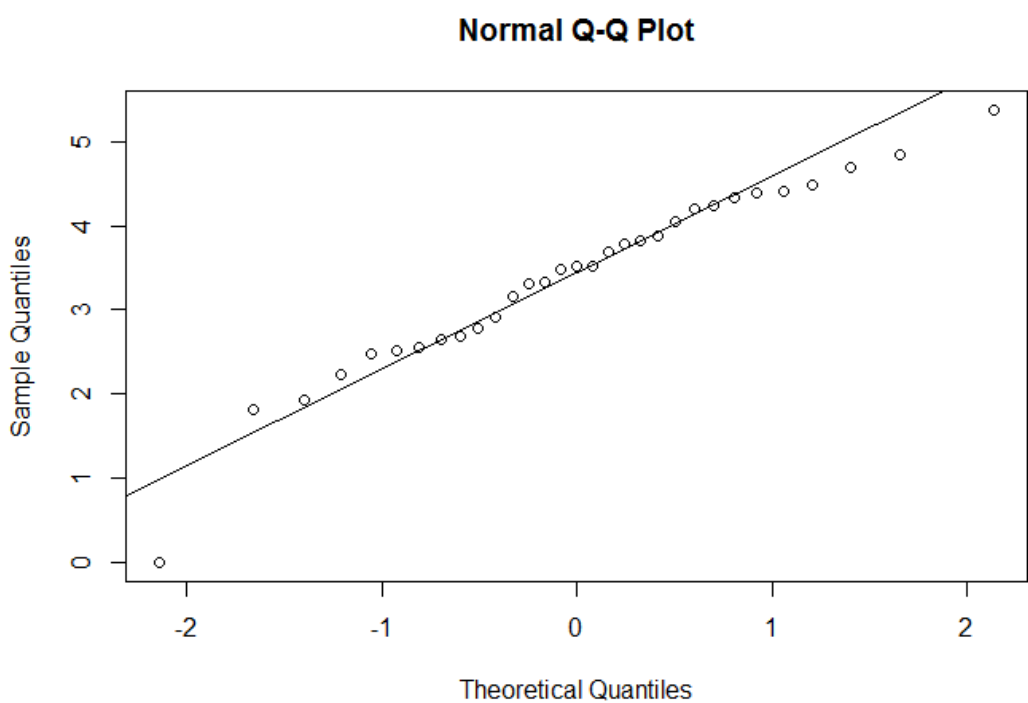


Figure 5.3 Q-Q plot and line of best fit of the residuals of Analysis 2 after a logarithmic transformation.

Table 5.6 Results of testing the assumptions of an ANOVA (Analysis 2 after a logarithmic transformation).

| Assumption  | W-value | Df | F-value | P-value |
|-------------|---------|----|---------|---------|
| Normality   | 0.95    | -  | -       | 0.21    |
| Homogeneity | -       | 4  | 0.72    | 0.58    |

As the assumptions for an ANOVA were met with the logarithmically transformed data, a one-way ANOVA was conducted on these two variables. The results of this test (Table 5.7) showed that the two variables were not

significantly related ( $F_{4,26}=0.37$ ,  $p=0.83$ ) indicating that none of the weapons exhibited significantly different means of this feature.

*Table 5.7 Analysis 2 one-way ANOVA results.*

|                  | <i>Df</i> | <i>Sum Sq</i> | <i>Mean Sq</i> | <i>F value</i> | <i>P value</i> |
|------------------|-----------|---------------|----------------|----------------|----------------|
| <i>Values</i>    | 4         | 1.92          | 0.48           | 0.37           | 0.83           |
| <i>Residuals</i> | 26        | 33.86         | 1.30           | -              | -              |

### 5.2.3. Analysis 3: Diameter of the Entrance Defect (Without Reconstruction)

This test compared the means of the diameter of the entrance defect without reconstruction using dislodged fragments between each of the five weapons examined in the subsection of this study which included exit defect features. In testing the assumptions for an ANOVA test, it was found that the residuals were not normally distributed (Figure 5.4) and did not exhibit homoscedasticity (Table 5.8). A logarithmic transformation was attempted in order to transform the data to better fit a normal distribution. Though the residuals in this data were found to exhibit homoscedasticity, they were found to not have a normal distribution (Table 5.9) (Figure 5.5).

*Table 5.8 Results of testing the assumptions of an ANOVA (Analysis 3).*

| <i>Assumption</i>  | <i>W-value</i> | <i>Df</i> | <i>F-value</i> | <i>P-value</i> |
|--------------------|----------------|-----------|----------------|----------------|
| <i>Normality</i>   | 0.81           | -         | -              | <0.01          |
| <i>Homogeneity</i> | -              | 4         | 5.41           | <0.01          |

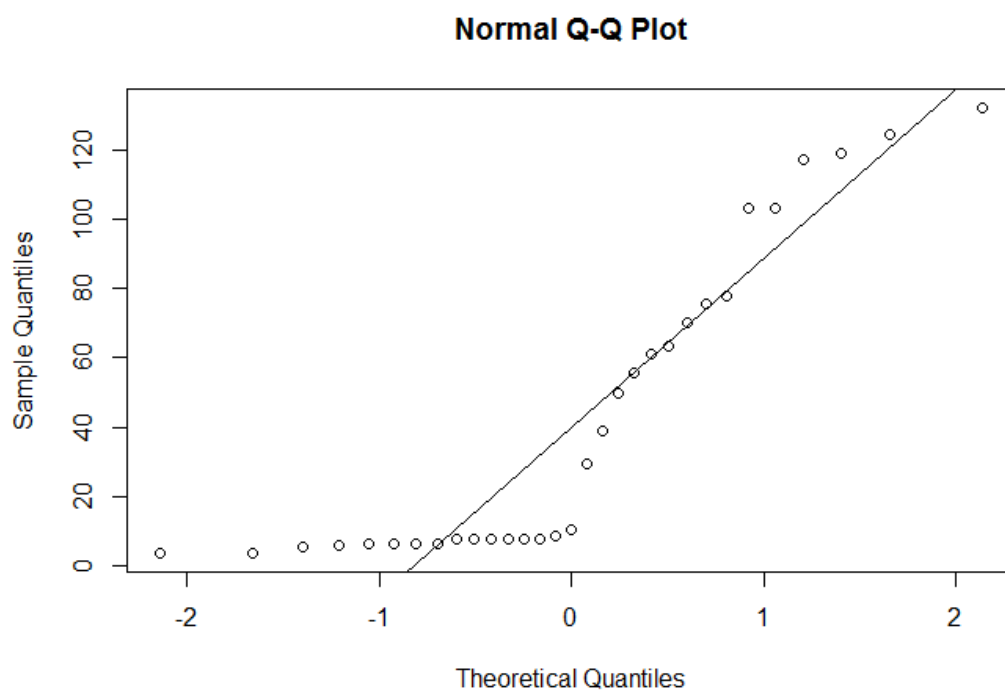


Figure 5.4 Q-Q plot and line of best fit of the residuals of Analysis 3.

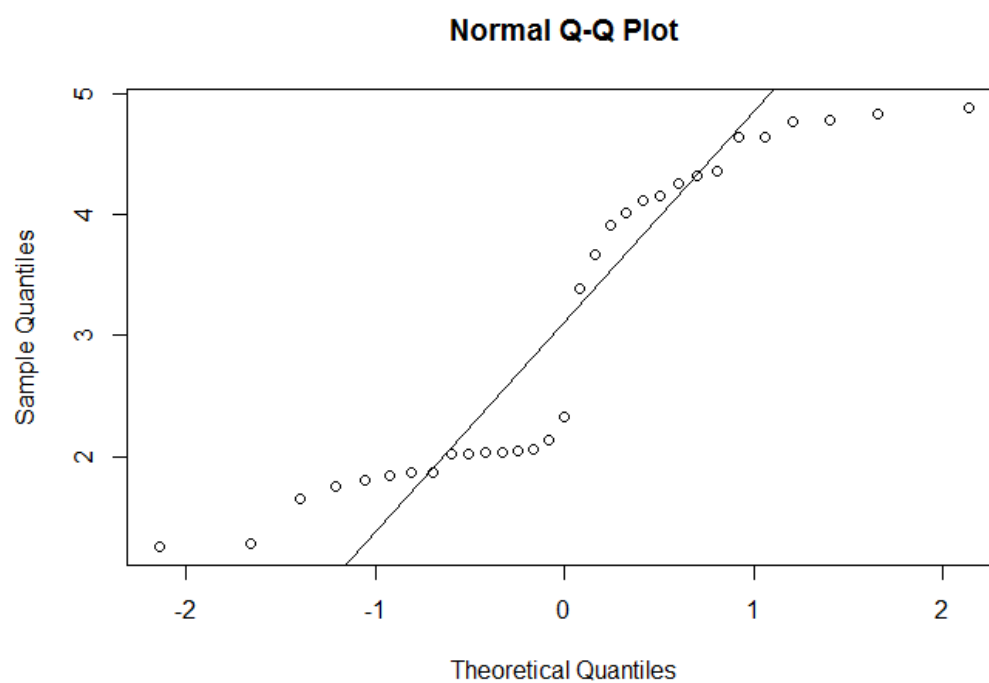


Figure 5.5 Q-Q plot and line of best fit of the residuals of Analysis 3 after a logarithmic transformation.

*Table 5.9 Results of testing the assumptions of an ANOVA (Analysis 3 after a logarithmic transformation).*

| <i>Assumption</i>  | <i>W-value</i> | <i>Df</i> | <i>F-value</i> | <i>P-value</i> |
|--------------------|----------------|-----------|----------------|----------------|
| <i>Normality</i>   | 0.85           | -         | -              | <0.01          |
| <i>Homogeneity</i> | -              | 4         | 1.63           | 0.20           |

As the assumptions for a one-way ANOVA were not met, a Kruskal-Wallis test was conducted on these two variables. The results of this test showed that the two variables were significantly related ( $H(4)=16.30$ ,  $p<0.01$ ) signifying that there were at least two weapons which exhibited significantly different means of this feature.

Because the data is non-parametric, a Dunn post hoc test was conducted to distinguish which of the weapons had means which significantly differed. It was found that two pairs of weapons produced significantly different entrance defect diameters. Samples which were shot with the mechanical broadhead-tipped crossbow bolts differed from samples shot with the rifle ( $p<0.01$ ) and samples shot with the handgun also differed from the samples which were shot with the rifle ( $p<0.01$ ).

#### 5.2.4. Analysis 4: Minimum Fragment Length of Fragments Originating from the Entrance Defect

This test compared the means of the minimum fragment length of fragments that originated from the entrance defect between each of the five weapons examined in the subsection of this study which included exit defect features. In testing the assumptions for an ANOVA test, it was found that the while the residuals exhibited homoscedasticity, they were not normally distributed (Figure 5.6) (Table 5.10). A logarithmic transformation was attempted in

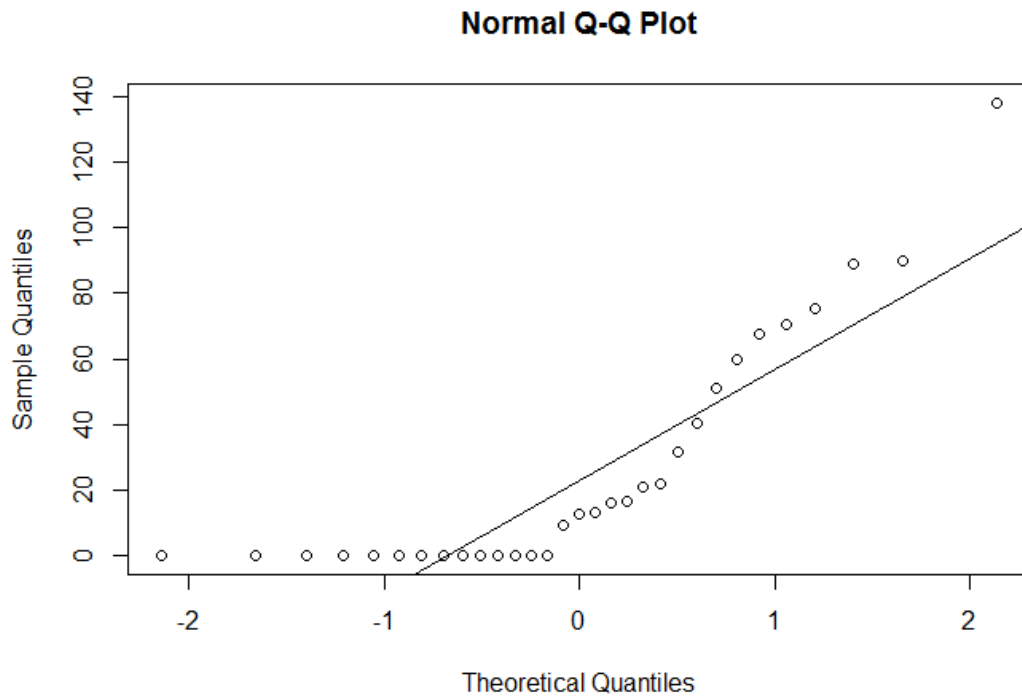


Figure 5.6 Q-Q plot and line of best fit of the residuals of Analysis 4.

Table 5.10 Results of testing the assumptions of an ANOVA (Analysis 4).

| Assumption  | W-value | Df | F-value | P-value |
|-------------|---------|----|---------|---------|
| Normality   | 0.77    | -  | -       | <0.01   |
| Homogeneity | -       | 4  | 1.27    | 0.31    |

order to transform the data to better fit a normal distribution. Though the residuals in this data maintained homoscedasticity, they were still found to not have a normal distribution (Figure 5.7) (Table 5.11).

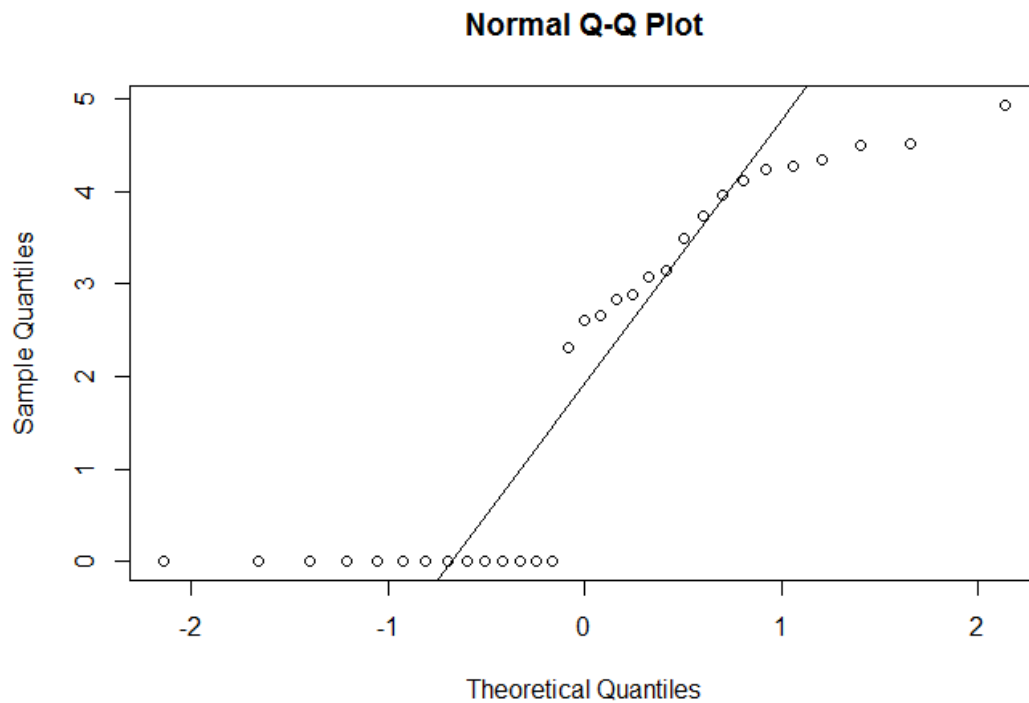


Figure 5.7 Q-Q plot and line of best fit of the residuals of Analysis 4 after a logarithmic transformation.

Table 5.11 Results of testing the assumptions of an ANOVA (Analysis 4 after a logarithmic transformation).

| Assumption  | W-value | Df | F-value | P-value |
|-------------|---------|----|---------|---------|
| Normality   | 0.79    | -  | -       | <0.01   |
| Homogeneity | -       | 4  | 0.45    | 0.77    |

As the data did not meet the assumptions of a one-way ANOVA, a Kruskal-Wallis test was conducted on these two variables. The results of this test showed that the two variables were not significantly related ( $H(4)=5.84$ ,  $p=0.21$ ) signifying that none of the weapons exhibited significantly different means of this feature.



### 5.2.5. Analysis 5: Diameter of the Exit Defect After Reconstruction

This test compared the means of the diameter of the exit defect after reconstruction using any dislodged fragments between each of the five weapons examined in the subsection of this study which included exit defect features. In testing the assumptions for an ANOVA test, it was found that the while the residuals exhibited homoscedasticity, they were not normally distributed (Figure 5.8) (Table 5.12). A logarithmic transformation was

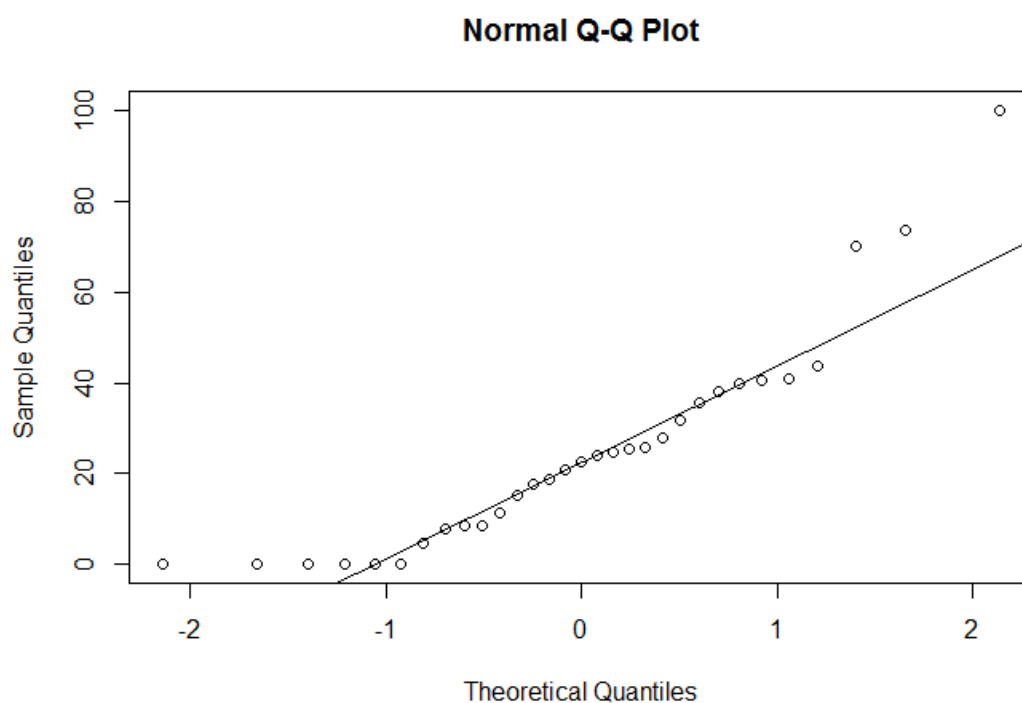


Figure 5.8 Q-Q plot and line of best fit of the residuals of Analysis 5.

Table 5.12 Results of testing the assumptions of an ANOVA (Analysis 5).

| Assumption  | W-value | Df | F-value | P-value |
|-------------|---------|----|---------|---------|
| Normality   | 0.87    | -  | -       | <0.01   |
| Homogeneity | -       | 4  | 1.37    | 0.27    |

attempted in order to transform the data to better fit a normal distribution. Though the residuals in this data maintained homoscedasticity, they were still found to not have a normal distribution (Figure 5.9) (Table 5.13).

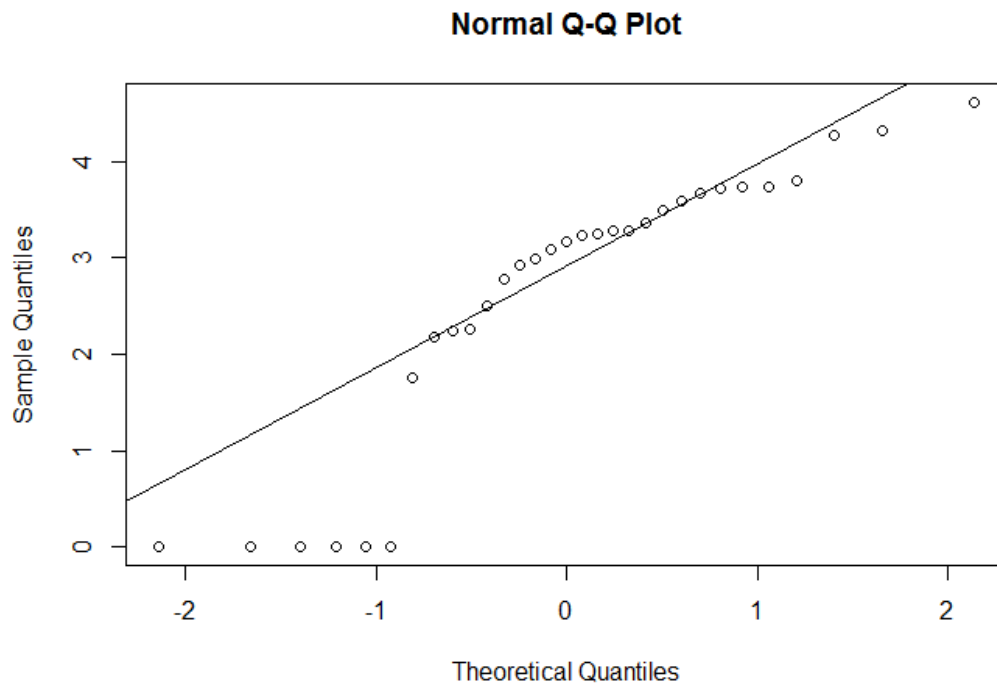


Figure 5.9 Q-Q plot and line of best fit of the residuals of Analysis 5 after a logarithmic transformation.

Table 5.13 Results of testing the assumptions of an ANOVA (Analysis 5 after a logarithmic transformation).

| Assumption  | W-value | Df | F-value | P-value |
|-------------|---------|----|---------|---------|
| Normality   | 0.83    | -  | -       | <0.01   |
| Homogeneity | -       | 4  | 1.11    | 0.37    |

As the data did not meet the assumptions of a one-way ANOVA, a Kruskal-Wallis test was conducted on these two variables. The results of this test showed that the two variables were significantly related ( $H(4)=11.79$ ,  $p=0.02$ )

signifying that there were at least two weapons which exhibited significantly different means of this feature.

Because the data is non-parametric, a Dunn post hoc test was conducted to distinguish which of the weapons had means which significantly differed. It was found that one pair of weapons produced significantly different exit defect diameters after reconstruction: samples which were shot with the fixed broadhead-tipped crossbow bolts differed from samples shot with the rifle ( $p=0.02$ ).

#### 5.2.6. Analysis 6: Maximum Fracture Length on the External Surface of the Exit Defect

This test compared the means of the length of the longest fracture on the external surface of the exit defect between each of the five weapons examined in the subsection of this study which included exit defect features. In testing the assumptions for an ANOVA test, it was found that while the residuals were normally distributed, they did not exhibit homoscedasticity (Table 5.14) (Figure 5.10). A logarithmic transformation was attempted in order to transform the data to better fit a normal distribution. In this transformation, the residuals in this data exhibited homoscedasticity, but were not normally distributed (Figure 5.11) (Table 5.15).

*Table 5.14 Results of testing the assumptions of an ANOVA (Analysis 6).*

| <i>Assumption</i>  | <i>W-value</i> | <i>Df</i> | <i>F-value</i> | <i>P-value</i> |
|--------------------|----------------|-----------|----------------|----------------|
| <i>Normality</i>   | 0.96           | -         | -              | 0.27           |
| <i>Homogeneity</i> | -              | 4         | 2.99           | 0.04           |

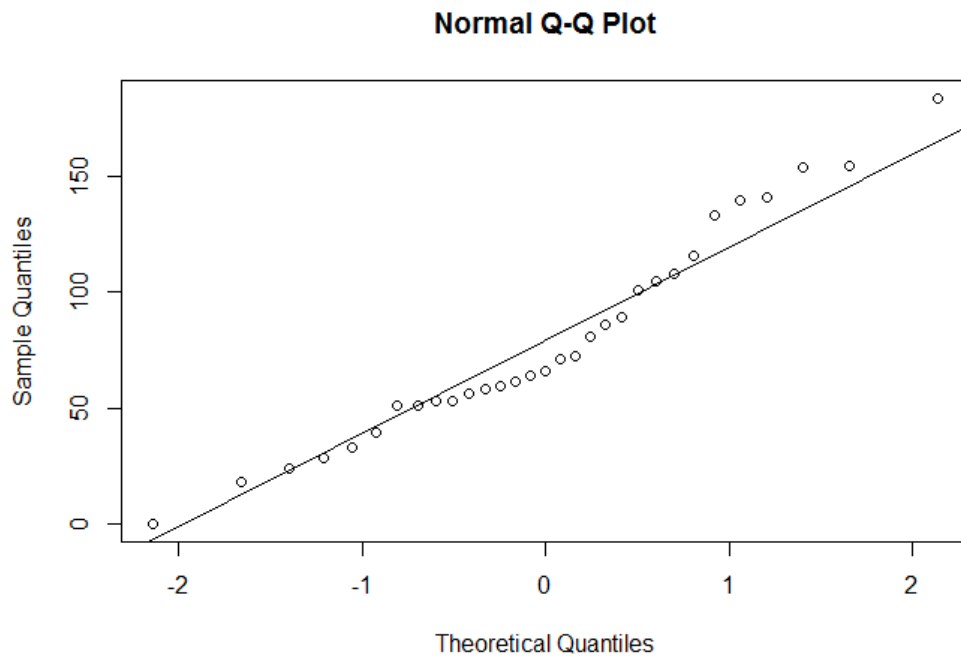


Figure 5.10 Q-Q plot and line of best fit of the residuals of Analysis 6.

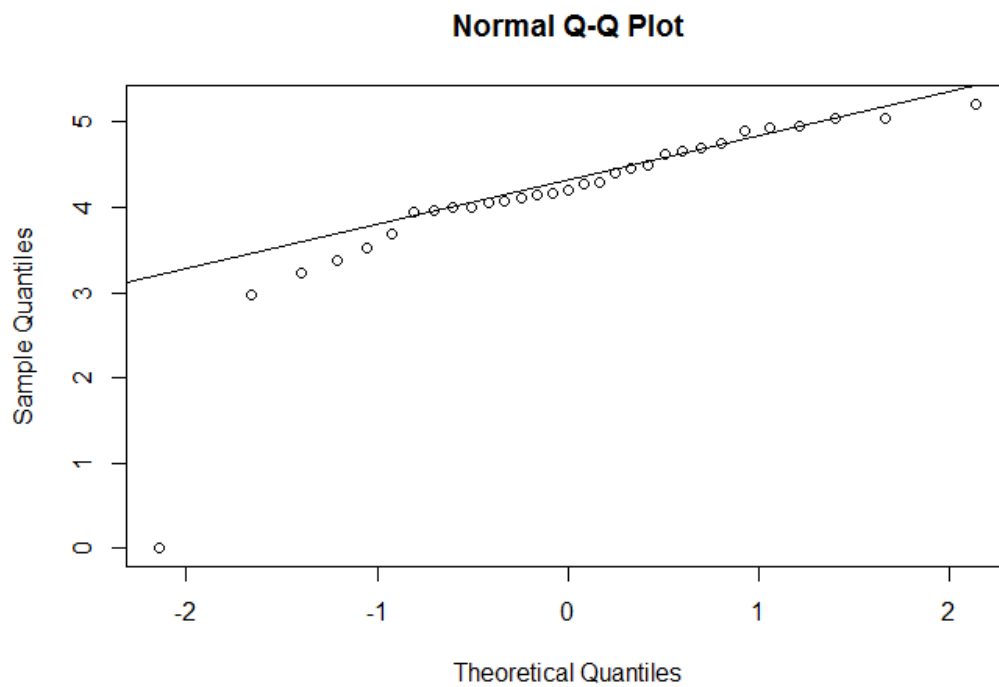


Figure 5.11 Q-Q plot and line of best fit of the residuals of Analysis 6 after a logarithmic transformation.

*Table 5.15 Results of testing the assumptions of an ANOVA (Analysis 6 after a logarithmic transformation).*

| <i>Assumption</i>  | <i>W-value</i> | <i>Df</i> | <i>F-value</i> | <i>P-value</i> |
|--------------------|----------------|-----------|----------------|----------------|
| <i>Normality</i>   | 0.74           | -         | -              | <0.01          |
| <i>Homogeneity</i> | -              | 4         | 1.64           | 0.19           |

As the data did not meet the assumptions of a one-way ANOVA, a Kruskal-Wallis test was conducted on these two variables. The results of this test showed that the two variables were not significantly related ( $H(4)=4.65$ ,  $p=0.33$ ) signifying that none of the weapons exhibited significantly different means of this feature.

#### 5.2.7. Analysis 7: Diameter of the Entrance Defect After Reconstruction

This test compared the means of the diameter of the entrance defect after reconstructing using dislodged fragments between each of the five weapons examined in the subsection of this study which included exit defect features. In testing the assumptions for an ANOVA test, it was found that the while the residuals exhibited homoscedasticity, they were not normally distributed (Figure 5.12) (Table 5.16). A logarithmic transformation was attempted in order to transform the data to better fit a normal distribution. Though the residuals in this data maintained homoscedasticity, they were still found to not have a normal distribution (Table 5.17) (Figure 5.13).

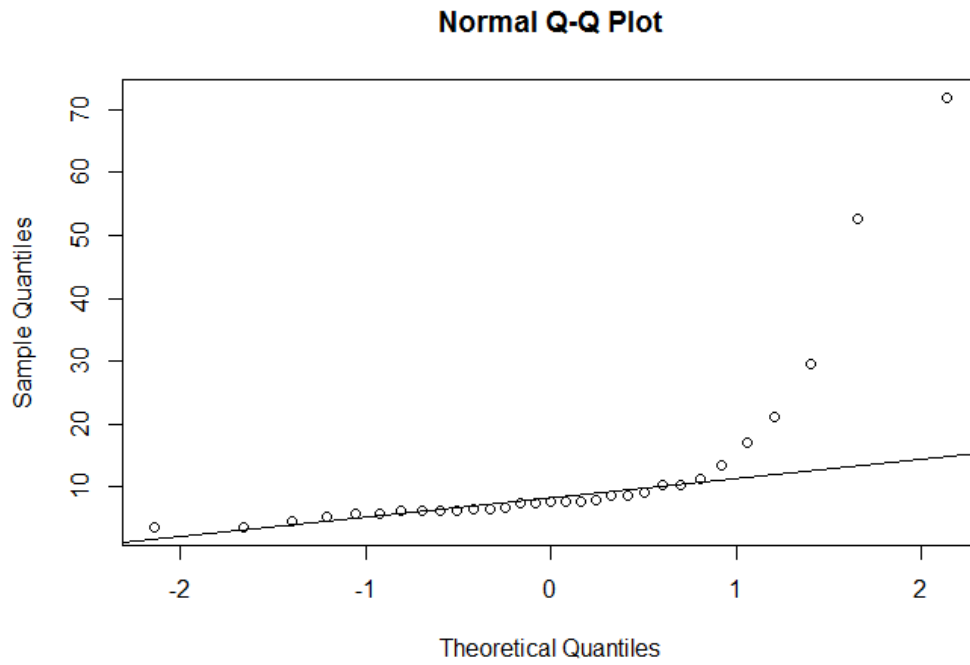


Figure 5.12 Q-Q plot and line of best fit of the residuals of Analysis 7.

Table 5.16 Results of testing the assumptions of an ANOVA (Analysis 7).

| Assumption  | W-value | Df | F-value | P-value |
|-------------|---------|----|---------|---------|
| Normality   | 0.53    | -  | -       | <0.01   |
| Homogeneity | -       | 4  | 0.87    | 0.49    |

Table 5.17 Results of testing the assumptions of an ANOVA (Analysis 7 after a logarithmic transformation).

| Assumption  | W-value | Df | F-value | P-value |
|-------------|---------|----|---------|---------|
| Normality   | 0.82    | -  | -       | <0.01   |
| Homogeneity | -       | 4  | 1.06    | 0.40    |

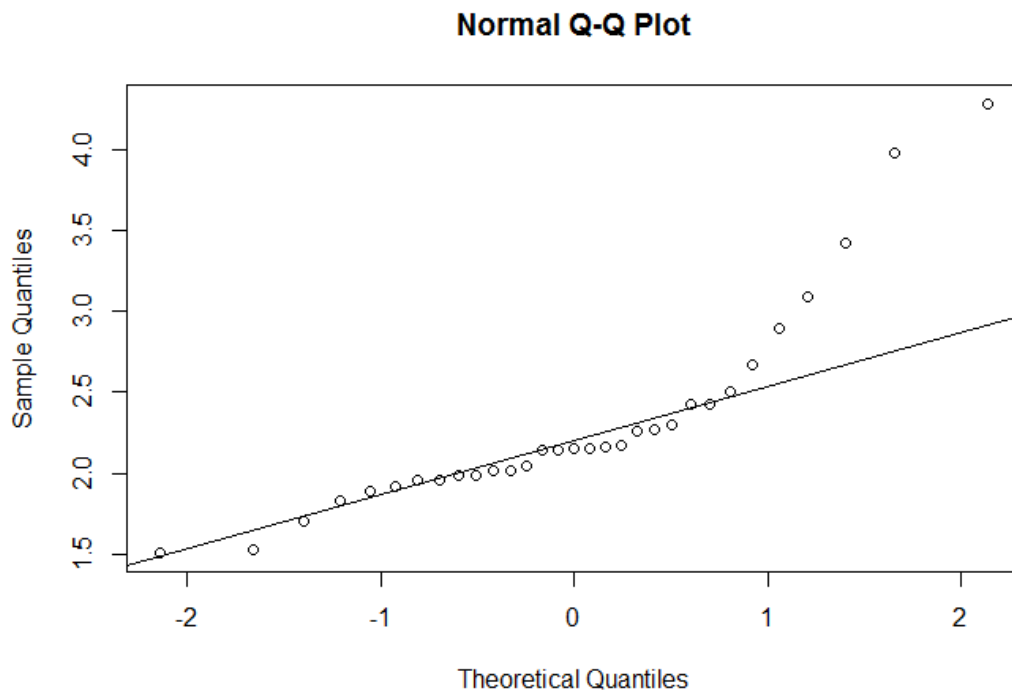


*Figure 5.13 Q-Q plot and line of best fit of the residuals of Analysis 7 after a logarithmic transformation.*

As the data did not meet the assumptions of a one-way ANOVA, a Kruskal-Wallis test was conducted on these two variables. The results of this test showed that the two variables were significantly related ( $H(4)=10.32$ ,  $p=0.04$ ) signifying that there were at least two weapons which exhibited significantly different means of this feature.

Because the data is non-parametric, a Dunn post hoc test was conducted to distinguish which of the weapons had means which significantly differed. It was found that two pairs of weapons produced significantly different entrance defect diameters. Samples which were shot with the mechanical broadhead-tipped crossbow bolts differed from samples shot with the rifle ( $p=0.02$ ) and samples shot with the handgun also differed from the samples which were shot with the rifle ( $p=0.04$ ).

### 5.2.8. Analysis 8: Maximum Fracture Length on the External Surface of the Entrance Defect

This test compared the means of the length of the longest fracture on the external surface of the entrance defect between each of the eight weapons examined in the subsection of this study which excluded exit defect features. In testing the assumptions for an ANOVA test, it was found that the while the residuals exhibited homoscedasticity, they were not normally distributed (Figure 5.14) (Table 5.18). A logarithmic transformation was attempted in order to transform the data to better fit a normal distribution. Though the residuals in this data maintained homoscedasticity, they were still found to not have a normal distribution (Figure 5.15) (Table 5.19).

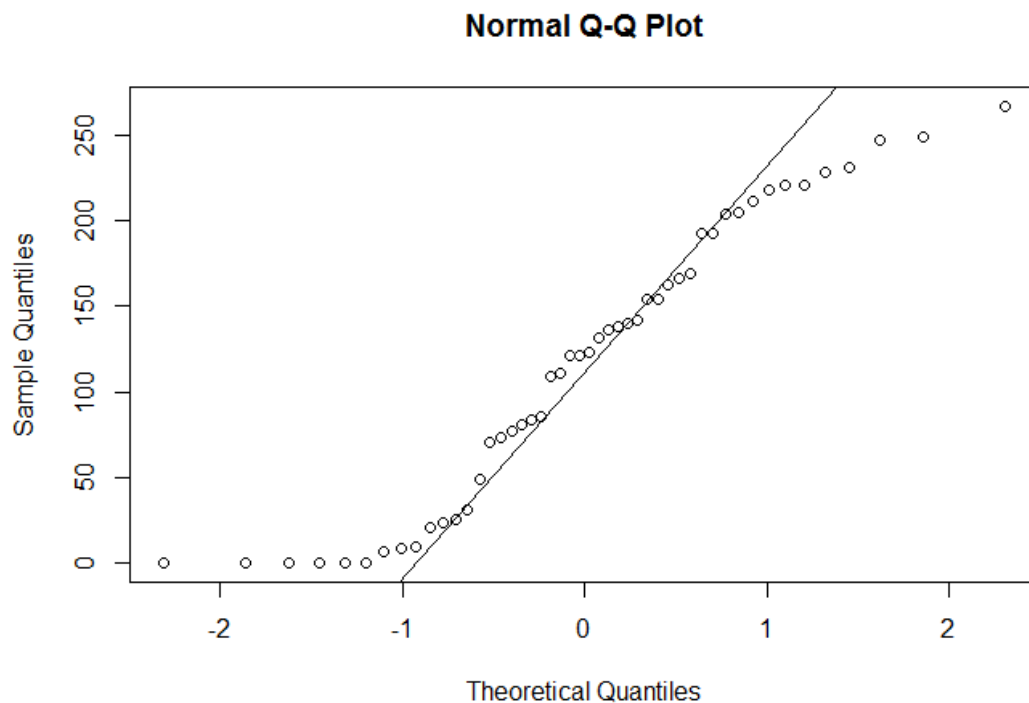


*Figure 5.14 Q-Q plot and line of best fit of the residuals of Analysis 8.*



Table 5.18 Results of testing the assumptions of an ANOVA (Analysis 8).

| Assumption  | W-value | Df | F-value | P-value |
|-------------|---------|----|---------|---------|
| Normality   | 0.93    | -  | -       | <0.01   |
| Homogeneity | -       | 7  | 1.30    | 0.28    |

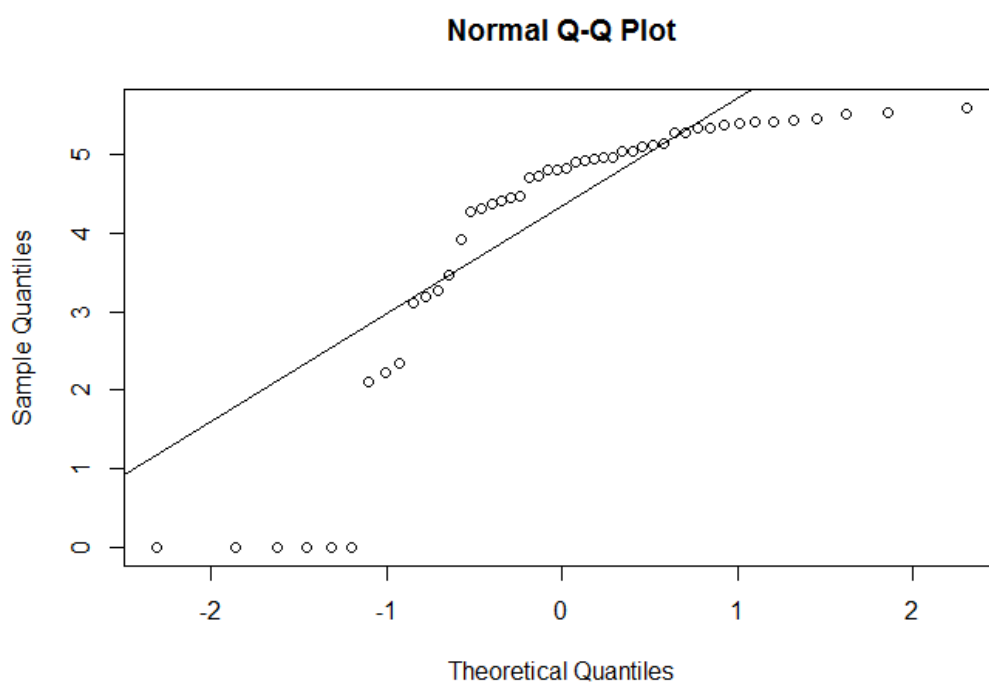


Figure 5.15 Q-Q plot and line of best fit of the residuals of Analysis 8 after a logarithmic transformation.

Table 5.19 Results of testing the assumptions of an ANOVA (Analysis 8 after a logarithmic transformation).

| Assumption  | W-value | Df | F-value | P-value |
|-------------|---------|----|---------|---------|
| Normality   | 0.74    | -  | -       | <0.01   |
| Homogeneity | -       | 7  | 0.34    | 0.93    |

As the assumptions of a one-way ANOVA were not met, a Kruskal-Wallis test was conducted on these two variables. The results of this test showed that the two variables were significantly related ( $H(4)=33.89$ ,  $p<0.01$ ) signifying that there were at least two weapons which exhibited significantly different means of this feature.

Because the data is non-parametric, a Dunn post hoc test was conducted to distinguish which of the weapons had means which significantly differed. It was found that five pairs of weapons produced significantly different maximum fracture lengths on the external table of the entrance defect: handgun and recurve bow ( $p<0.01$ ), compound bow and rifle ( $p=0.03$ ), recurve bow and rifle ( $p<0.01$ ), mechanical broadhead-tipped crossbow bolts and recurve bow ( $p=0.01$ ), and fixed broadhead-tipped crossbow bolts and recurve bow ( $p=0.02$ ).

#### 5.2.9. Analysis 9: Diameter of the Entrance Defect (Without Reconstruction)

This test compared the means of the diameter of the entrance defect prior to reconstructing using dislodged fragments between each of the eight weapons examined in the subsection of this study which excluded exit defect features. In testing the assumptions for an ANOVA test, it was found that the residuals were not normally distributed and did not exhibit homoscedasticity (Table 5.20) (Figure 5.16). A logarithmic transformation was attempted in order to transform the data to better fit a normal distribution, but the residuals in this data maintained heteroscedasticity and were still found to not have a normal distribution (Figure 5.17) (Table 5.21).

Table 5.20 Results of testing the assumptions of an ANOVA (Analysis 9).

| Assumption  | W-value | Df | F-value | P-value |
|-------------|---------|----|---------|---------|
| Normality   | 0.77    | -  | -       | <0.01   |
| Homogeneity | -       | 7  | 4.71    | <0.01   |

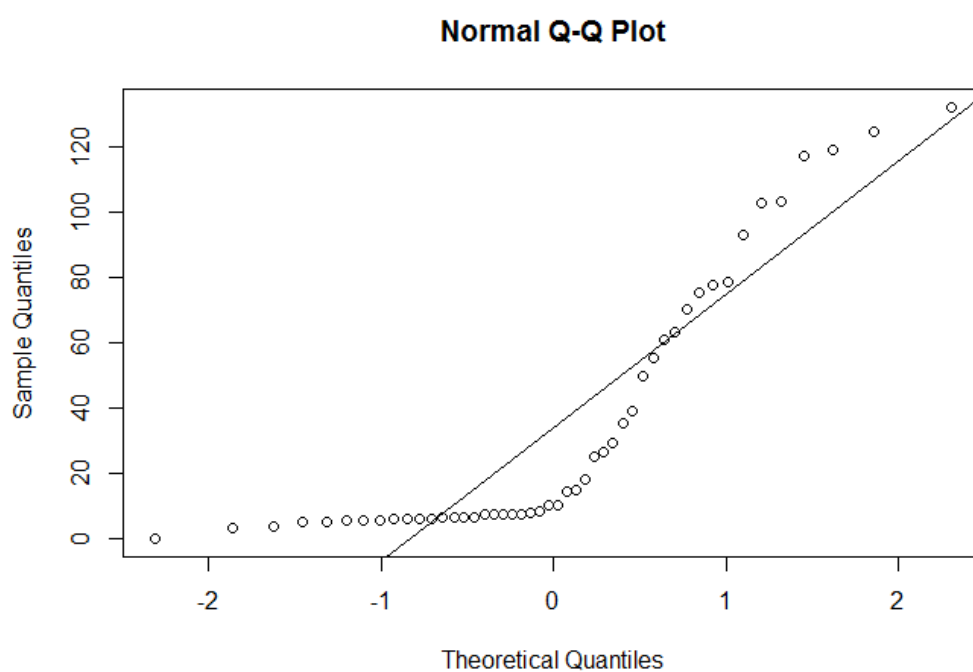


Figure 5.16 Q-Q plot and line of best fit of the residuals of Analysis 9.

Table 5.21 Results of testing the assumptions of an ANOVA (Analysis 9 after a logarithmic transformation).

| Assumption  | W-value | Df | F-value | P-value |
|-------------|---------|----|---------|---------|
| Normality   | 0.90    | -  | -       | <0.01   |
| Homogeneity | -       | 7  | 2.68    | <0.01   |

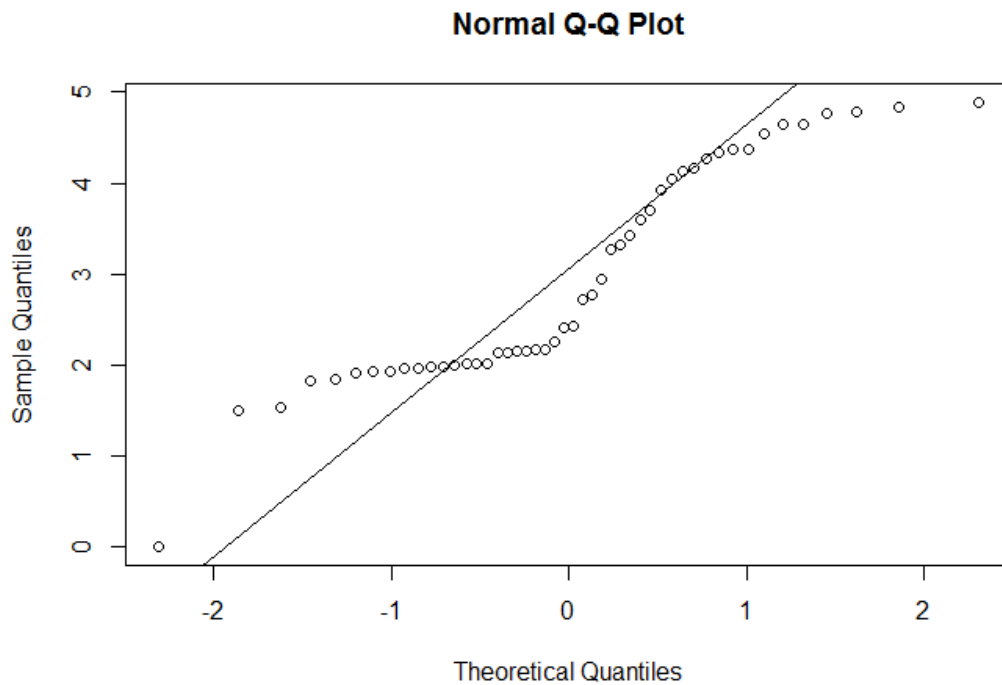


Figure 5.17 Q-Q plot and line of best fit of the residuals of Analysis 9 after a logarithmic transformation.

As the assumptions of a one-way ANOVA were not met, a Kruskal-Wallis test was conducted on these two variables. The results of this test showed that the two variables were significantly related ( $H(4)=23.77$ ,  $p<0.01$ ) signifying that there were at least two weapons which exhibited significantly different means of this feature.

Because the data is non-parametric, a Dunn post hoc test was conducted to distinguish which of the weapons had means which significantly differed. It was found that three pairs of weapons produced significantly different entrance defect diameters: handgun and recurve bow ( $p=0.01$ ), handgun and rifle ( $p<0.01$ ), and mechanical broadhead-tipped crossbow bolts ( $p=0.01$ ).

### 5.2.10. Analysis 10: Minimum Fracture Length on the External Surface of the Entrance Defect

This test compared the means of the shortest fracture on the external surface of the entrance defect between each of the eight weapons examined in the subsection of this study which excluded exit defect features. In testing the assumptions for an ANOVA test, it was found that the residuals were not normally distributed, but a slight homoscedasticity was noted (Figure 5.18) (Table 5.22). A logarithmic transformation was attempted in order to transform the data to better fit a normal distribution. The residuals in this data were found to have a roughly normal distribution and exhibited homoscedasticity (Figure 5.19) (Table 5.23).

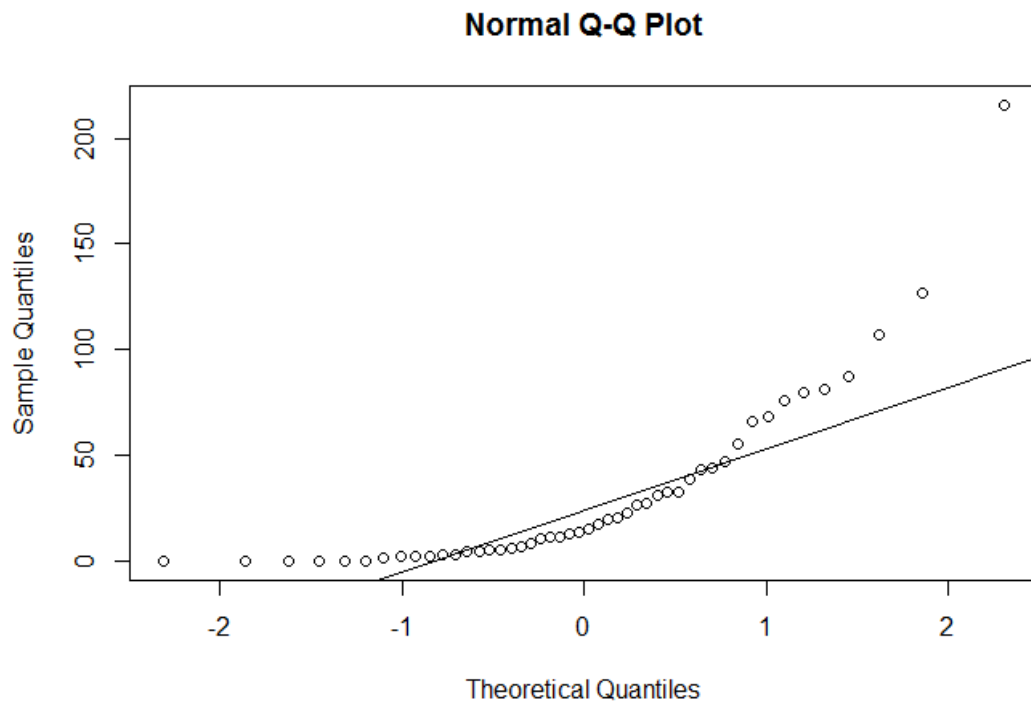


*Figure 5.18 Q-Q plot and line of best fit of the residuals of Analysis 10.*

Table 5.22 Results of testing the assumptions of an ANOVA (Analysis 10).

| Assumption  | W-value | Df | F-value | P-value |
|-------------|---------|----|---------|---------|
| Normality   | 0.73    | -  | -       | <0.01   |
| Homogeneity | -       | 7  | 2.14    | 0.06    |

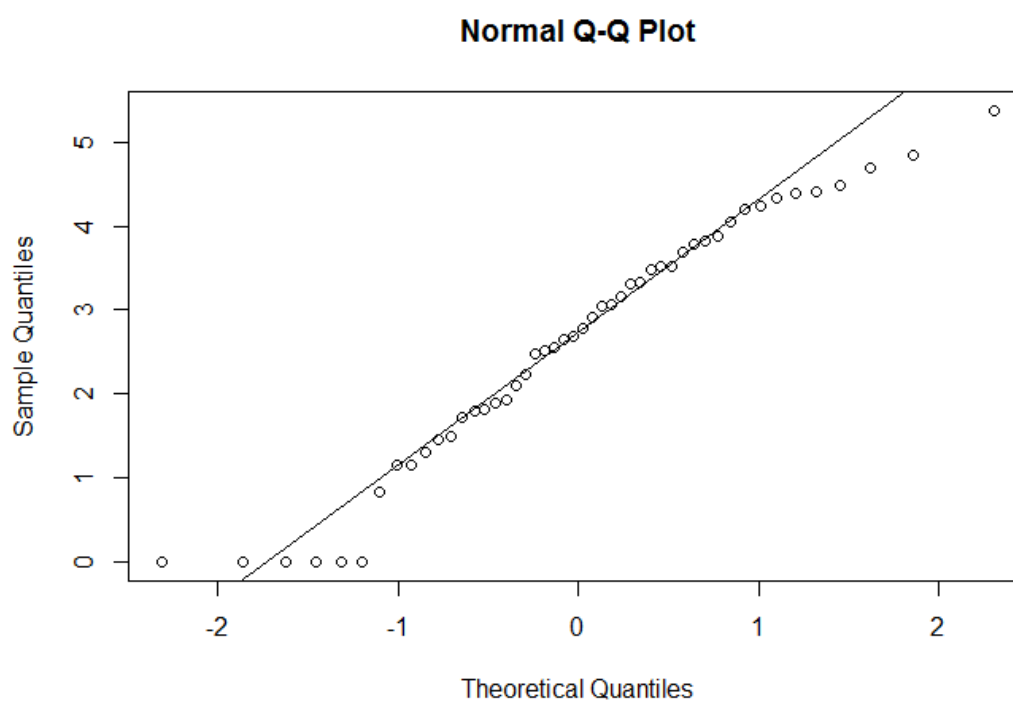


Figure 5.19 Q-Q plot and line of best fit of the residuals of Analysis 10 after a logarithmic transformation.

Table 5.23 Results of testing the assumptions of an ANOVA (Analysis 10 after a logarithmic transformation).

| Assumption  | W-value | Df | F-value | P-value |
|-------------|---------|----|---------|---------|
| Normality   | 0.96    | -  | -       | 0.07    |
| Homogeneity | -       | 7  | 0.87    | 0.54    |

After verifying that the assumptions of an ANOVA were met after a logarithmic transformation of the data, a one-way ANOVA test was conducted on these two variables. The results of this test (Table 5.24) showed that the two variables were significantly related ( $F_{7,40}=8.80$ ,  $p<0.01$ ) signifying that there were at least two weapons which exhibited significantly different means of this feature.

*Table 5.24 Analysis 10 one-way ANOVA results.*

|                  | <i>Df</i> | <i>Sum Sq</i> | <i>Mean Sq</i> | <i>F value</i> | <i>P value</i> |
|------------------|-----------|---------------|----------------|----------------|----------------|
| <i>Values</i>    | 7         | 62.39         | 8.90           | 8.80           | <0.01          |
| <i>Residuals</i> | 40        | 40.52         | 1.01           | -              | -              |

A Tukey post hoc test was then conducted to distinguish which of the weapons had means which significantly differed. Seven weapon pairings were found to have significantly different means of the minimum fracture length on the external table of the entrance defect: recurve bow and field-tipped crossbow bolts ( $p<0.01$ ), recurve bow and fixed broadhead-tipped crossbow bolts ( $p<0.01$ ), recurve bow and mechanical broadhead-tipped crossbow bolts ( $p<0.01$ ), recurve bow and handgun ( $p<0.01$ ), shotgun and handgun ( $p<0.01$ ), rifle and recurve bow ( $p<0.01$ ), and shotgun and rifle ( $p<0.01$ ).

#### 5.2.11. Analysis 11: Diameter of the Entrance Defect After Reconstruction

This test compared the means of the diameter of the entrance defect after reconstructing using dislodged fragments between each of the eight weapons examined in the subsection of this study which excluded exit defect features.

In testing the assumptions for an ANOVA test, it was found that the residuals were not normally distributed and did not exhibit homoscedasticity (Table 5.25) (Figure 5.20). A logarithmic transformation was attempted in order to transform the data to better fit a normal distribution, but the residuals in this data maintained heteroscedasticity and were still found to not have a normal distribution (Table 5.26) (Figure 5.21).

*Table 5.25 Results of testing the assumptions of an ANOVA (Analysis 11).*

| <i>Assumption</i>  | <i>W-value</i> | <i>Df</i> | <i>F-value</i> | <i>P-value</i> |
|--------------------|----------------|-----------|----------------|----------------|
| <i>Normality</i>   | 0.59           | -         | -              | <0.01          |
| <i>Homogeneity</i> | -              | 7         | 1.36           | 0.25           |

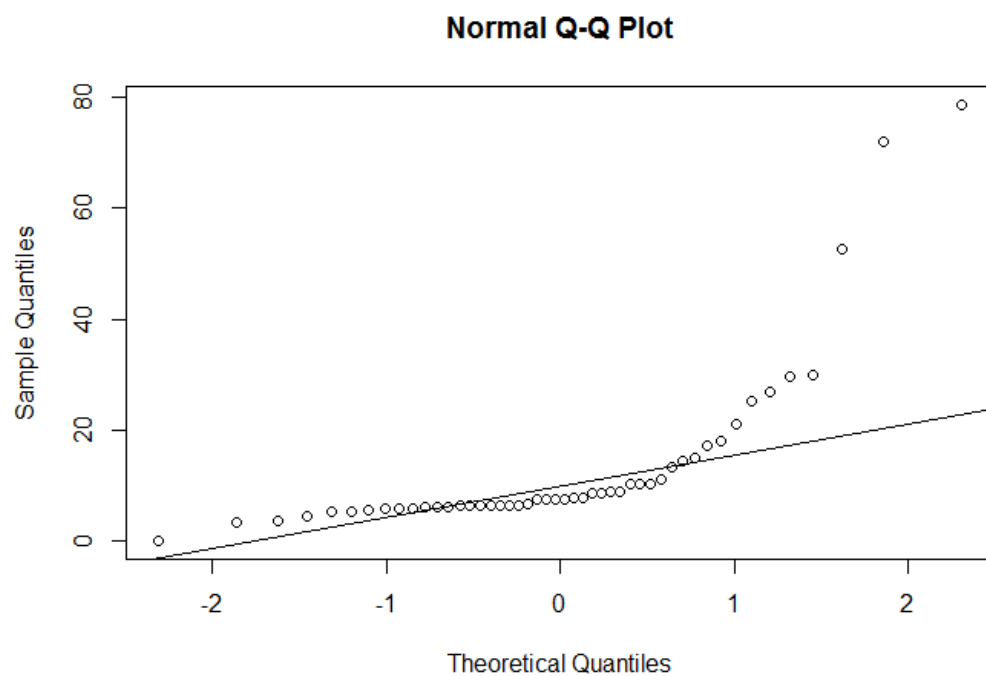


*Figure 5.20 Q-Q plot and line of best fit of the residuals of Analysis 11.*



Table 5.26 Results of testing the assumptions of an ANOVA (Analysis 11 after a logarithmic transformation).

| Assumption  | W-value | Df | F-value | P-value |
|-------------|---------|----|---------|---------|
| Normality   | 0.88    | -  | -       | <0.01   |
| Homogeneity | -       | 7  | 2.27    | 0.05    |

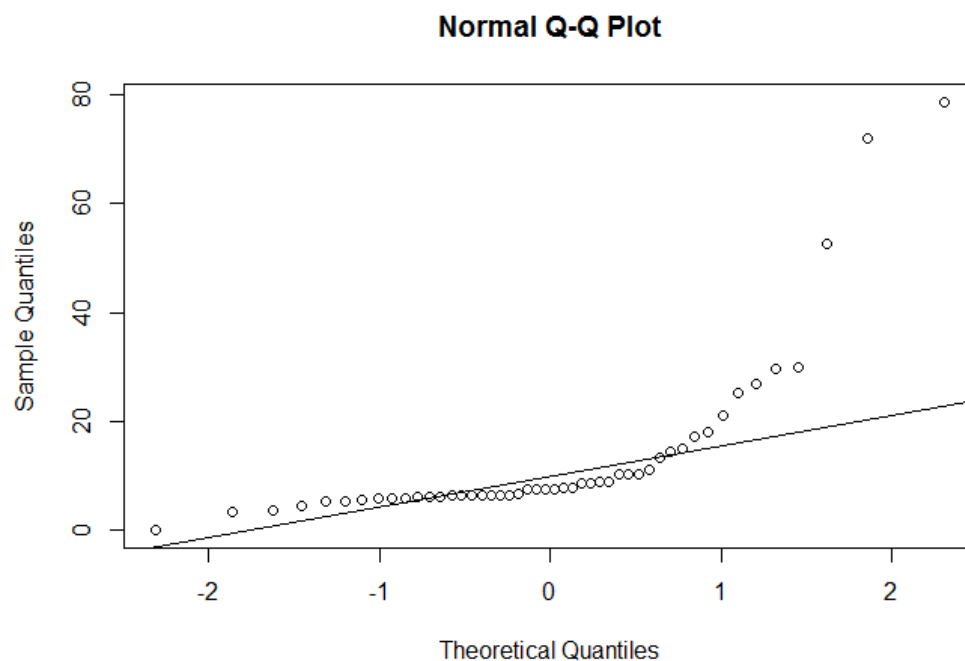


Figure 5.21 Q-Q plot and line of best fit of the residuals of Analysis 11 after a logarithmic transformation.

As the data did not meet the assumptions of a one-way ANOVA, a Kruskal-Wallis test was conducted on these two variables. The results of this test showed that the two variables were significantly related ( $H(4)=15.64$ ,  $p=0.03$ ) signifying that there were at least two weapons which exhibited significantly different means of this feature.

Because the data is non-parametric, a Dunn post hoc test was conducted to distinguish which of the weapons had means which significantly differed. It was found that one pair of weapons produced significantly different entrance defect diameters after reconstruction. Samples which were shot with the compound bow differed from samples shot with the rifle ( $p=0.01$ ).

### 5.3. Linear Discriminant Analysis

Linear discriminant analysis was then conducted on each principal component analysis as a means of machine learning. In training the program to predict the weapon of origin based on the most influential features found through the principal component analyses, weapon of origin could be predicted for future samples of projectile trauma where the weapon of origin is unknown.

#### 5.3.1. Exit Included

Within samples where an exit defect was present, the weapon of origin was correctly predicted for 23 (74.19%) of the 31 samples and incorrectly predicted for eight (25.82%) samples (Figure 5.22). The rifle and field tip crossbow samples were the most consistently accurate predictions: weapon of origin was correctly predicted for all ten samples. The handgun samples contained the most samples in which the weapon of origin was incorrectly predicted: four samples (36.36%; 4/11) were incorrectly predicted. These incorrect predictions were inconsistent with each other: one was predicted to be rifle, one was predicted to be field tip crossbow, one was predicted to be fixed broadhead crossbow, and one was predicted to be mechanical broadhead crossbow.

The mechanical broadhead samples were consistently inconsistent: three samples (60.00%; 3/5) were correctly predicted, but two (40.00%; 2/5) were

incorrectly predicted as fixed broadhead samples. Similarly, three of the five fixed broadhead samples (60.00%) were correctly predicted. Of the incorrectly predicted weapons of origin, however, one sample (20.00%) was predicted to be mechanical broadhead while the other incorrectly predicted sample was predicted to be handgun.

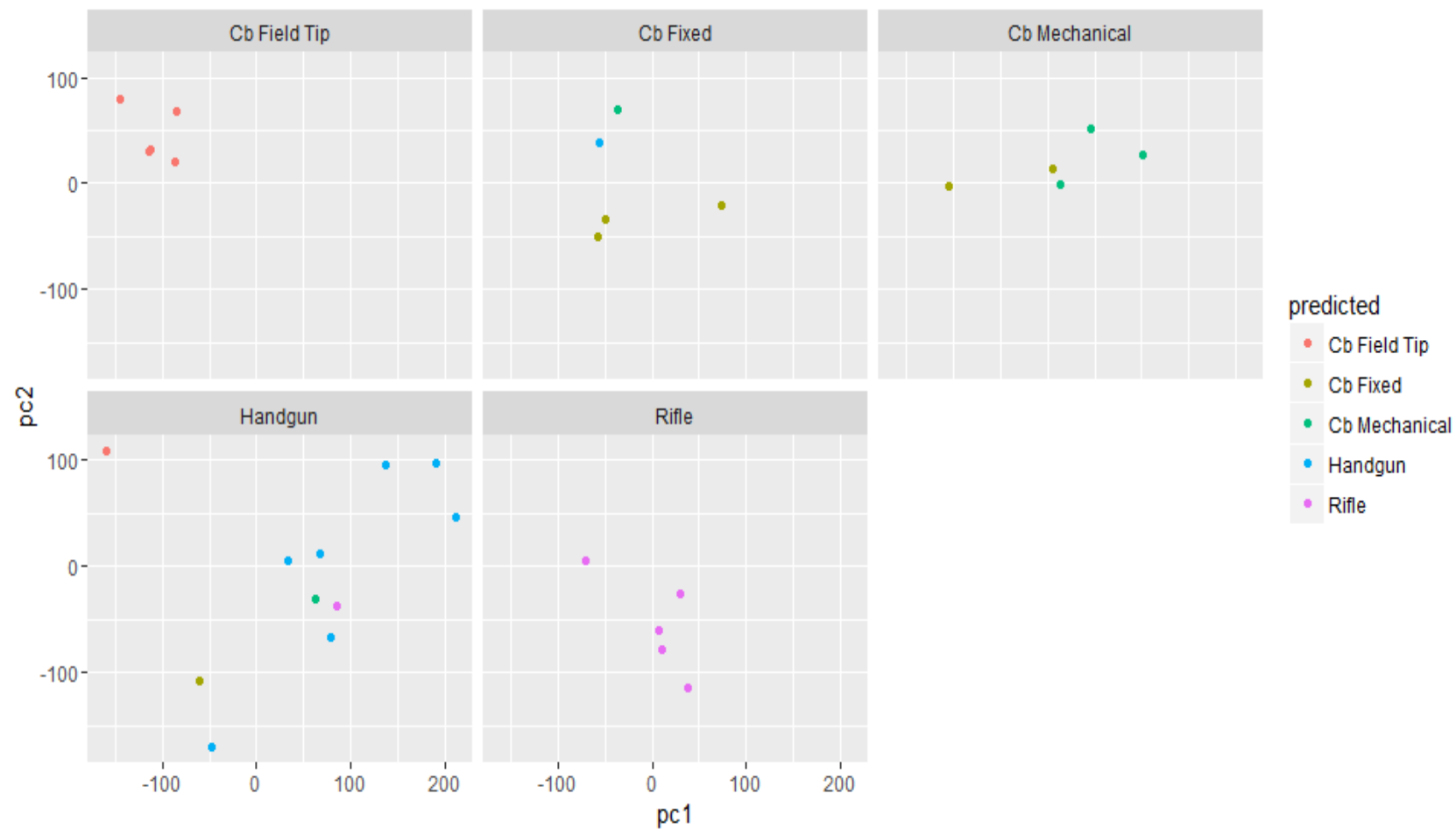


Figure 5.22. Linear discriminant analysis plot comparing the computer-predicted weapon of origin (colour) to true weapon of origin (grids) for samples with an exit site.

### 5.3.2. Exit Excluded

When the features of the exit defect were not included, the program was able to correctly predict the weapon of origin for 28 (60.87%) of the 46 samples (Figure 5.23). Of all the weapons examined in this study, the recurve bow was the only weapon which was predicted correctly in 100% of the recurve samples. Following this, the rifle and field tip crossbow were the next most correct, where four of each five rifle and crossbow samples (80.00%) were correctly predicted. The one rifle sample (20.00%) which was incorrectly predicted was predicted as fixed broadhead crossbow. The one field tip crossbow sample (20.00%) which was incorrectly predicted was predicted as recurve bow. The handgun samples were also consistently predicted correctly, with nine (81.82%; 9/11) samples being correctly predicted as handgun. One of the incorrectly predicted handgun samples (9.09%) was predicted as recurve bow while the other was predicted as rifle.

The compound bow, fixed broadhead crossbow, mechanical broadhead crossbow, and shotgun samples, however, were not as consistent as the previously discussed weapons. The predictions for the shotgun samples were the most inconsistent, with only one sample (20.00%; 1/5) being correctly predicted as shotgun while each of the other samples was predicted as other weapons (field tip crossbow, fixed broadhead crossbow, compound bow, and recurve bow).

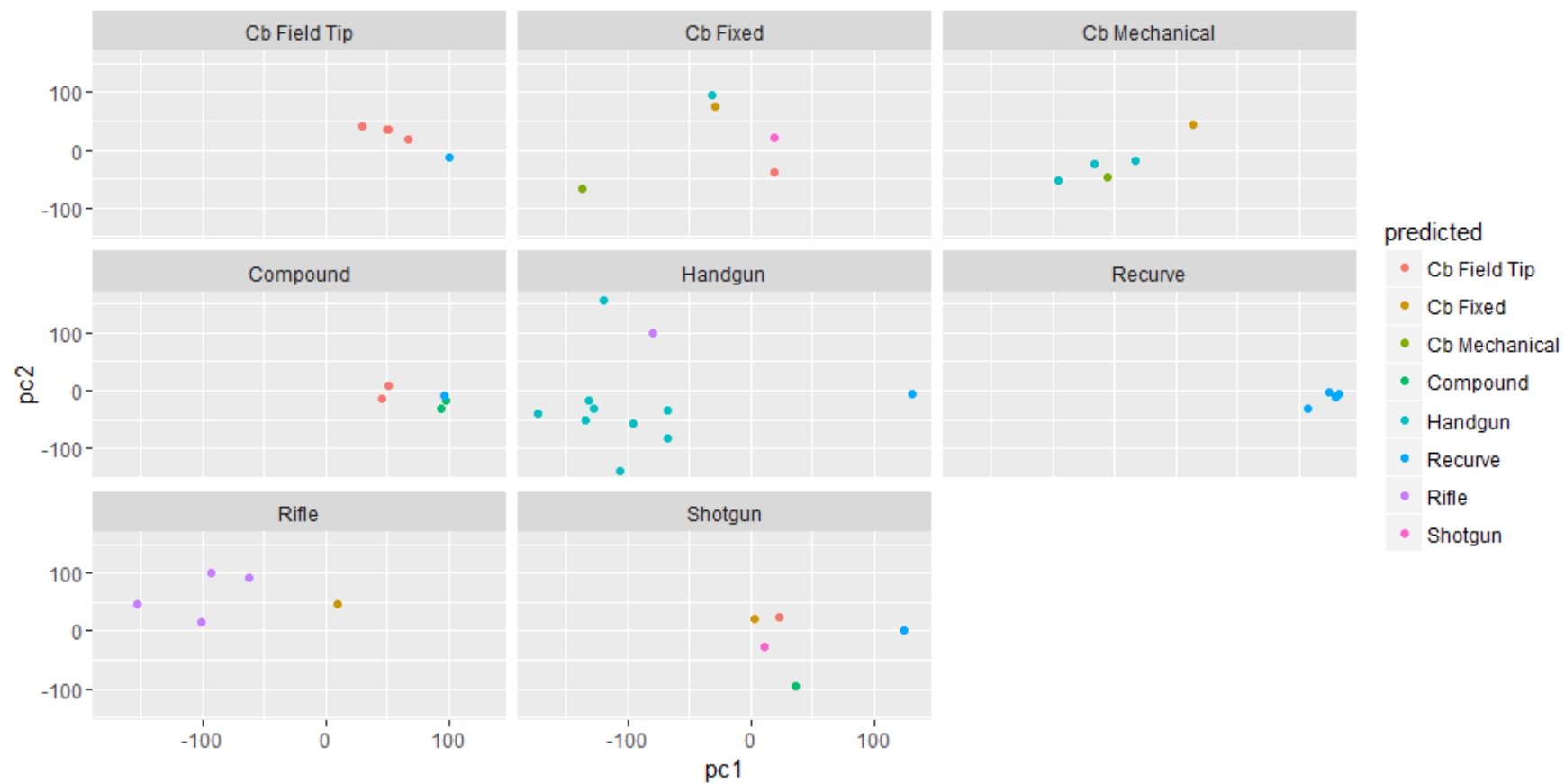


Figure 5.23 Linear discriminant analysis plot comparing the computer-predicted weapon of origin (colour) to true weapon of origin (grids) (excluding exit site features).

The findings described in this chapter show that the features of cranial trauma observed in the current study can be used to successfully identify the projectile weapon which was used. The most distinguishing features, however, were found to be quantitative features which are not currently used as a part of weapon identification methods. These observations and their implications will be discussed in the following chapter.

## 6. Discussion

The analysis and interpretation of perimortem trauma is an essential component of the forensic anthropologist's examination of skeletal remains for the purpose of determining the circumstances around the death of an individual. Although the currently existing methods of trauma identification are consistent with differentiating projectile trauma from sharp and blunt force trauma, they are not reliable when trying to distinguish which class of projectile weapon created the observed trauma. Many examiners will automatically assume projectile trauma to be caused by a form of firearm, yet there are many projectile weapons, such as archery weapons, which do not fall into the category of "firearm." This overgeneralisation of terminology restricts the ability to adequately assess the trauma and, therefore, blurs the details of the perimortem period.

As previously discussed, qualitative methods for examining projectile trauma have been utilised exclusively over the years with minor expansions, primarily examining keyhole defects (Berryman and Gunther, 2000; Nayak *et al.*, 2010; Delannoy *et al.*, 2016), but most of the recent literature regarding projectile trauma has consisted of case reports (Prahlow and McClain, 1997; Prahlow *et al.*, 2003; Viel *et al.*, 2009) or examination of postcranial trauma (Langley, 2007; Fragkouli *et al.*, 2018). Some studies have tested the accuracy of synthetic bone material and its applicability in experimental studies (Smith *et al.* 2015; Appleby-Thomas *et al.*, 2017; Henwood and Appleby-Thomas, 2020; Pullen *et al.*, 2021). These studies, however, have focused on comparing results obtained using synthetic bone with real life cases of cranial projectile trauma using the methods of trauma analysis which have been used for the past three decades and have not developed new methods of weapon identification.

While qualitative features, such as the presence of radiating fractures and bevelling (Smith *et al.* 1987; Berryman and Haun, 1996; Berryman and



Symes, 1999; Smith *et al.* 2001), have typically been used to identify cases of cranial projectile trauma, these features were found to be present on nearly all of the samples regardless of which weapon caused the trauma. Yet there has been practically no examination of quantitative features of projectile trauma, such as number of fragments and fracture lengths. One study (Smith *et al.*, 2015) had touched upon a single quantitative feature (defect dimension), but did not extensively examine all quantitative features of projectile trauma. This lack of research neglects possible avenues of measurable features which can be used for weapon identification. This is problematic as accurate weapon identification can be a key part of a forensic investigation or in understanding the interpersonal violence patterns of archaeological cultures.

A key driving factor in the differences observed between these weapons is the kinetic energy produced by each projectile (described in Section 2.2.3.). Table 2.1 explains the calculations of the kinetic energy of each weapon with the projectiles used in this study. The velocity of each projectile is based on product specifications.

The examination of the entrance defects of all samples featured two sets of variables, qualitative and quantitative, which will be discussed separately.

## 6.1. Qualitative Features

This section explains the characteristic features of projectile trauma as they were observed in the dataset of this study. Features of the entrance and exit defect will be examined separately.

### 6.1.1. Entrance Defect Features

Of the regularly observed characteristics of projectile trauma, concentric heaving fractures were the only feature to not be present in at least one

sample of each of the examined weapons. The presence of tertiary fractures varied significantly with the only uniformity in its absence from the recurve bow, compound bow, and shotgun samples. All other weapons showed some samples where concentric heaving fractures were present and some where concentric heaving fractures were absent. This absence is to be expected as tertiary fractures only occur if the force of the projectile is great enough to expand beyond the secondary (radiating) fractures (Smith *et al.*, 1987; Bird and Fleischman, 2015; Symes *et al.*, 2019) while the two hand bows and shotgun were the weapons with the least amount of energy which transferred to the bone. In the samples where concentric heaving fractures were present, however, it indicated that each of these weapons, which includes archery weapons such as crossbow with all of the three tips, was capable of producing enough force to create not only secondary fractures, but also the tertiary fractures.

Similarly, the primary defect was an initial indication of the level of energy for each weapon. The recurve bow and shotgun were the only two weapons which failed to produce a complete entry point in all respective samples. In all but one of the recurve samples, the arrow did not have enough energy to break through both the external and internal table, only causing damage to the external table and the diploe layer. One sample (RcFt 4b), however, did have a complete entrance, showing that a recurve bow is capable of generating enough energy to break through both tables of the cranial vault, it just is not as likely as other projectile weapons. The shotgun, on the other hand, produced complete entrance defects in all but one of the samples (Sh 2). Even within the samples which did have a complete entrance, there was a high level of variance in the diameter of the defect: 5.90-93.10 mm without reconstruction and 5.90-78.70 mm with reconstruction. This is most likely due to the fact that there are multiple projectiles in one shot and the amount of energy can change based on the dispersal of the pellets.

The shapes of the entrance defects, however, were not distinctly indicative of weapon type. Most of the samples had entrance defects that were circular in

shape, with a few irregularly shaped, but three of the weapons did not follow this pattern (crossbow mechanical broadheads, recurve, and shotgun). Most of the samples shot with either the shotgun or the mechanical broadhead bolts (crossbow) had irregularly shaped entrance defects while the recurve samples were more often conical in shape. The irregularity of the shotgun entrance is caused by a combination of multiple projectiles and the spread of the shot. All of the other weapons examined only had one point of impact, which produced one entry point which commonly reflected the shape of the projectile itself. While the individual impact points of the shotgun shot reflected the shape of the pellet, the overall shape of the entry defect reflects the concentration of the pellets. When the shot leaves the barrel of the gun, the pellets start in a circular concentration, but the further from the target the weapon is discharged, the more the shot will spread. In this study, it was most commonly seen that the shot was able to maintain a central concentration after traveling 10 m, but this concentration did not maintain its original circular shape, distorting to an irregular shape.

The entry defects within the samples shot with the mechanical broadhead tips were mostly irregularly shaped, which differed from the entrance shape of the fixed broadhead tips (both crossbow and compound hand bow), which were nearly all circular in shape. The difference between these two tips is that the mechanical tip of the broadhead is designed to expand upon impact with a target while the fixed broadhead consists of immobile blades. This expansion creates a wider area of impact than the immobile blades, potentially resulting in a larger primary fracture. But the larger contact area between the projectile and the target is only one component of the resulting disparity between the entrance shapes of the fixed and mechanical broadheads. A projectile will begin to transfer its energy to the target as it first comes into contact with the target along its flight path. This energy is transferred through any point of contact between the projectile and the target. The movement of the blades on a mechanical broadhead tip at the point of entry produces an altering size and shape of the projectile as it first enters the target. This movement then, in turn, affects the way in which the energy

is transferred to the target and differs from the fixed shape and size of the fixed broadhead tips. The irregularity of this energy transfer explains the tendency for the mechanical broadhead tips to produce an irregular entrance defect instead of the consistent circular defect created by the fixed broadhead tips.

The final qualitative feature regarding the entrance defect is the presence of bevelling. All of the samples which had a complete entrance defect had bevelling present on at least one of the tables of the synthetic bone. While all of these samples had bevelling on the internal table of the entrance defect, some samples had bevelling on both tables. Furthermore, only three of the weapons (rifle, recurve bow, and field tip crossbow) did not have at least one sample which had bevelling on both tables of the entrance defect. In some cases, such as the handgun, compound bow, and shotgun samples, when bevelling was present on both tables of the entrance defect, it was due to a tangential strike (Figure 6.1). In the formation of an entrance keyhole defect, the circular portion is expected to bevel on the internal table while the triangular portion is expected to bevel on the external table. In the case of the shotgun samples, the spread of the pellets was wider than the spheres. This means that even though all samples were shot at a perpendicular angle, some of the pellets will tangentially hit the sides of the spheres and potentially create small keyhole defects.

As previously discussed, the mechanical broadhead tip is designed to expand upon impact with the target. The expansion of the blades could force the bone in a direction which differs from the direction of the flight path of the shaft, such as sideways or even backwards, depending on the position of the blades in relation to the bone. Thus, the direction of the force that is being applied to the bone can alter which of the two tables is under tensile strain and likely to fail. The initial entry of the point of the tip would apply tensile force to the internal table, causing the characteristic internal bevelling of an entrance defect in projectile trauma. But the expansion of the blades could concurrently push the bone outwards, applying tensile force to the external



*Figure 6.1. Sample Hg 4 (9 mm), where bevelling is present on both the external (top) and internal (bottom) table of the entrance defect due to a tangential strike.*

table of the entrance defect. This would cause the external table to fail before the internal table, resulting in bevelling on the external table of the entrance defect. But when the fixed broadhead tips and bullets struck at a perpendicular angle and still produced bevelling on both the external and internal tables, no definitive explanation could be provided. While such cases have been observed in a forensic context (Coe, 1982), it is not known why this phenomenon occurs.

These findings show that the identifying features that have typically been used to assess projectile trauma are consistently found on not only samples shot with firearms, but also samples shot with archery weapons. Though “projectile weapon” has, in a forensic context, become synonymous with “firearm,” archery weapons, both modern and archaeological, are also projectile weapons and produce these qualitative features of trauma through the same mechanisms as firearms.

### 6.1.2. Exit Defect Features

The presence or absence of an exit defect was the most consistent feature (according to weapon) within this dataset: an exit defect was present in all samples except the samples which were shot with a recurve bow, compound bow, or shotgun. These three weapons produced the lowest energy of the examined weapons, allowing the projectile to be halted prior to impacting with the opposite side of the cranial vault. This section will only discuss samples which have an exit defect and the weapons which they were shot with.

All weapons produced both exit defects which were circular in shape and exit defects which were irregularly shaped. Most of the weapons showed no strong tendencies towards one shape or the other. The fixed broadhead tip, however, created mostly circular exits, with one sample which was irregularly shaped. When reconstructed, these circular defects fractured and fragmented in a pattern which reflects the Y-shape of the three-blade configuration. As the tip passed through the bone, the blades guided the

radiating fractures, after which concentric fractures formed (Figure 6.2) between these fractures. This resulted in fragments being dislodged from the sphere, leaving a circular pattern formed by the concentric fractures.

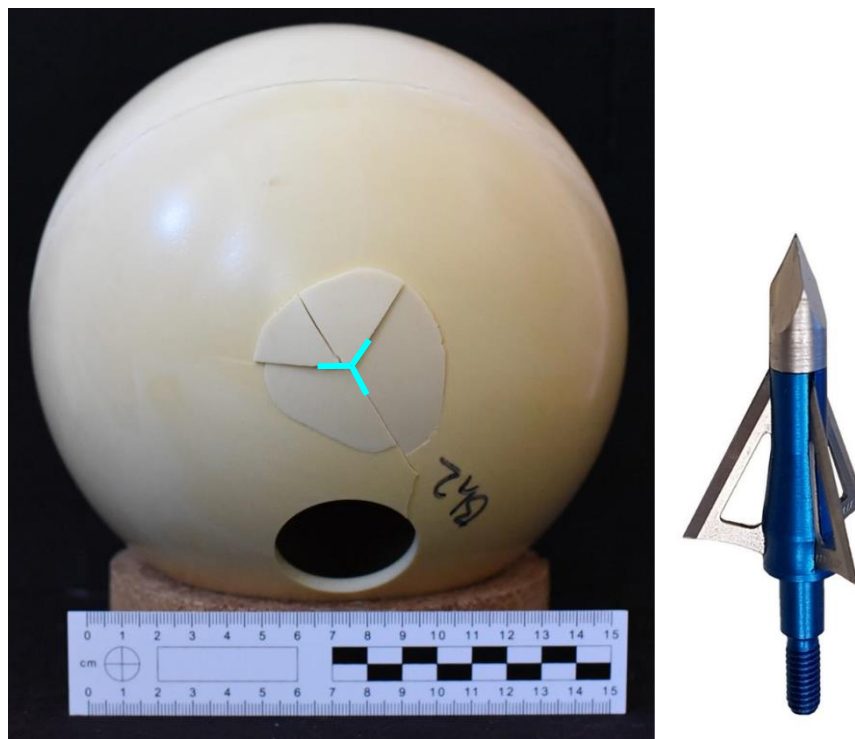


*Figure 6.2. Fractures at the exit site which reflect the Y-shape of the fixed broadhead tip (blue) (Sample CbBh 2). Right: broadhead tip used with the fixed broadhead samples (crossbow).*

The presence and location of bevelling were also not clearly indicative of weapon type. Almost all samples had bevelling present on at least one table of the exit defect, but the rifle and crossbow (with fixed broadhead tips) each produced one sample where no bevelling was present. These instances are attributed to normal variation, as bevelling is not always present at the entrance and/or exit defects in cases of projectile trauma (Quatrehomme and İşcan 1997b; Humphrey *et al.*, 2017). The exit defects which did have bevelling all showed this on the external table, following the commonly observed pattern of bevelling in projectile trauma.

Following the primary defect of the exit defect, all weapons exhibited at least one sample with both secondary and tertiary fractures. This shows that weapons which produce enough energy to travel through at least the entire width of the skull-brain model are able to produce enough energy to still

cause tertiary fractures after having travelled through the gelatine. As the gelatine (or brain material) is much denser than open air, more energy needs to be spent to continue along its flight path. Because of this, there is significantly less energy transfer in the formation of the exit defect than there is at the entrance defect.

Generally speaking, the qualitative features (between all relevant weapons) observed at the exit defects were more consistent than the entrance defects. This consistency of observations between the weapons indicates that these features are not reliable when attempting to differentiate trauma caused by different projectile weapons.

## 6.2. Quantitative Features – Statistical Findings

Thus far, only features which are commonly used in projectile trauma analysis, solely qualitative features, have been discussed. Each of these features can be present as long as the impact mechanism is the same and there is enough energy. But once a projectile has passed this threshold of “enough” energy, the current analytical methods do not provide useful insights into distinguishing different types of projectile weapons. By examining quantitative features, however, features of projectile trauma can be measured on a spectrum and without limitation rather than a binary of “present” or “absent.” Because of this, quantitative analysis is better able to take different types of projectile weapons into consideration when attempting weapon identification.

The current study employed two subsets of features, entrance features and the combination of entrance and exit features, to better distinguish different weapons. Each will be discussed separately.



### 6.2.1. Exit Excluded

As discussed in the previous chapter, the most relevant entrance features for differentiating weapon of origin were found to be (in descending order): the maximum fracture length on the external table, the width of the entrance defect (without reconstruction), the minimum fracture length on the external table, and the width of the reconstructed entrance defect. It is important to note that no qualitative features of the entrance defect were found to be effective in distinguishing the weapon of origin.

When examining the measurements, it is clear that the maximum fracture length on the external table of the entrance defect is more widely and evenly dispersed between weapons than the distribution of the other examined features. This is reflected in the principal component analysis, which shows that this feature accounts for the largest level of variation (62.83%) amongst the examined features of the entrance defect. The Kruskal-Wallis analysis further supports the significance of the relationship between these two variables ( $p < 0.01$ ).

The distribution of the longest fracture lengths (Figure 6.3) mostly shows a direct relation with the amount of energy behind each projectile: as the initial energy increases, the maximum fracture length on the external table of the entrance defect increases. The two exceptions to this were the rifle and field tip crossbow samples. Though the initial energy of the .22 bullet is lower than most of the other projectiles, it expends much less of this energy in the continued travel due to its low mass (Table 2.1). Though the crossbow bolts, for example, have approximately 22.00-27.00% more initial energy than the .22 bullets, their individual masses are more than ten times greater. Because of this, more energy must be expended to maintain the propulsion of the bolt along the flight path.

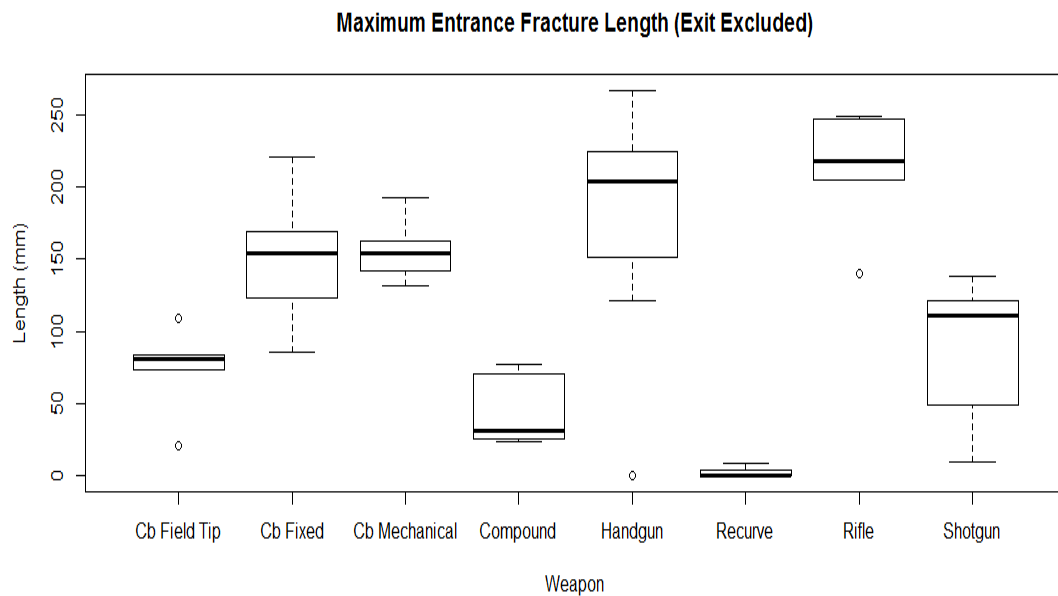


Figure 6.3. Boxplot of the maximum fracture lengths along the external table of the entrance defect. (crossbow field tip, fixed broadhead, mechanical broadhead, compound bow, rifle, and shotgun:  $n=5$ ; handgun:  $n=11$ ; recurve bow:  $n=7$ .)

The field tip crossbow bolt samples only slightly deviate from the direct relation between kinetic energy and maximum fracture lengths. All three crossbow bolts are most closely related to each other's initial energy, with the fixed broadhead having 4.36 J (1.96%) more than the field tip and the mechanical broadhead having 9.23 J (4.07%) more than the fixed broadhead. But the maximum fracture lengths of the field tip bolt samples were generally shorter than or equal to samples produced by the fixed broadhead bolts. This could be caused by the blade configuration of the broadhead tip: as the blades drive into the bone, they create a wedge, breaking apart the bone and weakening it at these points. It is then more likely that more energy which is transferred from the projectile to the bone will travel at these points, along the path of least resistance.

The results of the Dunn test further exemplified both how the amount of a projectile's kinetic energy affects the lengths of the fractures and how the mass of a projectile influences its terminal kinetic energy. Of the five weapon pairs with significantly different means, three of the pairs consisted of the lowest energy projectile (recurve bow) being significantly different from the

three highest energy weapons (handgun, mechanical broadhead-tipped crossbow bolts, and fixed broadhead-tipped crossbow bolts). The remaining two pairs consisted of the second lowest energy projectile (rifle) being significantly different from the lowest (recurve bow) and third lowest energy projectiles (compound bow). As previously discussed, while the .22 bullet shot with the rifle had less initial kinetic energy than the compound bow, the .22 bullet spent less energy on continued travel due to its lower mass. This resulted in more energy being transferred to the target upon impact, producing significantly longer fractures than the compound bow.

Even with these two exceptions to the general pattern of this feature, the relationship between the energy of the projectile and the length of the longest fractures at the entrance defect is clear enough to be able to identify a degree of clustering within the data. Though this relationship is noticeable in the dataset, observing maximum fracture length alone was not distinct enough to distinguish all weapons of origin from each other, accounting for slightly more than the majority of the variation (62.83%).

The widest point of the entrance defect opening prior to reconstruction was not nearly as indicative of weapon of origin as the maximum fracture length on the external table of the entrance defect, accounting for 21.33% of the variation within the samples when only examining features of the entrance defect. The Kruskal-Wallis analysis further supports the significance of the relationship between these two variables ( $p < 0.01$ ).

The diameter of the entrance defect prior to reconstruction is, in its essence, a summary of the combination of fracture and dislodged fragment features. The number of fractures in a single sample can be directly related to the number of dislodged fragments as fragments will not be produced without the formation of fractures. That is not to say that a high number of fractures will always produce fragments, but the number of fragments cannot be high if the number of fractures is low.

Unlike the reconstructed entrance defect, the diameter of the defect prior to reconstruction is a more conclusive reflection of the trauma caused by the projectile. When observing the diameter of the reconstructed entrance defect, the reconstruction of the entrance defect is dependent on the examiner(s) ability to locate dislodged fragments. The fraction of the total dislodged fragments which are recovered is a variable which can be influenced by many external factors, such as the terrain of the remains, post-mortem interval, or if the remains had been moved. If not all fragments are recovered, however, the diameter of the reconstructed defect reflects not only the size of the primary fracture, but also the size of any missing fragments. Examining the diameter of the entrance defect prior to reconstruction is a more directly related feature of the trauma caused by the projectile without the risk of observer error. As such, the measurements of this feature in this study were found to be more indicative of the weapon of origin than the width of the reconstructed entrance defect.

The results of the Dunn test conducted on these two variables further exemplified this concept. Of the three weapon pairs in which the entrance diameters significantly differed from each other, all three pairs included one of the two weapons in which none of the samples required reconstruction of the entrance defect (rifle and recurve bow) (see Section 5.2.9.). As these entrance defects did not require reconstruction, the openings were reflective of the external diameter of the projectiles themselves. These means significantly differed from the means of the two projectiles with the highest initial kinetic energy (handgun and mechanical broadhead-tipped crossbow bolts), which produced openings which were significantly larger than the external diameters of the projectiles.

Following both the maximum fracture length and the width of the entrance defect prior to reconstruction, the minimum fracture length on the external table of the entrance defect is the next most indicative feature, yet it only accounts for 7.68% of the data's variation. The one-way ANOVA test further

supports the significance of the relationship between these two variables ( $p < 0.01$ ).

While there is a good amount of overlap amongst the minimum fracture lengths which were caused by different weapons, there are some weapons which do stand out from the rest. The shotgun samples, for instance, consistently had fractures which were 3.50 mm in length or less. This is noticeably lower than other weapons' samples, such as the rifle samples, where the mean minimum fracture length was 56.74 mm. The small fractures created by the shotgun are a result of the shot load itself. The load propelled forward by the shotgun is not one singular projectile, but many smaller projectiles forced forward together. When the load does strike the target, the pellets have spread and will not all strike at the same location. Because each pellet has significantly less mass than the collective load, the energy transferred by a single pellet at each point of impact is less than a single projectile with a mass equal to the collective load. With less energy transferred to the bone, the bone is less likely to fail. When it does fail, the transferred energy is spent after the fracture travels a short distance.

Beyond simply the comparatively small fractures, the spread of the minimum fracture length per sample is very narrow (1.30-3.50 mm) (Figure 6.4). The precision of these measurements reflects a consistent pattern of the range which could be expected for future instances of shotgun trauma of the same gauge. Both the recurve bow and compound bow also showed a similar precision within their measurements, though not as precise as the shotgun samples. Not all of the recurve bow samples had fractures to begin with, but the minimum fracture length for those that did have fractures had a spread of 2.70-7.20 mm with a mean of 5.00 mm. The compound bow, however, was slightly less precise when compared to the recurve bow and shotgun, but still had a very narrow range of 4.60-20.40 mm with a mean of 11.10 mm.

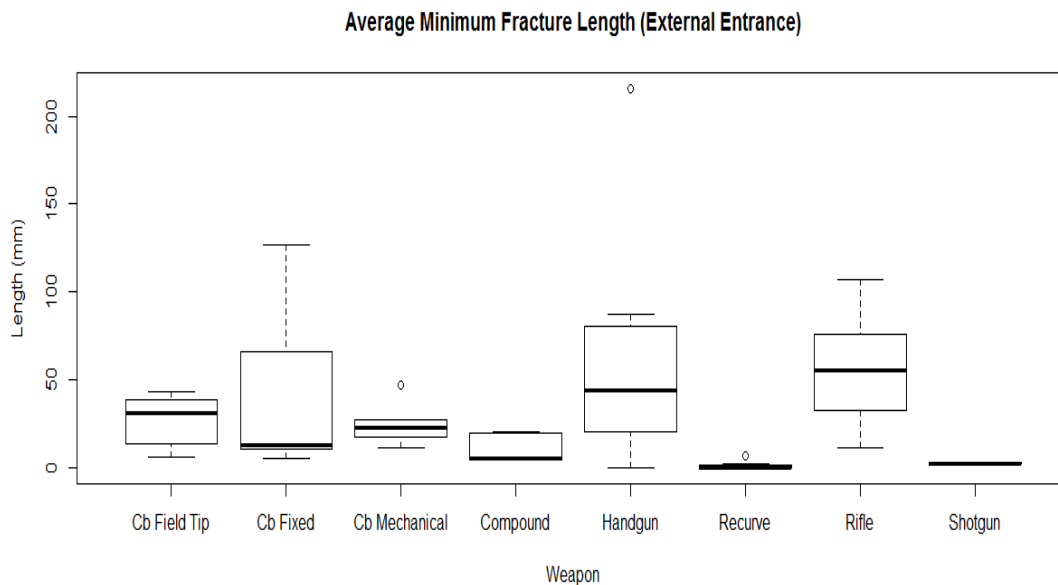


Figure 6.4. Boxplot of the minimum fracture lengths along the external table of the entrance site. (crossbow field tip, fixed broadhead, mechanical broadhead, compound bow, rifle, and shotgun:  $n=5$ ; handgun:  $n=11$ ; recurve bow:  $n=7$ ).

The concise ranges of both the shotgun and recurve bow minimum fracture lengths contribute to the significant differences when compared to the other weapons of this study. The results of the Tukey post hoc test show that of the six weapon pairs with significantly different means, all six include either the shotgun or the recurve bow (see Section 5.2.10.).

While the other weapons exhibited a much larger spread of measurements, there are three which stand out based on the length of the minimum fractures: rifle, fixed broadhead crossbow bolts, and handgun. Of these three weapons, the rifle produced the most evenly distributed spread of measurements, with a median of 55.60 mm and a total range of 33.00-107.30 mm. These are noticeably longer than the minimum fractures of many of the other weapons, even though the .22 bullet has the lowest amount of initial energy (183.50 J).

When compared against the weapon with the highest amount of initial energy (handgun; 493.35 J), the minimum fracture lengths produced by the .22 bullets are either equal or even greater than the minimum fracture lengths produced by the handguns, even though the 9 mm bullets had two to three

times the amount of energy. The handgun samples, however, typically exhibited a higher number of fractures at the entrance defect than the rifle samples did. After a fracture is produced as a result of an energy transfer, the overload of energy will continue to travel at the point(s) where the bone has already failed, elongating the fracture. If there are more points in which the bone has failed, the energy has more pathways and can distribute amongst all fractures. Where there are less fail points, the energy transferred to the bone will still travel along the path(s) of least resistance, elongating the fractures more than they would have if there had been more fractures.

The fixed broadhead bolt samples, however, do not have more fractures along the external table of the entrance defect than the rifle samples do. When considering the size of both the .22 bullet and the crossbow bolt, specifically their length, it is clear that the bolt is much longer than the bullet, 508 mm and approximately 13 mm respectively. Each projectile will use more energy to pass through bone than it would for the internal soft tissue. As the tip of the crossbow bolt passes through soft tissue, more of its energy is being transformed into heat through the friction created by the shaft passing through the bone. With more energy being transformed into heat, less energy would be transferred to the bone, resulting in shorter fractures.

Finally, the widest point of the entrance defect opening after reconstruction accounted for a relatively small proportion of the variation (4.05%) within the samples when only examining features of the entrance defect. While this feature only accounts for less than a tenth of the variation that the maximum fracture length accounted for, it is still a key component in weapon identification when measured in tandem with the three previously discussed features. Measuring all four of these features together accounts for 95.89% of the variation within the current data, with statistical significance being achieved at accounting for 95.00% of the variation. The Kruskal-Wallis test further supports the moderate significance of the relationship between these two variables ( $p=0.03$ ).

Most of the entrance defects of the samples could be almost completely reconstructed, with only the primary fracture remaining open. In these cases, the width of the defect after reconstruction would approximately reflect (typically within 5 mm) the diameter of the projectile itself. It is, however, worth noting that some samples, mainly within the handgun and rifle samples, exhibited primary fractures which were smaller than the actual projectile. This is due to the fact that these bullets are made of relatively soft metals (lead and copper) which are prone to shape deformation or even fragmentation, causing the diameter of the bullet to decrease upon impact. The other projectiles in this study, however, are made of materials (such as aluminium, platinum, and fiberglass) which are all stronger than copper and lead by weight. This gives these projectiles a rigidity which the handgun and rifle bullets do not have, decreasing the chances that the projectile will deform in shape or size upon impact. That is to say that primary fractures created by bullets can be smaller than the diameter of the projectile, but primary defects created by arrows or bolts are not likely to be smaller than the diameter of the shaft of the projectile.

The initial diameters of each of the projectiles do differ between weapons, but not greatly. With the diameters of these projectiles ranging from 5.50 mm to 9.70 mm, there is only so much room for size variation. Clusters of entrance defects which reflect the diameter of the projectile of origin are vaguely observable (with the smallest defects originating from the .22 bullets and field tip arrows and the largest originating from the crossbow bolts and 9 mm bullets), but there is indistinguishable overlap between some of the projectiles, such as the crossbow bolt and the 9 mm handgun bullets.

For samples in which the reconstructed defect did not reflect the diameter of the projectile, it was typically the dislodged fragments which influenced the width of the defect. Dislodged fragments were collected after each sample was shot, but this only reflects a minimum number of dislodged fragments. There are some samples in which not all fragments could be located, mainly due to the height of the grass at both outdoor facilities, which leaves the



reconstruction of the entrance defect only partially complete. The width of the opening would then reflect not only the primary fracture, but also the size of the missing fragment(s). As such, the inconsistent distribution of these measurements is purely a result of the limitations of the facilities' terrains.

This limitation was apparent in the results of the Dunn post hoc test. The only two weapons which significantly differed from each other were the rifle and the compound bow ( $p=0.01$ ). The compound bow produced the most samples in which the entrance defects could not be reconstructed due to lost fragments and therefore did not reflect the external diameter of the shaft of the arrow (80.00%; 4/5) while the entrance defects of the rifle samples could not be reconstructed because none of the samples had fragments which affected the size of the primary defect. The other weapons mostly exhibited diameters which reflected the external diameters of the respective projectiles, which were more consistently comparable to the external diameter of the .22 bullets.

#### 6.2.2. Exit Included

As discussed in Section 5.1.1., the most relevant features for differentiating weapon of origin (when an exit is present) were found to be (in descending order): the maximum fracture length on the external table of the entrance defect, the minimum fracture length on the external table of the entrance defect, the width of the entrance defect (without reconstruction), the minimum entrance fragment length, the width of the reconstructed exit defect, the maximum fracture length on the external table of the exit defect, and the width of the reconstructed entrance defect. It is important to note that no qualitative features (of either the entrance or exit defect) were found to be effective in distinguishing the weapon of origin.

All four of the features which were found to be the most relevant in identifying weapon of origin when the exit defect was excluded were also amongst the

seven most distinguishing features when the exit defect was included, but accounted for different levels of variation within the dataset.

The maximum fracture length on the external table of the entrance defect still accounted for the largest level of the variation, but here it only accounted for 42.95% of the variation (compared to 62.33% when the exit was excluded). The one-way ANOVA conducted further confirmed the significance of the relationship between these two variables ( $p < 0.01$ ). As discussed in Section 6.2.1., the results of the Tukey post hoc test show that the relatively low-energy field-tipped crossbow bolts produced significantly different maximum fracture lengths from both the high-energy handgun ( $p = 0.01$ ) and rifle ( $p < 0.01$ ). Though the rifle had a lower initial kinetic energy than the field-tipped crossbow bolts, the low mass of the .22 bullet minimised the amount of energy spent on travel and resulted in more energy transfer upon impact.

Following this, the minimum fracture length on the external table of the entrance defect was found to be the second most distinguishing feature, accounting for 21.41% of the variation in this dataset, while the width of the entrance defect prior to reconstruction was the third most distinguishing feature, accounting for 14.52% of the variation. This is the opposite hierarchy between these two features as was seen in the subset where the exit features were excluded. This is most likely due to the fact that in examining both the entrance and exit defects, some weapons (recurve bow, compound bow, and shotgun) were removed as they were not able to produce an exit defect. The recurve and compound bows were both distinct clusters in entrance width diameter. Where many samples were able to produce an entrance defect which reflected the diameter of the projectile through reconstruction, the recurve and compound bows produced samples which either reflected or were not much larger than the diameter of the arrows' shafts without reconstruction. This was able to distinguish these samples as they were much smaller than samples which required reconstruction.

The removal of the recurve and compound bow samples would have also decreased the levels of variation when examining the entrance defect

diameters prior to reconstruction. Because of this, the proportion of variation which this feature accounts for is lower when these weapons are excluded. The results of the one-way ANOVA between weapon and minimum fracture length at the entrance defect, however, implies that the two variables do not exhibit significantly different means between weapon groups ( $p=0.83$ ). This could be a result of the small sample size of this study and further studies to increase the number of samples is recommended.

The Kruskal-Wallis test conducted between weapon and the diameter of the entrance defect prior to reconstruction, however, implies that there is a strongly significant relationship ( $p<0.01$ ) between these two variables. The Dunn post hoc test exhibits a significant difference in two pairs of weapons: rifle and mechanical broadhead-tipped crossbow bolts ( $p<0.01$ ) and rifle and handgun ( $p<0.01$ ). As none of the rifle samples required reconstruction of the entrance defects, the diameters of the entry openings would be significantly smaller than the defect sizes produced by the handgun and mechanical broadhead-tipped crossbow bolts, the two weapons with the highest amounts of initial kinetic energy.

Finally, the width of the entrance defect following reconstruction was found to be the seventh most distinguishing feature of weapon identification. This measurement did not account for a large portion of the variance, only 1.77%, even less than it did in the subset where the exit features were excluded. While this may be only a small fraction of the total variance in the data, the other six variables found to be more useful and accounted for 94.97% of the variance, just below statistical significance. When all seven of these variables are examined together, 96.74% of the variance in the dataset is accounted for. Additionally, the results of the Kruskal-Wallis test implied a slightly significant relationship ( $p=0.04$ ) between these two variables. The Dunn post hoc test results show that the means between rifle and mechanical broadhead-tipped crossbow bolts were moderately different ( $p=0.02$ ) while the means between rifle and handgun were only slightly different ( $p=0.04$ ). These differences are most likely because all of the rifle samples reflected

the diameter of the .22 bullets while both the handgun and the mechanical broadhead-tipped crossbow bolts produced entrance defects which could not be completely reconstructed.

The minimum fragment length of the entrance fragments (per sample) accounted for a relatively small portion of the variation (7.29%). Yet even though there is a low level of distinction between the weapons, there is still a gradual spread of measurements up to 138.20 mm. This spread is a clear direct relationship between the amount of initial energy a projectile has and fragment size: as the energy increases, the length of the fragment increases (Figure 6.5). As such, the handgun produced the longest fragments, followed by the mechanical broadhead bolts. While the .22 bullet was the projectile with the least amount of initial energy (183.50 J), its shortest fragments were still comparable to the fixed broadhead bolts and longer than the field tip bolts. The field tip bolts, however, did not typically create any fragments at the entrance defect, which explains this inconsistency in the current trend. Though this general pattern can be seen, the fragment lengths are not

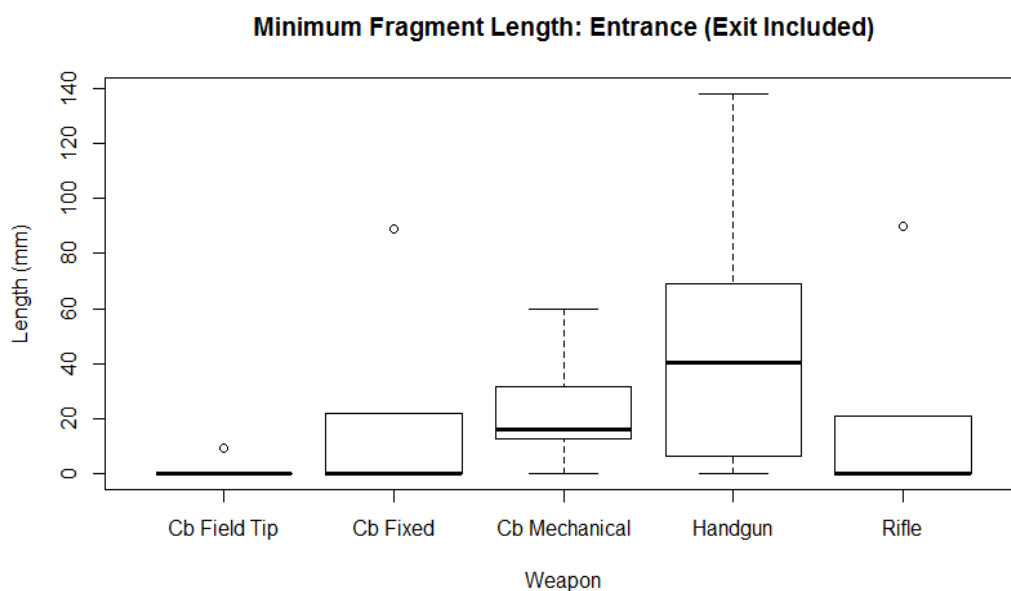


*Figure 6.5. Boxplot of the minimum fragment lengths of fragments originating from the entrance defect. (crossbow field tip, fixed broadhead, mechanical broadhead, compound bow, rifle, and shotgun: n=5; handgun: n=11; recurve bow: n=7).*

different enough to be able to clearly distinguish one weapon from another, which is why the proportion of the variance is so low for this feature.

The results of the Kruskal-Wallis test between weapon and minimum entrance fragment length, however, implies that the two variables do not exhibit significantly different means between weapon groups ( $p=0.21$ ). This could be a result of the small sample size of this study and further studies to increase the number of samples is recommended.

The diameter of the reconstructed exit defect follows the same logic of the reconstructed entrance defect: it has the potential to be influenced by which fragments are and are not recovered. This could account for why the proportion of variance is only 5.45% and why it is less indicative of weapon than the width of the entrance defect prior to reconstruction. But there were multiple samples within this study which could be completely reconstructed, guaranteeing that all dislodged fragments were retrieved. When a sample was completely reconstructed, the entire exit defect was closed up with no presence of an opening bigger than the radiating fractures. The Kruskal-Wallis test conducted on these variables further implies a moderately significant relationship ( $p=0.02$ ) between these two variables.

Nearly all samples which could be completely reconstructed were shot with the crossbow (all three types of tip), but the exit defect of one handgun (.22) sample was also completely reconstructed. This shows a moderate relation between initial energy and complete reconstructability as these weapons all are on the lower end of the energy range in this study (Table 2.1). Even in the case of the handgun sample, the bullet used (.22) is of significantly lower energy: the mass of the .22 bullet is nearly a third of the mass of the 9 mm bullet. This alteration of a component within the kinetic energy equation would be enough to lower the energy of the bullet, producing trauma which is more similar to the archery weapons.

Each of these projectiles will have also spent a significant amount of energy to have passed through the bone at the initial point of impact, as well as to

have travelled through the soft tissue within the cranial vault. While the amount of potential energy to be transferred to the opposite side of the cranial vault is much lower than the initial amount of energy, there was still enough to break through and create an exit defect. The energy transfer, however, was only enough to break apart the bone, not enough to leave a distinct exit hole which reflected the shape and size of the projectile.

The .22 rifle, however, gives the .22 bullet a higher muzzle velocity, resulting in a higher amount of energy than a .22 bullet shot using a handgun. The rifle samples in this study created a distinct cluster in the width of the reconstructed exit defect (Figure 6.6). A bullet shot by a rifle will expend less energy in order to pass through the gelatine due to its small size and, therefore, lower level of drag. This means that the bullet will then have relatively more potential energy upon impact on the opposite side of the cranial vault. Contrary to the .22 handgun sample, all rifle samples maintained an open exit defect after reconstruction. The diameters of these defects were highly precise, with a range of 9 mm (18.90 mm-27.90 mm). Not only is this range very narrow, but it also does not greatly overlap with the

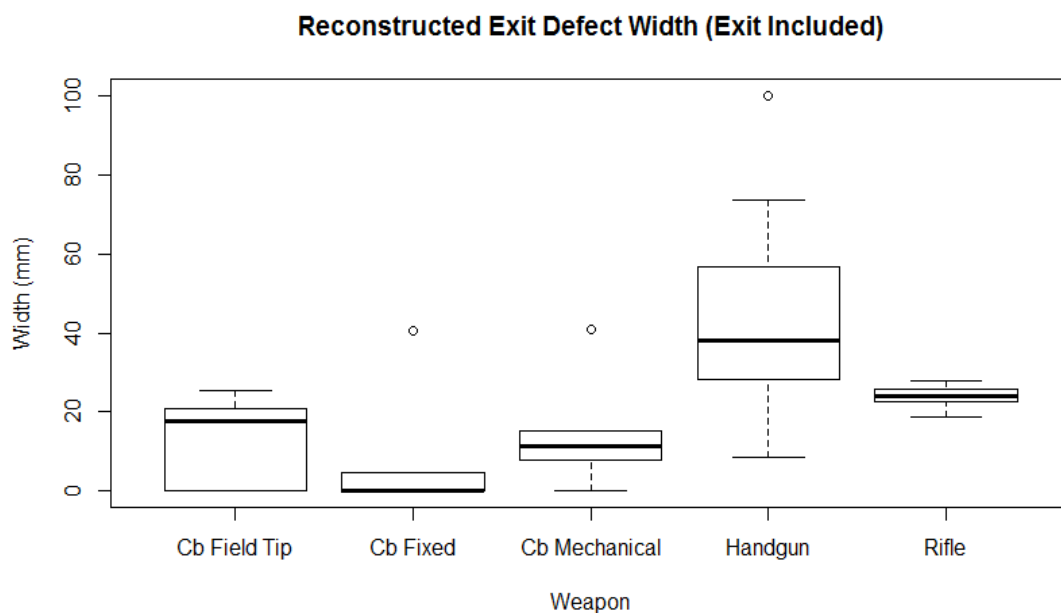


*Figure 6.6. Boxplot of the widths of the reconstructed exit defects. (crossbow field tip, fixed broadhead, mechanical broadhead, and rifle: n=5; handgun: n=11).*

measurements of the other weapons and falls between the high energy handgun samples and the lower energy crossbow samples.

The Dunn post hoc test conducted on these variables, however, only indicated a significant relationship ( $p=0.02$ ) between the means of the samples shot with fixed broadhead-tipped crossbow bolts and handgun. The fixed broadhead-tipped crossbow bolts produced the most samples in which the exit defect could be completely reconstructed (60.00%; 3/5), leaving no opening, while the handgun produced some of the largest reconstructed exit openings, measuring up to 77.90 mm. This relationship exhibits the significant difference between the smallest and largest reconstructed exit defects.

Finally, the maximum fracture length on the external table of the exit defect accounted for the smallest significant proportion of the variation within this dataset. As previously mentioned, not all of a projectile's energy is spent upon initial impact. The drag caused by the higher amount of surface area of the crossbow bolts compared to the bullets decreases the energy of the bolts as they pass through the hard and soft tissues to a greater extent. This is reflected in the maximum fracture lengths on the external table of the entrance defects. There is a direct relation between initial energy and maximum fracture length, except in the case of the .22 rifle. The rifle has the lowest initial energy, but the bullet expends less energy traveling through the hard and soft tissues than the other projectiles due to its small size. This is, however, only a general pattern within the data, there is still a high level of overlap between the weapons (Figure 6.7) with no clearly distinct clustering. Because of this, the maximum fracture length on the external table of the exit defect only accounts for 3.35% of the variation within the data.

The results of the Kruskal-Wallis test between weapon and maximum fracture length on the external table of the exit defect, however, implies that the two variables do not exhibit significantly different means between weapon groups ( $p=0.33$ ). This could be a result of the small sample size of this study and further studies to increase the number of samples is recommended.

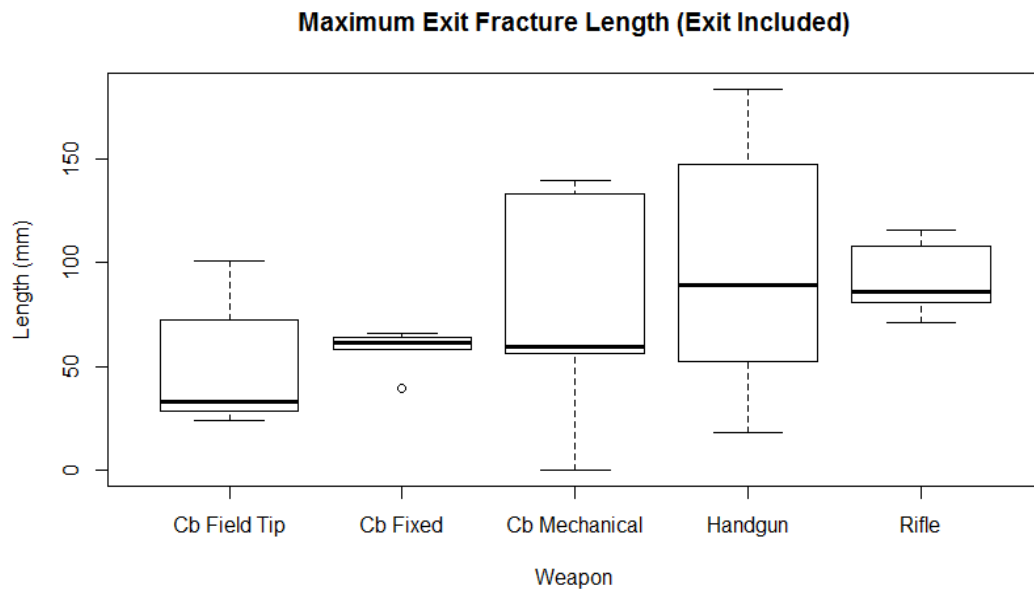


Figure 6.7. Boxplot of the maximum fracture lengths along the external table of the exit defects. (crossbow field tip, fixed broadhead, mechanical broadhead, and rifle:  $n=5$ ; handgun:  $n=11$ ).

### 6.3. New Weapon Identification Protocol

The following protocols were created based on the results of the previously described statistical analyses. Two protocols were created: one which includes feature of the exit defect and one which only includes features of the entrance defect. The first protocol (Figure 6.8) is to be used when both an entrance and an exit defect are present. This protocol was created so that each path would end when a minimum of five samples fit the criteria of that path. A total of three samples (9.68%; 3/31) in this dataset were misclassified when following this protocol.

The second protocol (Figure 6.9) is to be used when the projectile did not produce an exit defect and can also be used with partial skeletal remains in which only the entrance defect is observable. This protocol was created so that each path would end when a minimum of five samples fit the criteria of that path. A total of eight samples (16.67%; 8/48) in this dataset were misclassified when following this protocol.



## Protocol 1: Entrance and Exit Defect Features

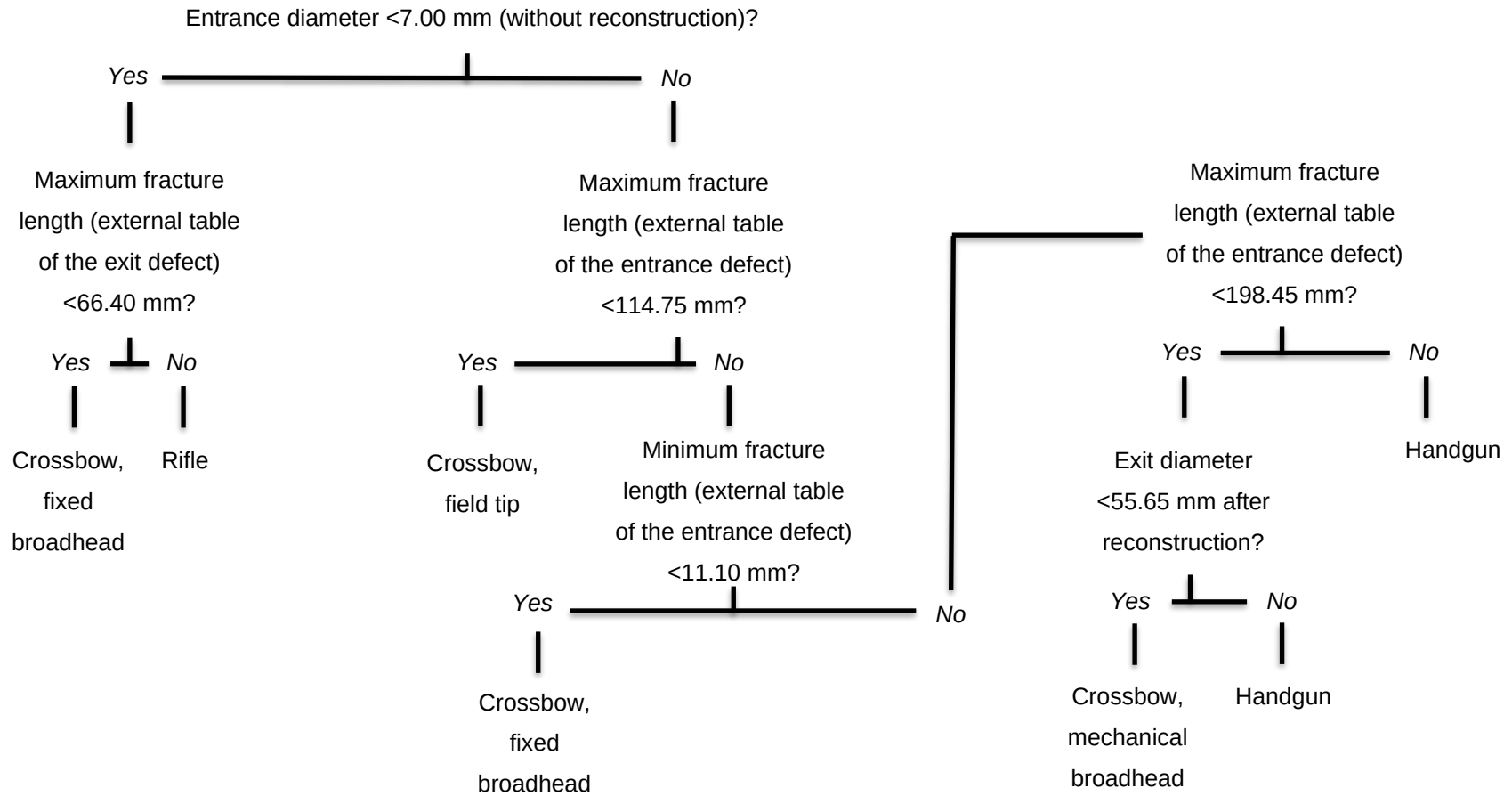


Figure 6.8 Protocol 1: to be used when both an entrance and an exit defect are present.

Maximum fracture length (external table of the entrance defect) <115.75 mm?

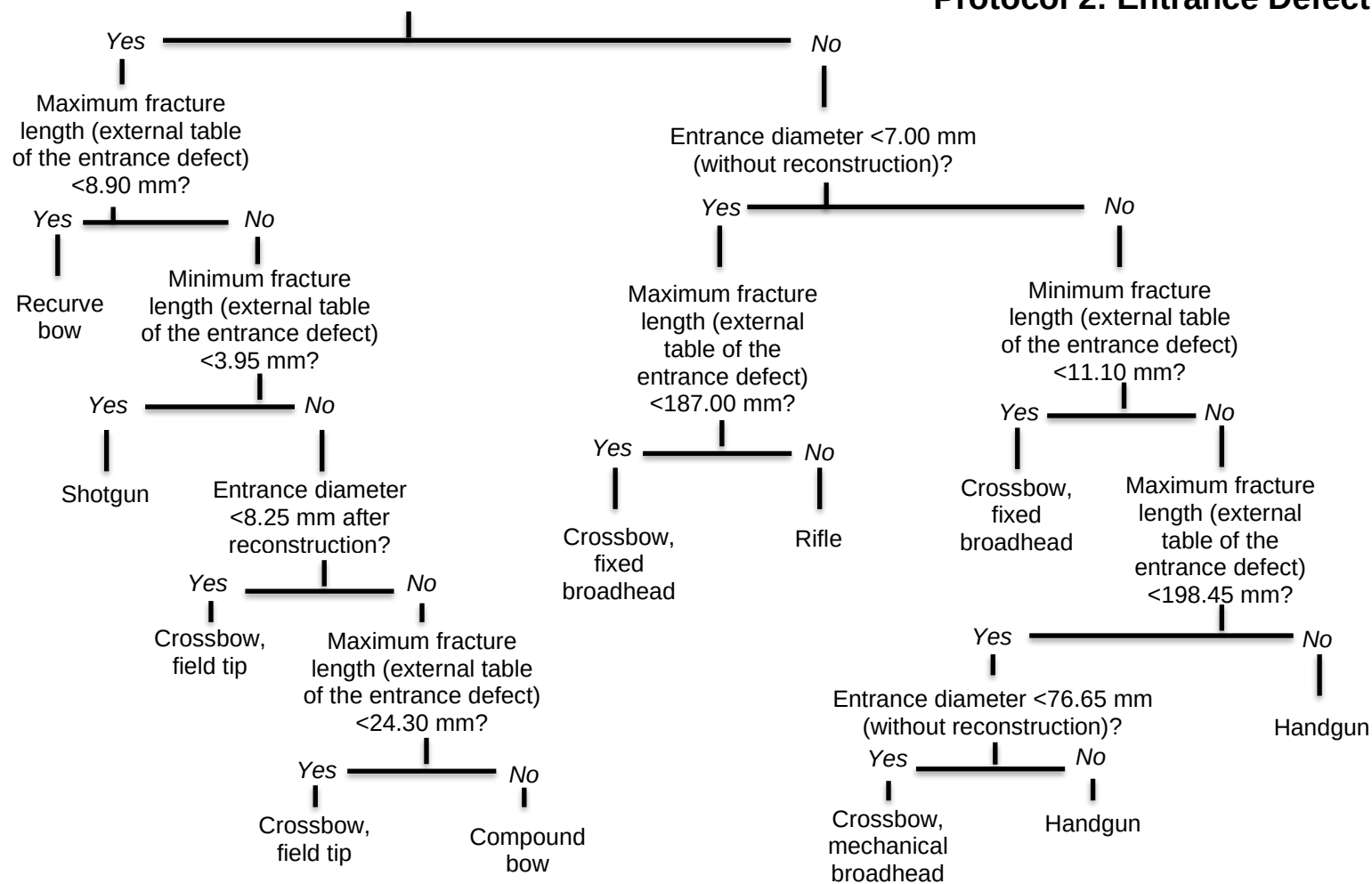


Figure 6.9 Protocol 2: to be used when an entrance defect is present.

## 6.4. Forensic and Archaeological Applications

This study sought to review the current methods of projectile trauma weapon identification, which are entirely based on qualitative features of trauma, while exploring features of trauma that are not typically measured to determine what methods are best for weapon identification. It was found that while the current methods of weapon identification, such as observing the presence of fractures and bevelling, are useful for generally categorising trauma as projectile trauma, they cannot differentiate the numerous types of projectile weapons. Furthermore, the results of this study indicate that the quantitative features were the most differentiating features of the weapon of origin and yet none of the common methods of projectile trauma analysis examine quantitative features.

While the features discussed in this chapter were observed on synthetic bone material, the same features have been noted in cases of trauma to real bone material. The commonly assessed qualitative indicators of projectile trauma are typically what is presented in case reports. Circular (Pomara *et al.*, 2007; Viel *et al.*, 2009) and keyhole (Dixon, 1982; Harada *et al.*, 2012; Bonaccorso *et al.*, 2014; Berryman, 2019) defects are commonly reported and tend to be instantly recognisable as projectile trauma, usually noted as gunshot trauma. These same features were replicated in the samples of this study using synthetic bone material. Additionally, bevelling is regularly reported to be found on the internal table of the entrance defect (Dixon, 1982; Quatrehomme and İscan, 1998; Berryman and Gunther, 2000; Bird and Fleischman, 2015; Berryman, 2019) and external table of the exit defect (Downs *et al.*, 1994; Quatrehomme and İscan, 1999; Viel *et al.*, 2009; Delannoy *et al.*, 2013). The synthetic bone material samples in this study not only mimicked this pattern of bevelling, but also replicated the bevelling on both tables observed in keyhole defects (Dixon, 1982; Harada *et al.*, 2012; Delannoy *et al.*, 2016; Özsoy and Tugcu, 2016; Quatrehomme and Alunni, 2019).

In addition to the primary defect, the synthetic bone material produced secondary (radiating) and tertiary (concentric) fractures seen in cases of trauma on real bone (Downs *et al.*, 1994; Viel *et al.*, 2009; Austin *et al.*, 2013; Bird and Fleischman, 2015; Panata *et al.*, 2017). Furthermore, the fixed broadhead tips used with both the compound hand bow and crossbow consistently produced entrance defects and radiating fractures which reflected the Y-shape of the tips, as seen in the cases described by Downs *et al.* (1994) and Panata *et al.* (2017). As seen in the first case described by Downs *et al.* (1994) (see Section 2.7.3.), the three-blade fixed broadhead tip produced fractures which reflected the configuration of the blades and the same phenomenon (also with a three-blade fixed broadhead) was observed in the case described by Panata *et al.* (2017). When examining the samples of the current study, all compound bow samples and crossbow (fixed broadhead) samples contained at least three fractures at the entrance defect which reflected the three-blade configuration of the tips. In the crossbow samples, this was also true for the exit defect. The blades of the broadheads created a pre-set pathway for fracture formation as it cut through the bone, creating a weaker point in the bone. The energy then travelled along the path of least resistance, extending the fractures beyond the blades' cuts.

These findings show that the features of trauma observed on the synthetic bone material mirror features of trauma found on real bone described in case reports. As it is not common practice to measure quantitative features of projectile trauma, features such as fracture length are not typically included in case reports. As such, the comparability of synthetic bone material to real bone could not be assessed in regard to the quantitative measurements of this study. Additional studies should be conducted to assess the quantifiable accuracy of synthetic bone material (see Section 6.5.).

The existing literature discussing cranial projectile trauma is severely lacking in terms of methods of examination. Because the commonly used methods of projectile weapon identification focus on qualitative features, such as bevelling location and the shape of entrance and exit defects, there is a

general trend of omitting quantitative features when reporting instances of skeletal trauma in both forensic and archaeological contexts (Hain 1989; Betz *et al.*, 1997; Karger *et al.*, 2004; Bailey and Mitchell 2007; de la Grandmaison *et al.*, 2008). Though the current study provides proof based on the results of experimental research that qualitative features are not significantly indicative of weapon and that quantitative features of projectile trauma more adequately differentiate the weapon which created the trauma, published case reports could not be utilised to corroborate these findings.

Quantitative features, such as fracture lengths and fragment dimensions, are not typically extensively reported if they are reported at all. When such quantitative features are reported, they tend to be limited to entrance and/or exit defect dimensions (Dixon, 1982; Berryman and Haun, 1996; Byard *et al.*, 1999; Pomara *et al.*, 2007; Bonaccorso *et al.*, 2014), neglecting the characteristics regarding fractures and fragments. Furthermore, the entrance and exit defect dimensions were found not to be the most indicative quantitative features of trauma. When considering features of both the entrance and exit defects, the diameter of the entrance defect accounted for only 14.52% (without reconstructing using any dislodged fragments) and 1.77% (after reconstruction using any dislodged fragments) of the variation between the means of all weapons considered in this subset. In the same subset, the diameter of the exit defect (after reconstruction using any dislodged fragments) only accounted for 5.45% of the variation in this dataset while the diameter of the exit defect without reconstruction did not account for a significant proportion of the variance (see Table 5.1). When only considering features of the entrance defect, the diameter of the defect prior to reconstruction was only the second most indicative feature of weapon of origin (following the maximum fracture length on the external table of the entrance defect; 62.83% of the variance in this dataset), accounting for 21.33% of the variance within this subset of the data. The diameter of the entrance defect after reconstruction, however, only accounted for 4.05% of the variation within this subset (see Table 5.2).

Spatola (2015) further corroborates these findings in his description of a case where a child had been struck with the end of an umbrella. As previously discussed in Section 2.8., another child was swinging the umbrella when the end of the umbrella detached and became an atypical projectile. The projectile struck the left anterior cranial vault and produced trauma which “gave the appearance of a ‘textbook’ gunshot wound.” (Spatola, 2015: 18): a circular entry defect which measures 9.00 mm in diameter and bevelled on the internal surface of the cranial vault. Spatola notes that had the weapon not been previously known, it is likely that this would have been misclassified as gunshot trauma, further arguing for the abandonment of classification into types of trauma. But had the examiner used more inclusive terminology (i.e., “projectile trauma” in place of “gunshot trauma”), this weapon would not have been misclassified as the umbrella tip did exhibit the characteristics of a projectile. While the qualitative features would have correctly indicated the trauma classification, the diameter of the entrance defect would not have been an explicit indicator of the specific weapon, the most likely (and incorrect) conclusion would have been a 9.00 mm bullet of which the umbrella tip in this case shared the same diameter.

The lack of presence in the literature reflects the lack of measuring quantitative features in postmortem examinations of skeletal trauma. This limitation not only impedes the anthropologist's ability to provide concise conclusions to assist in legal investigations, but also prevents future studies from accessing usable quantifiable data without gaining access to the remains, which is not always possible. By reporting the quantitative features of trauma in published case reports, researchers would have access to data from a more diverse collection of real-case samples to develop more extensive methods of trauma analysis.

Additionally, images of skeletal trauma in published case reports could potentially be used to approximate the values of quantitative features of projectile trauma, but most quantitative characteristics would require that a scale be included in the image. The exceptions to this requirement would be

number of fractures and number of dislodged fragments (if applicable), though neither of these features proved to account for significant proportions of variance in the dataset of the current study (see Section 5.1.). It is, however, very common for images in case reports to not include scales at all, limiting the number of quantitative features which can be deduced from these images alone. For the few images that do include a scale (Byard *et al.*, 1999; Humphrey *et al.*, 2017; Panata *et al.*, 2017), the approximation of certain measurements, such as fracture length, would not be accurate as it would be impossible to consider the three-dimensional curvature of the cranial vault in a two-dimensional representation. The inclusion of a scale would, however, be adequate to approximate the diameter of the entrance and/or exit defects.

The results of the current study established that quantitative features of skeletal trauma are more effective in identifying projectile weapons. This emphasises the importance of the inclusion of scales in all images included in published case reports, but also the need for the examiners to prioritise both measuring and reporting quantitative features of skeletal trauma.

The expansion of the current projectile trauma analysis methods to include the measurement of quantitative features would also expand the process of projectile weapon identification to be more inclusive of weapon models. Weapon identification studies have been conducted for both sharp force trauma (Bartelink *et al.*, 2001; Capuani *et al.*, 2013; Downing and Fibiger, 2017; Norman *et al.*, 2018) and blunt force trauma (Alcantara *et al.*, 1994; Aromatario *et al.*, 2016; Dyer and Fibiger, 2017), but are severely lacking regarding projectile trauma as this trauma has become synonymous with “gunshot” trauma, at least in a forensic context. Simply focusing on gunshot in clinical and forensic cases ignores the wide array of weapons, including both firearms and non-firearms, which are classified as projectile weapons, neglecting the consideration of projectile trauma in pre-firearm periods. Even though firearms are very commonly involved in forensic investigations, little attempt has been made to differentiate the trauma inflicted by handguns, rifles, and shotguns. Because non-firearm projectile weapons, such as

archery weapons, are not as prominently involved in forensic cases, even less research has been conducted on the damage they can cause to bone (Smith *et al.*, 2007; O'Driscoll and Thompson, 2014; Smith *et al.*, 2015; Forsom and Smith, 2017).

Yet these weapons are still involved in forensic cases as many individuals own these weapons for hunting purposes or for sport. It is essential in a forensic investigation for the forensic anthropologist to be able to provide as much detail on the perimortem period as possible. The current study provides two quantitative weapon identification protocols, both of which account for multiple classes of projectile weapons. Protocol 1 is to be used in cases where both an entrance and exit defect are present and Protocol 2 is to be used in cases where only an entrance defect is measurable. By placing more of an emphasis on the quantifiable measurements of the trauma, the anthropologist would be able to more concisely estimate the type of weapon which was used in a homicide based on skeletal remains, this information can assist law enforcement with locating the weapon as well as provide more substantial evidence in the court proceedings.

A 2017 study conducted by Humphrey and colleagues (Humphrey *et al.*, 2017) examined the macroscopic features of cranial projectile trauma found in the skeletal remains of the Hamann-Todd Human Osteological Collection. This collection consists of the skeletal remains of over 3,000 unclaimed individuals who died between 1912 and 1938. There were 13 skulls which exhibited evidence of projectile trauma, but two of these skulls (individuals 1926 and 1903) did not have an exit defect. While the trauma found on the skull of individual 1926 does not show a clear entrance defect (most likely having been caused by the grazing strike of a projectile), there is a distinctly circular entrance defect on the skull of individual 1903 but no complete exit defect (Figure 6.10). There is, however, fracturing on the opposite side of the cranial vault, where the exit defect would have been. The authors of this 2017 study hypothesise that the projectile (assumably a small projectile such as a bullet) entered the cranial vault and struck the opposite side of the vault



and ricocheted off of the internal surface of the bone, causing the observed damage without creating a complete exit defect. The projectile itself was never recovered.

The findings of the current study, however, expose another possible scenario in the case of individual 1903 (Humphrey *et al.*, 2017). The observed trauma in this individual shows a projectile which contained enough energy to break through bone to enter the cranial vault, but did not retain enough energy to create a complete exit after it had entered and travelled the length of the cranial vault. Upon the initial observation of the gross morphology of both the complete entrance and incomplete exit defects, the form of these defects in individual 1903 reflect the trauma observed in sample CbFt 3 of the current study (Figure 6.10). Both entrance defects show distinctly circular entrance defects with the entrance defect on individual 1903 measuring approximately 10 mm in diameter, similar to the 7.6 mm diameter of the entrance defect on sample CbFt 3. This measurement on individual 1903 falls directly within the range of entrance defect diameters observed on the samples of the current study which were shot with the crossbow using field tip bolts (7.50 mm to 10.30 mm; SD=  $\pm 1.21$  mm). Furthermore, the number of radiating fractures on both the external and internal tables of individual 1903 mirror the number of fractures on sample CbFt 3 (four fractures).

While individual 1903 (Humphrey *et al.*, 2017) lacked a complete exit defect, there was a region opposite the entrance defect which exhibited extensive fracturing on both the internal and external tables of the cranial vault (estimated to be approximately 8-10 and 14-15 fractures, respectively) (Figure 6.10). Sample CbFt 3 did show a complete exit defect, but the defect could be completely reconstructed with dislodged fragments, displaying a defect which reflects the incomplete exit defect on individual 1903 (Figure 6.10). This discrepancy in the completeness of the exit defect could be a result of a number of variables such as the difference in power between 20th

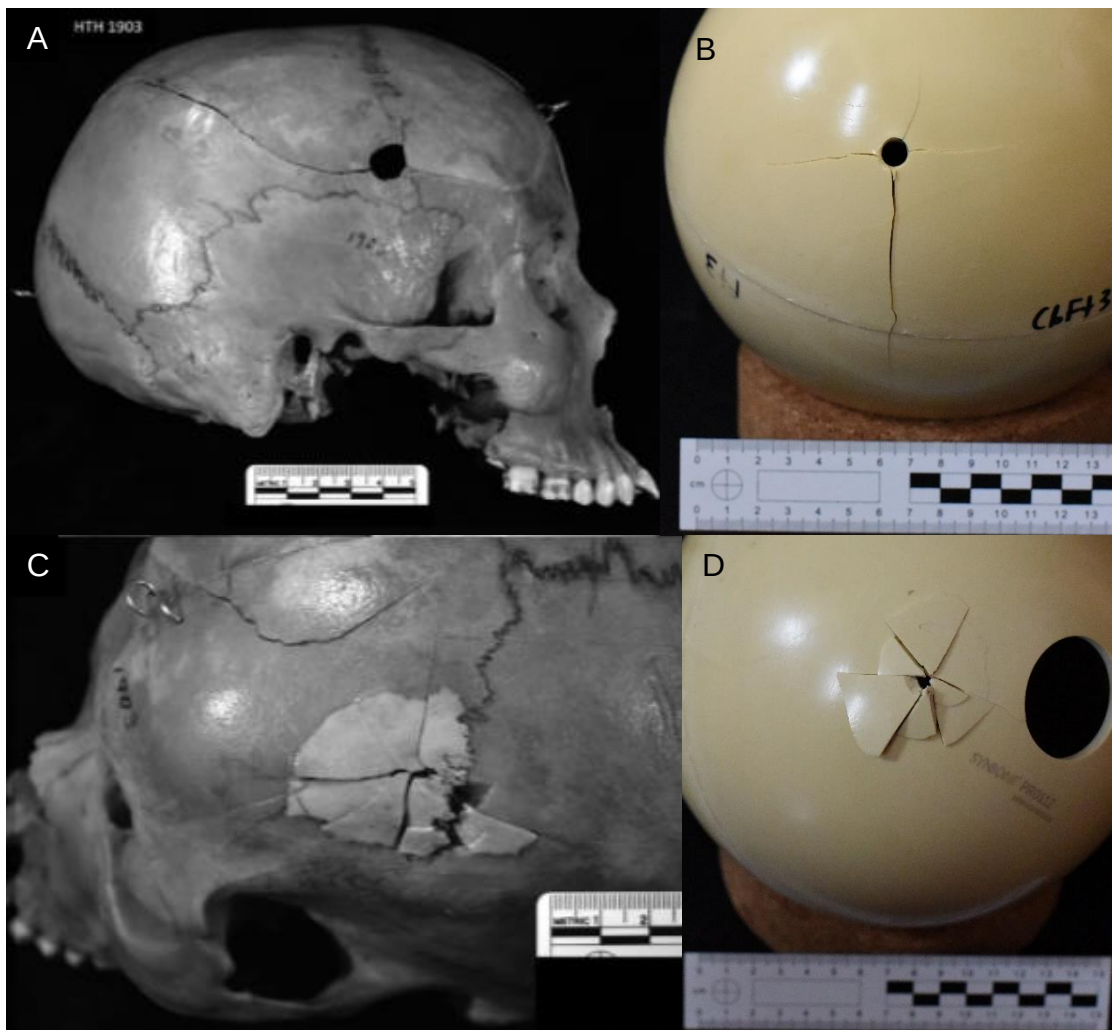


Figure 6.10 Entrance and exit defects on real bone and Synbone®. (A) Entrance defect of individual 1903 (source: Humphrey et al., 2017: 292) (B) Entrance defect of sample CbFt 3 (C) Incomplete exit defect of individual 1903 (source: Humphrey et al., 2017: 292) (D) Exit defect of sample CbFt 3 after reconstruction using dislodged fragments.

and 21st-century weaponry, difference in firing distance, etc. The inconclusive conclusions regarding individual 1903 exemplify the need to expand both the commonly used methods of projectile trauma analysis to include more quantitative measurements as well as the weapons which are taken into consideration when attempting to identify the projectile weapon used in an instance of trauma.

When examining remains which are from an archaeological context, the current qualitative methods of trauma analysis are even more problematic. As firearms were only developed in the last millennium, acknowledging all projectile trauma as “gunshot” would be neglecting the possibility that

projectile trauma could be present in more ancient remains. Yet non-firearm projectile weapons have been used in cultures dating back as far as the Palaeolithic. Because of this overgeneralisation, instances of projectile trauma may be overlooked in the assessment of archaeological remains. In her discussion of violence patterns amongst prehistoric societies of California, Lambert (2014) states that “the exclusion of all but the most certain (i.e., points embedded in bones) is likely to result in a serious under-representation of the actual number of victims.” (Lambert, 2014: 93). The same can be applied to excluding less frequently used weapons: the exclusion of all but the most common (i.e., firearms) is likely to result in a serious under-representation of the actual number of cases.

While Gill *et al.* (1984) were some of the few to readily report quantitative features of skeletal trauma, only the diameter of the defect (12 mm; no reconstruction required) was given. They estimated that the most likely weapon was either a .44 or .45 calibre weapon, probably firearm based on the weaponry of the time period. The findings of the current study show that the diameter of the entrance defect (without reconstruction) is the third most distinguishing feature (Proportion of Variance: 14.52%; Cumulative Proportion: 78.87%) and the reconstructed entrance diameter is the seventh most indicative feature (Proportion of Variance: 1.77%; Cumulative Proportion: 96.74%) when characteristics of both the entrance and exit defects are observed. In the case described by Gill *et al.* (1984), the diameter of the entrance defect reflects the diameter of a .44 or .45 calibre bullet (10.90 mm and 11.43 mm, respectively), potentially corroborating the weapon used in this case. It is, however, worth noting that it is not specified how the ballistic expert concluded that the weapon was either .44 or .45 calibre. It is possible that this conclusion could have been based on which calibre bullet most closely reflected the diameter of the defect. Further quantitative analysis would have benefited the conclusions described in this publication.

As seen in forensic case reports, archaeological case reports of projectile trauma lack necessary quantitative details. Cases of projectile trauma in an archaeological context are most frequently identified by lithic tips embedded in bone or matching the shape of the skeletal defect to the profile of the projectile (Jurmain, 2001; Smith *et al.*, 2007; Lambert, 2014; Creighton *et al.*, 2020). Both methods are problematic in that they rely solely on qualitative features which could either not occur or could be distorted by external factors. Yet, as seen with forensic case reports, quantitative features of projectile injury are rarely reported in the literature or are limited to defect dimensions (Dixon, 1982; Berryman and Haun, 1996; Byard *et al.*, 1999; Novak, 2007; Pomara *et al.*, 2007; Bonaccorso *et al.*, 2014). The results of the current study emphasised the need to both measure and report quantitative features of trauma (specifically regarding fractures, fragments, and defect dimensions) to facilitate accurate weapon identification.

In order to understand the trends of interpersonal violence within a culture, bioarchaeologists must not only be able to accurately categorise any observed trauma as sharp force, blunt force, or projectile, but trends of specific weapon use should also be assessed through the accurate identification of weapon based on the features of trauma. These trends can give insight on both weapon use in specific cultures as well as the evolution of projectile weaponry. As with the assessment of forensic remains, this distinction is more concisely observed by measuring quantitative features of the trauma.

For example, improved methods of weapon identification would have proved to be beneficial in the study conducted by Cohen and colleagues (2012) on skeletal remains from a span of 6,000 years in the Levant. The findings of this study reported cases of trauma throughout this entire time period, but only noted projectile trauma which was caused by bullets during the most modern subsection (640-1917 CE) of the total time period. Had this study incorporated methods which could identify non-firearm weapons, projectile trauma could have been assessed in all of their samples.

Another study which would have benefitted from the improved methods of weapon identification proposed in this project is the study conducted by Fibiger and colleagues (2013). This cross regional study examined the Neolithic skeletal remains of Denmark and Sweden (3,900-1,700 BC), assessing the patterns of violence through the trauma found on the remains. Though this study extensively examines the skeletal aspect of trauma, recording and analysing the traumatic lesions to analyse their frequencies between the sexes and age groups and comparing the Danish and Swedish populations, specific weapon identification was not explicitly examined amongst these samples. Quantitative methods of projectile weapon identification could have expanded the analysis to identify the weapons which produced the observed trauma, allowing an analysis of which weapons were more frequently used during this period. Even further, an analysis then could have been conducted to see if there were any correlations between the weapon used and the sex and age of the individual which they were used against.

The shortcomings of both studies illustrate the necessity for improved methods of projectile weapon identification to include an expansion of weapon models considered during examination. The diversity of time periods, geographic areas, and weapon classes between these studies exemplify widespread applications of the new protocols proposed in the current study.

## 6.5. Further Research

Though this study has established important baseline data, it is important to note that the sample size is fairly small and it would be beneficial to repeat the methods used in this study in order to increase the number of replicates. By increasing the number of replicates, the amount of data would also increase, which would provide more support for the observed trends.

Firstly, the applicability of synthetic bone material to real bone cases needs to be studied further. The statistical analysis of this study shows that the most indicative features of weapon identification are quantitative features. Most case reports, however, do not include measurements of quantitative features such as fracture lengths. Future studies should be conducted to compare the measurements found using synthetic bone material to measurements of real cases (of both forensic and archaeological contexts) in order to assess the applicability of the conclusions made using synthetic bone material.

Some projectiles examined in the current study not only meet the criteria for projectile weaponry, but also contain elements of sharp force weaponry, mainly the broadhead tips for both. The trauma produced by these projectiles also showed evidence of both projectile and sharp force trauma, sometimes in more obvious ways than others. If the projectile struck the sphere at an angle which was not perpendicular, the cut marks would spread along the surface of the sphere. Even in cases where the projectiles struck the spheres perpendicularly, the radiating fractures would typically originate from the cuts produced by the broadheads' blades and the surface of the cut would be observable if portions of the defect broke away from the sphere. Sung and colleagues (2017b) observed similar findings in the soft tissue, noting that broadheads with two-blade configurations resembled stab wounds. Future studies could examine these similarities, differentiating projectile sharp force weapons from handheld sharp force weapons in both skeletal material and soft tissue.

The findings of this study expose a significant gap in the existing literature regarding projectile trauma analysis. While this study focused on one aspect of this gap, there are still many other lines of research which still have yet to be examined. One area which should be expanded is weapon selection. This study focused on a more forensic context, examining eight modern weapon designs, but there are still some common modern projectile weapons which have not been examined, such as slingshot. Future forensic studies could also examine different designs of the weapons used in this study, such as a

recurve crossbow, compound hand bow using a field-tipped arrow, or different blade configurations for any and all broadhead tips. Alternative models of these weapons could also be used in future studies in order to test how the different specifications affect the damage inflicted to the bone.

The weapon selection could also be expanded in such a way that it shifts to more of an archaeological focus, using ancient designs of the modern weapons (where possible). Such a study could also include weapons which are not considered to be part of modern weaponry, such as longbows, slings, and atlatls. The findings of these studies would be particularly useful in projectile weapon identification in cases which are from pre-firearm periods, such as the cases in the medieval necropolis in Lombardy (Licata and Armocida, 2015) or the remains from the pre-Arab Levant (Cohen *et al.*, 2012).

Additionally, further study should be conducted from varying distances and not just 10 m. When a force puts a projectile in motion, the energy of the force is transferred to the projectile itself (kinetic energy), which allows the projectile to continue its path of motion. As the projectile travels through open space (assuming this is not a vacuum), this amount of energy decreases due to drag. The further a projectile travels, the more the energy decreases. This means that if there is a significantly different distance between the shooter and the target, there will be a different amount of energy which is transferred to the bone, and therefore different trauma patterns, than what was observed in the current study.

Another study could focus more on the statistical analysis of these findings. The current study sought to isolate the most indicative features of projectile trauma by measuring one explanatory variable and 35 response variables, statistically analysing all of the variables together. A more statistics-focused study could examine each variable individually to analyse the relationships between the weapon type and each feature of trauma.

An additional study could examine the features of projectile trauma to compare them to the features of blast trauma. As secondary blast trauma is produced through a mechanism which is similar to trauma caused by projectile weapons, the cranial damage inflicted by explosions could mirror the features of trauma observed in the current study. Future studies could attempt to differentiate blast injuries from projectile injuries based on skeletal trauma.

## 6.6. Limitations

The most apparent limitation was the sample size of this project. Due to the limited time frame and limited resources, replicate groups were kept at  $n=5$  for each sample type. While this was enough to test for statistical significance, these findings may not be inherently representative of all cases of projectile trauma inflicted by the individual weapons. Additional studies with more extensive sample sizes should be conducted in the future.

Another limitation is the use of synthetic bone. While Synbone® spheres have become commonly accepted as a proxy for human crania in experimental studies (Thali *et al.*, 2002; Smith *et al.*, 2015), they do not entirely match the architecture of the human cranium. The consistent shape of the spheres can cause the synthetic bone to react to force differently from the irregular shape of the human cranium. The features of real bone, with areas of different thickness within any one cranium, means differences in the resistance to energy that is transferred from the projectile to the bone upon impact. With the mostly uniform structure of the polyurethane spheres, the synthetic bone material would maintain a uniform level of resistance throughout the path of the energy, which could potentially influence the observed trauma.

The outdoor setting of these experiments also presents another limitation as some dislodged fragments were lost in the foliage. All measurements



regarding dislodged fragments were based on the fragments which were recovered, but some samples may have had other fragments which were not recovered. Data regarding these fragments could not be gathered and was, therefore, missing from this study. Ideally, future studies should be conducted in a location which does not have the issue of foliage, such as an indoor shooting range.

A limitation within the experimental design of the current study was the high amount of control during the shooting process. In the experimental procedure of the current study, each sphere was secured in place when being shot to prevent it from rolling off the platform and causing damage which was not caused by the projectile. But in a real case of violence which involved a projectile weapon, the person who was shot would not have been secured in place and the movement that the projectile causes could alter the flight path and/or energy transfer and, therefore, affect the observed trauma.

Additionally, the spheres were set up so that each marksman would be able to shoot the spheres at a perpendicular angle. But cranial vaults are not always hit at a perpendicular angle and are often struck tangentially, which would produce different characteristics of trauma. These methods were designed so that the weapon used was the only differing variable between the samples while all other variables remained constant so that it was guaranteed that the differences which were observed in the samples were a result of only the one variable. Future studies could examine different isolated explanatory variables or even whether multiple variables would have a combined effect on the trauma outcome.

## 7. Conclusions

The purpose of this study was to compare the macroscopic characteristics of trauma which different types of projectile weapons produce (from a distance of 10 m) in order to determine if and how the weapon used can be identified based on these features. In designing an experimental approach using Synbone® spheres filled with ballistic gelatine, it was determined that the weapon could be approximated based on multiple quantitative features of trauma. Using a combination of principal component analysis, one-way ANOVA tests (or Kruskal-Wallis tests), linear discriminant analysis, and tree diagrams, a new projectile weapon identification protocol was created to assist in the analysis of skeletal remains.

In addition to assessing skeletal remains regarding identification methods (such as age, sex, and stature), part of the role of the forensic anthropologist is to comment on any abnormal skeletal features which could either assist in the identification of the remains or relate to cause of death. Cause of death can either be pathological or traumatic, both of which require regularly updated research in order to account for all forms of disease or weapons and a clear idea of specific identifying features they leave on the bone. In terms of trauma analysis, methods need to be updated in order to keep up with ever-changing weapon design. The analysis of projectile trauma, however, has been long left unchanged, with the regularly used identification methods dating back to the early 1980's. Such methods have relied upon features such as radiating fractures and bevelling to identify general projectile trauma. Yet within these methods, there has been little effort to expand in order to be able to differentiate trauma caused by projectile weapons that are not the generic firearm.

Furthermore, the current methods accepted as standard only examine qualitative features with no regard to quantitative features. As most projectile weapons function in a similar way and apply the same types of forces to bone upon impact, qualitative assessment of trauma can only give so much

information. By examining only qualitative features, the power behind different projectile weapons is ignored, hindering accurate weapon identification. In a forensic investigation, accurate identification could be crucial in the outcome of the case. It is therefore important to understand the physics of all aspects of the observed trauma.

To best assess the trauma, a number of qualitative and quantitative variables were selected and measured on synthetic bone spheres which had been shot with firearms and archery weapons from a distance of 10 m. These findings were then statistically analysed using principal component analysis and linear discriminant analysis to extract the most distinguishing features of projectile trauma within the samples obtained in this study. This was followed by either a one-way ANOVA or a Kruskal-Wallis test to test for significant differences in means of a feature between the examined weapons as well as a post hoc test (Tukey or Dunn) to determine which weapons had significantly different means. The findings from these tests can be used to estimate the weapon used in future cases of trauma.

With these considerations in mind, the following conclusions were drawn from this research.

## 7.1. Current Qualitative Methods

This study sought to answer the question of whether the current osteological methods of projectile trauma analysis, which are typically based on qualitative features, can accurately identify the weapon used. The results of this study showed that qualitative features of trauma alone are not indicative of weapon of origin. All weapons which were examined in this study, both firearms and archery weapons, exhibited the characteristic features of projectile trauma, such as the presence of radiating fractures and bevelling. This confirms that the current methods which are used for projectile trauma identification can be applied successfully to non-firearm projectile weapons,

but cannot be used to differentiate trauma caused by different types of projectile weapon. The most notable exception to this is the trauma caused by the recurve bow with field tip arrows as characteristics of projectile trauma were not present in most of these samples. Only one sample exhibited a complete entrance where the projectile broke through both the external and internal table of the cranial vault. All other samples had damage to only the external table, creating a unique conical entrance shape.

## 7.2. New Quantitative Methods

This research also sought to pinpoint which features were most able to distinguish the weapons examined in this study. Though quantitative features are rarely considered in the examination of projectile trauma, only quantitative features were found to be greatly indicative of weapon of origin. Given the fact that some samples did not exhibit an exit defect, it was necessary to create two classification systems: one which only examined the features of the entrance defect and one which examined the features of both the entrance and exit defects.

When examining only entrance features, it was found through principal component analysis that four features cumulatively accounted for more than 95.00% (95.89%) of the variation within this dataset. These features were the maximum fracture length on the external table of the entrance defect (62.83%), the maximum width of the entrance defect prior to reconstruction (21.33%), the minimum fracture length on the external table of the entrance defect (7.68%), and the maximum width of the reconstructed entrance defect (4.05%). These features were then used in machine learning (linear discriminant analysis) in order to be able to predict future instances of projectile trauma. In testing the prediction abilities of the linear discriminant analysis, it was found that the prediction of weapon of origin was 60.87% accurate.

When examining the features of both entrance and exit defects, it was found through principal component analysis that seven features cumulatively accounted for more than 95.00% (96.74%) of the variation within this dataset. These features were the maximum fracture length on the external table of the entrance defect (42.95%), the minimum fracture length on the external table of the entrance defect (21.41%), the maximum width of the entrance defect prior to reconstruction (14.52%), the minimum fragment length of the entrance fragments (per sample) (7.29%), the maximum width of the reconstructed exit defect (5.45%), the maximum fracture length on the external table of the exit defect (3.35%), and the maximum width of the reconstructed entrance defect (1.77%). These features were then used in machine learning (linear discriminant analysis) in order to be able to predict future instances of projectile trauma. In testing the prediction abilities of the linear discriminant analysis, it was found that the prediction of weapon of origin was 74.19% accurate.

Based on these findings, two quantitative protocols for projectile weapon identification were created. Protocol 1 is to be used in cases when both an entrance and exit defect are present. Protocol 2 is to be used in cases when only an entrance defect is present. It was found that when using Protocol 1, three samples (9.68%; 3/31) in this dataset were misclassified and when using Protocol 2, eight samples (16.67%; 8/48) in this dataset were misclassified.

Generally, it was observed that projectiles which had higher levels of initial energy produced more extensive features of trauma (i.e. longer fractures, larger fragments, etc.). There are, however, other factors which can affect the observed trauma and create exceptions to this trend, such as projectile mass and dimensions. This brings to attention the need to integrate more concepts within the field of physics with trauma analysis in order to properly predict the unknown cause (weapon) of a known outcome (cranial trauma).

Overall, this study proves that more than just firearms are capable of producing the characteristic features of projectile trauma. This reveals an

inherent bias within the current trauma identification methods and a reluctance to acknowledge non-firearm projectile weapons. While the accuracy of weapon identification is important in forensic investigations, it is also important in the assessment of archaeological material. Characteristics of interpersonal violence, such as frequency or types of weapon used, is one key component to understanding the workings of a past culture. Trauma analysis greatly limits itself in assuming that all projectile trauma can be considered "gunshot" trauma, as archaeological contexts which are of a pre-firearm period can still have utilised non-firearm projectile weapons.

This study has introduced a new methodology for identifying trauma origins as it was found that quantitative measurements of projectile trauma need to be considered to identify the weapon of origin more accurately. Quantitative measurements, such as fracture lengths and entrance/exit defect diameters, are more likely to reflect the specifications of projectile weapons, such as energy produced and the diameter of the projectile itself. The use of these new methods has the potential to substantially enhance the anthropological aspect of forensic investigation by improving their ability to provide an accurate weapon involved in violent deaths.

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# Appendix A: Principal Component Analysis

## Code Input and Output

### Exit Features Included

```
> str(TraumaExitP)
'data.frame':      31 obs. of  40 variables:
 $ weapon      : Factor w/ 5 levels "Crossbow (Field Tip)",...: 4 4 4
4 4 4 4 4 4 4 ...
 $ Entrance    : num  1 1 1 1 1 1 1 1 1 1 ...
 $ Exit        : num  1 1 1 1 1 1 1 1 1 1 ...
 $ numfracEnEx : num  0 5 2 10 10 12 5 6 12 11 ...
 $ numfracEnIn : num  0 5 10 9 11 11 5 6 12 11 ...
 $ numfracExEx : num  3 9 7 8 5 14 15 15 7 6 ...
 $ numfracExIn : num  5 6 8 7 7 15 15 15 7 6 ...
 $ radfracEnEx : num  0 1 1 1 1 1 1 1 1 1 ...
 $ radfracEnIn : num  0 1 1 1 1 1 1 1 1 1 ...
 $ radfracExEx : num  1 1 1 1 1 1 1 1 1 1 ...
 $ radfracExIn : num  1 1 1 1 1 1 1 1 1 1 ...
 $ confracEnEx : num  0 0 1 1 1 1 0 0 1 1 ...
 $ confracEnIn : num  0 1 1 1 1 1 0 0 1 1 ...
 $ confracExEx : num  0 0 0 0 0 1 1 1 0 1 ...
 $ confracExIn : num  0 1 1 1 1 1 1 1 0 1 ...
 $ maxfracEnEx : num  0 220 231 267 204 ...
 $ minfracEnEx : num  0 87.2 215.9 26.6 68.2 ...
 $ maxfracExEx : num  18.4 51 53.3 53.3 154.1 ...
 $ minfracExEx : num  12.9 9.7 26.3 5 14.3 28.1 31.5 41.4 11.1 19.5
...
 $ numfragEn   : num  0 0 0 3 4 3 1 1 7 3 ...
 $ numfragEx   : num  5 0 0 4 3 7 1 1 3 0 ...
 $ maxfraglenEn: num  0 0 0 81.6 106.6 ...
 $ minfraglenEn: num  0 0 0 40.5 75.2 ...
 $ maxfragwidEn: num  0 0 0 53.1 63.4 66 79.3 59.1 43.5 50.2 ...
 $ minfragwidEn: num  0 0 0 27.7 42.4 39.2 79.3 59.1 11.6 8.4 ...
 $ maxfraglenEx: num  31.3 0 0 31.6 27.6 ...
 $ minfraglenEx: num  15 0 0 15.8 17.9 ...
 $ maxfragwidEx: num  20.3 0 0 17.2 18.3 ...
 $ minfragwidEx: num  13.8 0 0 9.4 10.3 ...
 $ Enshape     : num  2 2 2 2 2 2 2 2 2 2 ...
 $ reconEndia  : num  6.3 6.3 7.5 8.7 6.1 10.3 4.5 9 17.1 52.7 ...
 $ Endia       : num  6.3 8.5 7.5 124.6 39.1 ...
 $ reconExdia  : num  31.7 8.5 24.7 35.5 38.1 ...
 $ Exdia       : num  0 31.9 24.7 50.9 38.9 ...
 $ Exshape     : num  2 3 3 3 2 3 2 2 2 3 ...
 $ residue     : num  1 1 1 1 1 1 1 1 1 1 ...
 $ bevEn       : num  1 1 1 1 1 1 1 1 1 1 ...
 $ bevEnloc    : num  1 1 1 2 2 1 1 1 1 2 ...
 $ bevEx       : num  1 1 1 1 1 1 1 1 1 1 ...
 $ bevExloc    : num  3 3 3 3 3 3 3 3 3 3 ...

> measures <- TraumaExitP[,2:40]
> pcsP <- prcomp(measures)
> summary(pcsP)
Importance of components:
              PC1          PC2
Standard deviation  93.6976 66.1562
Proportion of Variance  0.4295 0.2141
Cumulative Proportion  0.4295 0.6436
```

|                        |          |          |
|------------------------|----------|----------|
|                        | PC3      | PC4      |
| Standard deviation     | 54.4753  | 38.60911 |
| Proportion of Variance | 0.1452   | 0.07292  |
| Cumulative Proportion  | 0.7887   | 0.86165  |
|                        | PC5      |          |
| Standard deviation     | 33.38745 |          |
| Proportion of Variance | 0.05453  |          |
| Cumulative Proportion  | 0.91618  |          |
|                        | PC6      |          |
| Standard deviation     | 26.18373 |          |
| Proportion of Variance | 0.03354  |          |
| Cumulative Proportion  | 0.94972  |          |
|                        | PC7      |          |
| Standard deviation     | 19.01861 |          |
| Proportion of Variance | 0.01769  |          |
| Cumulative Proportion  | 0.96741  |          |
|                        | PC8      |          |
| Standard deviation     | 13.96109 |          |
| Proportion of Variance | 0.00953  |          |
| Cumulative Proportion  | 0.97695  |          |
|                        | PC9      |          |
| Standard deviation     | 12.02070 |          |
| Proportion of Variance | 0.00707  |          |
| Cumulative Proportion  | 0.98402  |          |
|                        | PC10     | PC11     |
| Standard deviation     | 10.15398 | 9.68846  |
| Proportion of Variance | 0.00504  | 0.00459  |
| Cumulative Proportion  | 0.98906  | 0.99365  |
|                        | PC12     | PC13     |
| Standard deviation     | 6.3992   | 5.86030  |
| Proportion of Variance | 0.0020   | 0.00168  |
| Cumulative Proportion  | 0.9957   | 0.99734  |
|                        | PC14     | PC15     |
| Standard deviation     | 4.55930  | 4.06847  |
| Proportion of Variance | 0.00102  | 0.00081  |
| Cumulative Proportion  | 0.99835  | 0.99916  |
|                        | PC16     | PC17     |
| Standard deviation     | 2.53058  | 2.19672  |
| Proportion of Variance | 0.00031  | 0.00024  |
| Cumulative Proportion  | 0.99948  | 0.99971  |
|                        | PC18     | PC19     |
| Standard deviation     | 1.64650  | 1.35559  |
| Proportion of Variance | 0.00013  | 0.00009  |
| Cumulative Proportion  | 0.99984  | 0.99993  |
|                        | PC20     | PC21     |
| Standard deviation     | 0.73420  | 0.53304  |
| Proportion of Variance | 0.00003  | 0.00001  |
| Cumulative Proportion  | 0.99996  | 0.99997  |
|                        | PC22     | PC23     |
| Standard deviation     | 0.49016  | 0.33409  |
| Proportion of Variance | 0.00001  | 0.00001  |
| Cumulative Proportion  | 0.99999  | 0.99999  |
|                        | PC24     | PC25     |
| Standard deviation     | 0.2791   | 0.2168   |
| Proportion of Variance | 0.0000   | 0.0000   |
| Cumulative Proportion  | 1.0000   | 1.0000   |
|                        | PC26     | PC27     |
| Standard deviation     | 0.1939   | 0.0944   |
| Proportion of Variance | 0.0000   | 0.0000   |

|                        |           |         |
|------------------------|-----------|---------|
| Cumulative Proportion  | 1.0000    | 1.0000  |
|                        | PC28      | PC29    |
| Standard deviation     | 0.06608   | 0.03895 |
| Proportion of Variance | 0.00000   | 0.00000 |
| Cumulative Proportion  | 1.00000   | 1.00000 |
|                        | PC30      |         |
| Standard deviation     | 0.006756  |         |
| Proportion of Variance | 0.000000  |         |
| Cumulative Proportion  | 1.000000  |         |
|                        | PC31      |         |
| Standard deviation     | 8.379e-15 |         |
| Proportion of Variance | 0.000e+00 |         |
| Cumulative Proportion  | 1.000e+00 |         |

> pcsp

Standard deviations:

|      |              |              |              |
|------|--------------|--------------|--------------|
| [1]  | 9.369758e+01 | 6.615618e+01 | 5.447530e+01 |
| [4]  | 3.860911e+01 | 3.338745e+01 | 2.618373e+01 |
| [7]  | 1.901861e+01 | 1.396109e+01 | 1.202070e+01 |
| [10] | 1.015398e+01 | 9.688458e+00 | 6.399228e+00 |
| [13] | 5.860304e+00 | 4.559298e+00 | 4.068473e+00 |
| [16] | 2.530575e+00 | 2.196723e+00 | 1.646496e+00 |
| [19] | 1.355588e+00 | 7.342043e-01 | 5.330381e-01 |
| [22] | 4.901586e-01 | 3.340854e-01 | 2.791335e-01 |
| [25] | 2.168111e-01 | 1.939359e-01 | 9.440008e-02 |
| [28] | 6.607649e-02 | 3.895041e-02 | 6.755649e-03 |
| [31] | 8.378507e-15 |              |              |

Rotation:

|              |               |               |
|--------------|---------------|---------------|
|              | PC1           | PC2           |
| Entrance     | 1.110223e-16  | 0.000000e+00  |
| Exit         | 0.000000e+00  | 1.110223e-16  |
| numfracEnEx  | 1.956702e-02  | 2.232435e-03  |
| numfracEnIn  | 1.480108e-02  | -5.775587e-03 |
| numfracExEx  | 1.082251e-02  | 1.276776e-02  |
| numfracExIn  | 1.189309e-02  | 1.204247e-02  |
| radfracEnEx  | 6.095115e-04  | -8.313958e-04 |
| radfracEnIn  | 6.095115e-04  | -8.313958e-04 |
| radfracExEx  | 3.995629e-04  | 1.662409e-05  |
| radfracExIn  | 3.995629e-04  | 1.662409e-05  |
| confracEnEx  | 1.657142e-03  | -1.415330e-03 |
| confracEnIn  | 8.723969e-04  | -1.627890e-03 |
| confracExEx  | 3.184800e-04  | 3.355316e-03  |
| confracExIn  | 5.289822e-04  | 4.381911e-04  |
| maxfracExEn  | 4.157253e-01  | -7.822223e-01 |
| minfracEnEx  | 5.988364e-02  | -4.317080e-01 |
| maxfracExEx  | 3.703696e-01  | 1.090354e-01  |
| minfracExEx  | 7.168142e-02  | 5.126331e-03  |
| numfragEn    | 9.157164e-03  | 2.718999e-03  |
| numfragEx    | -3.921923e-03 | 7.424492e-03  |
| maxfraglenEn | 3.640104e-01  | 5.699959e-02  |
| minfraglenEn | 2.871076e-01  | 5.475700e-02  |
| maxfragwidEn | 2.398230e-01  | 5.441801e-02  |
| minfragwidEn | 1.892223e-01  | 7.527527e-02  |
| maxfraglenEx | 2.344843e-01  | 2.216017e-01  |
| minfraglenEx | 2.180333e-01  | 1.551592e-01  |
| maxfragwidEx | 1.785302e-01  | 1.559354e-01  |
| minfragwidEx | 1.498339e-01  | 1.082137e-01  |
| Enshape      | 6.067193e-04  | 5.935165e-04  |
| reconEndia   | 4.324022e-02  | 6.662845e-02  |
| Endia        | 3.463678e-01  | 1.709946e-01  |
| reconExdia   | 1.237029e-01  | 7.559692e-02  |
|              | PC3           | PC4           |
| Entrance     | -3.469447e-17 | -1.110223e-16 |
| Exit         | -7.632783e-17 | 5.551115e-17  |

|              |               |               |
|--------------|---------------|---------------|
| numfracEnEx  | 2.691820e-02  | 3.187900e-02  |
| numfracEnIn  | 1.594644e-02  | 1.395021e-02  |
| numfracExEx  | -1.032954e-02 | -1.098764e-02 |
| numfracExIn  | -1.244801e-02 | -2.064256e-02 |
| radfracEnEx  | -5.122213e-05 | 7.445067e-04  |
| radfracEnIn  | -5.122213e-05 | 7.445067e-04  |
| radfracExEx  | -7.494317e-05 | -1.413221e-04 |
| radfracExIn  | -7.494317e-05 | -1.413221e-04 |
| confracEnEx  | 1.853169e-03  | 3.397046e-03  |
| confracEnIn  | 2.173785e-03  | 2.794714e-03  |
| confracExEx  | -2.489047e-03 | 2.384195e-03  |
| confracExIn  | -1.822830e-03 | 1.046729e-03  |
| maxfracExEn  | 6.139554e-02  | 3.323741e-01  |
| minfracEnEx  | -4.086954e-01 | -4.826171e-01 |
| maxfracExEx  | -2.955115e-01 | 1.209894e-01  |
| minfracExEx  | -1.033557e-01 | 1.605493e-02  |
| numfragEn    | 1.690580e-02  | 1.233788e-02  |
| numfragEx    | 8.406290e-03  | 7.905559e-03  |
| maxfraglenEn | 3.518501e-01  | -3.029102e-01 |
| minfraglenEn | 1.443077e-01  | -5.316132e-01 |
| maxfragwidEn | 2.394493e-01  | -1.209198e-01 |
| minfragwidEn | 8.603312e-02  | -2.535171e-01 |
| maxfraglenEx | -3.366712e-01 | 6.819884e-02  |
| minfraglenEx | -3.367572e-01 | -5.481961e-02 |
| maxfragwidEx | -2.731558e-01 | 6.987460e-02  |
| minfragwidEx | -2.753530e-01 | -5.045510e-02 |
| Enshape      | 3.613462e-04  | 2.477593e-03  |
| reconEndia   | 2.093772e-02  | 9.889700e-02  |
| Endia        | 3.697415e-01  | 2.228238e-01  |
| reconExdia   | 3.530887e-02  | 1.469917e-03  |
|              | PC5           | PC6           |
| Entrance     | 1.318390e-16  | 1.526557e-16  |
| Exit         | -1.110223e-16 | 2.775558e-17  |
| numfracEnEx  | -1.423166e-02 | -7.177501e-03 |
| numfracEnIn  | -3.281435e-02 | -1.728726e-02 |
| numfracExEx  | 3.613855e-03  | -2.827658e-02 |
| numfracExIn  | 6.142762e-03  | -2.517744e-02 |
| radfracEnEx  | -2.072716e-04 | 2.989327e-04  |
| radfracEnIn  | -2.072716e-04 | 2.989327e-04  |
| radfracExEx  | -1.171748e-03 | 1.255464e-03  |
| radfracExIn  | -1.171748e-03 | 1.255464e-03  |
| confracEnEx  | -1.703500e-03 | 5.262128e-04  |
| confracEnIn  | -2.355555e-03 | 5.793515e-04  |
| confracExEx  | 7.511986e-04  | 2.605383e-04  |
| confracExIn  | -1.399129e-03 | -2.572253e-04 |
| maxfracExEn  | 2.707326e-01  | 5.500270e-02  |
| minfracEnEx  | -4.667668e-01 | -3.722043e-01 |
| maxfracExEx  | -3.626522e-01 | 6.528401e-01  |
| minfracExEx  | -8.487764e-03 | 1.111558e-02  |
| numfragEn    | -1.400656e-02 | 2.536130e-03  |
| numfragEx    | 2.175843e-02  | 1.270814e-02  |
| maxfraglenEn | -5.737891e-02 | 1.845719e-01  |
| minfraglenEn | 1.638003e-01  | 9.835222e-02  |
| maxfragwidEn | 6.006405e-02  | 1.719452e-02  |
| minfragwidEn | 1.760271e-01  | -5.643907e-02 |
| maxfraglenEx | 2.551581e-01  | -1.308101e-01 |
| minfraglenEx | 2.523656e-01  | -1.534593e-01 |
| maxfragwidEx | 1.930958e-01  | -7.988327e-02 |
| minfragwidEx | 1.984338e-01  | -1.171416e-01 |
| Enshape      | -1.558132e-03 | -8.715841e-04 |
| reconEndia   | -1.815921e-01 | -7.290383e-02 |
| Endia        | -1.907094e-01 | -5.391942e-01 |
| reconExdia   | -3.947141e-01 | 5.637099e-05  |
|              | PC7           | PC8           |
| Entrance     | 2.775558e-16  | -7.459311e-17 |
| Exit         | -1.110223e-16 | 2.064321e-16  |
| numfracEnEx  | 1.749838e-02  | -2.127974e-02 |

|              |               |               |
|--------------|---------------|---------------|
| numfracEnIn  | 1.406976e-02  | -2.520508e-02 |
| numfracExEx  | -3.012783e-02 | -5.193828e-03 |
| numfracExIn  | -2.127816e-02 | -1.314068e-02 |
| radfracEnEx  | -1.867881e-03 | 1.908938e-04  |
| radfracEnIn  | -1.867881e-03 | 1.908938e-04  |
| radfracExEx  | -1.792968e-03 | -1.605537e-03 |
| radfracExIn  | -1.792968e-03 | -1.605537e-03 |
| confracEnEx  | 3.012613e-03  | -9.199794e-03 |
| confracEnIn  | 3.161160e-03  | -7.192598e-03 |
| confracExEx  | -3.903426e-03 | -6.208669e-03 |
| confracExIn  | -4.424760e-03 | -6.414913e-03 |
| maxfracExEn  | 1.274289e-01  | -1.391914e-02 |
| minfracEnEx  | -1.685983e-01 | -5.954404e-02 |
| maxfracExEx  | -2.168877e-01 | -3.088295e-03 |
| minfracExEx  | -8.745396e-03 | -2.210103e-01 |
| numfragEn    | -1.599191e-02 | 1.689740e-02  |
| numfragEx    | -5.547333e-02 | -5.365237e-02 |
| maxfraglenEn | -4.036509e-02 | 1.358919e-01  |
| minfraglenEn | 2.645895e-03  | -3.468462e-02 |
| maxfragwidEn | 4.615938e-02  | -1.574177e-01 |
| minfragwidEn | -5.451026e-03 | -1.668813e-01 |
| maxfraglenEx | -1.041895e-01 | -3.811330e-01 |
| minfraglenEx | 2.181649e-01  | 4.162956e-01  |
| maxfragwidEx | 4.036148e-02  | -3.013641e-01 |
| minfragwidEx | 2.030669e-01  | 3.459516e-01  |
| Enshape      | -6.681249e-03 | 9.897017e-04  |
| reconEndia   | 3.355106e-01  | -5.357173e-01 |
| Endia        | -2.192145e-01 | 3.352290e-02  |
| reconExdia   | 7.750735e-01  | 5.125227e-02  |
|              | PC9           | PC10          |
| Entrance     | -2.775558e-16 | 1.422473e-16  |
| Exit         | 0.000000e+00  | 1.942890e-16  |
| numfracEnEx  | 2.796942e-02  | -1.030582e-02 |
| numfracEnIn  | 2.274716e-02  | 2.627405e-02  |
| numfracExEx  | -8.576170e-02 | 1.513368e-01  |
| numfracExIn  | -6.723140e-02 | 1.333342e-01  |
| radfracEnEx  | -1.415296e-03 | 1.543492e-03  |
| radfracEnIn  | -1.415296e-03 | 1.543492e-03  |
| radfracExEx  | 7.182861e-04  | 2.313089e-03  |
| radfracExIn  | 7.182861e-04  | 2.313089e-03  |
| confracEnEx  | 1.450145e-02  | -4.625336e-03 |
| confracEnIn  | 1.246333e-02  | 3.697430e-04  |
| confracExEx  | -7.504536e-03 | 1.206515e-02  |
| confracExIn  | -1.036298e-02 | 1.962713e-02  |
| maxfracExEn  | -7.652573e-02 | -1.838910e-02 |
| minfracEnEx  | 9.717272e-02  | 1.866109e-02  |
| maxfracExEx  | -1.236922e-01 | 1.566241e-01  |
| minfracExEx  | 3.772329e-01  | -9.935234e-02 |
| numfragEn    | 3.836578e-02  | -2.647285e-02 |
| numfragEx    | 1.569122e-02  | 8.028789e-03  |
| maxfraglenEn | 3.695861e-01  | -4.854194e-01 |
| minfraglenEn | -5.156561e-01 | -1.502289e-01 |
| maxfragwidEn | 5.545420e-01  | 5.012139e-01  |
| minfragwidEn | -1.778366e-01 | 5.614041e-01  |
| maxfraglenEx | 7.288930e-02  | -2.679697e-01 |
| minfraglenEx | 3.674564e-02  | 5.066648e-03  |
| maxfragwidEx | -3.539240e-02 | -3.730937e-02 |
| minfragwidEx | 1.337613e-01  | 4.846414e-02  |
| Enshape      | 3.717070e-03  | -6.222799e-03 |
| reconEndia   | -9.090786e-02 | -1.319484e-01 |
| Endia        | -1.720863e-01 | -1.921424e-02 |
| reconExdia   | -6.421386e-02 | 2.621209e-02  |
|              | PC11          | PC12          |
| Entrance     | -8.604228e-16 | 2.012279e-16  |
| Exit         | 1.665335e-16  | -3.053113e-16 |
| numfracEnEx  | 2.823872e-02  | 9.969095e-02  |
| numfracEnIn  | 5.110022e-02  | 1.323234e-01  |

|              |               |               |
|--------------|---------------|---------------|
| numfracExEx  | -2.535474e-02 | 5.929126e-03  |
| numfracExIn  | -9.016238e-03 | -1.211083e-03 |
| radfracEnEx  | -7.220793e-03 | 5.197546e-03  |
| radfracEnIn  | -7.220793e-03 | 5.197546e-03  |
| radfracExEx  | 3.020812e-03  | -6.489483e-03 |
| radfracExIn  | 3.020812e-03  | -6.489483e-03 |
| confracEnEx  | 1.254285e-02  | -1.508462e-03 |
| confracEnIn  | 1.144676e-02  | 1.220153e-03  |
| confracExEx  | -1.603728e-02 | -1.832471e-02 |
| confracExIn  | 2.452901e-03  | -2.322008e-03 |
| maxfracExEn  | -1.638040e-02 | -4.346500e-03 |
| minfracEnEx  | 2.961464e-02  | 7.998887e-02  |
| maxfracExEx  | 2.786629e-01  | 6.037819e-02  |
| minfracExEx  | -4.769732e-02 | -7.433116e-01 |
| numfragEn    | 1.291063e-02  | 5.958299e-02  |
| numfragEx    | 9.755035e-03  | 1.708332e-02  |
| maxfraglenEn | -6.377845e-02 | 2.153313e-01  |
| minfraglenEn | -1.896037e-01 | -2.634349e-01 |
| maxfragwidEn | -3.133076e-02 | 8.737990e-02  |
| minfragwidEn | -9.035635e-02 | 4.227708e-02  |
| maxfraglenEx | 9.123364e-02  | 1.290220e-01  |
| minfraglenEx | 1.789376e-02  | 1.821954e-01  |
| maxfragwidEx | 4.617786e-02  | -1.319665e-01 |
| minfragwidEx | 7.668536e-02  | 1.289851e-02  |
| Enshape      | 1.827311e-03  | -1.272847e-03 |
| reconEndia   | -2.497146e-01 | 3.958561e-01  |
| Endia        | 4.711105e-01  | -7.606461e-02 |
| reconExdia   | 1.270928e-01  | -2.102273e-01 |
|              | PC13          | PC14          |
| Entrance     | -3.469447e-16 | 1.819725e-15  |
| Exit         | 2.220446e-16  | -2.949030e-16 |
| numfracEnEx  | -7.492615e-02 | 9.194832e-02  |
| numfracEnIn  | -1.470974e-01 | 1.011067e-01  |
| numfracExEx  | 1.922508e-01  | 2.674784e-01  |
| numfracExIn  | 1.989013e-01  | 2.935217e-01  |
| radfracEnEx  | -4.043136e-03 | 2.797110e-03  |
| radfracEnIn  | -4.043136e-03 | 2.797110e-03  |
| radfracExEx  | -3.495854e-03 | 9.832569e-03  |
| radfracExIn  | -3.495854e-03 | 9.832569e-03  |
| confracEnEx  | -2.717630e-02 | 1.471852e-02  |
| confracEnIn  | -3.669380e-02 | 8.554124e-03  |
| confracExEx  | -4.357501e-03 | 2.360547e-02  |
| confracExIn  | -8.573518e-03 | 1.817106e-02  |
| maxfracExEn  | 1.995368e-02  | 2.345146e-02  |
| minfracEnEx  | 3.681452e-02  | -3.907632e-02 |
| maxfracExEx  | -1.375567e-01 | -4.952340e-03 |
| minfracExEx  | -3.903401e-01 | 1.837354e-01  |
| numfragEn    | -1.825628e-02 | -2.836661e-02 |
| numfragEx    | 7.680288e-02  | 9.073715e-02  |
| maxfraglenEn | 1.140286e-01  | -8.510068e-02 |
| minfraglenEn | -7.605594e-02 | 4.344868e-02  |
| maxfragwidEn | 8.510958e-02  | 8.762562e-03  |
| minfragwidEn | -7.707688e-02 | -2.115756e-02 |
| maxfraglenEx | 3.216923e-01  | 3.968935e-01  |
| minfraglenEx | -2.773569e-01 | 2.990105e-01  |
| maxfragwidEx | 2.928035e-01  | -6.218537e-01 |
| minfragwidEx | -1.959546e-01 | -3.443546e-01 |
| Enshape      | -3.573592e-03 | -1.176529e-02 |
| reconEndia   | -4.757231e-01 | -4.554536e-02 |
| Endia        | -1.463075e-01 | -2.388398e-02 |
| reconExdia   | 3.372790e-01  | 1.036230e-01  |
|              | PC15          | PC16          |
| Entrance     | 5.793976e-16  | 3.246969e-15  |
| Exit         | -2.151057e-16 | -3.903128e-16 |
| numfracEnEx  | -1.421749e-01 | -2.393673e-01 |
| numfracEnIn  | -2.027739e-01 | -3.501618e-01 |
| numfracExEx  | -5.462975e-01 | 5.825800e-02  |

|              |               |               |
|--------------|---------------|---------------|
| numfracEnIn  | -5.602620e-01 | -1.499349e-02 |
| radfracEnEx  | -8.850591e-03 | -2.846113e-03 |
| radfracEnIn  | -8.850591e-03 | -2.846113e-03 |
| radfracExEx  | -1.515213e-02 | -1.314972e-03 |
| radfracExIn  | -1.515213e-02 | -1.314972e-03 |
| confracEnEx  | -8.257834e-03 | -6.594271e-02 |
| confracEnIn  | -1.433394e-02 | -5.684982e-02 |
| confracExEx  | -1.562756e-02 | -2.976988e-02 |
| confracExIn  | -1.221929e-02 | -3.931740e-02 |
| maxfracExEn  | 4.616959e-03  | -1.576121e-02 |
| minfracEnEx  | 1.521763e-02  | 2.608895e-02  |
| maxfracExEx  | -3.257199e-03 | 3.695500e-02  |
| minfracExEx  | -8.522237e-02 | -7.803101e-02 |
| numfragEn    | -2.977010e-02 | -2.680106e-02 |
| numfragEx    | -1.281789e-01 | 1.715001e-02  |
| maxfraglenEn | -1.019969e-01 | -1.572599e-01 |
| minfraglenEn | -3.783858e-02 | 1.720802e-01  |
| maxfragwidEn | 2.422947e-02  | 3.453573e-01  |
| minfragwidEn | 2.369556e-01  | -4.415045e-01 |
| maxfraglenEx | 2.617820e-01  | -2.089249e-01 |
| minfraglenEx | 7.706145e-02  | 4.021403e-01  |
| maxfragwidEx | -2.199679e-01 | 2.036144e-01  |
| minfragwidEx | -2.523517e-01 | -3.874222e-01 |
| Enshape      | 1.108812e-02  | 5.633551e-02  |
| reconEndia   | -1.563232e-01 | 1.056841e-01  |
| Endia        | -1.493699e-02 | 6.477053e-02  |
| reconExdia   | 1.244430e-01  | -9.262750e-02 |
| PC17         |               | PC18          |
| Entrance     | 2.224241e-16  | 5.231059e-15  |
| Exit         | 9.571337e-16  | -1.143183e-15 |
| numfracEnEx  | -4.816094e-02 | -4.911865e-01 |
| numfracEnIn  | 1.294925e-01  | -5.492906e-01 |
| numfracExEx  | 5.121686e-02  | 3.296564e-01  |
| numfracExIn  | 8.032792e-02  | 4.810597e-02  |
| radfracEnEx  | -6.158326e-04 | -1.004371e-02 |
| radfracEnIn  | -6.158326e-04 | -1.004371e-02 |
| radfracExEx  | 4.806270e-03  | 5.858114e-02  |
| radfracExIn  | 4.806270e-03  | 5.858114e-02  |
| confracEnEx  | 2.740102e-02  | -6.360187e-02 |
| confracEnIn  | 3.580762e-02  | -1.355582e-02 |
| confracExEx  | -3.444921e-03 | 5.009530e-02  |
| confracExIn  | 1.230103e-02  | 5.834276e-02  |
| maxfracExEn  | -4.724095e-03 | 1.951521e-02  |
| minfracEnEx  | 2.832227e-03  | -1.587991e-02 |
| maxfracExEx  | -3.309671e-02 | 3.376961e-02  |
| minfracExEx  | 1.415090e-01  | 5.336316e-02  |
| numfragEn    | 1.039041e-01  | -9.251041e-02 |
| numfragEx    | -1.212081e-01 | -2.631443e-01 |
| maxfraglenEn | 2.784646e-01  | 1.539223e-01  |
| minfraglenEn | -3.026600e-01 | -1.834658e-01 |
| maxfragwidEn | -3.108187e-01 | -1.493576e-01 |
| minfragwidEn | 3.794592e-01  | 1.818261e-01  |
| maxfraglenEx | -2.166598e-01 | 6.243490e-02  |
| minfraglenEx | 3.420509e-01  | -9.684185e-02 |
| maxfragwidEx | 3.155062e-01  | -1.854546e-01 |
| minfragwidEx | -4.777530e-01 | 1.999277e-01  |
| Enshape      | 5.351852e-03  | 1.331407e-02  |
| reconEndia   | -6.460987e-02 | 1.617249e-01  |
| Endia        | -3.046800e-02 | 4.400934e-02  |
| reconExdia   | 2.043190e-02  | -4.278748e-02 |
| PC19         |               | PC20          |
| Entrance     | 5.146925e-15  | 4.848552e-16  |
| Exit         | -8.951173e-16 | -3.231790e-15 |
| numfracEnEx  | 2.570401e-01  | 6.178995e-01  |
| numfracEnIn  | 1.074550e-01  | -3.088675e-01 |
| numfracExEx  | 1.843775e-01  | 2.198684e-01  |
| numfracExIn  | -8.214917e-02 | -2.490837e-01 |

|              |               |               |
|--------------|---------------|---------------|
| radfracEnEx  | 4.790344e-02  | 4.590032e-02  |
| radfracEnIn  | 4.790344e-02  | 4.590032e-02  |
| radfracExEx  | -1.101344e-02 | -2.998226e-02 |
| radfracExIn  | -1.101344e-02 | -2.998226e-02 |
| confracEnEx  | 6.715346e-03  | -1.900901e-01 |
| confracEnIn  | 8.634595e-02  | -1.496400e-01 |
| confracExEx  | 3.329182e-02  | 6.474771e-02  |
| confracExIn  | 3.924093e-02  | 1.268082e-01  |
| maxfracExEn  | -8.598350e-03 | -9.718124e-03 |
| minfracEnEx  | -4.926378e-03 | 1.549497e-02  |
| maxfracExEx  | -5.205605e-03 | 5.474543e-03  |
| minfracExEx  | -2.899130e-02 | 2.663636e-02  |
| numfragEn    | 1.283494e-01  | -4.507824e-01 |
| numfragEx    | -8.822178e-01 | 7.981676e-02  |
| maxfraglenEn | -7.247367e-02 | 6.425860e-02  |
| minfraglenEn | 9.007865e-02  | -6.586925e-02 |
| maxfragwidEn | 1.146524e-01  | -6.914887e-02 |
| minfragwidEn | -1.328232e-01 | 7.449109e-02  |
| maxfraglenEx | 7.134566e-02  | -7.373255e-02 |
| minfraglenEx | -4.393152e-02 | 6.235771e-02  |
| maxfragwidEx | 2.433454e-02  | 6.527320e-02  |
| minfragwidEx | -4.902133e-02 | -5.221964e-02 |
| Enshape      | 5.219141e-02  | -5.802039e-02 |
| reconEndia   | -5.620940e-02 | -8.588437e-03 |
| Endia        | -1.979437e-02 | 6.620092e-03  |
| reconExdia   | -2.307221e-02 | -7.974421e-03 |
| PC21         |               | PC22          |
| Entrance     | -2.506242e-15 | 1.321339e-14  |
| Exit         | 4.763551e-15  | -1.477984e-15 |
| numfracEnEx  | -1.839291e-01 | -3.039313e-01 |
| numfracEnIn  | 2.709682e-01  | 3.536056e-01  |
| numfracExEx  | -2.860981e-02 | 4.235262e-01  |
| numfracExIn  | -2.108128e-02 | -4.688026e-01 |
| radfracEnEx  | 7.734723e-02  | 9.667645e-02  |
| radfracEnIn  | 7.734723e-02  | 9.667645e-02  |
| radfracExEx  | -8.543088e-02 | -3.837089e-02 |
| radfracExIn  | -8.543088e-02 | -3.837089e-02 |
| confracEnEx  | 1.232106e-01  | 1.080421e-01  |
| confracEnIn  | 6.376417e-03  | 2.681772e-01  |
| confracExEx  | 1.064023e-01  | -1.548896e-01 |
| confracExIn  | 1.426303e-01  | -7.912615e-02 |
| maxfracExEn  | -2.318537e-03 | -3.152275e-04 |
| minfracEnEx  | -1.703018e-03 | -7.307848e-03 |
| maxfracExEx  | -8.723863e-03 | -5.621213e-03 |
| minfracExEx  | -3.139003e-02 | -1.236028e-02 |
| numfragEn    | -6.318875e-01 | -1.444646e-01 |
| numfragEx    | -6.648528e-02 | 7.324549e-02  |
| maxfraglenEn | 1.426673e-02  | 2.701544e-03  |
| minfraglenEn | 6.540561e-03  | 1.695372e-02  |
| maxfragwidEn | 5.422302e-02  | 7.714860e-03  |
| minfragwidEn | -6.878346e-02 | -3.170108e-02 |
| maxfraglenEx | 1.910790e-02  | -2.569603e-03 |
| minfraglenEx | -1.509521e-02 | 1.329906e-02  |
| maxfragwidEx | 1.561977e-02  | 2.988110e-02  |
| minfragwidEx | -4.297539e-03 | -2.489885e-02 |
| Enshape      | 8.805576e-02  | -1.372799e-01 |
| reconEndia   | -2.579401e-02 | -2.534844e-02 |
| Endia        | -9.266945e-03 | -3.566490e-04 |
| reconExdia   | -2.520078e-03 | 1.158941e-02  |
| PC23         |               | PC24          |
| Entrance     | 2.224739e-14  | 1.593994e-15  |
| Exit         | -1.911665e-15 | 2.951632e-15  |
| numfracEnEx  | -5.156910e-02 | -2.188499e-01 |
| numfracEnIn  | 2.101374e-02  | 2.716265e-01  |
| numfracExEx  | -1.541315e-01 | -9.359497e-02 |
| numfracExIn  | 1.577606e-01  | 4.575868e-02  |
| radfracEnEx  | 1.169653e-01  | 1.084569e-01  |



|              |               |               |
|--------------|---------------|---------------|
| radfracEnIn  | 1.169653e-01  | 1.084569e-01  |
| radfracExEx  | 9.880748e-02  | -3.988033e-03 |
| radfracExIn  | 9.880748e-02  | -3.988033e-03 |
| confracEnEx  | 3.880848e-01  | -3.464452e-01 |
| confracEnIn  | 2.561533e-01  | -5.044967e-01 |
| confracExEx  | 3.075332e-01  | 4.245086e-01  |
| confracExIn  | 2.203947e-01  | 2.921504e-01  |
| maxfracExEn  | -1.314848e-03 | 1.527805e-03  |
| minfracEnEx  | -2.370746e-03 | -7.466445e-03 |
| maxfracExEx  | 1.979418e-03  | -8.248916e-04 |
| minfracExEx  | -2.332702e-02 | -1.253661e-03 |
| numfragEn    | -7.721820e-02 | 1.143553e-01  |
| numfragEx    | -7.332252e-03 | -8.859702e-02 |
| maxfraglenEn | -7.162315e-04 | -6.342873e-03 |
| minfraglenEn | 1.160444e-02  | 1.257695e-02  |
| maxfragwidEn | -1.137501e-02 | 1.834667e-02  |
| minfragwidEn | -1.588248e-02 | -3.535370e-02 |
| maxfraglenEx | -4.439041e-02 | -2.685364e-03 |
| minfraglenEx | 4.171249e-02  | 3.585817e-03  |
| maxfragwidEx | 4.542697e-02  | 2.018569e-02  |
| minfragwidEx | -3.362026e-02 | -7.251560e-03 |
| Enshape      | 1.595166e-01  | -2.217353e-01 |
| reconEndia   | 1.420753e-03  | -1.128194e-02 |
| Endia        | 1.134947e-02  | 6.859460e-03  |
| reconExdia   | -5.689415e-03 | 9.426700e-04  |
| PC25         |               | PC26          |
| Entrance     | 5.443562e-15  | -8.676870e-16 |
| Exit         | -1.850083e-15 | 6.587612e-16  |
| numfracEnEx  | -5.221783e-02 | 6.870463e-02  |
| numfracEnIn  | -1.532294e-02 | -1.462911e-01 |
| numfracExEx  | 3.612639e-02  | 1.953405e-01  |
| numfracExIn  | -1.889235e-02 | -2.647982e-01 |
| radfracEnEx  | 2.272513e-01  | 1.155749e-01  |
| radfracEnIn  | 2.272513e-01  | 1.155749e-01  |
| radfracExEx  | -2.020208e-03 | -1.270846e-01 |
| radfracExIn  | -2.020208e-03 | -1.270846e-01 |
| confracEnEx  | 9.965436e-02  | -1.928648e-02 |
| confracEnIn  | -2.923919e-01 | 3.355035e-01  |
| confracExEx  | 1.922431e-01  | 3.355170e-01  |
| confracExIn  | -7.320037e-02 | 4.752480e-01  |
| maxfracExEn  | 2.480742e-03  | 6.930654e-04  |
| minfracEnEx  | 2.545489e-03  | 1.041997e-02  |
| maxfracExEx  | 4.729364e-03  | -1.093035e-02 |
| minfracExEx  | 2.885013e-03  | -2.796248e-03 |
| numfragEn    | -2.278319e-01 | 3.875664e-01  |
| numfragEx    | 3.459151e-02  | 2.339249e-01  |
| maxfraglenEn | 3.121846e-02  | -2.174639e-02 |
| minfraglenEn | -3.003164e-02 | 2.430290e-02  |
| maxfragwidEn | -9.469705e-03 | 1.872830e-02  |
| minfragwidEn | 6.949365e-03  | -1.945720e-02 |
| maxfraglenEx | 9.853816e-03  | 1.383074e-02  |
| minfraglenEx | 7.658419e-03  | -1.129521e-03 |
| maxfragwidEx | -2.212354e-02 | -9.911484e-03 |
| minfragwidEx | -5.320562e-03 | 6.888480e-03  |
| Enshape      | 1.196018e-03  | -1.134697e-01 |
| reconEndia   | 3.118379e-02  | -9.640931e-03 |
| Endia        | 8.180233e-03  | -1.060021e-02 |
| reconExdia   | -1.328904e-02 | 2.586229e-02  |
| PC27         |               | PC28          |
| Entrance     | -2.848001e-14 | -3.718938e-14 |
| Exit         | -3.024089e-14 | -5.198550e-15 |
| numfracEnEx  | 4.978135e-02  | 2.371398e-02  |
| numfracEnIn  | -2.639036e-02 | -4.610128e-02 |
| numfracExEx  | -4.893671e-02 | -5.901509e-02 |
| numfracExIn  | -6.927499e-03 | 5.255610e-02  |
| radfracEnEx  | 1.379364e-01  | 1.297020e-02  |
| radfracEnIn  | 1.379364e-01  | 1.297020e-02  |

|              |               |               |
|--------------|---------------|---------------|
| radfracExEx  | 5.542637e-01  | 1.502308e-02  |
| radfracExIn  | 5.542637e-01  | 1.502308e-02  |
| confracEnEx  | 1.271401e-01  | 1.782041e-01  |
| confracEnIn  | -8.465819e-03 | -5.711733e-02 |
| confracExEx  | -2.757928e-01 | -1.313323e-01 |
| confracExIn  | 2.723995e-01  | 4.583800e-01  |
| maxfracExEn  | -2.764513e-03 | 2.381582e-04  |
| minfracEnEx  | 3.382925e-03  | 3.619480e-04  |
| maxfracExEx  | -6.546635e-03 | -2.321518e-03 |
| minfracExEx  | -1.872018e-02 | -1.277853e-02 |
| numfragEn    | -3.011664e-02 | -2.307767e-02 |
| numfragEx    | -6.879080e-03 | 4.912443e-03  |
| maxfraglenEn | -1.240046e-02 | 1.291851e-02  |
| minfraglenEn | 1.655427e-02  | -1.099242e-02 |
| maxfragwidEn | 2.858596e-02  | -3.222276e-03 |
| minfragwidEn | -3.075253e-02 | 8.860598e-03  |
| maxfraglenEx | 2.510204e-03  | 4.081984e-03  |
| minfraglenEx | 4.654623e-03  | -1.155996e-02 |
| maxfragwidEx | 1.529691e-02  | -4.713551e-03 |
| minfragwidEx | -1.499503e-02 | 1.767193e-02  |
| Enshape      | -3.792309e-01 | 6.375373e-01  |
| reconEndia   | -1.098429e-02 | 1.544696e-03  |
| Endia        | -5.929064e-03 | -4.204208e-03 |
| reconExdia   | 3.841382e-05  | 2.173700e-03  |
| PC29         |               | PC30          |
| Entrance     | 6.467811e-14  | -8.252436e-13 |
| Exit         | -7.470635e-14 | 6.753966e-14  |
| numfracEnEx  | -9.060235e-02 | -2.800781e-02 |
| numfracEnIn  | 5.067086e-02  | 1.741706e-01  |
| numfracExEx  | -5.880189e-02 | 2.330811e-01  |
| numfracExIn  | 1.066748e-01  | -2.818556e-01 |
| radfracEnEx  | 1.491082e-01  | 8.714759e-02  |
| radfracEnIn  | 1.491082e-01  | 8.714759e-02  |
| radfracExEx  | -2.495853e-01 | 2.604552e-01  |
| radfracExIn  | -2.495853e-01 | 2.604552e-01  |
| confracEnEx  | -2.532684e-01 | -3.063592e-01 |
| confracEnIn  | -6.220055e-02 | -2.034492e-01 |
| confracExEx  | -6.460857e-01 | -3.750475e-02 |
| confracExIn  | 4.071783e-01  | -1.330597e-01 |
| maxfracExEn  | 1.710911e-03  | 2.564774e-03  |
| minfracEnEx  | -8.397990e-03 | -3.377550e-03 |
| maxfracExEx  | 1.259980e-03  | -1.120715e-02 |
| minfracExEx  | 2.935295e-02  | 2.369054e-02  |
| numfragEn    | 5.600733e-03  | 1.889403e-01  |
| numfragEx    | -2.151694e-02 | 1.349642e-01  |
| maxfraglenEn | 2.423873e-04  | -1.711596e-02 |
| minfraglenEn | 1.492637e-03  | 1.734570e-02  |
| maxfragwidEn | -1.450955e-02 | -1.291122e-02 |
| minfragwidEn | 5.340685e-03  | 1.782181e-02  |
| maxfraglenEx | 1.835866e-03  | 1.608550e-02  |
| minfraglenEx | -1.027090e-03 | -1.350856e-02 |
| maxfragwidEx | -1.434669e-02 | -8.876312e-03 |
| minfragwidEx | 3.048094e-03  | 8.206396e-03  |
| Enshape      | -7.261252e-02 | 5.568199e-01  |
| reconEndia   | 1.252761e-02  | -2.311267e-02 |
| Endia        | 3.841118e-03  | -1.373706e-02 |
| reconExdia   | -3.865826e-03 | 2.929330e-02  |
| PC31         |               |               |
| Entrance     | -9.758348e-01 |               |
| Exit         | 1.705857e-01  |               |
| numfracEnEx  | 2.803016e-03  |               |
| numfracEnIn  | -8.356539e-03 |               |
| numfracExEx  | -1.795533e-02 |               |
| numfracExIn  | 1.874837e-02  |               |
| radfracEnEx  | 9.750379e-03  |               |
| radfracEnIn  | 7.937103e-02  |               |
| radfracExEx  | 6.267935e-02  |               |

```

radfracExIn -6.153378e-02
confracEnEx -3.283051e-02
confracEnIn 3.571736e-02
confracExEx 3.437112e-03
confracExIn -2.573822e-02
maxfracExEn -3.424516e-05
minfracEnEx 4.958255e-05
maxfracExEx 4.670180e-04
minfracExEx -1.844687e-04
numfragEn -3.528901e-03
numfragEx -1.217550e-03
maxfraglenEn 6.928136e-04
minfraglenEn -1.719538e-03
maxfragwidEn -9.989035e-04
minfragwidEn 2.160019e-03
maxfraglenEx 2.342515e-04
minfraglenEx -8.811900e-04
maxfragwidEx -7.451229e-04
minfragwidEx 1.261368e-03
Enshape 8.502920e-03
reconEndia 1.718207e-04
Endia 6.138443e-04
reconExdia 9.910731e-05
[ reached getOption("max.print") -- omitted 7 rows ]
> pcTraumaExitP <- TraumaExitP
> pcTraumaExitP$pc1 <- pcsP$x[,1]
> pcTraumaExitP$pc2 <- pcsP$x[,2]
> str(pcTraumaExitP)
'data.frame': 31 obs. of 42 variables:
 $ Weapon : Factor w/ 5 levels "Crossbow (Field Tip)",...: 4 4 4
4 4 4 4 4 4 4 ...
 $ Entrance : num 1 1 1 1 1 1 1 1 1 1 ...
 $ Exit : num 1 1 1 1 1 1 1 1 1 1 ...
 $ numfracEnEx : num 0 5 2 10 10 12 5 6 12 11 ...
 $ numfracEnIn : num 0 5 10 9 11 11 5 6 12 11 ...
 $ numfracExEx : num 3 9 7 8 5 14 15 15 7 6 ...
 $ numfracExIn : num 5 6 8 7 7 15 15 15 7 6 ...
 $ radfracEnEx : num 0 1 1 1 1 1 1 1 1 1 ...
 $ radfracEnIn : num 0 1 1 1 1 1 1 1 1 1 ...
 $ radfracExEx : num 1 1 1 1 1 1 1 1 1 1 ...
 $ radfracExIn : num 1 1 1 1 1 1 1 1 1 1 ...
 $ confracEnEx : num 0 0 1 1 1 1 0 0 1 1 ...
 $ confracEnIn : num 0 1 1 1 1 1 0 0 1 1 ...
 $ confracExEx : num 0 0 0 0 0 1 1 1 0 1 ...
 $ confracExIn : num 0 1 1 1 1 1 1 1 0 1 ...
 $ maxfracExEn : num 0 220 231 267 204 ...
 $ minfracEnEx : num 0 87.2 215.9 26.6 68.2 ...
 $ maxfracExEx : num 18.4 51 53.3 53.3 154.1 ...
 $ minfracExEx : num 12.9 9.7 26.3 5 14.3 28.1 31.5 41.4 11.1 19.5
...
 $ numfragEn : num 0 0 0 3 4 3 1 1 7 3 ...
 $ numfragEx : num 5 0 0 4 3 7 1 1 3 0 ...
 $ maxfraglenEn: num 0 0 0 81.6 106.6 ...
 $ minfraglenEn: num 0 0 0 40.5 75.2 ...
 $ maxfragwidEn: num 0 0 0 53.1 63.4 66 79.3 59.1 43.5 50.2 ...
 $ minfragwidEn: num 0 0 0 27.7 42.4 39.2 79.3 59.1 11.6 8.4 ...
 $ maxfraglenEx: num 31.3 0 0 31.6 27.6 ...
 $ minfraglenEx: num 15 0 0 15.8 17.9 ...
 $ maxfragwidEx: num 20.3 0 0 17.2 18.3 ...
 $ minfragwidEx: num 13.8 0 0 9.4 10.3 ...
 $ Enshape : num 2 2 2 2 2 2 2 2 2 ...
 $ reconEndia : num 6.3 6.3 7.5 8.7 6.1 10.3 4.5 9 17.1 52.7 ...
 $ Endia : num 6.3 8.5 7.5 124.6 39.1 ...
 $ reconExdia : num 31.7 8.5 24.7 35.5 38.1 ...
 $ Exdia : num 0 31.9 24.7 50.9 38.9 ...
 $ Exshape : num 2 3 3 3 2 3 2 2 2 3 ...
 $ residue : num 1 1 1 1 1 1 1 1 1 1 ...

```

```

$ bevEn      : num  1 1 1 1 1 1 1 1 1 1 ...
$ bevEnloc   : num  1 1 1 2 2 1 1 1 1 2 ...
$ bevEx      : num  1 1 1 1 1 1 1 1 1 1 ...
$ bevExloc   : num  3 3 3 3 3 3 3 3 3 3 ...
$ pc1        : num -160.5 -61 -47.3 79 84.8 ...
$ pc2        : num  109.2 -107.5 -170.9 -67.5 -37.1 ...

```

## Exit Features Excluded

```

> measuresA <- TraumaExitA[,2:21]
> pcsA <- prcomp(measuresA)
> pcsA

```

Standard deviations:

```

[1] 94.2136363 54.8902066 32.9429004 23.9253495
[5] 14.5544182 13.2691223 9.9254238 8.8153749
[9] 2.7186952 2.2726027 1.7269937 0.6929487
[13] 0.4574706 0.3833629 0.3410266 0.2449010
[17] 0.1671448 0.1383068 0.1317736 0.1066058

```

Rotation:

|              | PC1           | PC2           | PC3           |
|--------------|---------------|---------------|---------------|
| Entrance     | -0.002166654  | 0.0002675824  | -0.0012572906 |
| numfracEnEx  | -0.019277912  | -0.0321959708 | -0.0578312892 |
| numfracEnIn  | -0.021255165  | -0.0226684141 | -0.0581630179 |
| radfracEnEx  | -0.001887319  | 0.0003101986  | -0.0010368521 |
| radfracEnIn  | -0.002126832  | 0.0004794906  | -0.0016026759 |
| confracEnEx  | -0.002775171  | -0.0002812141 | -0.0024958811 |
| confracEnIn  | -0.002724217  | 0.0003506550  | -0.0022946242 |
| maxfracEnEx  | -0.853223314  | 0.3349841511  | -0.3500928918 |
| minfracEnEx  | -0.248879050  | 0.3995705863  | 0.6939647433  |
| numfragEn    | 0.003331384   | -0.0404035391 | -0.1153172563 |
| maxfraglenEn | -0.269115395  | -0.4667092391 | 0.2130306014  |
| minfraglenEn | -0.197758719  | -0.3014111249 | 0.4535081352  |
| maxfragwidEn | -0.173050416  | -0.3124624133 | 0.0603020762  |
| minfragwidEn | -0.119765596  | -0.2138940071 | 0.2186423402  |
| Enshape      | -0.001092895  | -0.0005578258 | -0.0044351382 |
| reconEndia   | -0.008952263  | -0.0960035086 | -0.1328577387 |
| Endia        | -0.230849720  | -0.5134929832 | -0.2358601993 |
| residue      | -0.002590273  | 0.0006709136  | -0.0018799680 |
| bevEn        | -0.001256673  | 0.0002187721  | -0.0006724284 |
| bevEnloc     | -0.001924702  | -0.0018355335 | -0.0028931559 |
|              | PC4           | PC5           | PC6           |
| Entrance     | 0.0009988077  | -0.0030590474 | 0.004663497   |
| numfracEnEx  | 0.0480255211  | -0.1488946543 | 0.076011834   |
| numfracEnIn  | 0.0967433926  | -0.1508228685 | 0.175098010   |
| radfracEnEx  | 0.0006823520  | -0.0029518570 | 0.003667008   |
| radfracEnIn  | 0.0016449873  | -0.0026655820 | 0.003900997   |
| confracEnEx  | 0.0017874624  | -0.0001264790 | -0.003121775  |
| confracEnIn  | 0.0018435709  | 0.0001966821  | -0.003336163  |
| maxfracEnEx  | -0.1797805722 | 0.0402108431  | 0.041532354   |
| minfracEnEx  | 0.5272746723  | -0.0805521748 | -0.052687240  |
| numfragEn    | 0.0689822345  | -0.5625884100 | 0.279136412   |
| maxfraglenEn | -0.0796620446 | -0.5522862108 | -0.137872455  |
| minfraglenEn | -0.3436281840 | 0.2601348860  | 0.304256900   |
| maxfragwidEn | -0.0762960185 | -0.1641074790 | -0.068833635  |
| minfragwidEn | -0.1954309768 | 0.3607712480  | 0.162436115   |
| Enshape      | 0.0033813239  | -0.0042555451 | 0.007157287   |
| reconEndia   | 0.3538423627  | 0.0622809410  | 0.812571694   |
| Endia        | 0.6160899638  | 0.3110291146  | -0.279326485  |
| residue      | 0.0012991479  | -0.0038027198 | 0.002562221   |
| bevEn        | 0.0003576496  | -0.0020957602 | 0.002291068   |
| bevEnloc     | -0.0002998919 | -0.0037370130 | -0.003140435  |
|              | PC7           | PC8           | PC9           |

|              |               |               |               |
|--------------|---------------|---------------|---------------|
| Entrance     | -0.001011909  | 0.0006750869  | -0.008218626  |
| numfracEnEx  | -0.121407527  | 0.0282835962  | -0.116850755  |
| numfracEnIn  | -0.129232012  | 0.0241572548  | -0.904923179  |
| radfracEnEx  | -0.001294012  | 0.0008654953  | -0.012562241  |
| radfracEnIn  | -0.001367757  | -0.0002725789 | -0.014383631  |
| confracEnEx  | 0.014514987   | 0.0070852164  | -0.032508350  |
| confracEnIn  | 0.014715387   | 0.0078708579  | -0.036777222  |
| maxfracEnEx  | 0.008337097   | -0.0316126757 | 0.013173518   |
| minfracEnEx  | -0.035399462  | 0.0887794351  | 0.016720527   |
| numfragEn    | -0.687274938  | 0.0318989524  | 0.281967257   |
| maxfraglenEn | 0.360621840   | -0.2568593788 | -0.089217221  |
| minfraglenEn | -0.201405460  | -0.3957916856 | 0.088418214   |
| maxfragwidEn | 0.172350450   | 0.7468549358  | 0.142691846   |
| minfragwidEn | -0.283628111  | 0.4361475491  | -0.175298453  |
| Enshape      | -0.010476101  | -0.0048066933 | 0.025434489   |
| reconEndia   | 0.402926011   | 0.0240671419  | 0.121543318   |
| Endia        | -0.226322666  | -0.1317439952 | 0.039354716   |
| residue      | -0.002658101  | -0.0002427059 | -0.009864120  |
| bevEn        | -0.001008210  | 0.0006697996  | -0.013363719  |
| bevEnloc     | 0.002651269   | 0.0004948696  | -0.023394633  |
|              | PC10          | PC11          | PC12          |
| Entrance     | 0.0139202971  | -0.025633421  | 0.1739385085  |
| numfracEnEx  | 0.1091048235  | -0.954506195  | -0.0649215489 |
| numfracEnIn  | -0.2717859821 | 0.146548829   | 0.0003403455  |
| radfracEnEx  | 0.0139465031  | -0.058671351  | 0.2344472889  |
| radfracEnIn  | 0.0047305731  | -0.005764304  | 0.1220273786  |
| confracEnEx  | 0.0128126476  | -0.043468809  | -0.0580375813 |
| confracEnIn  | 0.0157982557  | -0.044224650  | -0.0526233102 |
| maxfracEnEx  | 0.0110025575  | 0.013262294   | -0.0032569465 |
| minfracEnEx  | -0.0005276817 | -0.010551659  | 0.0013371104  |
| numfragEn    | 0.0232975168  | 0.174110659   | 0.0024159204  |
| maxfraglenEn | 0.3513263411  | 0.078661876   | -0.0043647685 |
| minfraglenEn | -0.4143744807 | -0.093250288  | 0.0027228423  |
| maxfragwidEn | -0.4702195080 | -0.045620401  | 0.0085848645  |
| minfragwidEn | 0.6226472333  | 0.087067978   | -0.0052763876 |
| Enshape      | -0.0118448875 | -0.012724245  | 0.5305907915  |
| reconEndia   | 0.0721576046  | 0.027124475   | -0.0008404228 |
| Endia        | -0.0527271132 | 0.009837322   | -0.0001765435 |
| residue      | 0.0155689504  | -0.015563826  | 0.1944964300  |
| bevEn        | 0.0078215852  | -0.039437211  | 0.2268822548  |
| bevEnloc     | 0.0194136938  | -0.039042656  | 0.7201102027  |
|              | PC13          | PC14          | PC15          |
| Entrance     | -0.1710088149 | 0.3723995356  | -0.371728401  |
| numfracEnEx  | -0.0413341579 | -0.0697849523 | -0.005411665  |
| numfracEnIn  | -0.0170083130 | -0.0271961980 | -0.017926570  |
| radfracEnEx  | -0.1686404828 | 0.2700460164  | -0.052080347  |
| radfracEnIn  | -0.2145036578 | 0.4986788820  | 0.078086871   |
| confracEnEx  | 0.6194631339  | 0.2519524490  | 0.044293938   |
| confracEnIn  | 0.6362395868  | 0.3688368005  | -0.025897608  |
| maxfracEnEx  | -0.0014897449 | -0.0033119596 | 0.001625410   |
| minfracEnEx  | 0.0006084544  | -0.0015516867 | 0.001035046   |
| numfragEn    | 0.0287429779  | 0.0286322381  | 0.018637447   |
| maxfraglenEn | -0.0073893917 | -0.0131466860 | -0.009628342  |
| minfraglenEn | 0.0126934500  | 0.0164915051  | 0.010148899   |
| maxfragwidEn | -0.0025229112 | 0.0104639548  | 0.004210408   |
| minfragwidEn | -0.0049559607 | -0.0203169062 | -0.010811679  |
| Enshape      | 0.2396589423  | -0.3631947936 | -0.648520884  |
| reconEndia   | 0.0001679704  | -0.0008790772 | 0.006762003   |
| Endia        | 0.0022326047  | 0.0067949398  | 0.003053118   |
| residue      | -0.0957883469 | 0.2843811794  | -0.220396551  |
| bevEn        | -0.1520882365 | 0.3202002515  | 0.056716817   |
| bevEnloc     | 0.1222632812  | -0.1320015016 | 0.613936132   |
|              | PC16          | PC17          |               |
| Entrance     | 1.703060e-02  | -0.7324928436 |               |
| numfracEnEx  | 4.342090e-03  | 0.0131635927  |               |
| numfracEnIn  | -2.188939e-03 | -0.0002675778 |               |
| radfracEnEx  | -2.562216e-01 | 0.1325652353  |               |

```

radfracEnIn -4.321789e-01 0.4695847937
confracEnEx -3.700771e-02 -0.1142591420
confracEnIn 3.274672e-03 0.0818293858
maxfracEnEx -6.178100e-04 -0.0006826434
minfracEnEx -3.364513e-05 -0.0001568771
numfragEn 1.178554e-03 -0.0069376695
maxfraglenEn -6.011247e-03 0.0029233146
minfraglenEn 6.739872e-03 -0.0028724834
maxfragwidEn 5.478289e-03 -0.0010861753
minfragwidEn -8.192302e-03 0.0042964580
Enshape -2.252507e-01 0.1898671342
reconEndia 1.534280e-03 -0.0004581701
Endia 9.880238e-04 -0.0019071697
residue 8.250468e-01 0.3577305650
bevEn -4.939911e-02 -0.1503009677
bevEnloc 1.086915e-01 -0.1369170927

```

```

PC18 PC19
Entrance 0.0202006114 -1.277122e-01
numfracEnEx 0.0241102386 -3.104363e-02
numfracEnIn -0.0016762529 2.452856e-03
radfracEnEx -0.5789370755 6.469652e-01
radfracEnIn 0.3527014277 -2.607038e-01
confracEnEx 0.4978771889 5.296308e-01
confracEnIn -0.5004161226 -4.383922e-01
maxfracEnEx -0.0005395968 -5.761794e-05
minfracEnEx 0.0004757177 -3.998254e-04
numfragEn -0.0069131387 6.885555e-03
maxfraglenEn 0.0010396644 -5.838749e-04
minfraglenEn -0.0016108322 4.288119e-04
maxfragwidEn -0.0015731083 7.113946e-04
minfragwidEn 0.0035463906 -1.690268e-03
Enshape 0.1055296685 -6.305843e-02
reconEndia -0.0011061247 1.427250e-04
Endia -0.0017104657 1.373104e-03
residue 0.0692392013 8.039644e-02
bevEn 0.1577005765 -8.464162e-02
bevEnloc -0.0164973086 -7.638991e-02

```

```

PC20
Entrance 0.3303412955
numfracEnEx 0.0159366859
numfracEnIn -0.0025653311
radfracEnEx 0.0133444127
radfracEnIn 0.2904639107
confracEnEx 0.0352348636
confracEnIn -0.0504391943
maxfracEnEx -0.0008516886
minfracEnEx 0.0004135549
numfragEn -0.0024271587
maxfraglenEn -0.0038325649
minfraglenEn 0.0039569557
maxfragwidEn 0.0026524378
minfragwidEn -0.0037155994
Enshape -0.0739121267
reconEndia -0.0010204647
Endia -0.0001149557
residue 0.0547267611
bevEn -0.8722246908
bevEnloc 0.1816263846

```

> summary(pcsA)

Importance of components:

|                        | PC1     | PC2     | PC3      |
|------------------------|---------|---------|----------|
| Standard deviation     | 94.2136 | 54.8902 | 32.94290 |
| Proportion of Variance | 0.6283  | 0.2133  | 0.07682  |
| Cumulative Proportion  | 0.6283  | 0.8416  | 0.91837  |

|                        | PC4      | PC5      | PC6      |
|------------------------|----------|----------|----------|
| Standard deviation     | 23.92535 | 14.55442 | 13.26912 |
| Proportion of Variance | 0.04052  | 0.01499  | 0.01246  |

|                        |         |         |         |
|------------------------|---------|---------|---------|
| Cumulative Proportion  | 0.95889 | 0.97389 | 0.98635 |
|                        | PC7     | PC8     | PC9     |
| Standard deviation     | 9.92542 | 8.8154  | 2.71870 |
| Proportion of Variance | 0.00697 | 0.0055  | 0.00052 |
| Cumulative Proportion  | 0.99332 | 0.9988  | 0.99935 |
|                        | PC11    | PC12    | PC13    |
| Standard deviation     | 1.72699 | 0.69295 | 0.45747 |
| Proportion of Variance | 0.00021 | 0.00003 | 0.00001 |
| Cumulative Proportion  | 0.99992 | 0.99996 | 0.99997 |
|                        | PC14    | PC15    | PC16    |
| Standard deviation     | 0.38336 | 0.34103 | 0.2449  |
| Proportion of Variance | 0.00001 | 0.00001 | 0.0000  |
| Cumulative Proportion  | 0.99998 | 0.99999 | 1.0000  |
|                        | PC18    | PC19    | PC20    |
| Standard deviation     | 0.1383  | 0.1318  | 0.1066  |
| Proportion of Variance | 0.0000  | 0.0000  | 0.0000  |
| Cumulative Proportion  | 1.0000  | 1.0000  | 1.0000  |

```

> pcTraumaExitA <- TraumaExitA
> pcTraumaExitA$pc1 <- pcsA$x[,1]
> pcTraumaExitA$pc2 <- pcsA$x[,2]
> str(pcTraumaExitA)
'data.frame': 48 obs. of 23 variables:
 $ Weapon : Factor w/ 8 levels "Compound","Crossbow (Field
Tip)",...: 5 5 5 5 5 5 5 5 5 5 ...
 $ Entrance : int 1 1 1 1 1 1 1 1 1 1 ...
 $ numfracEnEx : int 0 5 2 10 10 12 5 6 12 11 ...
 $ numfracEnIn : int 0 5 10 9 11 11 5 6 12 11 ...
 $ radfracEnEx : int 0 1 1 1 1 1 1 1 1 1 ...
 $ radfracEnIn : int 0 1 1 1 1 1 1 1 1 1 ...
 $ confracEnEx : int 0 0 1 1 1 1 0 0 1 1 ...
 $ confracEnIn : int 0 1 1 1 1 1 0 0 1 1 ...
 $ maxfracEnEx : num 0 220 231 267 204 ...
 $ minfracEnEx : num 0 87.2 215.9 26.6 68.2 ...
 $ numfragEn : int 0 0 0 3 4 3 1 1 7 3 ...
 $ maxfraglenEn : num 0 0 0 81.6 106.6 ...
 $ minfraglenEn : num 0 0 0 40.5 75.2 ...
 $ maxfragwidEn : num 0 0 0 53.1 63.4 66 79.3 59.1 43.5 50.2 ...
 $ minfragwidEn : num 0 0 0 27.7 42.4 39.2 79.3 59.1 11.6 8.4 ...
 $ Enshape : int 2 2 2 2 2 2 2 2 2 2 ...
 $ reconEndia : num 6.3 6.3 7.5 8.7 6.1 10.3 4.5 9 17.1 52.7 ...
 $ Endia : num 6.3 8.5 7.5 124.6 39.1 ...
 $ residue : int 1 1 1 1 1 1 1 1 1 1 ...
 $ bevEn : int 1 1 1 1 1 1 1 1 1 1 ...
 $ bevEnloc : int 1 1 1 2 2 1 1 1 1 2 ...
 $ pc1 : num 132 -79 -120 -173 -127 ...
 $ pc2 : num -6.57 100.72 155.98 -40.9 -29.77 ...

```

# Appendix B: ANOVA/Kruskal-Wallis Code

## Input and Output

### Tests

Test 1: Exit features included; Maximum fracture length on the external table of the entrance defect

Test 2: Exit features included; Minimum fracture length on the external table of the entrance defect

Test 3: Exit features included; Entrance defect diameter (without reconstruction)

Test 4: Exit features included; Minimum fragment length (entrance)

Test 5: Exit features included; Reconstructed exit defect diameter

Test 6: Exit features included; Maximum fracture length on the external table of the exit defect

Test 7: Exit features included; Reconstructed entrance defect diameter

Test 8: Exit features excluded; Maximum fracture length on the external table of the entrance defect

Test 9: Exit features excluded; Entrance defect diameter (without reconstruction)

Test 10: Exit features excluded; Minimum fracture length on the external table of the entrance defect

Test 11: Exit features excluded; Reconstructed entrance defect diameter

### Test 1

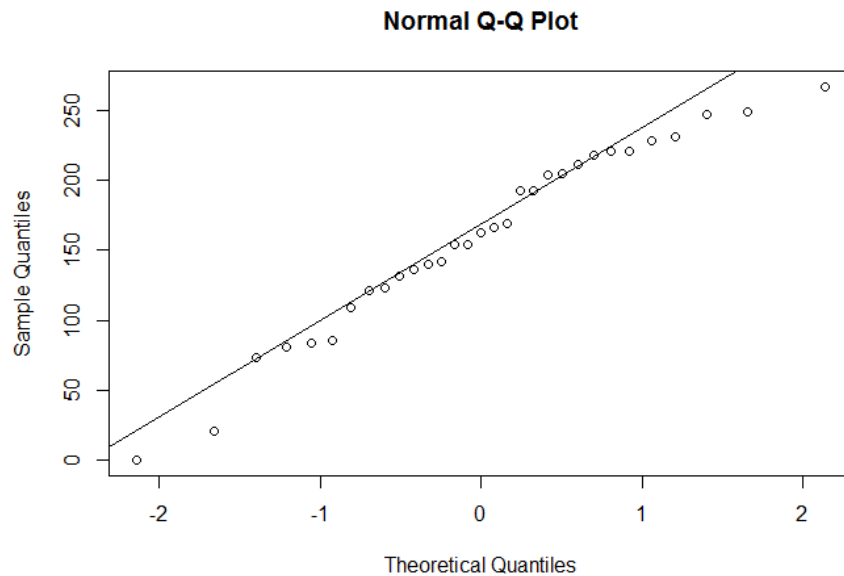
```
> shapiro.test(TraumaExitP$maxfracExEn)
```

```
      shapiro-wilk normality test
```

```
data:  TraumaExitP$maxfracExEn  
w = 0.9637, p-value = 0.3643
```

```
> qqnorm(TraumaExitP$maxfracExEn)  
> qqline(TraumaExitP$maxfracExEn)
```





```
> leveneTest(TraumaExitP$maxfracExEn~TraumaExitP$weapon)
Levene's Test for Homogeneity of Variance (center = median)
      Df F value Pr(>F)
group  4  0.7698 0.5547
      26

> test1 <- aov(TraumaExitP$maxfracExEn~TraumaExitP$weapon)
> summary(test1)
```

|                     | Df | Sum Sq |
|---------------------|----|--------|
| TraumaExitP\$weapon | 4  | 55633  |
| Residuals           | 26 | 78218  |

|                     | Mean Sq |
|---------------------|---------|
| TraumaExitP\$weapon | 13908   |
| Residuals           | 3008    |

|                     | F value |
|---------------------|---------|
| TraumaExitP\$weapon | 4.623   |
| Residuals           |         |

|                     | Pr(>F)     |
|---------------------|------------|
| TraumaExitP\$weapon | 0.00593 ** |
| Residuals           |            |

```
---
Signif. codes:
  0 '***' 0.001 '**' 0.01 '*'
  0.05 '.' 0.1 ' ' 1
> TukeyHSD(test1)
  Tukey multiple comparisons of means
    95% family-wise confidence level

Fit: aov(formula = TraumaExitP$maxfracExEn ~ TraumaExitP$weapon)

$`TraumaExitP$weapon`
                                diff
Crossbow (Fixed Broadhead)-Crossbow (Field Tip) 77.04000
Crossbow (Mechanical Broadhead)-Crossbow (Field Tip) 82.88000
Handgun-Crossbow (Field Tip) 106.22545
Rifle-Crossbow (Field Tip) 138.35400
Crossbow (Mechanical Broadhead)-Crossbow (Fixed Broadhead) 5.84000
```

|                                                            |           |
|------------------------------------------------------------|-----------|
| Handgun-Crossbow (Fixed Broadhead)                         | 29.18545  |
| Rifle-Crossbow (Fixed Broadhead)                           | 61.31400  |
| Handgun-Crossbow (Mechanical Broadhead)                    | 23.34545  |
| Rifle-Crossbow (Mechanical Broadhead)                      | 55.47400  |
| Rifle-Handgun                                              | 32.12855  |
|                                                            | lwr       |
| Crossbow (Fixed Broadhead)-Crossbow (Field Tip)            | -24.54644 |
| Crossbow (Mechanical Broadhead)-Crossbow (Field Tip)       | -18.70644 |
| Handgun-Crossbow (Field Tip)                               | 19.59225  |
| Rifle-Crossbow (Field Tip)                                 | 36.76756  |
| Crossbow (Mechanical Broadhead)-Crossbow (Fixed Broadhead) | -95.74644 |
| Handgun-Crossbow (Fixed Broadhead)                         | -57.44775 |
| Rifle-Crossbow (Fixed Broadhead)                           | -40.27244 |
| Handgun-Crossbow (Mechanical Broadhead)                    | -63.28775 |
| Rifle-Crossbow (Mechanical Broadhead)                      | -46.11244 |
| Rifle-Handgun                                              | -54.50466 |
|                                                            | upr       |
| Crossbow (Fixed Broadhead)-Crossbow (Field Tip)            | 178.6264  |
| Crossbow (Mechanical Broadhead)-Crossbow (Field Tip)       | 184.4664  |
| Handgun-Crossbow (Field Tip)                               | 192.8587  |
| Rifle-Crossbow (Field Tip)                                 | 239.9404  |
| Crossbow (Mechanical Broadhead)-Crossbow (Fixed Broadhead) | 107.4264  |
| Handgun-Crossbow (Fixed Broadhead)                         | 115.8187  |
| Rifle-Crossbow (Fixed Broadhead)                           | 162.9004  |
| Handgun-Crossbow (Mechanical Broadhead)                    | 109.9787  |
| Rifle-Crossbow (Mechanical Broadhead)                      | 157.0604  |
| Rifle-Handgun                                              | 118.7618  |
|                                                            | p adj     |
| Crossbow (Fixed Broadhead)-Crossbow (Field Tip)            | 0.2037252 |
| Crossbow (Mechanical Broadhead)-Crossbow (Field Tip)       | 0.1501624 |
| Handgun-Crossbow (Field Tip)                               | 0.0107743 |
| Rifle-Crossbow (Field Tip)                                 | 0.0040321 |
| Crossbow (Mechanical Broadhead)-Crossbow (Fixed Broadhead) | 0.9998070 |
| Handgun-Crossbow (Fixed Broadhead)                         | 0.8589129 |
| Rifle-Crossbow (Fixed Broadhead)                           | 0.4128870 |
| Handgun-Crossbow (Mechanical Broadhead)                    | 0.9314689 |
| Rifle-Crossbow (Mechanical Broadhead)                      | 0.5110758 |
| Rifle-Handgun                                              | 0.8119988 |

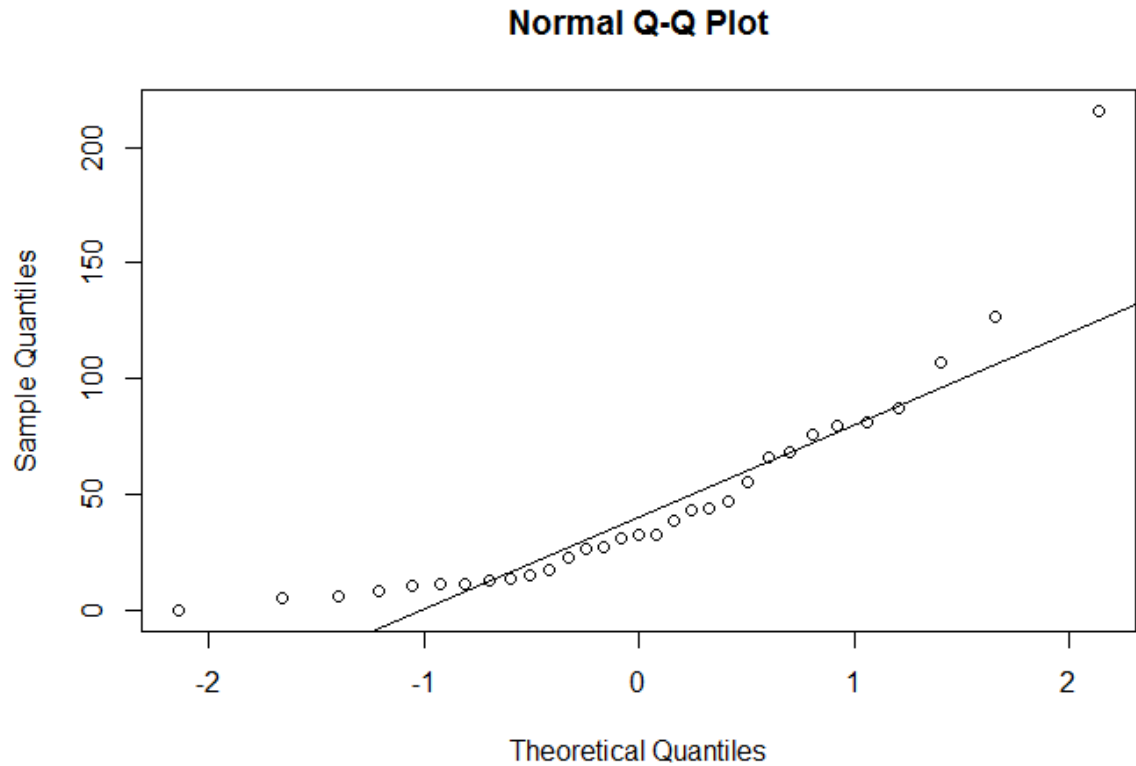
## Test 2

```
> shapiro.test(TraumaExitP$minfracEnEx)
```

Shapiro-wilk normality test

```
data: TraumaExitP$minfracEnEx
W = 0.8068, p-value =
6.918e-05
```

```
> qqnorm(TraumaExitP$minfracEnEx)
> qqline(TraumaExitP$minfracEnEx)
```

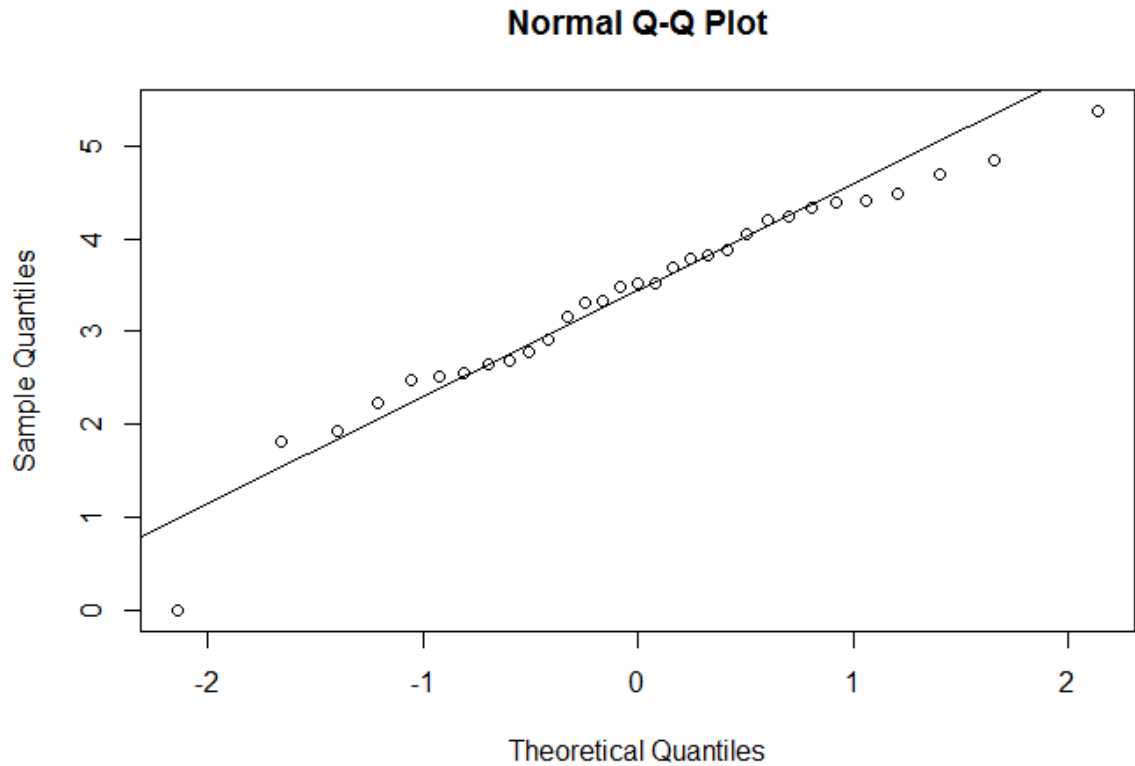


```
> leveneTest(TraumaExitP$minfracEnEx~TraumaExitP$Weapon)
Levene's Test for Homogeneity of Variance (center = median)
      Df F value Pr(>F)
group  4  1.0101 0.4203
      26
> t2log <- log(TraumaExitP$minfracEnEx + 1)
> shapiro.test(t2log)
```

Shapiro-wilk normality test

```
data:  t2log
w = 0.9548, p-value = 0.2111
```

```
> qqnorm(t2log)
> qqline(t2log)
```



```
> leveneTest(t2log~TraumaExitP$Weapon)
Levene's Test for Homogeneity of Variance (center = median)
      Df F value Pr(>F)
group  4  0.7225 0.5845
      26

> test2 <- aov(t2log~TraumaExitP$Weapon)
> summary(test2)

              Df Sum Sq
TraumaExitP$Weapon  4   1.92
Residuals          26  33.86
              Mean Sq
TraumaExitP$Weapon  0.4805
Residuals          1.3024
              F value
TraumaExitP$Weapon  0.369
Residuals

              Pr(>F)
TraumaExitP$Weapon  0.829
Residuals
```

### Test 3

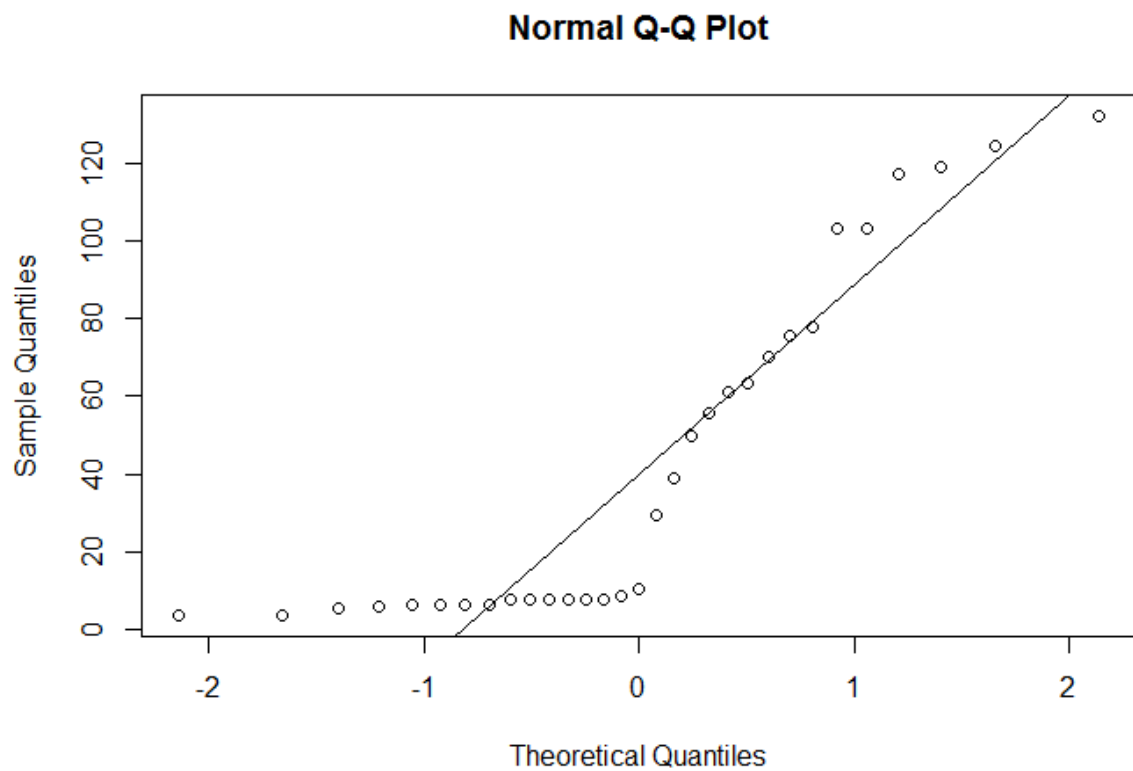
```
> shapiro.test(TraumaExitP$Endia)

      Shapiro-Wilk normality test

data:  TraumaExitP$Endia
```

```
w = 0.8056, p-value =  
6.577e-05
```

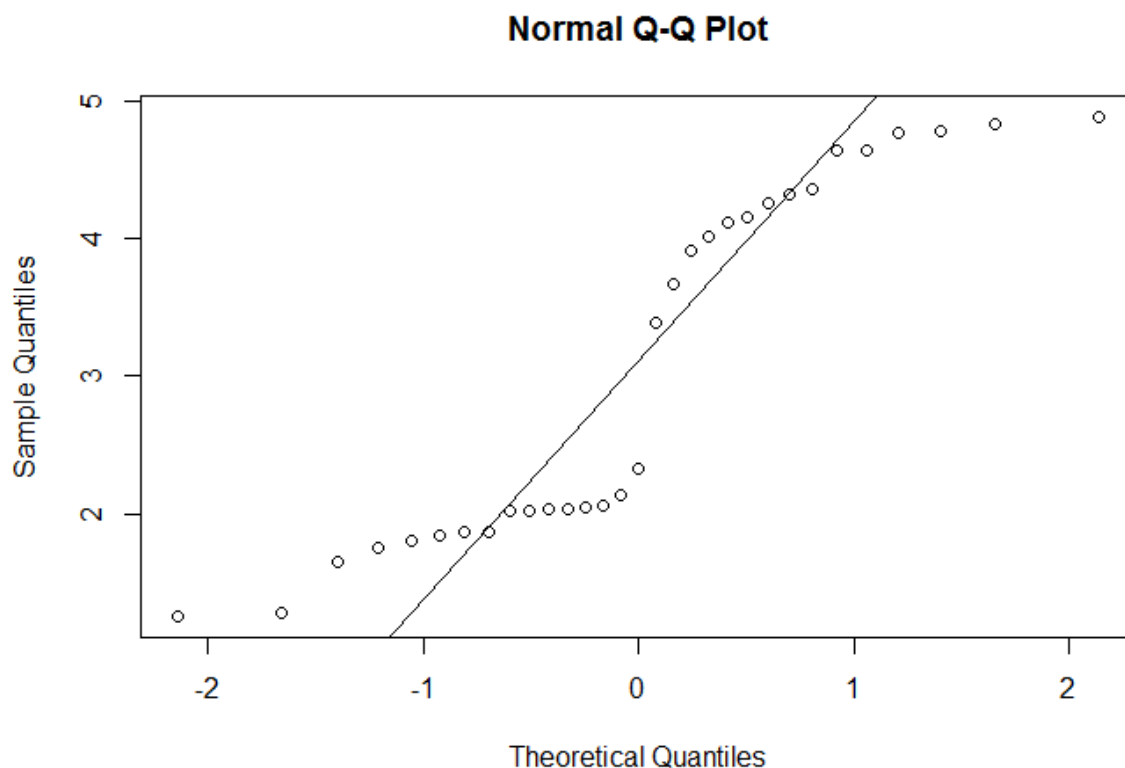
```
> qqnorm(TraumaExitP$Endia)  
> qqline(TraumaExitP$Endia)
```



```
> leveneTest(TraumaExitP$Endia~TraumaExitP$Weapon)  
Levene's Test for Homogeneity of Variance (center = median)  
      Df F value    Pr(>F)  
group  4  5.4088 0.002635 **  
      26  
---  
Signif. codes:  
  0 '***' 0.001 '**' 0.01 '*' 0.05  
  '.' 0.1 ' ' 1
```

```
> shapiro.test(t3log)  
  
      Shapiro-wilk normality test  
  
data:  t3log  
w = 0.8453, p-value =  
0.0004024
```

```
> qqnorm(t3log)
> qqline(t3log)
```



```
> leveneTest(t3log~TraumaExitP$Weapon)
```

Levene's Test for Homogeneity of Variance (center = median)

```
      Df F value Pr(>F)
group  4  1.6291 0.1969
      26
```

```
> kruskal.test(Endia~Weapon, data=TraumaExitP)
```

```
kruskal-wallis rank sum
test
```

```
data: Endia by weapon
kruskal-wallis chi-squared =
16.2953, df = 4, p-value =
0.002647
```

```
> dunn.test(TraumaExitPneat$Endia, TraumaExitPneat$Weapon, method="bonferroni")
```

```
kruskal-wallis rank sum test
```

```
data: x and group
kruskal-wallis chi-squared = 16.2953, df = 4, p-value = 0
```

Comparison of x by grou

p

(Bonferroni

)

| Col | Mean |  | Cb Field | Cb Fixed | Cb Mecha | Handgun |
|-----|------|--|----------|----------|----------|---------|
| Row | Mean |  |          |          |          |         |

|          |                     |                     |                     |                     |
|----------|---------------------|---------------------|---------------------|---------------------|
| Cb Fixed | -0.31311<br>1.0000  |                     |                     |                     |
| Cb Mecha | -1.722151<br>0.4252 | -1.409033<br>0.7941 |                     |                     |
| Handgun  | -1.839528<br>0.3292 | -1.472364<br>0.7046 | 0.179873<br>1.0000  |                     |
| Rifle    | 1.496010<br>0.6733  | 1.809128<br>0.3522  | 3.218161<br>0.0065* | 3.593756<br>0.0016* |

alpha = 0.05  
Reject Ho if  $p \leq \alpha/2$

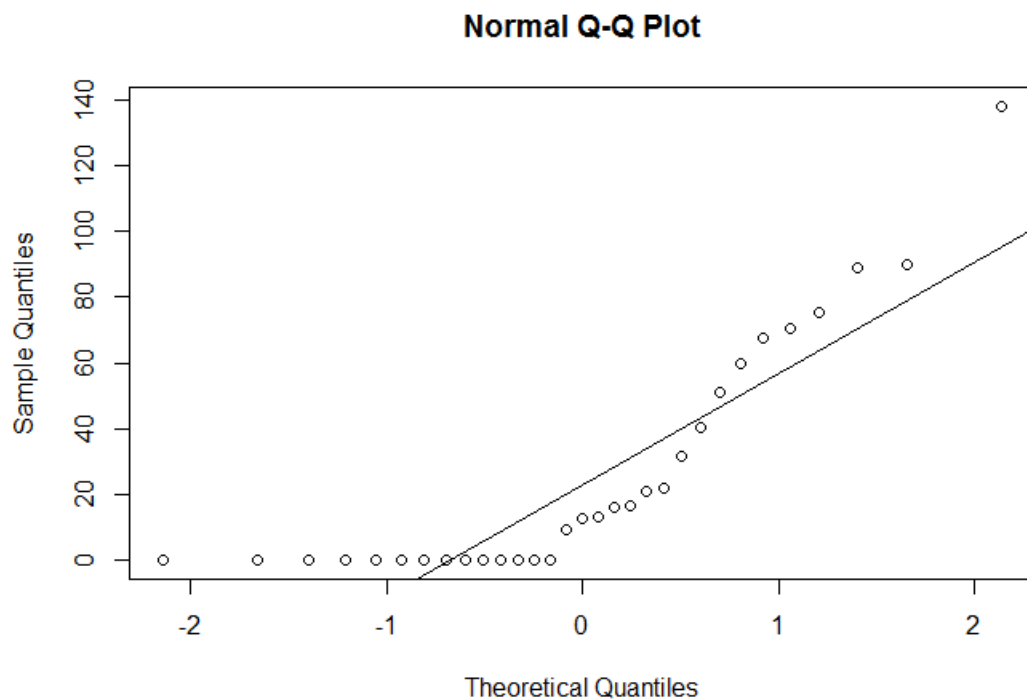
## Test 4

```
> shapiro.test(TraumaExitP$minfraglenEn)
```

Shapiro-wilk normality test

data: TraumaExitP\$minfraglenEn  
W = 0.7681, p-value =  
1.399e-05

```
> qqnorm(TraumaExitP$minfraglenEn)
> qqline(TraumaExitP$minfraglenEn)
```



```
> leveneTest(TraumaExitP$minfraglenEn~TraumaExitP$weapon)
Levene's Test for Homogeneity of Variance (center = median)
```

```

      Df F value Pr(>F)
group  4  1.2653 0.3088
      26

```

```
> shapiro.test(t4log)
```

Shapiro-wilk normality test

```

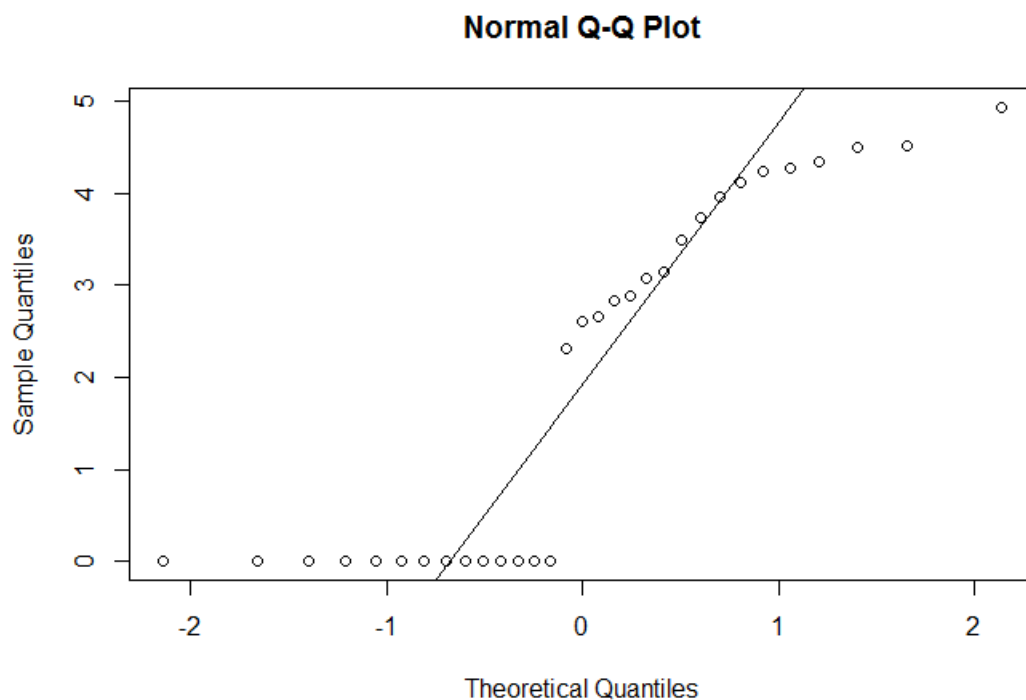
data:  t4log
W = 0.7943, p-value =
4.06e-05

```

```

> qqnorm(t4log)
> qqline(t4log)

```



```
> leveneTest(t4log~TraumaExitP$Weapon)
```

Levene's Test for Homogeneity of Variance (center = median)

```

      Df F value Pr(>F)
group  4  0.4476 0.7731
      26

```

```
> kruskal.test(minfraglenEn~Weapon, data=TraumaExitP)
```

Kruskal-wallis rank sum  
test

```

data:  minfraglenEn by Weapon
Kruskal-wallis chi-squared =
5.8404, df = 4, p-value =
0.2114

```



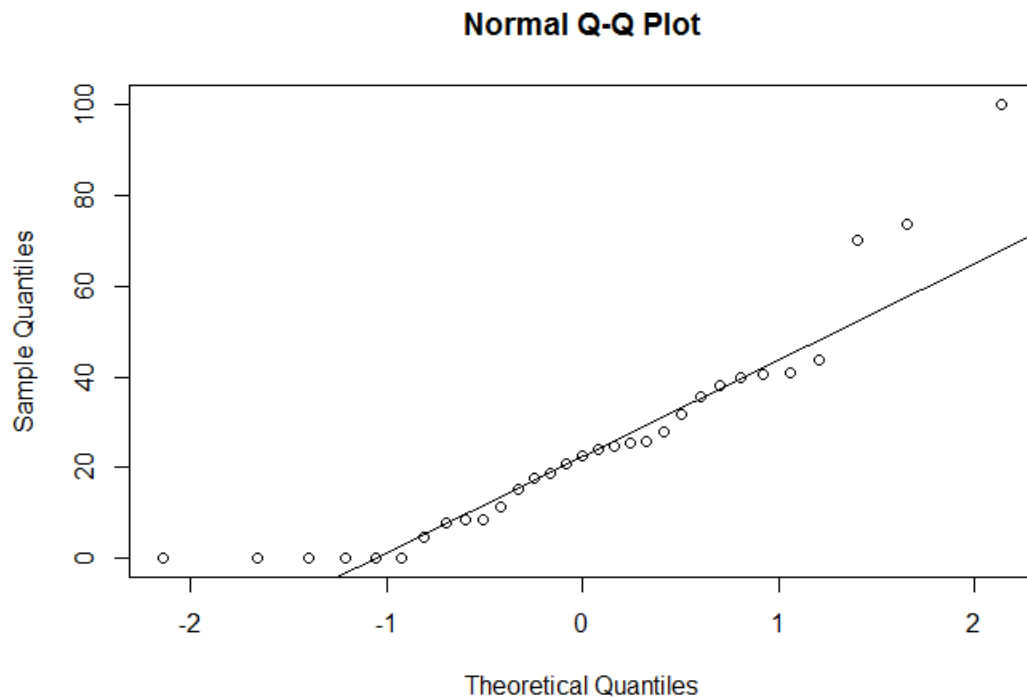
## Test 5

```
> shapiro.test(TraumaExitP$reconExdia)
```

Shapiro-wilk normality test

```
data: TraumaExitP$reconExdia  
W = 0.8689, p-value =  
0.001317
```

```
> qqnorm(TraumaExitP$reconExdia)  
> qqline(TraumaExitP$reconExdia)
```

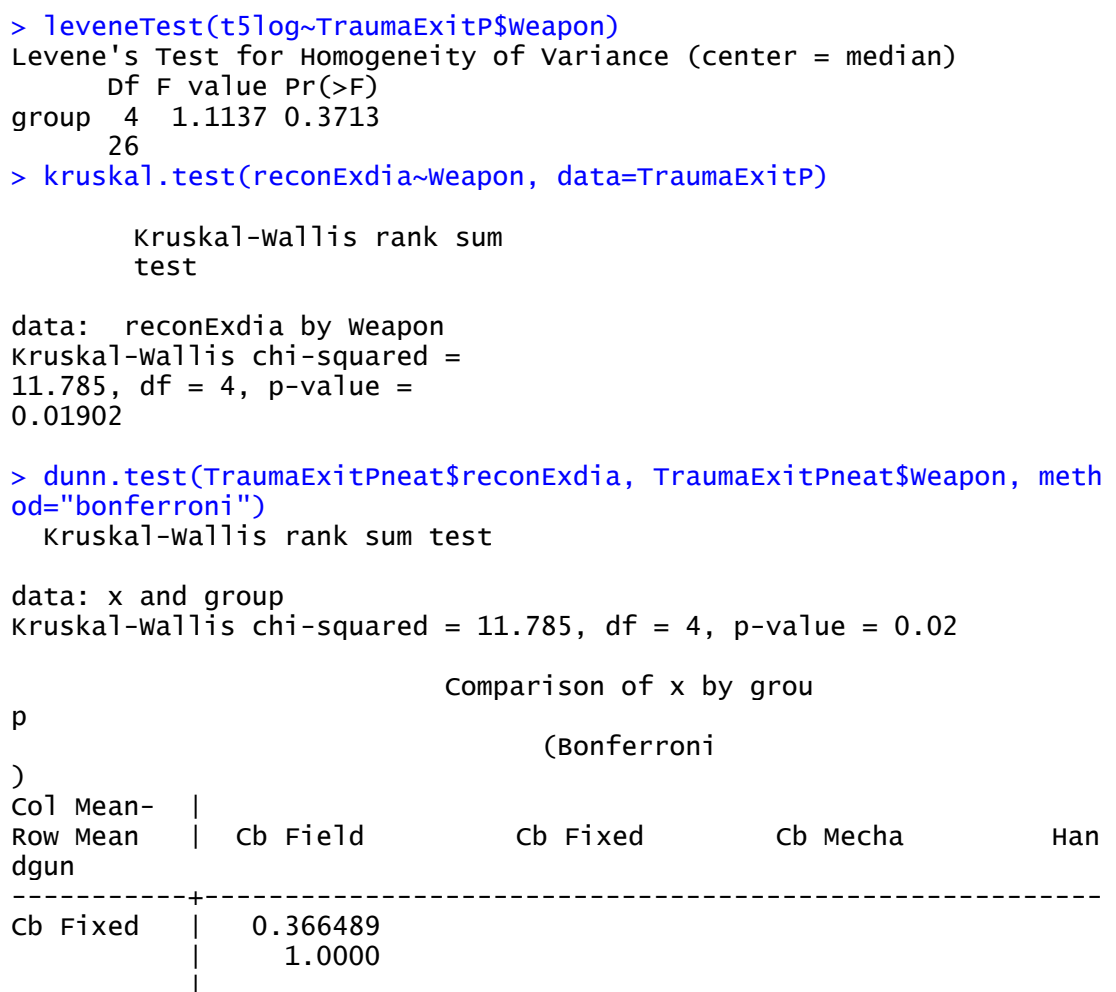


```
> leveneTest(TraumaExitP$reconExdia~TraumaExitP$weapon)  
Levene's Test for Homogeneity of Variance (center = median)  
      Df F value Pr(>F)  
group  4  1.3655 0.2731  
      26  
> shapiro.test(t5log)
```

Shapiro-wilk normality test

```
data: t5log  
W = 0.837, p-value =  
0.0002708
```

```
> qqnorm(t5log)  
> qqline(t5log)
```

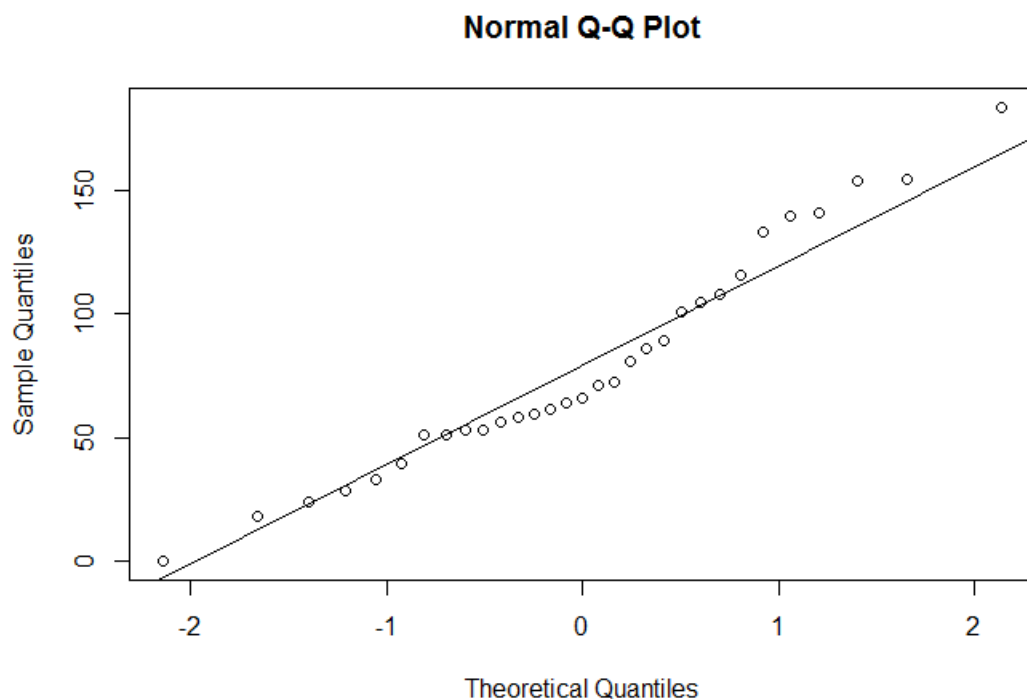


|          |                     |                      |                     |                    |
|----------|---------------------|----------------------|---------------------|--------------------|
| Cb Mecha | -0.261778<br>1.0000 | -0.628268<br>1.0000  |                     |                    |
| Handgun  | -2.422212<br>0.0771 | -2.851959<br>0.0217* | -2.115249<br>0.1720 |                    |
| Rifle    | -1.186728<br>1.0000 | -1.553218<br>0.6019  | -0.924950<br>1.0000 | 1.030649<br>1.0000 |

alpha = 0.05  
Reject Ho if  $p \leq \alpha/2$

## Test 6

```
> qqnorm(TraumaExitP$maxfracExEx)
> qqline(TraumaExitP$maxfracExEx)
```



```
> shapiro.test(TraumaExitP$maxfracExEx)
```

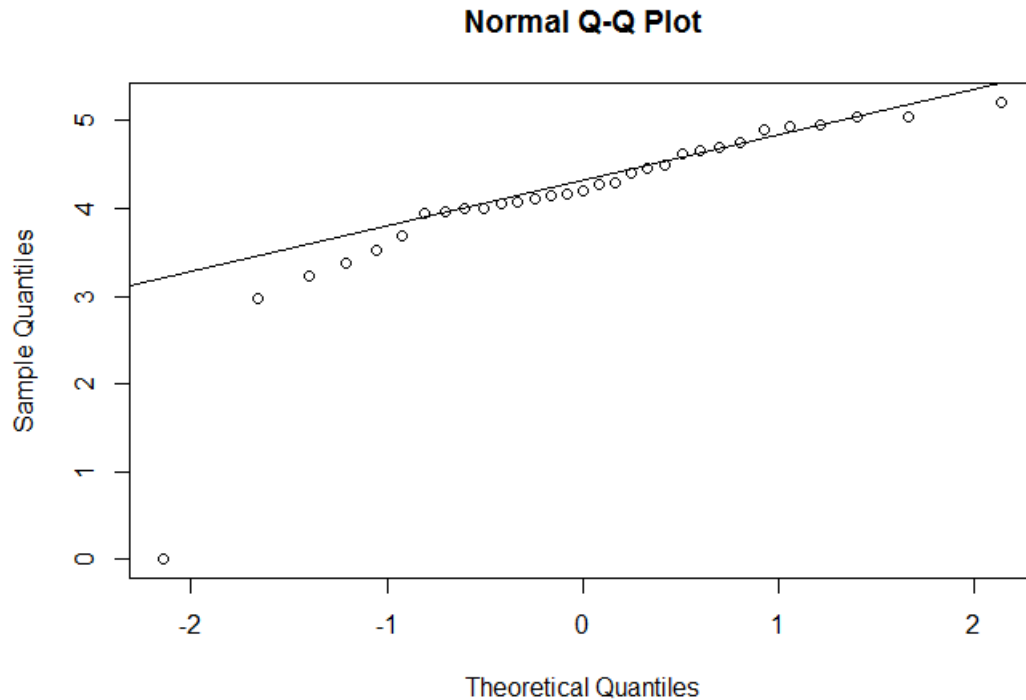
Shapiro-wilk normality test

data: TraumaExitP\$maxfracExEx  
w = 0.9587, p-value = 0.2687

```
> leveneTest(TraumaExitP$maxfracExEx~TraumaExitP$weapon)
Levene's Test for Homogeneity of Variance (center = median)
      Df F value Pr(>F)
group 4  2.9913 0.03715 *
      26
```

```
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
> qqnorm(t6log)
```

```
> qqline(t6log)
```



```
> shapiro.test(t6log)
```

Shapiro-wilk normality test

data: t6log  
W = 0.7365, p-value = 4.218e-06

```
> leveneTest(t6log~TraumaExitP$Weapon)
```

Levene's Test for Homogeneity of Variance (center = median)

|       | Df | F value | Pr(>F) |
|-------|----|---------|--------|
| group | 4  | 1.64    | 0.1943 |
|       | 26 |         |        |

```
> kruskal.test(maxfracExEx~Weapon, data=TraumaExitP)
```

Kruskal-wallis rank sum  
test

data: maxfracExEx by Weapon  
Kruskal-wallis chi-squared =  
4.6509, df = 4, p-value =  
0.325

## Test 7

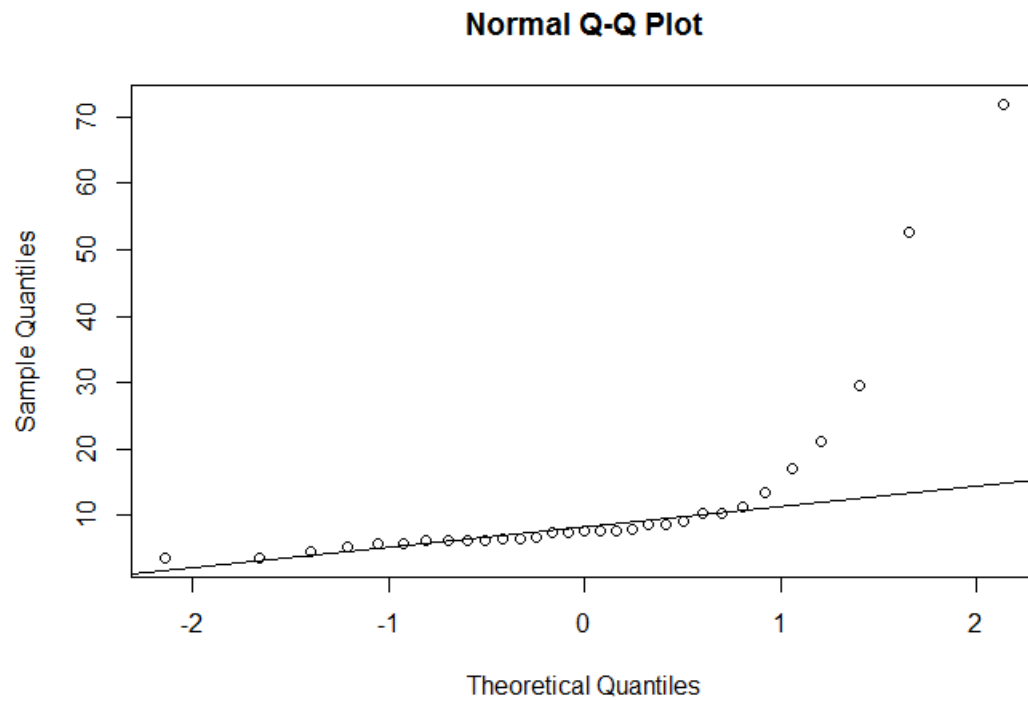
```
> shapiro.test(TraumaExitP$reconEndia)
```

Shapiro-wilk normality test

data: TraumaExitP\$reconEndia  
W = 0.5332, p-value =

8.545e-09

```
> qqnorm(TraumaExitP$reconEndia)
> qqline(TraumaExitP$reconEndia)
```



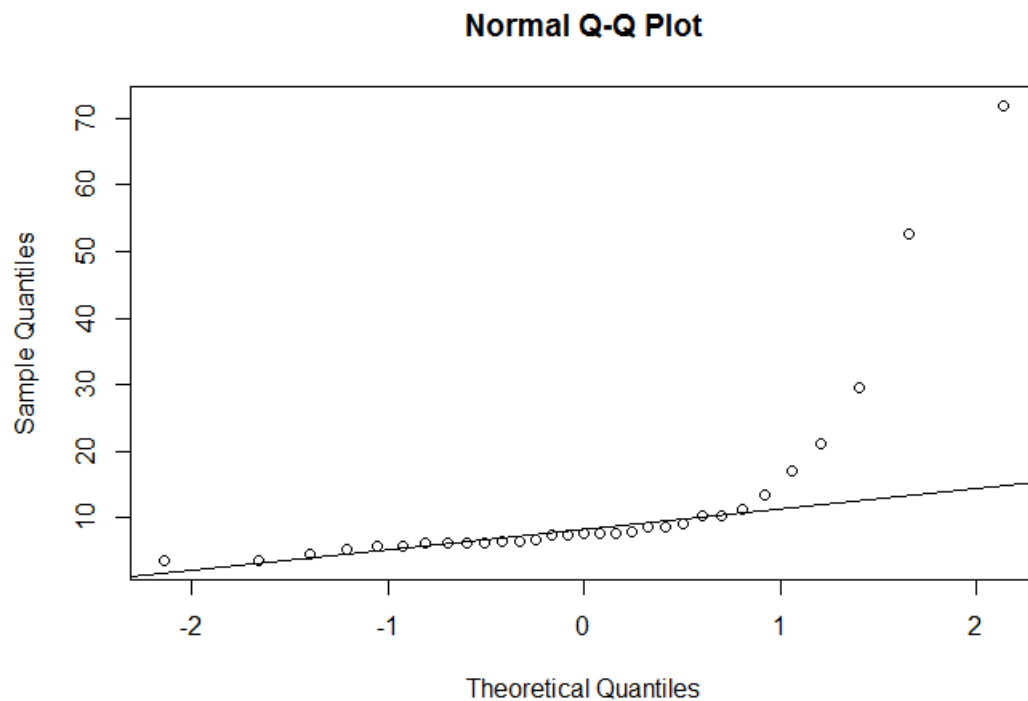
```
> leveneTest(TraumaExitP$reconEndia~TraumaExitP$weapon)
Levene's Test for Homogeneity of Variance (center = median)
      Df F value Pr(>F)
group  4  0.8726 0.4937
      26
> shapiro.test(t7log)
```

shapiro-wilk normality test

```
data:  t7log
w = 0.8179, p-value =
0.0001128
```

```
> qqnorm(t7log)
```

```
> qqline(t7log)
```



```
> leveneTest(t7log~TraumaExitP$Weapon)
```

Levene's Test for Homogeneity of Variance (center = median)

```
      Df F value Pr(>F)
group  4  1.0615 0.3954
      26
```

```
> kruskal.test(reconEndia~Weapon, data=TraumaExitP)
```

kruskal-wallis rank sum  
test

data: reconEndia by weapon  
kruskal-wallis chi-squared =  
10.3198, df = 4, p-value =  
0.03537

```
> dunn.test(TraumaExitPneat$reconEndia, TraumaExitPneat$Weapon, method="bonferroni")
```

kruskal-wallis rank sum test

data: x and group  
kruskal-wallis chi-squared = 10.3198, df = 4, p-value = 0.04

Comparison of x by group

p

(Bonferroni)

| Col Mean-<br>Row Mean | Cb Field           | Cb Fixed | Cb Mecha | Handgun |
|-----------------------|--------------------|----------|----------|---------|
| Cb Fixed              | 0.609025<br>1.0000 |          |          |         |

|          |                     |                     |                     |                    |
|----------|---------------------|---------------------|---------------------|--------------------|
| Cb Mecha | -0.765632<br>1.0000 | -1.374658<br>0.8462 |                     |                    |
| Handgun  | -0.050082<br>1.0000 | -0.764228<br>1.0000 | 0.847700<br>1.0000  |                    |
| Rifle    | 2.192492<br>0.1417  | 1.583467<br>0.5666  | 2.958125<br>0.0155* | 2.621008<br>0.0438 |

alpha = 0.05  
Reject Ho if  $p \leq \alpha/2$

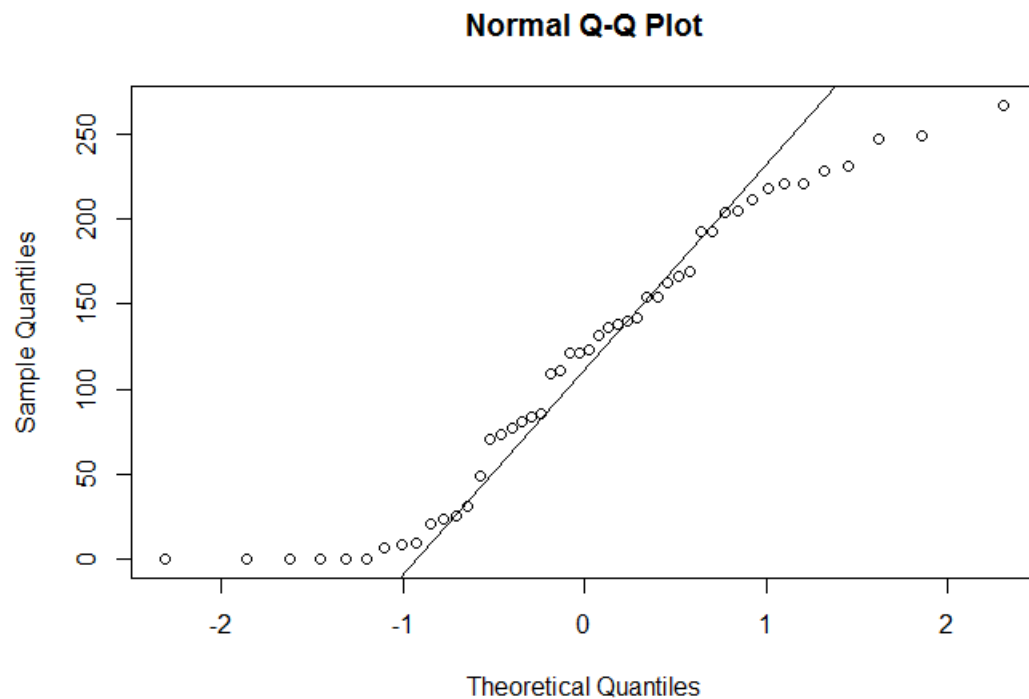
## Test 8

```
> shapiro.test(TraumaExitA$maxfracEnEx)
```

Shapiro-wilk normality test

data: TraumaExitA\$maxfracEnEx  
w = 0.9324, p-value =  
0.008398

```
> qqnorm(TraumaExitA$maxfracEnEx)
> qqline(TraumaExitA$maxfracEnEx)
```

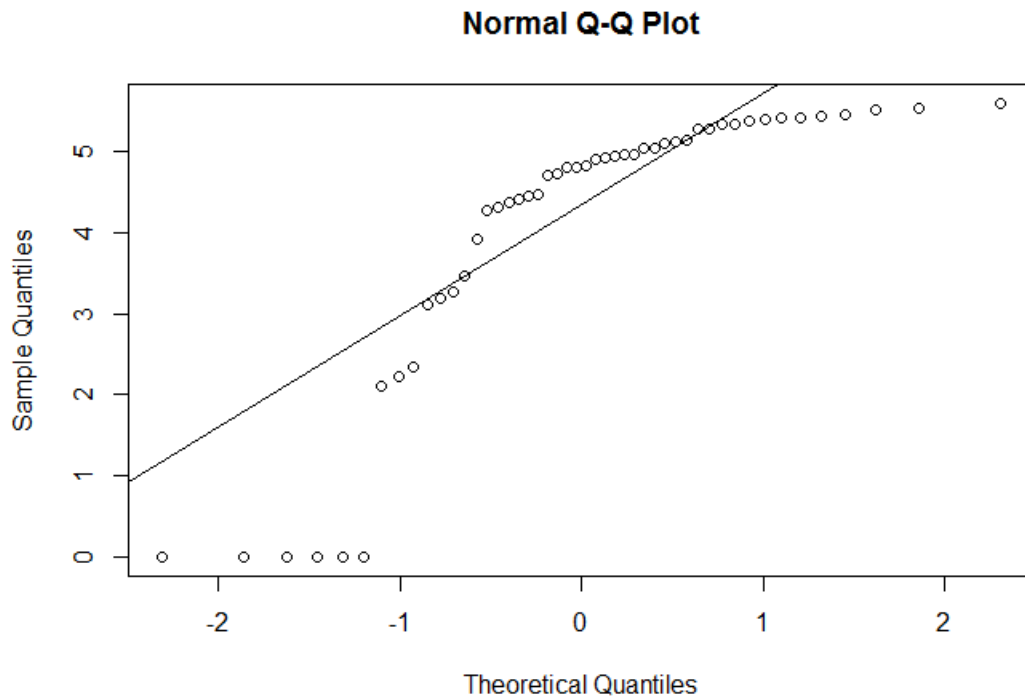


```
> leveneTest(TraumaExitA$maxfracEnEx~TraumaExitA$weapon)
Levene's Test for Homogeneity of Variance (center = median)
      Df F value Pr(>F)
group  7  1.2972 0.2767
      40
> shapiro.test(t8log)
```

Shapiro-wilk normality test

```
data: t8log  
w = 0.7423, p-value =  
8.038e-08
```

```
> qqnorm(t8log)  
> qqline(t8log)
```



```
> leveneTest(t8log~TraumaExitA$Weapon)
```

```
Levene's Test for Homogeneity of Variance (center = median)  
      Df F value Pr(>F)  
group  7  0.3438 0.9286  
      40
```

```
> kruskal.test(maxfracEnEx~Weapon, data=TraumaExitA)
```

```
kruskal-wallis rank sum  
test
```

```
data: maxfracEnEx by weapon  
Kruskal-wallis chi-squared =  
33.8941, df = 7, p-value =  
1.803e-05
```

```
> dunn.test(TraumaExitAneat$maxfracEnEx, TraumaExitAneat$Weapon, met  
hod="bonferroni")
```

```
kruskal-wallis rank sum test
```

```
data: x and group  
kruskal-wallis chi-squared = 33.8941, df = 7, p-value = 0
```



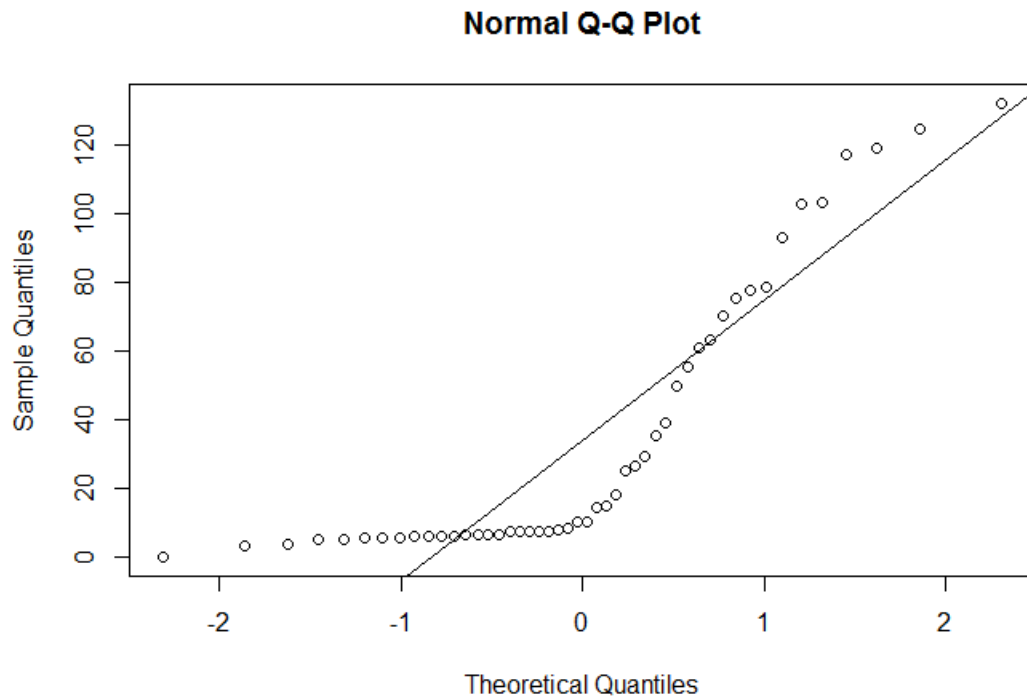
```
alpha = 0.05
Reject H0 if p <= alpha/2
```

```
> shapiro.test(TraumaExitA$Endia)

      Shapiro-Wilk normality test

data:  TraumaExitA$Endia
W = 0.7716, p-value = 3.136e-07

> qqnorm(TraumaExitA$Endia)
> qqline(TraumaExitA$Endia)
```



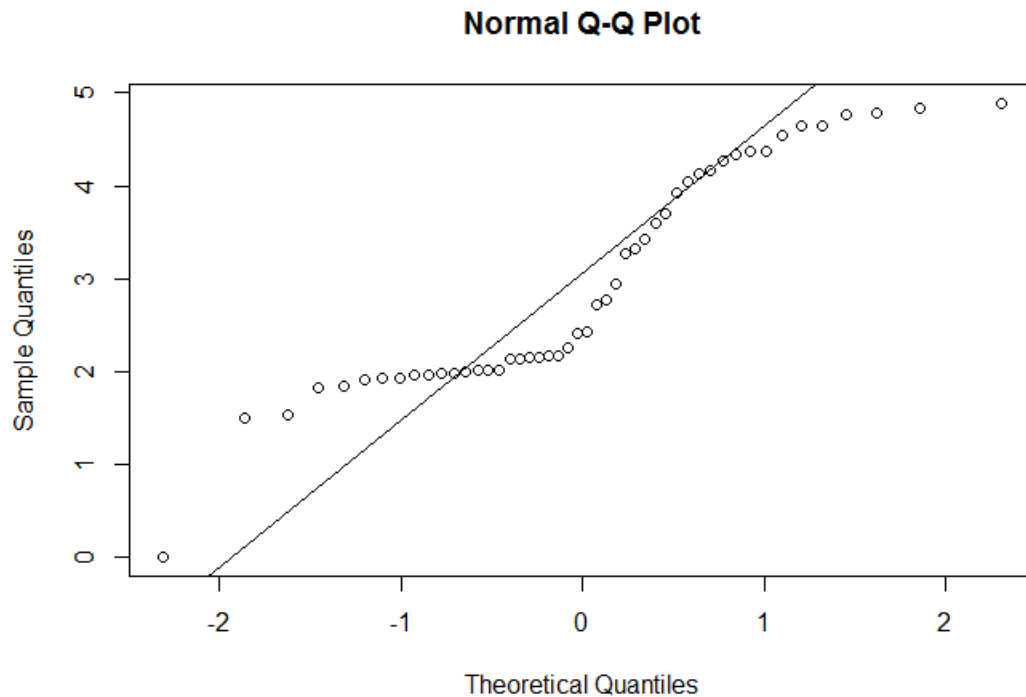
```
> leveneTest(TraumaExitA$Endia~TraumaExitA$weapon)
Levene's Test for Homogeneity of Variance (center = median)
      Df F value    Pr(>F)
group  7  4.7137 0.0006279 ***
      40

---
Signif. codes:
  0 '***' 0.001 '**' 0.01 '*'
  0.05 '.' 0.1 ' ' 1
> shapiro.test(t9log)

      Shapiro-Wilk normality test

data:  t9log
W = 0.8981, p-value =
0.0005481

> qqnorm(t9log)
> qqline(t9log)
```



```
> leveneTest(t9log~TraumaExitA$Weapon)
Levene's Test for Homogeneity of Variance (center = median)
      Df F value Pr(>F)
group  7  2.684 0.02237 *
.t      40
---
Signif. codes:
  0 '***' 0.001 '**' 0.01 '*'
  0.05 '.' 0.1 ' ' 1
> kruskal.test(Endia~Weapon, data=TraumaExitA)

      kruskal-wallis rank sum
      test

data: Endia by weapon
kruskal-wallis chi-squared =
23.7674, df = 7, p-value =
0.001252

> dunn.test(TraumaExitAneat$Endia, TraumaExitAneat$Weapon, method="b
onferroni")
      kruskal-wallis rank sum test

data: x and group
kruskal-wallis chi-squared = 23.7674, df = 7, p-value = 0

      Comparison of x by grou
p
      (Bonferroni
)
Col Mean-|
Row Mean | Cb Field   Cb Fixed   Cb Mecha   Compound   Handgun   R
ecurve
```

|           |                     |                     |                     |                     |                     |                    |
|-----------|---------------------|---------------------|---------------------|---------------------|---------------------|--------------------|
| Cb Fixed  | -0.485754<br>1.0000 |                     |                     |                     |                     |                    |
| Cb Mecha  | -1.773567<br>1.0000 | -1.287813<br>1.0000 |                     |                     |                     |                    |
| Compound  | -0.915025<br>1.0000 | -0.429271<br>1.0000 | 0.858542<br>1.0000  |                     |                     |                    |
| Handgun   | -1.932777<br>0.7457 | -1.363179<br>1.0000 | 0.146915<br>1.0000  | -0.859814<br>1.0000 |                     |                    |
| Recurve   | 0.958707<br>1.0000  | 1.483381<br>1.0000  | 2.874379<br>0.0567  | 1.947047<br>0.7214  | 3.317155<br>0.0127* |                    |
| Rifle     | 1.558931<br>1.0000  | 2.044686<br>0.5724  | 3.332499<br>0.0120* | 2.473957<br>0.1871  | 3.760786<br>0.0024* | 0.72513<br>1.0000  |
| Shotgun   | -0.338898<br>1.0000 | 0.146855<br>1.0000  | 1.434669<br>1.0000  | 0.576127<br>1.0000  | 1.535383<br>1.0000  | -1.32476<br>1.0000 |
| Col Mean- |                     |                     |                     |                     |                     |                    |
| Row Mean  | Rifle               |                     |                     |                     |                     |                    |
| Shotgun   | -1.897830<br>0.8081 |                     |                     |                     |                     |                    |

alpha = 0.05  
Reject Ho if p <= alpha/2

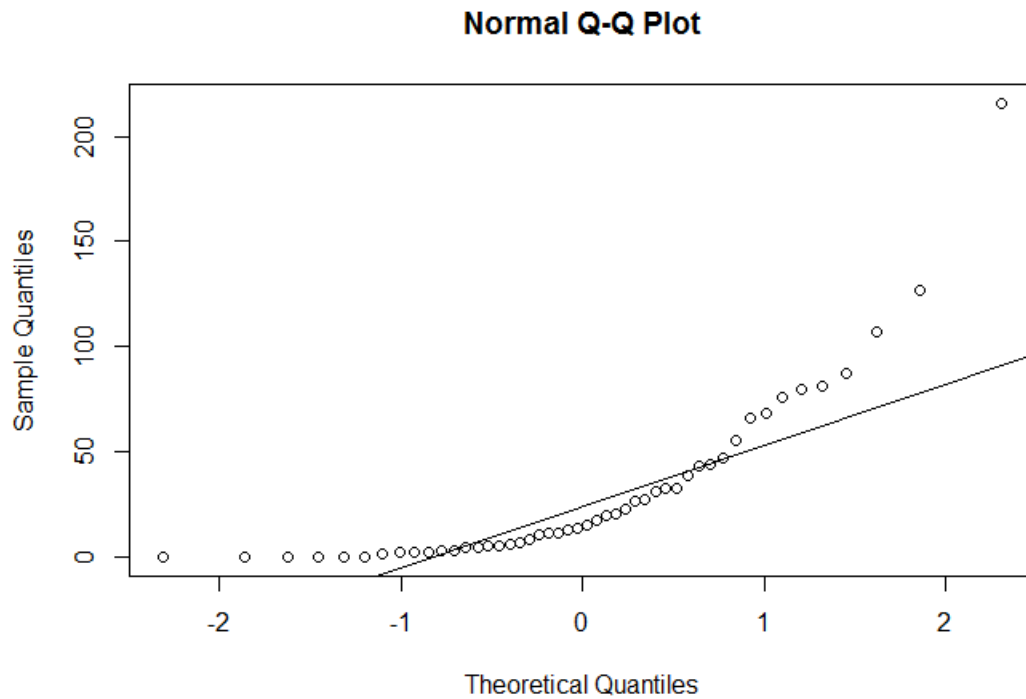
## Test 10

```
> shapiro.test(TraumaExitA$minfracEnEx)
```

Shapiro-wilk normality test

```
data: TraumaExitA$minfracEnEx
W = 0.7327, p-value =
5.258e-08
```

```
> qqnorm(TraumaExitA$minfracEnEx)
> qqline(TraumaExitA$minfracEnEx)
```



```
> leveneTest(TraumaExitA$minfracEnEx~TraumaExitA$weapon)
Levene's Test for Homogeneity of Variance (center = median)
      Df F value Pr(>F)
group  7  2.1402 0.06114 .
      40

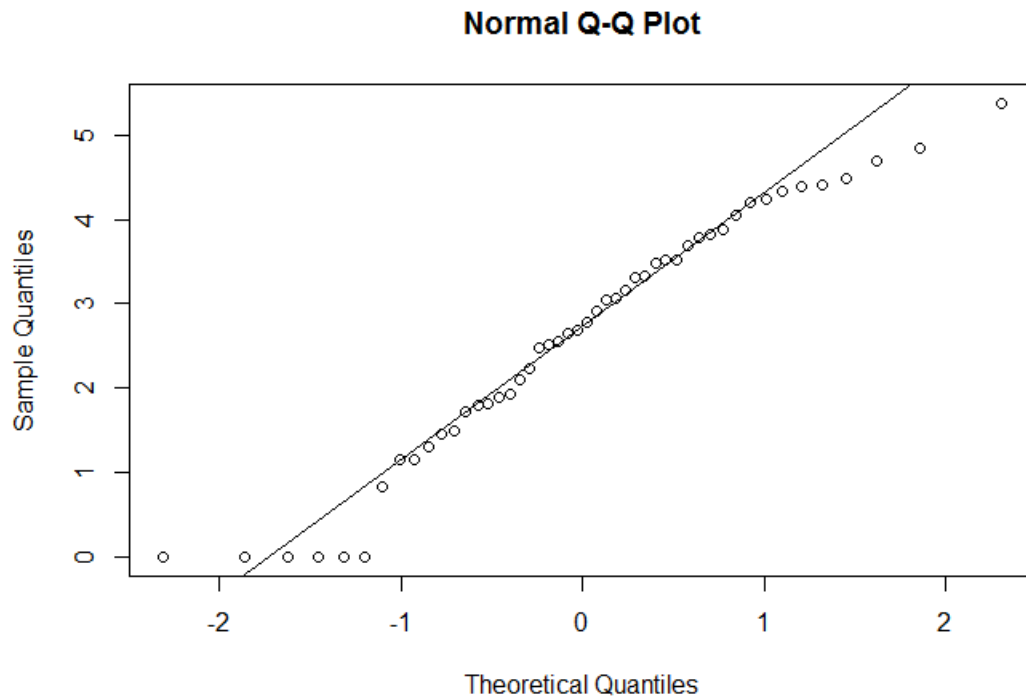
---
Signif. codes:
  0 '***' 0.001 '**' 0.01 '*'
  0.05 '.' 0.1 ' ' 1

> shapiro.test(t10log)

      Shapiro-Wilk normality test

data:  t10log
W = 0.9561, p-value =
0.07029

> qqnorm(t10log)
> qqline(t10log)
```



```
> leveneTest(t10log~TraumaExitA$Weapon)
Levene's Test for Homogeneity of Variance (center = median)
      Df F value Pr(>F)
group  7  0.8694 0.5388
      40

> test10 <- aov(t10log~TraumaExitA$Weapon)
> summary(test10)
```

|                     | Df | Sum Sq | Mean Sq | F value | Pr(>F)       |
|---------------------|----|--------|---------|---------|--------------|
| TraumaExitA\$Weapon | 7  | 62.39  | 8.913   | 8.799   | 1.64e-06 *** |
| Residuals           | 40 | 40.52  | 1.013   |         |              |

```
---
Signif. codes:
  0 '***' 0.001 '**' 0.01 '*'
  0.05 '.' 0.1 ' ' 1

> TukeyHSD(test10)
Tukey multiple comparisons of means
 95% family-wise confidence level

Fit: aov(formula = t10log ~ TraumaExitA$Weapon)

$`TraumaExitA$Weapon`

```

|                               | di         |
|-------------------------------|------------|
| ff                            |            |
| Crossbow (Field Tip)-Compound | 0.81198962 |

|                                                            |             |
|------------------------------------------------------------|-------------|
| Crossbow (Fixed Broadhead)-Compound                        | 0.89637641  |
| Crossbow (Mechanical Broadhead)-Compound                   | 0.85631208  |
| Handgun-Compound                                           | 1.20122911  |
| Recurve-Compound                                           | -1.81741411 |
| Rifle-Compound                                             | 1.52347219  |
| Shotgun-Compound                                           | -1.08052876 |
| Crossbow (Fixed Broadhead)-Crossbow (Field Tip)            | 0.08438679  |
| Crossbow (Mechanical Broadhead)-Crossbow (Field Tip)       | 0.04432245  |
| Handgun-Crossbow (Field Tip)                               | 0.38923949  |
| Recurve-Crossbow (Field Tip)                               | -2.62940373 |
| Rifle-Crossbow (Field Tip)                                 | 0.71148257  |
| Shotgun-Crossbow (Field Tip)                               | -1.89251838 |
| Crossbow (Mechanical Broadhead)-Crossbow (Fixed Broadhead) | -0.0400643  |
| Handgun-Crossbow (Fixed Broadhead)                         | 0.30485270  |
| Recurve-Crossbow (Fixed Broadhead)                         | -2.71379052 |
| Rifle-Crossbow (Fixed Broadhead)                           | 0.62709578  |
| Shotgun-Crossbow (Fixed Broadhead)                         | -1.97690517 |
| Handgun-Crossbow (Mechanical Broadhead)                    | 0.34491704  |
| Recurve-Crossbow (Mechanical Broadhead)                    | -2.67372618 |
| Rifle-Crossbow (Mechanical Broadhead)                      | 0.66716011  |
| Shotgun-Crossbow (Mechanical Broadhead)                    | -1.93684083 |
| Recurve-Handgun                                            | -3.01864322 |
| Rifle-Handgun                                              | 0.32224308  |
| Shotgun-Handgun                                            | -2.28175787 |
| Rifle-Recurve                                              | 3.34088630  |
| Shotgun-Recurve                                            | 0.73688535  |
| Shotgun-Rifle                                              | -2.60400095 |
| lwr                                                        |             |
| Crossbow (Field Tip)-Compound                              | -1.2226967  |
| Crossbow (Fixed Broadhead)-Compound                        | -1.1383099  |
| Crossbow (Mechanical Broadhead)-Compound                   | -1.1783742  |
| Handgun-Compound                                           | -0.5339572  |
| Recurve-Compound                                           | -3.7011676  |
| Rifle-Compound                                             | -0.5112141  |
| Shotgun-Compound                                           | -3.1152150  |
| Crossbow (Fixed Broadhead)-Crossbow (Field Tip)            | -1.9502995  |
| Crossbow (Mechanical Broadhead)-Crossbow (Field Tip)       | -1.9903638  |
| Handgun-Crossbow (Field Tip)                               | -1.3459468  |
| Recurve-Crossbow (Field Tip)                               | -4.5131572  |
| Rifle-Crossbow (Field Tip)                                 | -1.3232037  |
| Shotgun-Crossbow (Field Tip)                               | -3.9272047  |
| Crossbow (Mechanical Broadhead)-Crossbow (Fixed Broadhead) | -2.0747506  |
| Handgun-Crossbow (Fixed Broadhead)                         | -1.4303336  |
| Recurve-Crossbow (Fixed Broadhead)                         | -4.5975440  |
| Rifle-Crossbow (Fixed Broadhead)                           | -1.4075905  |
| Shotgun-Crossbow (Fixed Broadhead)                         | -4.0115915  |
| Handgun-Crossbow (Mechanical Broadhead)                    | -1.3902693  |
| Recurve-Crossbow (Mechanical Broadhead)                    | -4.5574796  |
| Rifle-Crossbow (Mechanical Broadhead)                      | -1.3675262  |
| Shotgun-Crossbow (Mechanical Broadhead)                    | -3.9715271  |
| Recurve-Handgun                                            | -4.5741014  |
| Rifle-Handgun                                              | -1.4129432  |
| Shotgun-Handgun                                            | -4.0169442  |
| Rifle-Recurve                                              | 1.4571328   |
| Shotgun-Recurve                                            | -1.1468681  |
| Shotgun-Rifle                                              | -4.6386872  |
| upr                                                        |             |
| Crossbow (Field Tip)-Compound                              | 2.84667591  |
| Crossbow (Fixed Broadhead)-Compound                        | 2.93106270  |

|                                                            |             |
|------------------------------------------------------------|-------------|
| Crossbow (Mechanical Broadhead)-Compound                   | 2.89099836  |
| Handgun-Compound                                           | 2.93641541  |
| Recurve-Compound                                           | 0.06633935  |
| Rifle-Compound                                             | 3.55815848  |
| Shotgun-Compound                                           | 0.95415753  |
| Crossbow (Fixed Broadhead)-Crossbow (Field Tip)            | 2.11907307  |
| Crossbow (Mechanical Broadhead)-Crossbow (Field Tip)       | 2.07900874  |
| Handgun-Crossbow (Field Tip)                               | 2.12442578  |
| Recurve-Crossbow (Field Tip)                               | -0.74565027 |
| Rifle-Crossbow (Field Tip)                                 | 2.74616885  |
| Shotgun-Crossbow (Field Tip)                               | 0.14216791  |
| Crossbow (Mechanical Broadhead)-Crossbow (Fixed Broadhead) | 1.99462195  |
| Handgun-Crossbow (Fixed Broadhead)                         | 2.04003900  |
| Recurve-Crossbow (Fixed Broadhead)                         | -0.83003706 |
| Rifle-Crossbow (Fixed Broadhead)                           | 2.66178207  |
| Shotgun-Crossbow (Fixed Broadhead)                         | 0.05778112  |
| Handgun-Crossbow (Mechanical Broadhead)                    | 2.08010333  |
| Recurve-Crossbow (Mechanical Broadhead)                    | -0.78997272 |
| Rifle-Crossbow (Mechanical Broadhead)                      | 2.70184640  |
| Shotgun-Crossbow (Mechanical Broadhead)                    | 0.09784545  |
| Recurve-Handgun                                            | -1.46318499 |
| Rifle-Handgun                                              | 2.05742937  |
| Shotgun-Handgun                                            | -0.54657157 |
| Rifle-Recurve                                              | 5.22463976  |
| Shotgun-Recurve                                            | 2.62063881  |
| Shotgun-Rifle                                              | -0.56931466 |
| p adj                                                      |             |
| Crossbow (Field Tip)-Compound                              | 0.9024470   |
| Crossbow (Fixed Broadhead)-Compound                        | 0.8481301   |
| Crossbow (Mechanical Broadhead)-Compound                   | 0.8756265   |
| Handgun-Compound                                           | 0.3660645   |
| Recurve-Compound                                           | 0.0654422   |
| Rifle-Compound                                             | 0.2722601   |
| Shotgun-Compound                                           | 0.6887035   |
| Crossbow (Fixed Broadhead)-Crossbow (Field Tip)            | 1.0000000   |
| Crossbow (Mechanical Broadhead)-Crossbow (Field Tip)       | 1.0000000   |
| Handgun-Crossbow (Field Tip)                               | 0.9959711   |
| Recurve-Crossbow (Field Tip)                               | 0.0015279   |
| Rifle-Crossbow (Field Tip)                                 | 0.9490406   |
| Shotgun-Crossbow (Field Tip)                               | 0.0845292   |
| Crossbow (Mechanical Broadhead)-Crossbow (Fixed Broadhead) | 1.0000000   |
| Handgun-Crossbow (Fixed Broadhead)                         | 0.9991434   |
| Recurve-Crossbow (Fixed Broadhead)                         | 0.0009918   |
| Rifle-Crossbow (Fixed Broadhead)                           | 0.9740038   |
| Shotgun-Crossbow (Fixed Broadhead)                         | 0.0621625   |
| Handgun-Crossbow (Mechanical Broadhead)                    | 0.9981092   |
| Recurve-Crossbow (Mechanical Broadhead)                    | 0.0012184   |
| Rifle-Crossbow (Mechanical Broadhead)                      | 0.9636224   |
| Shotgun-Crossbow (Mechanical Broadhead)                    | 0.0720453   |
| Recurve-Handgun                                            | 0.0000064   |
| Rifle-Handgun                                              | 0.9987748   |
| Shotgun-Handgun                                            | 0.0032846   |
| Rifle-Recurve                                              | 0.0000356   |
| Shotgun-Recurve                                            | 0.9112131   |
| Shotgun-Rifle                                              | 0.0045526   |



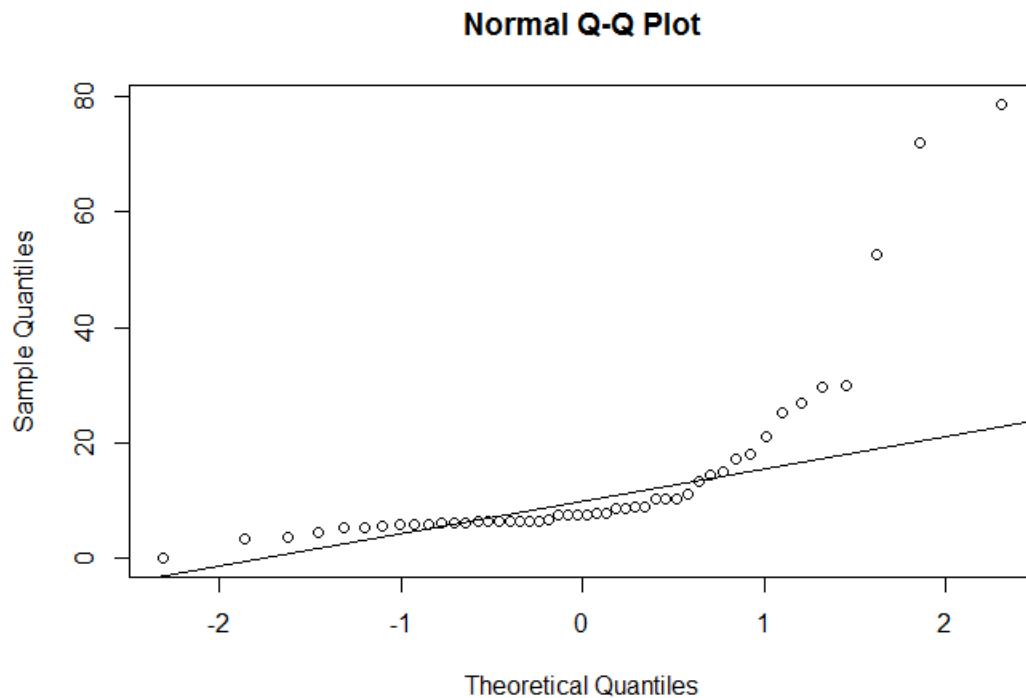
## Test 11

```
> shapiro.test(TraumaExitA$reconEndia)
```

Shapiro-wilk normality test

```
data: TraumaExitA$reconEndia  
W = 0.5918, p-value =  
2.518e-10
```

```
> qqnorm(TraumaExitA$reconEndia)  
> qqline(TraumaExitA$reconEndia)
```



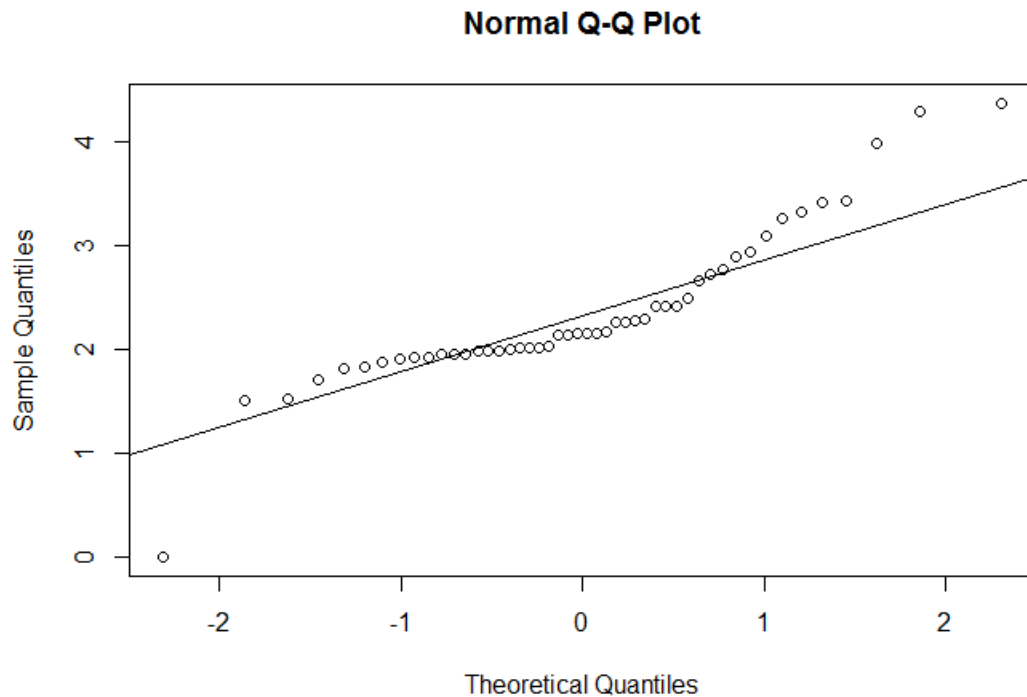
```
> leveneTest(TraumaExitA$reconEndia~TraumaExitA$weapon)  
Levene's Test for Homogeneity of Variance (center = median)  
      Df F value Pr(>F)  
group 7  1.364 0.2471  
      40
```

```
> shapiro.test(t11log)
```

Shapiro-wilk normality test

```
data: t11log  
W = 0.883, p-value =  
0.0001852
```

```
> qqnorm(t11log)  
> qqline(t11log)
```



```
> leveneTest(t11log~TraumaExitA$Weapon)
```

Levene's Test for Homogeneity of Variance (center = median)

|       | Df | F value | Pr(>F)   |
|-------|----|---------|----------|
| group | 7  | 2.2745  | 0.0477 * |
|       | 40 |         |          |

---

Signif. codes:

0 '\*\*\*' 0.001 '\*\*' 0.01 '\*'  
0.05 '.' 0.1 ' ' 1

```
> kruskal.test(reconEndia~Weapon, data=TraumaExitA)
```

kruskal-wallis rank sum  
test

data: reconEndia by weapon  
kruskal-wallis chi-squared  
= 15.6369, df = 7, p-value  
= 0.02865

```
> dunn.test(TraumaExitAneat$reconEndia, TraumaExitAneat$Weapon, meth  
od="bonferroni")
```

kruskal-wallis rank sum test

data: x and group  
kruskal-wallis chi-squared = 15.6369, df = 7, p-value = 0.03

Comparison of x by grou

p

(Bonferroni

)

Col Mean-|

| Row Mean              | Cb Field            | Cb Fixed            | Cb Mecha            | Compound            | Handgun             | Recurve             |
|-----------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|
| Cb Fixed              | 0.564937<br>1.0000  |                     |                     |                     |                     |                     |
| Cb Mecha              | -0.655327<br>1.0000 | -1.220265<br>1.0000 |                     |                     |                     |                     |
| Compound              | -1.265460<br>1.0000 | -1.830398<br>0.9407 | -0.610132<br>1.0000 |                     |                     |                     |
| Handgun               | -0.069858<br>1.0000 | -0.732306<br>1.0000 | 0.698581<br>1.0000  | 1.414025<br>1.0000  |                     |                     |
| Recurve               | 1.166358<br>1.0000  | 0.556156<br>1.0000  | 1.874193<br>0.8527  | 2.533212<br>0.1582  | 1.490460<br>1.0000  |                     |
| Rifle                 | 2.033776<br>0.5876  | 1.468838<br>1.0000  | 2.689103<br>0.1003  | 3.299236<br>0.0136* | 2.454672<br>0.1974  | 1.030370<br>1.0000  |
| Shotgun               | -0.214676<br>1.0000 | -0.779614<br>1.0000 | 0.440651<br>1.0000  | 1.050784<br>1.0000  | -0.181872<br>1.0000 | -1.398235<br>1.0000 |
| Col Mean-<br>Row Mean | Rifle               |                     |                     |                     |                     |                     |
| Shotgun               | -2.248452<br>0.3437 |                     |                     |                     |                     |                     |

alpha = 0.05  
Reject Ho if  $p \leq \alpha/2$

# Appendix C: Linear Discriminant Analysis

## Code Input and Output

### Exit Features Included

```
> daModelExitP <-
lda(weapon~maxfracExEn+minfracEnEx+Endia+minfraglenEn+reconExdia+max
fracExEx+reconEndia, TraumaExitP)
> daModelExitP
$prior
      Crossbow (Field Tip)
      0.1612903
      Crossbow (Fixed Broadhead)
      0.1612903
Crossbow (Mechanical Broadhead)
      0.1612903
      Handgun
      0.3548387
      Rifle
      0.1612903

$count
      Crossbow (Field Tip)
      5
      Crossbow (Fixed Broadhead)
      5
Crossbow (Mechanical Broadhead)
      5
      Handgun
      11
      Rifle
      5

$means
      maxfracExEn
Crossbow (Field Tip)      73.5600
Crossbow (Fixed Broadhead) 150.6000
Crossbow (Mechanical Broadhead) 156.4400
Handgun      179.7855
Rifle      211.9140
      minfracEnEx      Endia
Crossbow (Field Tip)      26.68000      8.14000
Crossbow (Fixed Broadhead) 44.36000      32.40000
Crossbow (Mechanical Broadhead) 25.16000      66.88000
Handgun      59.93636      69.73636
Rifle      56.74000      4.98000
      minfraglenEn
Crossbow (Field Tip)      1.82000
Crossbow (Fixed Broadhead) 22.24000
Crossbow (Mechanical Broadhead) 24.08000
Handgun      43.00909
Rifle      22.16000
      reconExdia
Crossbow (Field Tip)      12.80000
Crossbow (Fixed Broadhead) 9.10000
Crossbow (Mechanical Broadhead) 15.04000
Handgun      43.13636
Rifle      23.90000
```

```

maxfracExEx
Crossbow (Field Tip)      51.56000
Crossbow (Fixed Broadhead) 57.78000
Crossbow (Mechanical Broadhead) 77.68000
Handgun      95.71818
Rifle        92.14000

reconEndia
Crossbow (Field Tip)      8.14000
Crossbow (Fixed Broadhead) 11.22000
Crossbow (Mechanical Broadhead) 12.02000
Handgun      18.22727
Rifle        4.98000

$scaling
LD1 LD2 LD3
maxfracExEn -0.019642793 -0.0013986890 -0.0112655665
minfracEnEx 0.011505951 0.0152893379 0.0060996451
Endia 0.028847247 0.0296757401 -0.0060472546
minfraglenEn -0.004455212 -0.0009448423 -0.0005888685
reconExdia -0.053097159 0.0152372575 0.0436846935
maxfracExEx -0.005025335 -0.0061974232 -0.0026941853
reconEndia 0.032513714 0.0014132421 -0.0283259842
LD4
maxfracExEn -0.001158836
minfracEnEx -0.011212796
Endia 0.010853853
minfraglenEn -0.020200286
reconExdia 0.015844323
maxfracExEx 0.013976292
reconEndia -0.057135201

$lev
[1] "Crossbow (Field Tip)"
[2] "Crossbow (Fixed Broadhead)"
[3] "Crossbow (Mechanical Broadhead)"
[4] "Handgun"
[5] "Rifle"

$svd
[1] 3.261854 2.714316 1.303125 0.711253

$N
[1] 31

$call
lda(formula = weapon ~ maxfracExEn + minfracEnEx + Endia +
minfraglenEn +
reconExdia + maxfracExEx + reconEndia, data = TraumaExitP)

$terms
weapon ~ maxfracExEn + minfracEnEx + Endia + minfraglenEn +
reconExdia +
maxfracExEx + reconEndia
attr(,"variables")
list(weapon, maxfracExEn, minfracEnEx, Endia, minfraglenEn,
reconExdia,
maxfracExEx, reconEndia)
attr(,"factors")
maxfracExEn minfracEnEx Endia
weapon 0 0 0
maxfracExEn 1 0 0
minfracEnEx 0 1 0
Endia 0 0 1
minfraglenEn 0 0 0
reconExdia 0 0 0
maxfracExEx 0 0 0
reconEndia 0 0 0

```

```

      minfraglenEn reconExdia maxfracExEx
weapon            0          0          0
maxfracExEn      0          0          0
minfracEnEx      0          0          0
Endia            0          0          0
minfraglenEn     1          0          0
reconExdia       0          1          0
maxfracExEx      0          0          1
reconEndia       0          0          0
      reconEndia
weapon            0
maxfracExEn      0
minfracEnEx      0
Endia            0
minfraglenEn     0
reconExdia       0
maxfracExEx      0
reconEndia       1
attr("term.labels")
[1] "maxfracExEn" "minfracEnEx" "Endia"
[4] "minfraglenEn" "reconExdia" "maxfracExEx"
[7] "reconEndia"
attr("order")
[1] 1 1 1 1 1 1 1
attr("intercept")
[1] 1
attr("response")
[1] 1
attr(".Environment")
<environment: R_GlobalEnv>
attr("predvars")
list(weapon, maxfracExEn, minfracEnEx, Endia, minfraglenEn,
      reconExdia,
      maxfracExEx, reconEndia)
attr("dataClasses")
      weapon maxfracExEn minfracEnEx      Endia
      "factor" "numeric" "numeric" "numeric"
minfraglenEn reconExdia maxfracExEx reconEndia
      "numeric" "numeric" "numeric" "numeric"

$xlevels
named list()

attr("class")
[1] "lda"
> predictionExitP <- predict(daModelExitP, TraumaExitP)
> predictionExitP
$class
[1] Crossbow (Field Tip)
[2] Crossbow (Fixed Broadhead)
[3] Handgun
[4] Handgun
[5] Rifle
[6] Crossbow (Mechanical Broadhead)
[7] Handgun
[8] Handgun
[9] Handgun
[10] Handgun
[11] Handgun
[12] Rifle
[13] Rifle
[14] Rifle
[15] Rifle
[16] Rifle
[17] Crossbow (Field Tip)
[18] Crossbow (Field Tip)
[19] Crossbow (Field Tip)

```

[20] Crossbow (Field Tip)  
 [21] Crossbow (Field Tip)  
 [22] Handgun  
 [23] Crossbow (Mechanical Broadhead)  
 [24] Crossbow (Fixed Broadhead)  
 [25] Crossbow (Fixed Broadhead)  
 [26] Crossbow (Fixed Broadhead)  
 [27] Crossbow (Fixed Broadhead)  
 [28] Crossbow (Mechanical Broadhead)  
 [29] Crossbow (Mechanical Broadhead)  
 [30] Crossbow (Mechanical Broadhead)  
 [31] Crossbow (Fixed Broadhead)  
 5 Levels: Crossbow (Field Tip) ...

\$posterior

|    | Crossbow (Field Tip) | Crossbow (Fixed Broadhead) |
|----|----------------------|----------------------------|
| 1  | 9.395161e-01         | 0.0314481955               |
| 2  | 3.496727e-02         | 0.3349848747               |
| 3  | 2.087747e-03         | 0.0373221999               |
| 4  | 1.759478e-04         | 0.0111797439               |
| 5  | 1.703642e-03         | 0.0084620733               |
| 6  | 4.006947e-03         | 0.2076573544               |
| 7  | 2.541676e-04         | 0.0004794775               |
| 8  | 2.393714e-03         | 0.0159652012               |
| 9  | 2.600772e-03         | 0.0191734011               |
| 10 | 1.702056e-04         | 0.0006998015               |
| 11 | 4.422717e-03         | 0.1359345291               |
| 12 | 5.520362e-04         | 0.0026080339               |
| 13 | 1.615706e-01         | 0.0955582608               |
| 14 | 4.256048e-05         | 0.0001795864               |
| 15 | 8.930972e-03         | 0.0247815171               |
| 16 | 2.329453e-04         | 0.0066939825               |
| 17 | 8.626739e-01         | 0.0897721733               |
| 18 | 5.957871e-01         | 0.1869733262               |
| 19 | 4.910370e-01         | 0.3418150916               |
| 20 | 7.350115e-01         | 0.1626611090               |
| 21 | 6.245248e-01         | 0.2217219405               |
| 22 | 2.098780e-01         | 0.2585281460               |
| 23 | 3.240439e-01         | 0.2565934384               |
| 24 | 1.037557e-02         | 0.5792515482               |
| 25 | 1.739552e-01         | 0.5493390385               |
| 26 | 1.600710e-01         | 0.5211495929               |
| 27 | 8.040491e-02         | 0.5317808295               |
| 28 | 2.103472e-03         | 0.0166110848               |
| 29 | 3.225117e-02         | 0.2382806657               |
| 30 | 9.567834e-02         | 0.2142707395               |
| 31 | 3.252337e-01         | 0.4595850126               |

|    | Crossbow (Mechanical Broadhead) | Handgun     |
|----|---------------------------------|-------------|
| 1  | 1.512434e-02                    | 0.013724053 |
| 2  | 9.366216e-02                    | 0.307363682 |
| 3  | 1.308685e-02                    | 0.946360918 |
| 4  | 8.535735e-02                    | 0.902161033 |
| 5  | 4.087293e-03                    | 0.222304168 |
| 6  | 5.955035e-01                    | 0.192545013 |
| 7  | 2.549247e-03                    | 0.996684169 |
| 8  | 2.175278e-02                    | 0.705691584 |
| 9  | 2.322114e-01                    | 0.745561636 |
| 10 | 8.409196e-04                    | 0.987377076 |
| 11 | 1.148012e-01                    | 0.744820993 |
| 12 | 4.679034e-04                    | 0.010165679 |
| 13 | 3.721688e-02                    | 0.059497123 |
| 14 | 6.046798e-05                    | 0.002299672 |
| 15 | 1.017519e-02                    | 0.099917092 |
| 16 | 3.593533e-04                    | 0.054185125 |
| 17 | 3.647921e-02                    | 0.011003522 |
| 18 | 6.914639e-02                    | 0.142860502 |
| 19 | 1.505103e-01                    | 0.013998111 |

|    |              |             |
|----|--------------|-------------|
| 20 | 9.761881e-02 | 0.003385539 |
| 21 | 8.842973e-02 | 0.063946009 |
| 22 | 1.100853e-01 | 0.349835366 |
| 23 | 4.073126e-01 | 0.012030823 |
| 24 | 2.204395e-01 | 0.178853437 |
| 25 | 1.827715e-01 | 0.071638120 |
| 26 | 2.103583e-01 | 0.107952649 |
| 27 | 3.417088e-01 | 0.045153607 |
| 28 | 4.975549e-01 | 0.483653246 |
| 29 | 5.063586e-01 | 0.223021645 |
| 30 | 6.485329e-01 | 0.041147580 |
| 31 | 1.074656e-01 | 0.088848101 |

Rifle

|    |              |
|----|--------------|
| 1  | 1.872769e-04 |
| 2  | 2.290220e-01 |
| 3  | 1.142282e-03 |
| 4  | 1.125921e-03 |
| 5  | 7.634428e-01 |
| 6  | 2.871388e-04 |
| 7  | 3.293935e-05 |
| 8  | 2.541967e-01 |
| 9  | 4.527843e-04 |
| 10 | 1.091200e-02 |
| 11 | 2.054039e-05 |
| 12 | 9.862063e-01 |
| 13 | 6.461571e-01 |
| 14 | 9.974177e-01 |
| 15 | 8.561952e-01 |
| 16 | 9.385286e-01 |
| 17 | 7.116472e-05 |
| 18 | 5.232701e-03 |
| 19 | 2.639460e-03 |
| 20 | 1.323066e-03 |
| 21 | 1.377508e-03 |
| 22 | 7.167310e-02 |
| 23 | 1.928009e-05 |
| 24 | 1.107992e-02 |
| 25 | 2.229615e-02 |
| 26 | 4.684420e-04 |
| 27 | 9.518374e-04 |
| 28 | 7.731816e-05 |
| 29 | 8.793572e-05 |
| 30 | 3.704345e-04 |
| 31 | 1.886766e-02 |

\$x

|    | LD1         | LD2         | LD3         | LD4         |
|----|-------------|-------------|-------------|-------------|
| 1  | 1.42416165  | -1.07240944 | 2.37353073  | 0.44218806  |
| 2  | -0.77147754 | -0.53778790 | -0.69280630 | -0.67912753 |
| 3  | -0.35493835 | 1.62012507  | 0.64950886  | -1.92476616 |
| 4  | -0.58329740 | 2.27807434  | -1.20849851 | 0.71115825  |
| 5  | -2.21929568 | -0.15673128 | 0.16611128  | 0.28719932  |
| 6  | 0.89130406  | 1.11170676  | -1.93553490 | -0.10794082 |
| 7  | -0.34614345 | 3.00718071  | 2.26195231  | 0.48269392  |
| 8  | -1.73278235 | 0.50633195  | -0.05910356 | 0.75328118  |
| 9  | 0.23620768  | 1.82547468  | -0.39848236 | 1.54598744  |
| 10 | -2.01981653 | 1.88785077  | 1.71271692  | 0.03050236  |
| 11 | 1.21533301  | 2.13992012  | -0.02890256 | -1.96048816 |
| 12 | -2.51769330 | -1.30324594 | -0.30420176 | 0.03274593  |
| 13 | -0.88802164 | -1.70176660 | 0.18079137  | 0.86378571  |
| 14 | -3.24388889 | -1.30945229 | -0.40031333 | 0.95412391  |
| 15 | -1.71723749 | -0.89928043 | -0.10244158 | 0.47183989  |
| 16 | -2.74169833 | -0.48184448 | -0.24780044 | -1.91809838 |
| 17 | 1.89315218  | -1.00136766 | 1.57643048  | -0.13893314 |
| 18 | 0.60878224  | -0.68549416 | 1.33750843  | -0.16848284 |
| 19 | 1.14451616  | -1.51823980 | -0.23306527 | 0.15111554  |
| 20 | 1.40235593  | -2.03882937 | -0.06011300 | 0.88108840  |



```

21  1.09073556 -0.78298937  1.02061834 -0.22548504
22 -0.22679554 -0.59837211  0.47936995 -0.03100155
23  2.48027415 -0.48312966 -0.27763302  0.39369004
24  0.05492875  0.06121037 -1.78401102 -1.30782141
25  0.34259114 -1.04623234 -0.63559450 -0.39881054
26  1.31028024 -0.09726050 -0.06287163 -1.07856478
27  1.17509414 -0.44688957 -1.13212187 -0.48566190
28  0.79124734  2.06884074 -0.79091798  2.13170584
29  1.47905737  0.95964865 -0.57056990 -0.18028081
30  1.45052407 -0.24532366 -0.96495965  1.08983415
31  0.37254081 -1.05971760  0.13140446 -0.61747686

> predictionExitP <- predict(daModelExitP, TraumaExitP)
> daTraumaExitP <- pcTraumaExitP
> daTraumaExitP$predicted <- predictionExitP$class
> ggplot(daTraumaExitP, aes(x=pc1, y=pc2, col=predicted)) +
  geom_point() + facet_wrap(~weapon)

```

## Exit Features Excluded

```

> daModelExitA <-
  lda(weapon~maxfracEnEx+Endia+minfracEnEx+reconEndia, TraumaExitA)
> daModelExitA
$prior
      Compound
      0.1041667
Crossbow (Field Tip)
      0.1041667
Crossbow (Fixed Broadhead)
      0.1041667
Crossbow (Mechanical Broadhead)
      0.1041667
      Handgun
      0.2291667
      Recurve
      0.1458333
      Rifle
      0.1041667
      Shotgun
      0.1041667

$countss
      Compound
      5
      Crossbow (Field Tip)
      5
      Crossbow (Fixed Broadhead)
      5
Crossbow (Mechanical Broadhead)
      5
      Handgun
      11
      Recurve
      7
      Rifle
      5
      Shotgun
      5

$means
      maxfracEnEx
Compound 45.600000

```

```

Crossbow (Field Tip)          73.560000
Crossbow (Fixed Broadhead)    150.600000
Crossbow (Mechanical Broadhead) 156.440000
Handgun                      179.785455
Recurve                      2.214286
Rifle                        211.914000
Shotgun                      85.654000
                             Endia
Compound                     23.060000
Crossbow (Field Tip)          8.140000
Crossbow (Fixed Broadhead)    32.400000
Crossbow (Mechanical Broadhead) 66.880000
Handgun                      69.736364
Recurve                      7.357143
Rifle                        4.980000
Shotgun                      38.400000
                             minfracEnEx
Compound                     11.140000
Crossbow (Field Tip)          26.680000
Crossbow (Fixed Broadhead)    44.360000
Crossbow (Mechanical Broadhead) 25.160000
Handgun                      59.936364
Recurve                      1.414286
Rifle                        56.740000
Shotgun                      2.500000
                             reconEndia
Compound                     17.780000
Crossbow (Field Tip)          8.140000
Crossbow (Fixed Broadhead)    11.220000
Crossbow (Mechanical Broadhead) 12.020000
Handgun                      18.227273
Recurve                      7.357143
Rifle                        4.980000
Shotgun                      25.740000

$scaling
                             LD1
maxfracEnEx 0.0178266147
Endia       0.0079008612
minfracEnEx 0.0054549003
reconEndia  0.0006125499
                             LD2
                             LD3
                             LD4
maxfracEnEx 0.005219603
Endia       0.008619812
minfracEnEx -0.022558586
reconEndia  -0.041183324

$lev
[1] "Compound"
[2] "Crossbow (Field Tip)"
[3] "Crossbow (Fixed Broadhead)"
[4] "Crossbow (Mechanical Broadhead)"
[5] "Handgun"
[6] "Recurve"
[7] "Rifle"
[8] "Shotgun"

$svd
[1] 3.8767520 2.0149464 0.9197631 0.6725966

$N
[1] 48

$call
lda(formula = weapon ~ maxfracEnEx + Endia + minfracEnEx +
    data = TraumaExitA)

```

```

$terms
Weapon ~ maxfracEnEx + Endia + minfracEnEx + reconEndia
attr("variables")
list(Weapon, maxfracEnEx, Endia, minfracEnEx, reconEndia)
attr("factors")
      maxfracEnEx Endia minfracEnEx reconEndia
Weapon           0     0           0         0
maxfracEnEx      1     0           0         0
Endia            0     1           0         0
minfracEnEx      0     0           1         0
reconEndia       0     0           0         1
attr("term.labels")
[1] "maxfracEnEx" "Endia"          "minfracEnEx"
[4] "reconEndia"
attr("order")
[1] 1 1 1 1
attr("intercept")
[1] 1
attr("response")
[1] 1
attr("Environment")
<environment: R_GlobalEnv>
attr("predvars")
list(Weapon, maxfracEnEx, Endia, minfracEnEx, reconEndia)
attr("dataClasses")
      Weapon maxfracEnEx      Endia minfracEnEx
      "factor"  "numeric"  "numeric"  "numeric"
reconEndia
      "numeric"

$levels
named list()

attr("class")
[1] "lda"
> predictionExitA <- predict(daModelExitA, TraumaExitA)
> predictionExitA
$class
[1] Recurve
[2] Rifle
[3] Handgun
[4] Handgun
[5] Handgun
[6] Handgun
[7] Handgun
[8] Handgun
[9] Handgun
[10] Handgun
[11] Handgun
[12] Recurve
[13] Recurve
[14] Recurve
[15] Recurve
[16] Recurve
[17] Recurve
[18] Recurve
[19] Crossbow (Field Tip)
[20] Recurve
[21] Shotgun
[22] Compound
[23] Crossbow (Fixed Broadhead)
[24] Rifle
[25] Crossbow (Fixed Broadhead)
[26] Rifle
[27] Rifle
[28] Rifle

```

```

[29] Compound
[30] Recurve
[31] Crossbow (Field Tip)
[32] Compound
[33] Crossbow (Field Tip)
[34] Recurve
[35] Crossbow (Field Tip)
[36] Crossbow (Field Tip)
[37] Crossbow (Field Tip)
[38] Crossbow (Field Tip)
[39] Shotgun
[40] Crossbow (Field Tip)
[41] Crossbow (Mechanical Broadhead)
[42] Crossbow (Fixed Broadhead)
[43] Handgun
[44] Crossbow (Mechanical Broadhead)
[45] Handgun
[46] Handgun
[47] Handgun
[48] Crossbow (Fixed Broadhead)
8 Levels: Compound ... Shotgun

```

```

$posterior
      Compound Crossbow (Field Tip)
1  2.088083e-01      1.272834e-01
2  6.367294e-04      6.885128e-03
3  4.307457e-05      4.951929e-04
4  8.494354e-06      3.666502e-05
5  1.580237e-03      9.372641e-03
6  1.590996e-04      5.181732e-04
7  1.210478e-03      8.665964e-04
8  4.571306e-04      2.079626e-03
9  5.379165e-04      7.637364e-04
10 1.185743e-02      7.831815e-03
11 1.555217e-02      3.028421e-03
12 2.727019e-01      1.187082e-01
13 2.074330e-01      1.274276e-01
14 2.060627e-01      1.275695e-01
15 2.101886e-01      1.271369e-01
16 2.256654e-01      1.509458e-01
17 2.253662e-01      1.526986e-01
18 2.019828e-01      1.279814e-01
19 8.718740e-02      2.706272e-01
20 1.837117e-01      1.621192e-01
21 5.483552e-02      8.887169e-03
22 3.132952e-01      6.494415e-02
23 5.488764e-02      1.553963e-01
24 4.081585e-04      4.492604e-03
25 4.531920e-02      1.857116e-01
26 5.219245e-05      9.369883e-04
27 1.581947e-03      1.452471e-02
28 8.495488e-05      1.524037e-03
29 3.683833e-01      1.517302e-01
30 2.775129e-01      2.197847e-01
31 2.496521e-01      2.691417e-01
32 3.777049e-01      1.418503e-01
33 2.501570e-01      2.513055e-01
34 2.782357e-01      1.918690e-01
35 2.064973e-01      3.591366e-01
36 1.289673e-01      3.146616e-01
37 2.195334e-01      3.377270e-01
38 2.146706e-01      3.594238e-01
39 9.484895e-02      1.216411e-01
40 1.756349e-01      1.937473e-01
41 7.154486e-04      3.409304e-03
42 1.289407e-02      7.220597e-02
43 1.318585e-02      6.040036e-02

```

|    |                                 |              |
|----|---------------------------------|--------------|
| 44 | 1.860982e-02                    | 4.599412e-02 |
| 45 | 2.462755e-04                    | 2.606381e-04 |
| 46 | 4.515510e-03                    | 8.460611e-03 |
| 47 | 2.460306e-02                    | 3.901493e-02 |
| 48 | 6.660638e-02                    | 2.201075e-01 |
|    | Crossbow (Fixed Broadhead)      |              |
| 1  | 0.002857189                     |              |
| 2  | 0.191844083                     |              |
| 3  | 0.041553502                     |              |
| 4  | 0.018913159                     |              |
| 5  | 0.235856404                     |              |
| 6  | 0.055018467                     |              |
| 7  | 0.007280561                     |              |
| 8  | 0.101352547                     |              |
| 9  | 0.035595183                     |              |
| 10 | 0.126309220                     |              |
| 11 | 0.036885339                     |              |
| 12 | 0.003232289                     |              |
| 13 | 0.002847756                     |              |
| 14 | 0.002838300                     |              |
| 15 | 0.002866597                     |              |
| 16 | 0.004388855                     |              |
| 17 | 0.004469639                     |              |
| 18 | 0.002809795                     |              |
| 19 | 0.220027956                     |              |
| 20 | 0.004227761                     |              |
| 21 | 0.026943280                     |              |
| 22 | 0.030218534                     |              |
| 23 | 0.257978552                     |              |
| 24 | 0.081223589                     |              |
| 25 | 0.278257512                     |              |
| 26 | 0.042892632                     |              |
| 27 | 0.229280420                     |              |
| 28 | 0.102325150                     |              |
| 29 | 0.011300713                     |              |
| 30 | 0.014029936                     |              |
| 31 | 0.088224967                     |              |
| 32 | 0.010313088                     |              |
| 33 | 0.085597734                     |              |
| 34 | 0.009654916                     |              |
| 35 | 0.126424684                     |              |
| 36 | 0.222868335                     |              |
| 37 | 0.070490269                     |              |
| 38 | 0.121539584                     |              |
| 39 | 0.184205379                     |              |
| 40 | 0.122855478                     |              |
| 41 | 0.166053963                     |              |
| 42 | 0.369418699                     |              |
| 43 | 0.285058865                     |              |
| 44 | 0.239519834                     |              |
| 45 | 0.017015852                     |              |
| 46 | 0.100397442                     |              |
| 47 | 0.183651684                     |              |
| 48 | 0.293447408                     |              |
|    | Crossbow (Mechanical Broadhead) | Handgun      |
| 1  | 0.0009767916                    | 0.0001895856 |
| 2  | 0.0345097658                    | 0.1451480329 |
| 3  | 0.0046898277                    | 0.9407092796 |
| 4  | 0.2976562620                    | 0.6783305477 |
| 5  | 0.1518058003                    | 0.4555729291 |
| 6  | 0.4049611611                    | 0.5250932857 |
| 7  | 0.1230260305                    | 0.8668352369 |
| 8  | 0.1316374134                    | 0.7403519690 |
| 9  | 0.4038277802                    | 0.5530213098 |
| 10 | 0.1029023310                    | 0.5732366091 |
| 11 | 0.0448677348                    | 0.7336409096 |
| 12 | 0.0011802468                    | 0.0003214355 |

|    |              |              |
|----|--------------|--------------|
| 13 | 0.0009720942 | 0.0001872103 |
| 14 | 0.0009674005 | 0.0001848612 |
| 15 | 0.0009814926 | 0.0001919873 |
| 16 | 0.0014470988 | 0.0003530911 |
| 17 | 0.0014904013 | 0.0003202381 |
| 18 | 0.0009533453 | 0.0001779687 |
| 19 | 0.0573676782 | 0.0151540004 |
| 20 | 0.0013449993 | 0.0002166458 |
| 21 | 0.0124582545 | 0.0548251335 |
| 22 | 0.1260329445 | 0.1298144631 |
| 23 | 0.0687560641 | 0.0271781443 |
| 24 | 0.0157688607 | 0.0130928256 |
| 25 | 0.0673666083 | 0.0239779700 |
| 26 | 0.0071643839 | 0.0110966458 |
| 27 | 0.0404222895 | 0.1138828243 |
| 28 | 0.0147023919 | 0.1053556862 |
| 29 | 0.0041568292 | 0.0020538243 |
| 30 | 0.0045436603 | 0.0012991243 |
| 31 | 0.0262946055 | 0.0173861732 |
| 32 | 0.0038637730 | 0.0020070168 |
| 33 | 0.0667876126 | 0.0378715338 |
| 34 | 0.0031230851 | 0.0011160603 |
| 35 | 0.0325939590 | 0.0251388542 |
| 36 | 0.0555663780 | 0.0364229199 |
| 37 | 0.0204147233 | 0.0057817199 |
| 38 | 0.0311096559 | 0.0274652290 |
| 39 | 0.0566538189 | 0.0413900518 |
| 40 | 0.1841111241 | 0.0909077417 |
| 41 | 0.3725378236 | 0.2997419538 |
| 42 | 0.0726626329 | 0.1439118190 |
| 43 | 0.0484323145 | 0.5464900342 |
| 44 | 0.3749887602 | 0.2199345646 |
| 45 | 0.2968570025 | 0.6832064348 |
| 46 | 0.2599277837 | 0.6106443979 |
| 47 | 0.3085844717 | 0.3687242859 |
| 48 | 0.0714700795 | 0.0383219547 |

|    | Recurve      | Rifle        | Shotgun      |
|----|--------------|--------------|--------------|
| 1  | 6.234546e-01 | 1.514082e-05 | 3.641500e-02 |
| 2  | 2.479371e-05 | 6.170130e-01 | 3.938464e-03 |
| 3  | 8.257264e-07 | 1.245360e-02 | 5.469506e-05 |
| 4  | 1.176376e-07 | 4.825106e-03 | 2.296486e-04 |
| 5  | 8.266926e-05 | 1.378947e-01 | 7.834592e-03 |
| 6  | 4.631720e-06 | 1.176520e-02 | 2.479983e-03 |
| 7  | 2.407595e-04 | 2.585835e-06 | 5.377515e-04 |
| 8  | 1.671280e-05 | 2.183982e-02 | 2.264783e-03 |
| 9  | 2.189009e-05 | 1.239004e-03 | 4.993180e-03 |
| 10 | 1.642088e-04 | 1.041931e-02 | 1.672791e-01 |
| 11 | 1.416474e-04 | 2.898827e-04 | 1.655939e-01 |
| 12 | 5.427772e-01 | 1.256520e-05 | 6.106621e-02 |
| 13 | 6.251493e-01 | 1.519870e-05 | 3.596784e-02 |
| 14 | 6.268365e-01 | 1.525650e-05 | 3.552547e-02 |
| 15 | 6.217524e-01 | 1.508286e-05 | 3.686700e-02 |
| 16 | 5.756280e-01 | 2.614431e-05 | 4.154566e-02 |
| 17 | 5.701445e-01 | 3.055285e-05 | 4.547994e-02 |
| 18 | 6.318525e-01 | 1.542945e-05 | 3.422682e-02 |
| 19 | 2.914938e-02 | 1.146227e-01 | 2.058637e-01 |
| 20 | 6.160347e-01 | 3.917680e-05 | 3.230588e-02 |
| 21 | 7.402092e-04 | 7.136826e-04 | 8.405968e-01 |
| 22 | 1.075311e-01 | 1.893786e-05 | 2.281447e-01 |
| 23 | 8.976702e-03 | 1.891681e-01 | 2.376584e-01 |
| 24 | 2.005100e-05 | 8.796480e-01 | 5.345890e-03 |
| 25 | 1.067366e-02 | 2.498553e-01 | 1.388382e-01 |
| 26 | 1.607409e-06 | 9.370091e-01 | 8.464718e-04 |
| 27 | 8.626756e-05 | 5.919451e-01 | 8.276440e-03 |
| 28 | 2.081329e-06 | 7.753172e-01 | 6.884749e-04 |
| 29 | 2.836062e-01 | 7.230891e-05 | 1.786966e-01 |
| 30 | 3.840155e-01 | 1.876164e-04 | 9.862651e-02 |

|    |              |              |              |
|----|--------------|--------------|--------------|
| 31 | 9.811452e-02 | 3.787768e-03 | 2.473982e-01 |
| 32 | 2.790023e-01 | 5.804591e-05 | 1.852005e-01 |
| 33 | 1.583707e-01 | 1.109846e-03 | 1.488000e-01 |
| 34 | 4.447431e-01 | 7.398204e-05 | 7.118420e-02 |
| 35 | 1.098522e-01 | 6.671959e-03 | 1.336845e-01 |
| 36 | 4.460986e-02 | 3.608815e-02 | 1.608155e-01 |
| 37 | 1.605067e-01 | 5.134221e-03 | 1.804120e-01 |
| 38 | 1.167678e-01 | 5.269067e-03 | 1.237543e-01 |
| 39 | 9.910488e-03 | 4.266634e-02 | 4.486839e-01 |
| 40 | 9.631499e-02 | 1.526327e-03 | 1.349021e-01 |
| 41 | 2.814161e-05 | 1.464206e-01 | 1.109273e-02 |
| 42 | 1.383043e-03 | 2.919926e-01 | 3.553113e-02 |
| 43 | 1.538168e-03 | 3.420199e-02 | 1.069241e-02 |
| 44 | 2.796087e-03 | 3.213177e-02 | 6.602505e-02 |
| 45 | 7.796969e-06 | 2.487846e-04 | 2.157215e-03 |
| 46 | 3.980691e-04 | 3.401722e-03 | 1.225446e-02 |
| 47 | 3.185989e-03 | 8.151832e-03 | 6.408375e-02 |
| 48 | 1.549916e-02 | 1.377637e-01 | 1.567838e-01 |

\$x

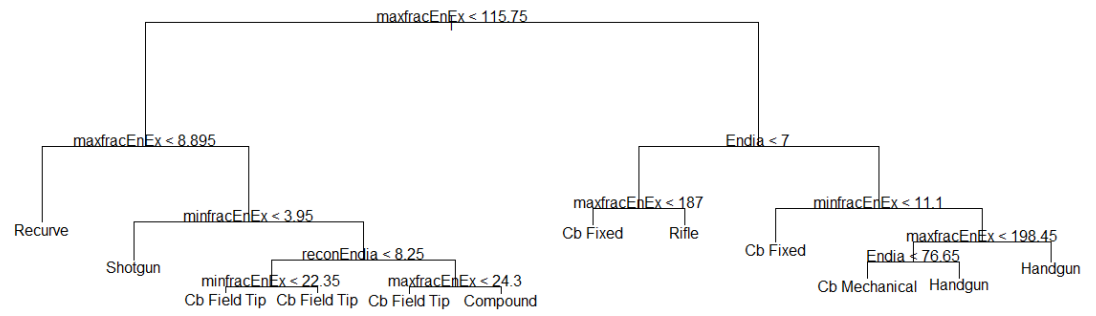
|    | LD1          | LD2          | LD3         | LD4         |
|----|--------------|--------------|-------------|-------------|
| 1  | -2.487434044 | -0.071236857 | 0.38926908  | 0.14631617  |
| 2  | 1.935670636  | 1.402358566  | 0.42700960  | -0.65111530 |
| 3  | 2.814521166  | -0.443508128 | 2.34932582  | -3.55857882 |
| 4  | 3.355297099  | -1.190686265 | 0.04047273  | 1.86129747  |
| 5  | 1.783810619  | 0.381576667  | 0.50233575  | -0.03537000 |
| 6  | 2.423091350  | -0.744837031 | -0.17599244 | 1.66437154  |
| 7  | 0.997493304  | -3.817881063 | 2.01915961  | -0.01019218 |
| 8  | 2.149600450  | -0.464289550 | 0.66398243  | -0.18369866 |
| 9  | 1.870056264  | -1.573281330 | -0.32194970 | 1.47257289  |
| 10 | 1.247156858  | -0.630391353 | -2.12198988 | -1.02261300 |
| 11 | 0.993591417  | -1.967029376 | -2.62708303 | -2.01224004 |
| 12 | -2.413367368 | -0.322046095 | -0.02682493 | -0.13698639 |
| 13 | -2.489136727 | -0.065471128 | 0.39883446  | 0.15282887  |
| 14 | -2.490839409 | -0.059705398 | 0.40839984  | 0.15934157  |
| 15 | -2.485731362 | -0.077002587 | 0.37970370  | 0.13980347  |
| 16 | -2.319807136 | -0.089085503 | 0.45965372  | 0.02147549  |
| 17 | -2.323893570 | -0.006471991 | 0.37583821  | 0.12547434  |
| 18 | -2.495947455 | -0.042408209 | 0.43709598  | 0.17887968  |
| 19 | -0.325383571 | 1.509276458  | -0.31224224 | 0.74024070  |
| 20 | -2.364802590 | 0.215884626  | 0.65203732  | 0.37167417  |
| 21 | 0.114343949  | -0.723528370 | -3.73083884 | -1.68310099 |
| 22 | -0.896095607 | -2.431792630 | -0.43613415 | 0.10792054  |
| 23 | 0.065186210  | 1.478950958  | -0.80265257 | 0.52872409  |
| 24 | 1.587256468  | 2.302142833  | -0.45772943 | 0.53522699  |
| 25 | 0.061512425  | 1.631772468  | -0.24436419 | 0.64616715  |
| 26 | 2.198613826  | 2.409121678  | -0.12680556 | 0.26623290  |
| 27 | 1.580037903  | 1.464677678  | 0.32912047  | -0.48431555 |
| 28 | 2.515322006  | 1.622892977  | 0.68006673  | -0.88614776 |
| 29 | -1.849094062 | -0.356124305 | -0.58802715 | -0.44661484 |
| 30 | -1.868731092 | 0.139390651  | 0.09952293  | 0.05306418  |
| 31 | -0.898549851 | 0.296254185  | -0.32693853 | -0.29139678 |
| 32 | -1.872456452 | -0.425381693 | -0.66323102 | -0.50338859 |
| 33 | -0.882780129 | -0.467301785 | 0.37634446  | 0.21189050  |
| 34 | -1.998395882 | -0.121197551 | 0.28593357  | -0.18406883 |
| 35 | -0.774411488 | 0.389829315  | 0.42604974  | -0.33493074 |
| 36 | -0.366784231 | 0.838041489  | 0.15194207  | -0.03924103 |
| 37 | -1.143691165 | 0.770306951  | -0.03033023 | 0.35517530  |
| 38 | -0.791251481 | 0.282616933  | 0.51003805  | -0.45448363 |
| 39 | -0.060901828 | 0.813290496  | -1.41390974 | -0.08561933 |
| 40 | -0.540074391 | -0.715232089 | 0.48325414  | 0.70155884  |
| 41 | 2.016197457  | 0.403178482  | -0.39098163 | 1.50952218  |
| 42 | 0.884661792  | 1.126975622  | 0.37938839  | -0.46521643 |
| 43 | 0.942415632  | -0.008248980 | 1.47994736  | -1.89002218 |
| 44 | 0.707479813  | 0.019918568  | 0.01478840  | 1.10318442  |
| 45 | 2.047728366  | -2.223806241 | -0.26825889 | 1.23805982  |
| 46 | 1.211702334  | -1.113704674 | 0.45444270  | 0.32477902  |

```
47  0.639340592 -0.621473300  0.03336346  0.47300193
48 -0.002527043  1.274665882 -0.14103657  0.27055683

> predictionExitA <- predict(daModelExitA, TraumaExitA)
> daTraumaExitA <- pcTraumaExitA
> daTraumaExitA$predicted <- predictionExitA$class
> ggplot(daTraumaExitA, aes(x=pc1, y=pc2, col=predicted)) +
  geom_point() + facet_wrap(~weapon)
```







```

> misclass.tree(TreeExitA)
[1] 8

```