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Comparison of direct and indirect ballistic trauma to porcine femora:
A contribution to the interpretation of patterns of skeletal trauma in
conflict casualties

Defence and Security
Forensic Archaeology and Anthropology

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the degree of Master of Science in Forensic Archaeology and
Anthropology

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ABSTRACT

Many types of skeletal trauma can be examined and identified on remains (blunt force, sharp force, ballistic, low-velocity projectile, sharp-blunt, thermal) and, due to the elastic and hardness properties of bone, each will present differently. Within ballistic trauma, there are further factors that will affect the visible patterns of trauma including the bone type, impact location and angle, and the shot distance. During humanitarian investigations, such as those carried out on casualties of the Spanish civil war, identification of the mechanism of trauma is essential when determining the manner and context of death for the individual. In order to do this studies must be conducted to provide comparison data for all factors affecting trauma. This study aims to contribute to the comparison data by examining the fracture and fragmentation patterns caused by the Mauser rifle by looking at direct and indirect impacts at varying shot distances. Twelve porcine femora were embedded in 20% ballistic gelatine and shot for direct and indirect impacts using 7.92mm Mauser ammunition at 10m and 20m distances. Once removed from the gelatine the size, shape, and edge characteristics of fragments were documented before reconstruction. The direct impacts presented with the (false) butterfly and double butterfly fracture patterns commonly seen in this type of trauma. Fragments from these bones showed semi-circular defects attributed to the entrance wound and edges consistent with peri-mortem trauma. Skimming impacts to the edge of the bone created elongated rectangular defects with fragments showing identifiable transverse edges. Indirect impacts showed simple fracture lines with no fragments but showed evidence of microfractures upon micro-CT scanning. Fragment analysis can be used to identify the mechanism of trauma in highly fragmented remains of humanitarian investigations; however, more research is needed to aid the identification of indirect ballistic trauma.

Keywords:

Forensic Anthropology, Spanish civil war, Mauser, long bones, fracture patterns, fragment analysis

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LIST OF ABBREVIATIONS

BFT	Blunt force trauma
SFT	Sharp force trauma

1 Introduction

Forensic anthropological examinations use a variety of methods and assess multiple different aspects of the human skeleton to create a profile of who the individual was and the context surrounding their death and deposition (White et al., 2012). One of the tasks to be carried out by the forensic anthropologist is to assess any visible trauma to the skeleton and report on the morphology of the trauma.

1.1 Skeletal Trauma Analysis

1.1.1 Background

The manner and cause of death are typically determined by the forensic pathologist through analysis of the soft tissues as well as other evidence (Shkrum and Ramsay, 2007). However, in the context of partially or fully skeletonised remains a forensic anthropologist may be needed to provide information on the signs of taphonomy and trauma on the skeletal remains to assist the pathologist (Ubelaker and Montaperto, 2014).

In forensic anthropology, accurate skeletal trauma analysis is essential in establishing the mechanism of injuries to bone. Analysing the morphology and size of fragments and the fracture patterns can help identify the particular mechanism of trauma that has affected the bone (Langley, 2017). To be able to do this, studies must be conducted to provide comparison material for examinations to be conducted against. Due to restrictions on the use of human material, these have been conducted using analogues for human tissue, which opens the study to their representativeness.

1.1.2 Human Bone Analogues for Trauma Experimentation

Schwab et al. (2023) studied the use of Synbone® cylinders and deer femora to reproduce long bone ballistic fracture patterns. Synbone® is a polyurethane material that is made to simulate the structure and biomechanical properties of human bone (Synbone®, n.d). They suggested that deer bone was more suitable than Synbone® for analysing skeletal trauma as it displayed a failure mechanism

more similar to human bone, therefore presenting a good approximation of fracture traits. Studies have shown that Synbone® may be used for more general studies of fragmentation, though should not be relied upon to visualise specific features such as entrance wounds (Henwood and Appleby-Thomas, 2019). Despite researchers naming deer as a suitable model for trauma research (Kieser et al., 2014; Hedgeland et al., 2016), it should be noted that the histological structure of pig bones is more similar to human bone (Hillier and Bell, 2007). Bonney and Goodman (2020) tested the validity of using porcine bone for sharp force trauma research. They reported that adolescent pigs present a similar bone hardness to adult humans and may be a good representation for trauma research.

1.1.3 Biomechanics of Bone

In order to understand the characteristics of skeletal trauma, it is important to have a strong knowledge of the biomechanics of bone. The way bone reacts to external forces is due to its composition of both organic (35%) and inorganic (40%) materials (Feng, 2009). Organic materials such as collagen provide the bone with its elastic properties, while inorganic materials such as hydroxyapatite give bone its resistance to compression forces (Wescott, 2013). These properties will allow the bone to withstand a certain level of stress and strain before deformation or failure, however, failure will occur once the strain levels reach the failure threshold (Wescott, 2013). When a slow loading force is applied to bone it will undergo elastic (temporary) deformation followed by plastic (permanent) deformation before finally failing. However, when a fast-loading force is applied bone will respond in a more brittle manner, failing without going through the stages of deformation (Love and Wiersema, 2016). This varying mechanical response to force will cause variation in fracture initiation and propagation, resulting in the characteristic fracturing seen within trauma types.

It is important to know the sequence in which this trauma occurred, specifically whether the trauma occurred before death (ante-mortem), after death (post-mortem) or around the time of death (peri-mortem). Post-mortem trauma is noticeable due to the jagged and irregular fracture edges. This is due to the loss

of collagen after death meaning the bone has lost its elastic properties and is behaving more brittle (Wieber and Wescott, 2008). Peri-mortem trauma will not have jagged edges and may show characteristics such as hinging. This is when, due to the bone retaining its elasticity, edges may lift away from the area of trauma (Symes et al., 2002). Ante-mortem trauma will show relatively smooth edges and will have signs of healing and remodelling (new bone growth). The extent of the remodelling will inform an estimated length of time since the trauma occurred (Langley, 2017).

1.1.4 Types of Trauma

In forensic anthropology, trauma is split into multiple categories. Each type can be identified on the bone as it will create different characteristics based on the speed, direction and origin of the forces used (Kimmerle and Baraybar, 2008).

Blunt force trauma (BFT): A slow-loaded force, impacting a specific focal area of bone and causing bone failure under tension and compression forces (e.g., fall from height, impact with a vehicle, blows with a blunt instrument) (Symes et al., 2012). Fracturing as a result of (BFT) can reflect the type of weapon used, how many impacts occurred, and the direction of the force (Love and Wiersema, 2016).

Sharp force trauma: Penetrating incision defects caused by a sharp object. A narrow focal area of bone undergoes dynamic, slow-loading, compressive forces which produce damage to both the soft tissue and the underlying bone (Symes et al., 2012). The wound morphology as a result of sharp force trauma will usually reflect the shape of the tool used to cause the trauma, for example, cutting trauma inflicted using a knife will present a V-shaped defect (Kimmerle and Baraybar, 2008).

Sharp-blunt trauma (corto-contundente): a combination of sharp and blunt trauma resulting in a smooth cut surface at the site of impact and a highly fragmented opposing layer due to the following blow (Kimmerle and Baraybar, 2008). Caused by tools such as a machete, hatchet, or axe.

Ballistic trauma: Damaged is caused by fast-loaded force from a high-velocity projectile such as a bullet from a gun or debris expelled by explosives (Symes et al., 2012). During a bullet's trajectory, it will create a temporary and permanent cavity. The permanent cavity is a result of the projectile crushing tissue along its trajectory and its size will be determined by the size of the projectile. The temporary cavity will stretch and disrupt the tissues surrounding the trajectory of the projectile for approximately 5 to 10 milliseconds before it collapses (Vellema and Scholtz, 2005).

Low-velocity projectile trauma: Trauma created by mechanisms such as small calibre ammunition, arrows, spears, and javelins that may show a combination of ballistic and blunt trauma traits (Blau, 2017). Due to the low velocity, they are likely to only perforate and not penetrate the bone (i.e., not passing completely through the bone) and so will show lower levels of fragmentation and fracturing (DiMaio, 2015).

Thermal trauma: Warping and fracturing of the bone caused by dehydration and loss of organic components when exposed to fire. The visible changes to the bone can be used to predict the intensity of the thermal trauma and details such as the presence or absence of soft tissue (Thompson, 2005).

Blast Trauma: A combination of sharp, blunt, and thermal trauma resulting from an explosion or explosive device. The trauma is caused by the blast wave (primary mechanism), shrapnel (secondary mechanism), sudden impact with surrounding surfaces (tertiary mechanism), and flash burns (quaternary mechanism) (Kimmerle and Baraybar, 2008).

1.2 Ballistic Trauma to Long Bones

Research surrounding wound characteristics resulting from ballistic trauma has primarily focused on crania with various contexts studied to aid in identification and differentiation from other trauma types (Hart, 2005; Pope and Smith, 2004; Smith et al., 2009). Examination of bone bevelling will determine the entrance and exit wounds and the angle at which the impact occurred. The pattern of

termination of fractures will reveal the order in which fractures occur, allowing the examiner to determine the order in which wounds were created (Matrille and Symes, 2019). It has been reported that patterns of radiating and concentric fractures that are visible in the cranium have a similar morphology in the long bones (Matrille and Symes, 2019).

Early research by Sir Bland-Sutton (1915) used radiographs and surgical experience to describe the fractures to the long bones due to ballistic injury. He suggests that an impact to the shaft of a long bone will commonly produce a comminuted “butterfly” fracture with varying numbers of fragments. These observations originated from military hospital patients and so are focused on a medical perspective of treating such injuries. The majority of research on the topic follows this perspective, using medical cases from different contexts to describe trauma patterns (Long et al., 2003; Ryan et al., 1981; Winquist and Hansen, 1980). Research has begun to evolve to include controlled experimental procedures to begin to better visualise and identify the varying fracture patterns. Bir et al. (2016) compared the fracture patterns that occurred from ballistic impact to human bone with the patterns visible in bone surrogates. This study describes the “butterfly” pattern seen previously but also includes further types of fractures including oblique, spiral, and linear patterns. It is the combination of these types of fractures that can create the comminuted fragmentation patterns that a butterfly fracture would be classified as. The focus of their study is, however, on the comparison between bone surrogates and their ability to simulate the effect of trauma on human bone. While this is an important area to research, there is still a lack of study into the identification and prevalence of specific fracture patterns in long bones compared with the research and knowledge gained on the effects of ballistic impact on the cranium.

More recent studies have begun to examine the fracture patterns in a more in-depth manner. Watson et al. (2023) used porcine long bones, some suspended in gelatine, as analogues for human tissue. These were then shot using varying types of hollow point ammunition to investigate the varying patterns of fracturing and fragmentation as a result of the ammunition. They observed the presence of

polygonal fragments resulting from the combination of different fracture types around the impact site. It was suggested that the level of jacketing to the bullet affected the size of fragments that were created. Phillips (2022) also followed on from current knowledge on ballistic trauma to crania and aimed to identify ballistic trauma and identify calibre on long bones. The study cast porcine femora into cylindrical gelatine moulds which were shot using 9x19mm and 7.62x39mm ammunition focusing on the analysis of the size and appearance of individual fragments in relation to the entry wounds for calibre determination. Most importantly, the study brings attention to the overlap in fracture patterns that occur in both blunt force and ballistic trauma to long bones. Analysis of the individual fragments is also shown to aid in this determination. Features of the edges may correlate with the curved shape of the entrance defect created by the bullet which may show bevelling and bullet wipe (soot residue)(DiMaio, 2015b). This idea of the differentiation between the mechanism of trauma has been well studied and documented in crania (Calce and Rogers, 2007; Hart, 2005; Donnellan et al., 2012; Taylor et al., 2022) but is limited in long bones.

There has been disagreement in the scientific community as to the use of nomenclature in trauma morphology to long bones, specifically with the term “butterfly fracture”. This terminology originates from Messerer’s description of wedge-shaped fractures resulting from BFT (Messerer, 1880) and is used to describe when shear failures create wing-shaped fragments from oblique fractures. This term began to be used in ballistic trauma analysis on long bones in the early 20th century due to the similarity in appearances (LeGarde, 1915). This is used to describe the double butterfly pattern created by four oblique fractures radiating from the entrance wound. Researchers have argued that these terms should not be used interchangeably for both types of trauma as it does not accurately describe the differences in the mechanisms that cause the trauma (L’Abbé et al., 2019), especially when only one ‘wing’ is created. This single wing fracture has been described as a ‘wedge-shaped’ fracture in BFT (Galloway and Wedel, 2014), and a ‘(false) butterfly’ fracture in ballistic trauma (Smith and Wheatley, 1984). For simplicity, in this study the term ‘double butterfly’ will be used to describe the ballistic fracture pattern that creates two winged shapes,

and the term '(false) butterfly' will be used to describe the ballistic fracture pattern that creates a single wing.

1.3 Indirect Ballistic Trauma

Indirect ballistic trauma is when the bullet does not impact the bone but instead passes close to the bone in the neighbouring tissues whilst still causing damage to the bone. The trauma to bone is then believed to have been caused by the impact of the temporary cavity created in the surrounding tissues (Sherman et al., 2007), though earlier studies believed this was due to the shock wave generated by the impact (Li et al., 1988). The temporary cavity is created by the bullet passing through the tissues causing them to expand but only exists for a brief period of time before collapsing (Kneubuehl, 2011).

Indirect ballistic injuries have been commonly noted in military contexts (Kieser et al., 2013), though many clinical cases have incorrectly been diagnosed as blunt force fractures due to the individual falling or running after the bullet impact (Ryan et al., 1981). This is likely due to the similarities that occur between the fracture patterns visible as a result of BFT and indirect ballistic trauma. Kieser et al. (2013) studied the mechanism of injury of indirect femoral fractures using fresh deer femora embedded in ballistic gelatine. They reported that the femora consistently presented with wedge-shaped fractures with the apex pointing towards the trajectory of the bullet. This wedge is also seen in BFT with the base of the wedge pointing towards the impact site, though it is most commonly seen in the tibia as a result of a pedestrian impact with a vehicle (Galloway and Wedel, 2014). Further patterns attributed to indirect impacts include spiral fractures (Smith and Wheatley, 1984) and transverse fractures (Kimmerle and Baraybar, 2008) (descriptions provided in Chapter 3.2.2). Despite there being research that has determined which fractures are observed as a result of this type of trauma, these fractures are also visible in multiple types of trauma. There is currently no research that determines what fracture patterns are specifically indicative of indirect ballistic trauma. The majority of current research focuses on the clinical issues surrounding the fractures and how they affect treatment plans (Baker et

al., 2022). However, research must be carried out to be able to identify this mechanism of trauma in archaeological remains.

The likelihood of indirect fractures occurring has been found to depend on two main factors; the bullet calibre and the distance between the bullet path and the bone. This is due to these factors affecting the size of the temporary cavity and the amount of energy transferred to the bone (Kieser et al., 2013). These two factors are reliant on each other, for example, a larger bullet calibre will create a larger temporary cavity which will transfer more energy to the surrounding tissues, however, this energy will only transfer to the bone causing fracturing if the bullet passes close enough to the bone's surface. Other factors that affect the likelihood of fracturing have been researched. Kieser et al. (2013b) investigated the effect of clothing on the appearance of indirect fractures in deer femora. Thicker layers of clothing were seen to increase the level of fracturing resulting in more comminution of clothed samples. This was due to the clothing making the bullet yaw earlier, causing a larger temporary cavity. Yawing is the deviation of the tip of the bullet from its line of flight causing it to tumble and cause more damage (DiMaio, 2015).

1.4 Humanitarian Context: The Spanish Civil War (1936-1939) and the Francoist regime that followed (1939-1975)

While it is known that trauma analysis is important in a modern forensic context, it is less thought of for its use in a humanitarian context. The purpose of trauma analysis in a humanitarian context is twofold; documentation of the manner and circumstances of death for judicial purposes and to identify and document the deceased for the families. It is one of the many stages carried out during cross-speciality investigations into historical conflicts and human rights cases which involve the exhumation and examination of victims of war. The disciplines involved in the Spanish civil war exhumations include forensic archaeologists, forensic anthropologists, and forensic pathologists (Owens, 2021).

At least 150,000 people (although this number is disputed) are believed to have been killed as a result of the civil war and the Franco regime (González-Ruibal et al., 2015). The victims did not only include soldiers involved in the fighting but also those who did not conform to the ideals of the fascist regime. Civilians were murdered and executed with many being buried in unmarked mass graves leaving many deaths and causes of death to go unrecorded (Owens, 2021). After the end of the Franco regime in 1975, many families wanted to recover the remains of their relatives, however, official investigation was not approved by the government. This led people to begin their own recovery efforts, exhuming remains from mass graves and identifying individuals as best as possible without examinations by a specialist (Passalacqua et al., 2015). Since official exhumations and identifications of these victims have begun in 2000, families have requested specialist examination on the identification of the individuals recovered and details regarding the manner of death. Teams have begun to exhume burial sites, using witness statements of locals to locate the sites. Forensic anthropologists have examined the remains to identify the individuals and the patterns of trauma the remains exhibit (Ríos et al., 2010).

The skeletal trauma visible in the victims of the Spanish civil war is commonly associated with either ballistic trauma or BFT (Passalacqua et al., 2015). This could then be compared to records recovered on deaths and executions to complete the knowledge surrounding an individual's death and identity. As previously mentioned, there are some similarities between the characteristic fracture patterns of these two trauma types so accurate background knowledge is essential in order to attribute the correct context of death to the remains.

1.5 Aims and Objectives

This study aims to contribute to the interpretation of the patterns of skeletal trauma caused by the Mauser rifle during the Spanish civil war. This will be addressed using the following objectives:

- To compare the patterns of trauma created by direct and indirect impacts.

- To investigate the characteristics of fragments created by ballistic trauma.
- To look at the distinctions between 10m and 20m shot distances.
- To compare patterns of trauma with known cases from the Spanish civil war.

2 Materials

2.1 Samples

A total of twelve porcine femora were sourced from three local butchers. Porcine bone was used as it is a commonly acceptable human analogue in experimental studies as it shares a similar macrostructure and microstructure with human bone (Pearce et al., 2007; Hillier and Bell, 2007). While it cannot be conclusively determined that the diet, environment, and lifestyle of the pigs were the same, the femora used were of generally consistent size, weight and age and showed no signs of disease. As they were sourced from the butchers on separate days; four of the twelve femora had been frozen and had to be defrosted over 24 hours prior to maceration. As the femora were only frozen for four days, this did not have a significant impact on the biomechanical properties of the bones (Linde and Sørensen, 1993). It was later discovered that two of the bones that were provided by the butcher were porcine humeri (bone 1/2 and bone 2/4), however, due to the quadrupedal nature of pigs, humeri have similar weight-bearing properties and hardness to femora (Bonney and Goodman, 2020) and so this was not deemed to have a significant impact on the results.

2.2 Maceration

All twelve femora were defleshed using manual maceration, involving the use of a scalpel to remove the majority of the flesh, as this method is shown to best retain the structural integrity of the bone (King and Birch, 2015). As the shot plan involved targeting the diaphysis of the femora, focus was taken to ensure a clean surface in this area to ensure fracture patterns were visible (Figure 1). Once cleaned they were refrigerated overnight in preparation for the gelatine.



Figure 1: Examples of the condition of porcine femora post maceration.

2.3 Gel Preparation

This experiment used a 20% ballistic gelatine (Gelita® ballistic 1)(80% water) concentration as it is the NATO testing standard and is of a similar density to human muscle (Kieser et al., 2013b). Two blocks of gelatine (200mm x 200mm x 300m) were made up and left to cool. A cotton string was tied around the femoral head and neck so the femora could be suspended from a metal rod in groups of three. Once the gelatine had cooled but was still in a liquid state, the femora were positioned in two offset rows, giving a total of six femora per block (

Figure 2). The gelatine was then left to cool further before being placed in the fridge for 24 hours to set.

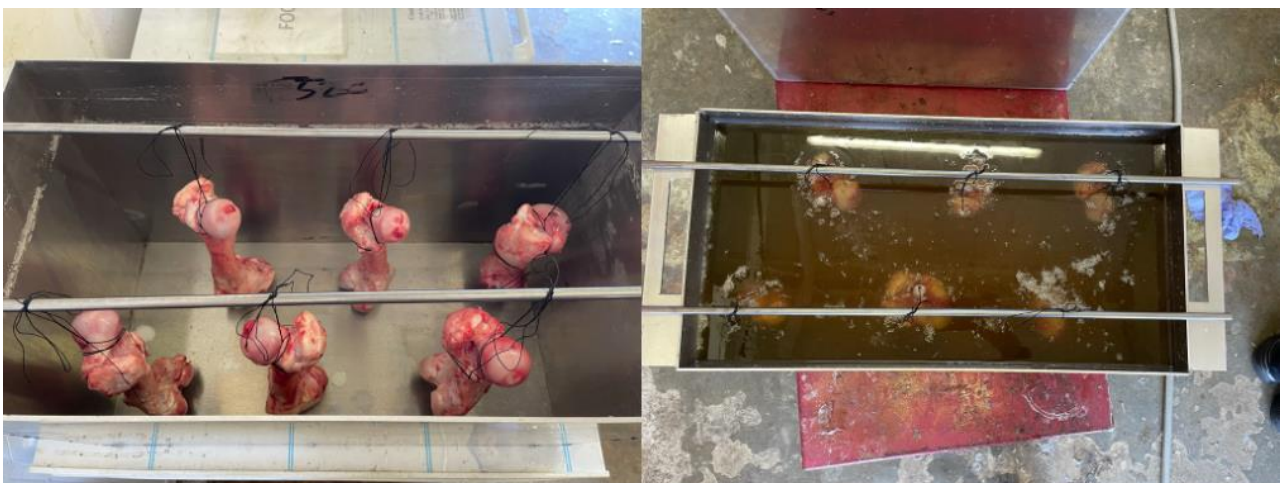


Figure 2: Positioning of femora in gelatine blocks before (left) and after (right) pouring of gelatine.

2.4 Firearms and Ammunition

A standard Mauser proof barrel was set up on a number 3 mount and fired with an electronic solenoid remote trigger mechanism and optical laser aiming (Figure 3). This was firing 7.92mm Mauser ammunition (Figure 4) as this was the most common firearm used during the Spanish civil war (Ruiz, 2017).



Figure 3: Image of number 3 mount as set for experimentation with Mauser barrel.



Figure 4: Image of 7.92mm Mauser ammunition.

3 Experimental Procedure

3.1 Shot procedure

The gelatine blocks were placed on a platform and set to be at the correct distance from the barrel. Bones were labelled according to the block they were in (e.g., 1 or 2) and the order in which they were shot (1-6). The shots taken can be seen in Table 1 below. Block one was left whole for the first three shots but was subsequently split into two rows as there was concern for damage to the rear femora, consequently, block 2 was split before firing. Direct shots were achieved by aiming at the centre of the diaphysis of the femur and indirect shots were achieved by aiming approximately 5mm away from the diaphysis. A Doppler radar (Weibel W700) was used to measure the impact velocity for each shot and, if possible, the residual velocity of the bullet after impact. All shots were filmed using a Phantom v1212 high-speed camera so that the impact could be viewed after shooting to ensure the correct impact was achieved. Some shots (indicated by * in Table 1) did not achieve the desired impact and so had to be repeated on the same bone. Shots 13 and 14 impacted too far away from the bone, and shot 11 impacted the bone directly, this shot had to be repeated for an indirect impact in a different area of the diaphysis.

Table 1: Documentation of shots including the bone aimed at, the distance, and any velocities measured. (*) indicates a shot that did not achieve the correct impact and had to be repeated.

Shot	Impact Type	Bone No.	Distance (m)	Impact Velocity (m/s)	Residual Velocity (m/s)
1	Direct	1/1	10	820.4	343
2	Direct	1/2	10	818.1	
3	Direct	1/3	10	818	321
4	Indirect	1/4	10	829.7	
5	Indirect	1/5	10	820.4	726
6	Indirect	1/6	10	825.1	688.9
7	Direct	2/1	20	816.9	
8	Direct	2/2	20	809.9	
9	Direct	2/3	20	805.3	
10	Indirect	2/4	20	813.4	
11	Indirect*	2/5	20	806.4	
12	Indirect	2/5	20		
13	Indirect*	2/6	20	815.8	
14	Indirect*	2/6	20	808.8	
15	Indirect	2/6	20	813.4	

Once all shots were completed the bones were photographed and documented inside the gelatine. The blocks were separated and stored in the freezer for one week before data collection could begin.

3.2 Reconstruction and Data Collection

3.2.1 Gelatine Removal

Each separated block was removed from the freezer and left to defrost at room temperature for 24 hours before the femora could be removed from the gelatine. The removal was carried out using a scalpel and forceps. Gelatine was removed in thin layers from the impact surface of the gelatine until bone could be seen and the impact site on the bone was visible. At this stage, the condition of the bone was photographed, and any visible fracture patterns were documented (Figure 5). The remaining gelatine was removed using wooden clay carving tools as wood is softer than bone and ensured that no damage was caused to the bone surface. Once the bone was fully removed from the gelatine the fragments could then be photographed and documented. The minimum and maximum measurement of each fragment was taken using electronic callipers and was documented alongside the shape, edge morphology, and number of fragments.



Figure 5: Bone 2/3 showing the process of gelatine removal. Gelatine has been removed until the surface of the bone is clear. The wooden pointer shows the bullet path and area of impact with bone.

At this stage two of the femora with an indirect impact (one from 10m and one from 20m) were scanned using micro-CT imaging to view if any microfractures were present. These two were chosen as they were the most intact and had little to no evidence of fracturing to the naked eye and micro-CT has been shown to aid in viewing the fine details of trauma to bone (Alsop et al., 2022). A Nikon XT H 225 was used with scan times of fifteen (bone 1/4) and thirty-three minutes (bone 2/6), achieving a resolution of 100µm.

3.2.2 Reconstruction

Prior to reconstruction, the femora were placed in a fume hood to dry out for 72 hours to ensure a dry surface for adhesion. The femora were then reconstructed using UHU superglue, focusing on the area of impact so that any entrance wound patterns were visible. This glue was used as its ingredients include cyanoacrylates, which have been shown to have promising bond strengths when used to bond bone (Böker et al., 2019).

Throughout the data collection stage, the bones were examined to determine the presence or absence of the following traits;

Bevelling: A cone-shaped chipping of the bone as a result of high-velocity projectile impact (Christensen and Rickman, 2022).

Linear Fractures: Straight fractures that can extend for the length of the bone shaft and run parallel to the diaphysis (Kimmerle and Baraybar, 2008).

Oblique Fractures: Diagonal fractures (Smith and Wheatley, 1984).

Concentric Fractures: Curved fractures that terminate at radiating fractures (Martrille and Symes, 2019).

Comminuted Fractures: When the fracturing splits the bone into more than two fragments (Bir et al., 2016)

False Butterfly Fracture: A V-shaped pattern created by two oblique fractures radiating from the entrance. The resulting fragment forms a wedge shape (Smith and Wheatley, 1984).

Double Butterfly Fracture: An X-shaped pattern created by four oblique fractures radiating from the entrance, resulting in two wedge-shaped fragments (Smith and Wheatley, 1984).

Wedge-shaped fracture: Triangular-shaped fragment with the apex pointing towards the impact of the temporary cavity (Kieser et al., 2013).

Transverse Fracture: A straight fracture perpendicular to the bone shaft (Kimmerle and Baraybar, 2008).

Spiral Fracture: A fracture that twists around the shaft of the long bone (Smith and Wheatley, 1984).

Microfractures: Microscopic fractures that are not visible to the naked eye (Kieser et al., 2014b).

Cortical Flaking: When the outer layer of the bone fractures away from the bone. Usually associated with trauma from a denser bullet (Henwood et al., 2019).

Bullet Wipe: The grey-black-coloured residue visible around the entrance wound created by soot (DiMaio, 2015b).

3.3 Statistical analysis

Independent t-tests were carried out using IBM SPSS statistics. These tests were to determine if there were any significant differences in the number of fragments produced (see Table 2) between the distances the femora were shot at and between the types of impact the femora experienced.

3.4 Ethical Approval

The methods carried out in this study were granted ethical approval by Cranfield University on the 7th of June 2023 through the Cranfield University research ethics system (CURES). See 6.1 Appendix A for the ethical approval letter.

4 Results

As previously mentioned in Chapter 3.1 there was difficulty in ensuring that the indirect impact shots did not hit the bone. After data collection, it was noted that the only bones that had experienced a true indirect impact were 1/4 and 2/6. With the exception of bone 2/5, which experienced an accidental direct impact, the remaining indirect shots skimmed the edge of the diaphysis of each bone, causing a higher level of fragmentation than expected but still forming observable patterns of fracturing and fragmentation. The six bones that were aimed for a direct impact (1/1, 1/2, 1/3, 2/1, 2/2, 2/3) experienced the impact to the centre of the diaphysis.

4.1 Fragment Analysis

For the t-test of fragment numbers (Table 2) between shot distances the observed t value was calculated to be 0.349 at $p=0.05$, indicating that there was no statistically significant difference between the number of fragments produced at 10m and 20m. When testing the significance of the types of impact the bone experienced, the observed t value was calculated to be 0.068 at $p=0.05$, also indicating that there is no statistically significant difference between the number of fragments produced by direct and indirect impacts. However, looking at bone 2/5 there was a visible irregularly high number of fragments produced for an indirect impact. This was deemed to be due to the aiming errors mentioned previously which caused this bone to be impacted directly before achieving an indirect impact in a different area of the shaft. Therefore, this value was disregarded as an outlier and the t-test was repeated, excluding bone 2/5. The t value was calculated to be 0.001 at $p=0.05$, indicating that there is a statically significant difference in the number of fragments produced by direct and indirect impacts.

Table 2: Number of fragments recovered for each bone. Note the irregularly high number of fragments for bone 2.5.

Bone	Distance	Impact	Number of Fragments
1.1	10	Direct	16
1.2	10	Direct	16
1.3	10	Direct	10
1.4	10	Indirect	0
1.5	10	Indirect	4
1.6	10	Indirect	8
2.1	20	Direct	17
2.2	20	Direct	17
2.3	20	Direct	12
2.4	20	Indirect	10
2.5	20	Indirect	22
2.6	20	Indirect	0

The general shapes and edge morphology of the fragments also did not seem to show any differences between the shot distances. There were, however, differences visible between the direct and indirect impact types (Figure 6). The bones that experienced a direct impact produced some fragments of irregular shapes with jagged and sharp edges though most had straight edges. The larger fragments produced by this type of impact did show regularity in the shapes which were most commonly triangular. The bones that experienced the indirect skimming impacts produced mainly irregular-shaped fragments with jagged edges, the most common shape being somewhat rectangular. In four of the direct

impact bones cortical flaking was visible three of which had been shot at the 20m distance.

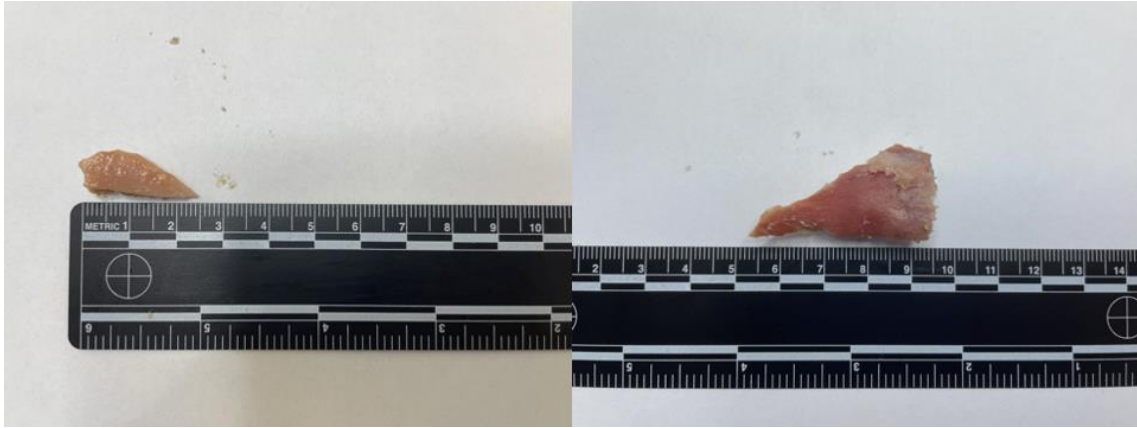


Figure 6: Examples of fragments. Left: Fragment from bone 1/1 with a triangular shape and straight/smooth edges. Right: Fragment from bone 2/4, showing irregular rectangular shape with jagged edges.

The fragment edges show a combination of post-mortem and peri-mortem characteristics. Many of the fragments showed jagged edges (indicative of post-mortem trauma), though the majority of the fragments presented with straight edges (indicative of peri-mortem trauma). All bones that experienced an impact by the bullet (10 out of 12) showed hinging to varying degrees.

The maximum and minimum lengths of each fragment were recorded and can be seen in Table 3.

Table 3: Minimum and maximum fragment measurements (mm) for each bon

Frag. No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Bone	Min / Max	Min / Max	Min / Max	Min / Max	Min / Max	Min / Max	Min / Max	Min / Max	Min / Max	Min / Max	Min / Max	Min / Max	Min / Max	Min / Max	Min / Max	Min / Max	Min / Max	Min / Max	Min / Max	Min / Max	Min / Max	Min / Max
1/1	19 / 34	18 / 30	16 / 27	14 / 24	7 / 27	11 / 16	8 / 22	5 / 15	4 / 16	5 / 14	7 / 25	5 / 35	9 / 24	3 / 14	4 / 9	9 / 20						
1/2	21 / 55	18 / 25	10 / 26	8 / 19	11 / 21	8 / 21	9 / 24	6 / 14	4 / 20	2 / 16	7 / 8	3 / 10	4 / 7	3 / 7	5 / 7	16 / 30						
1/3	8 / 25	6 / 24	5 / 15	5 / 12	4 / 14	2 / 13	3 / 10	3 / 21	5 / 19	7 / 21												
1/4																						
1/5	5 / 17	16 / 19	14 / 22	12 / 19																		
1/6	9 / 40	11 / 24	5 / 26	8 / 12	5 / 8	2 / 11	4 / 12	20 / 60														
2/1	17 / 52	14 / 50	7 / 29	10 / 28	4 / 20	10 / 23	6 / 14	7 / 14	4 / 15	3 / 13	7 / 8	1 / 12	3 / 6	3 / 8	14 / 26	12 / 20	16 / 39					
2/2	10 / 20	11 / 15	4 / 13	6 / 8	5 / 15	3 / 8	5 / 10	3 / 6	4 / 7	3 / 6	3 / 6	3 / 6	3 / 4	6 / 27	9 / 39	6 / 18	6 / 21					
2/3	7 / 24	7 / 18	9 / 11	8 / 9	4 / 13	6 / 23	12 / 30	6 / 30	6 / 23	11 / 28	10 / 28	7 / 18										
2/4	6 / 43	11 / 43	13 / 35	7 / 15	6 / 24	14 / 19	8 / 21	6 / 17	6 / 17	5 / 11												
2/5	12 / 26	5 / 21	7 / 24	5 / 26	10 / 21	7 / 17	12 / 19	5 / 19	18 / 15	6 / 12	6 / 13	4 / 11	4 / 9	3 / 9	3 / 12	5 / 9	3 / 9	4 / 7	8 / 28	9 / 31	8 / 17	12 / 24
2/6																						

In this study, entrance wound features were visible on the fragments in the direct impact samples. Bone 2/1 had a triangular fragment with a clear curved aspect indicative of an entrance wound (Figure 7). Also visible was bevelling on the external surface of the bone. Further fragments with curved aspects were also seen in bones 1/1 and 2/2, with the latter also showing bullet wipe (Figure 8). Bullet wipe was also seen on further fragments from bone 2/2 and from bones 2/5, 1/3, 1/2, and 1/1.



Figure 7: Fragment from bone 2/1 showing an entrance defect with bevelling.

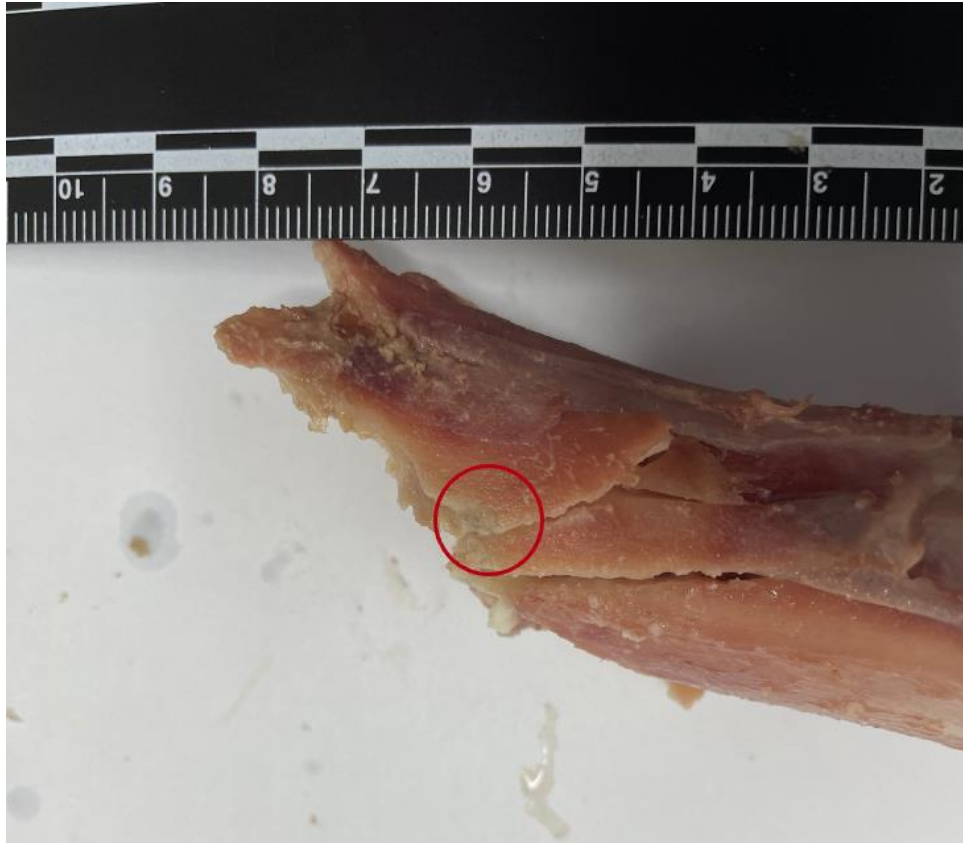


Figure 8: Fragment from bone 2/2 showing curved aspect indicative of an entrance defect with bullet wipe (red circle).

4.2 Fracture Lines

The types of fractures visible in each bone after reconstruction are shown in Table 4 below. With the exception of bone 1/4, which did not show any visible fractures, all of the bones showed oblique fracture lines mainly radiating from the impact point. This is the most common type of fracture in the study, regardless of impact type. All of the bones which had comminuted fracture patterns also had multiple oblique fractures.

Linear fractures were present in all of the direct impact samples and three of the indirect impact samples (1/5, 1/6, 2/5), with the indirect samples only showing one or two linear fractures. When spiral fractures were examined in the samples, they were always singular and did not create a complete fracture of the diaphysis due to it terminating at other fracture lines.

Bones 1/4 and 2/6 were the two true indirect impact samples. This means that there was no impact between the bone tissue and the bullet. Bone 2/6 showed visible fracture lines as a result of this. The bone presented a complete fracture, separating it into two parts. At the edge closest to the impact site the fracture is oblique. It then becomes a transverse fracture at around the midpoint of the diaphysis on the anterior surface and continues to be roughly transverse across the posterior of the diaphysis before joining with the oblique section to complete the fracture.

A further fracture to bone 2/6 was visible after micro-CT scanning. Radiating from the oblique section was an oblique microfracture (Figure 9). Microfractures were also visible on bone 1/4 which did not show any fractures on visual examination. This bone showed a small transverse then oblique fracture on the distal portion of the diaphysis (Figure 10) and a further linear fracture proximal to this that is shown to fracture completely through the cortex (Figure 11).



Figure 9: Micro-CT scan of bone 2/6 showing oblique microfracture (indicated by red arrow).



Figure 10: Micro-CT scan of bone 1/4 showing transverse/oblique microfracture (indicated by red arrow).

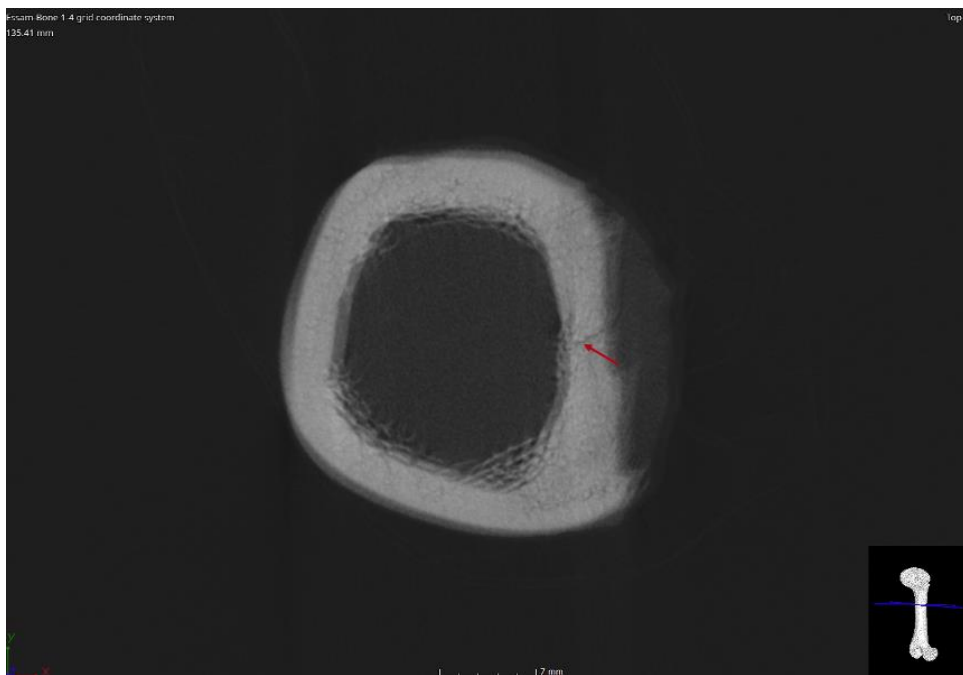


Figure 11: Micro-CT scan of bone 1/4 showing the extent of micro fracturing through the cortex (indicated by red arrow).

Table 4: Presence (indicated by /) and number (x) of types of fractures examined in the sample

Bone	Bevelling	Linear	Concentric	Oblique	Comminuted	(false) butterfly	Wedge- shaped	Double butterfly	Transverse	Flaking	Spiral	Microfracture
1/1		/(6)	/(1)	/(10)	/			/	/(6)		/(1)	
1/2		/(5)	/(1)	/(5)	/	/			/(9)		/(1)	
1/3		/(9)	/(1)	/(5)	/	/			/(11)	/		
1/4												/(2)
1/5		/(1)		/(3)	/				/(3)			
1/6		/(2)		/(7)	/				/(5)		/(1)	
2/1	/	/(5)	/(1)	/(7)	/	/			/(6)	/	/(1)	
2/2		/(3)	/(1)	/(11)	/	/				/	/(1)	
2/3		/(6)		/(7)	/				/(6)	/		
2/4			/(2)	/(9)	/	/						
2/5		/(1)		/(11)	/			/	/(6)			
2/6				/					/			/(1)

4.3 Fracture Patterns

Oblique fractures are the main fracture line that creates the false butterfly and butterfly fracture patterns. Although most samples in this study presented with oblique fractures, less than half of the samples showed these fracture patterns. This is likely due to the lack of concentric fractures in the samples which are required to create the butterfly pattern. Only two of the samples showed a double butterfly pattern (bones 1/1 and 2/5, Figure 12 and Figure 13) however five samples (four direct, one indirect) showed the false butterfly pattern. The indirect sample that showed this pattern was bone 2/4, which showed evidence of the bullet skimming the edge of the bone, therefore the bullet did come into direct contact with the diaphysis and was not a true indirect trauma. Therefore, the presence of the false butterfly pattern was only seen in bones which experienced an impact from the bullet.

A noticeable pattern in the samples (bones 1/2 and 2/3) appeared similar to a flower (Figure 14). A combination of linear and oblique fracture lines radiating from the entrance defect with transverse fractures joining them together created petal shapes around the entrance. This again was only seen in the direct impacts to the mid diaphysis.



Figure 12: Bone 1/1 showing double butterfly pattern (left). Right image with fracture tracing for clarity.



Figure 13: Bone 2/5 showing double butterfly pattern (left). Right image with fracture tracing for clarity.



Figure 14: Bone 1/2 presenting with 'flower' shaped fracture pattern (left). The right image shows tracing of fractures for clarity.

4.4 Entrance and Exit Defects

The direct impacts to the centre of the shaft exhibit the circular entrance defect whereas the bones which experienced the skimming impact produced a rectangular-shaped defect. This rectangle follows the path of the bullet through the bone (Figure 15). On bones 1/5 and 1/6 this rectangular pattern follows to end with a semi-circular exit defect that follows the shape of the bullet. Bone 2/4 has this semi-circular defect at the entrance defect of the rectangle.



Figure 15: Left: Anterior view of bone 1/5 showing rectangular defect created by the bullet skimming the bone. Right: Lateral view of bone 1/5 showing semi-circular exit defect.

5 Discussion

5.1 Comparison of impact-type fracture patterns

When looking at the indirect fracture visible on bone 2/6, the position of the bullet path in relation to the fracture suggests this fracture resulted from the bending of the bone due to the impact of the temporary cavity, however as multiple shots were conducted on this bone it is difficult to say which caused the fracturing and so in which direction this bending occurred (Figure 16). This fracture was very similar to the results of Zhang et al.'s (2015) study of indirect impacts of rifle ammunition. A 7.62mm bullet impacted 3cm away from a fresh pig marrowbone in ballistic gelatine. This resulted in a fracture that separated the bone into two parts due to a fracture that presented with both transverse and oblique sections, as is seen in this study. They concluded that the likelihood of these fractures occurring will increase with an increased bullet velocity or a decreased distance between the bone and the impact site. This is likely as it was noted that bone 1/4, which did not show any fractures, had an impact distance of 25mm whereas bone 2/6, which did fracture, had a shot distances of 16mm, 23mm, and 12mm. Other studies have described similar fractures with the term 'complete spiral' (Bir et al., 2016), though this does not accurately describe the complete morphology of the fracture seen in this study as it does not explain the clear transverse section. Therefore, this study suggests the use of the term 'false wedge' as the presence of a second oblique fracture in this pattern would cause it to appear more similarly to a wedge-shaped fracture.

Indirect and skimming impacts showed a lack of linear fractures, this is likely due to the lack of clear entrance and exit wounds. The multiple linear fractures visible in the direct impact bones were radiating from these defects whereas in bones 1/5 and 1/6 they were seen in other areas of the diaphysis due to it splitting from the pressure of the temporary cavity (Veenstra et al., 2022).



Figure 16: Bone 2/6 during the gelatine removal process. Wooden pointers showing the bullet paths.

As the only bones that presented with the false or double butterfly patterns experienced a direct shot to the centre of the diaphysis, this can be considered the main difference between the direct and indirect shots. This pattern was not in any indirect or skimming shots so these mechanisms can be ruled out during trauma examinations. The other direct trauma pattern to discuss is the ‘flower’ shape. This type of pattern has not been described in the literature so far but does seem similar to a double butterfly pattern, though with more fragments. For this study these patterns have been separated however it is possible that other studies have acknowledged this flower pattern as a double butterfly fracture.

The micro-CT images in this study present success in viewing further patterns of fracturing and details that could be used for further differentiation of trauma mechanisms. While micro-CT scans were not carried out on the direct impacts for comparison, it is likely that fractures would be visible if done so. This opens the possibility for variations in the microfracture patterns between indirect and

direct ballistic trauma that could be studied. Microfractures are more likely to be seen in wet bone due to its ability to resist the forces of trauma before failure (L'Abbé et al., 2013). Microfractures have been seen to radiate from the impact site in a similar way to visible fractures (Kieser et al., 2014b) which may indicate that microfractures also create observable patterns.

Despite the majority of the indirect impact bones experiencing a bullet-to-bone impact there is still clear variation between the direct impact bones and the skimming impact bones when looking at the shape of the entrance defect (circular vs rectangular). Keyhole-shaped defects (beveling at one side of the entrance wound) in long bones and crania have been seen to show the direction of the bullet when it impacts the bone at an angle (Berryman and Gunther, 2000). In this study, the bullet is shown to create a differing entrance shape without the angular bullet path but with a differing impact location. Following on from the examples seen in this study it would suggest that the shape of the entrance defect can be used to identify the position of origin of the bullet and determine the context of the injury.

The differences in fragment edge morphology between impact types could be due to the position of the bullet tract affecting the timing of the bullet tumble. When the bullet tumbles it will cause more fracturing to the bone, resulting in more irregular and jagged fragments usually seen at the exit wound (DiMaio, 2015b). when the bullet impacts the bone directly to the centre of the diaphysis it will begin to tumble during its passage through the bone, causing this type of fragmentation on the exit while the entrance remains having regular and straight fragments. When the bullet impacts the bone at an angle, such as in the indirect skimming impacts, it will tumble earlier causing irregular fragmentation during its path through the bone. While this could be an identifying morphology for impact types, this is not yet definitive as these jagged edges are also seen due to the trauma occurring post-mortem. More study is required to determine its usefulness in examinations.

5.2 Fragment characteristics

The fragments and reconstructed bones showed signs of peri-mortem trauma despite not using live pigs. This is due to the bones retaining their elastic properties after death and would be more accurately referred to as wet bone trauma and, by contrast, the post-mortem characteristics seen in this study would be referred to as dry bone trauma (Symes et al., 2013).

As mentioned in Chapter 4.1 bevelling was seen around the entrance defect in a fragment from bone 2/1. Bevelling is usually seen on the internal surface of the bone around the entrance wound and on the external surface of the bone around the exit wound. There have, however, been observed exceptions to this such as is seen in this example (DiMaio, 2015). The curved features that have been seen on the fragments, with or without bevelling, are the main identifier of ballistic impact to bone and with bevelling can identify the direction of the bullet path (DiMaio, 2015). The presence of bullet wipe on the majority of the direct impact samples can also be considered an identifier of ballistic trauma on fragments, particularly when seen with curved entrance features. It has also been shown that it is possible to identify the type of ammunition used through chemical analysis of the bullet wipe (Kieser et al., 2013b) and so is essential to be located during humanitarian examinations in order to complete the context of death.

The fragments seen in this study have shown to have identifiable edge and overall morphology as well as signs of entrance wounds. These features have shown to be connected with either direct (curved aspects) or skimming (long transverse edges) impacts. With further study, these fragment features could provide identification of different ballistic impact types. Fragment identification during humanitarian exhumations may aid in the initial determination of the mechanism of trauma before reconstruction can be carried out. During the exhumation of the Civil Cemetery of Almagro (Benito Sánchez et al., 2021) they uncovered multiple individuals that presented with perimortem trauma to the long bones. All of the fractures were comminuted and so each bone had multiple fragments to identify. In this state, the fractures could not be attributed to a particular type of trauma. Examination of the fragments to identify the above traits

could be useful in such situations to assess if ballistic trauma is a possible mechanism and the context behind it.

5.3 10m vs 20m shot distances

In four of the direct impact bones cortical flaking was visible three of which had been shot at the 20m distance. This has commonly been examined in the entrance wound, whereas in this study it is visible at and around the exit wounds (Figure 17). The cause of this phenomenon cannot be determined in this study though previous studies have suggested that this flaking occurs due to the pressure of the build-up of ballistic gases between the layers of bone (Amadasi et al., 2016). However, these studies have reported this occurring in close contact gunshot wounds whereas they were more prevalent in the 20m shots in this study. Again, the cause of this cannot be determined and so would require further study.



Figure 17: Bone 2/3 showing cortical flaking at the exit wound (red circle).

The maximum size of each fragment was taken and used to graphically display the data in order to review the variation in fragment size between the bones. There were no clear differences in the average size of the fragments between the bones (Figure 18), though this is likely due to the fact that each bone had a wide range of fragment sizes. When looking at the range of fragment sizes, the bones that were shot at 10m had more variation in ranges whereas the bones shot at 20m were more consistent (Figure 19). There was no clear variation between direct and indirect impacts.

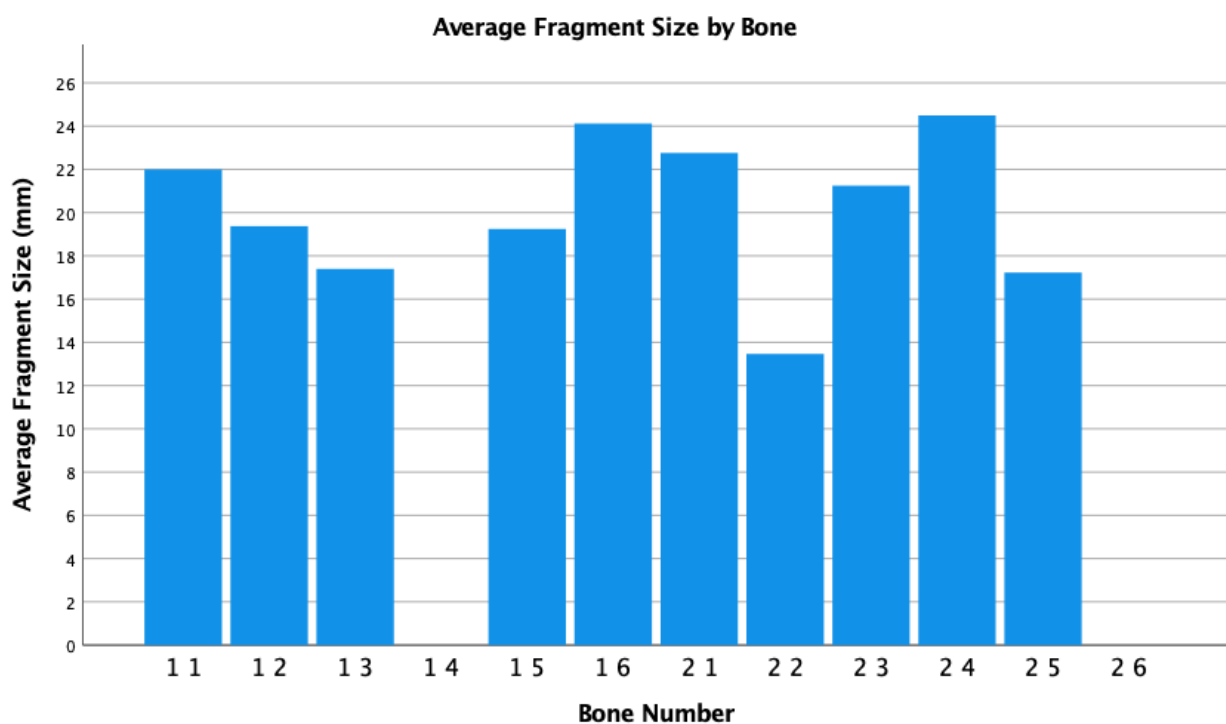


Figure 18: Bar graph displaying the average size of fragments of each bone.

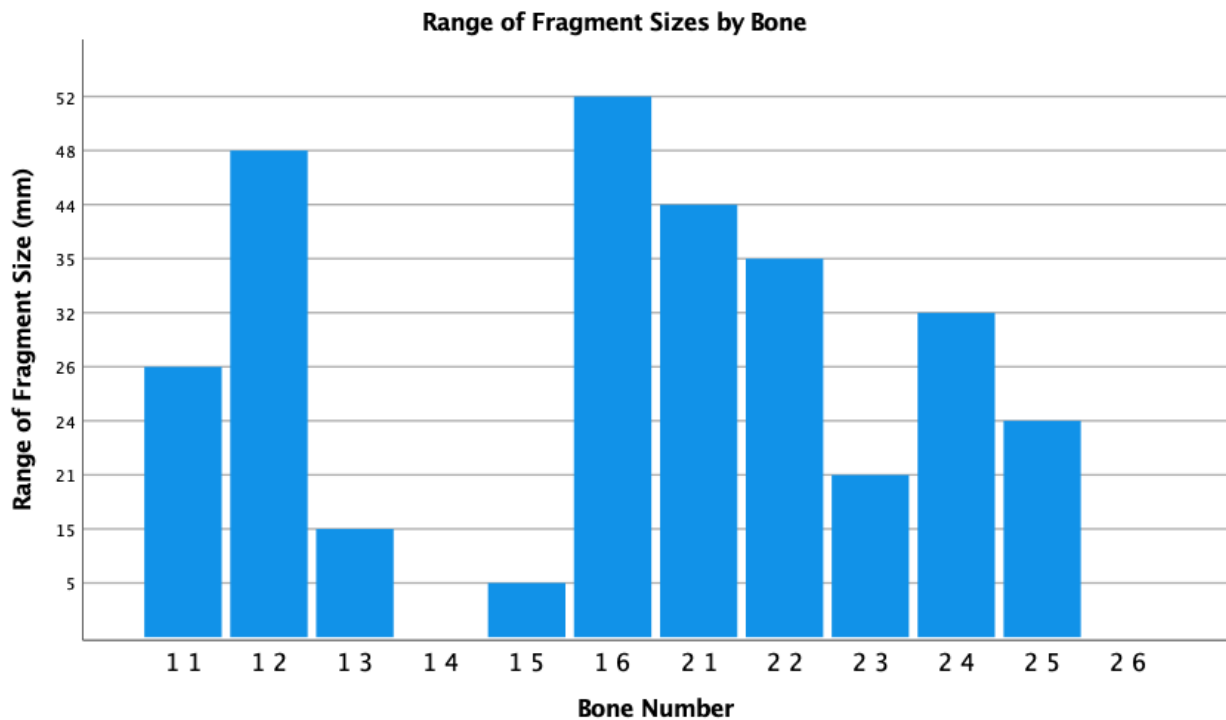


Figure 19: Bar graph displaying the fragment size range of each bone.

The correlation between oblique fracture lines and comminuted patterns suggests that it is the combination of multiple of these fractures that causes the bone to be separated into multiple fragments. The bones shot at the 20m distance seemed to have a slight increase in the prevalence of oblique fractures, with a range of 7-11 fractures for 20m bones as opposed to 3-10 fractures for 10m bones. Though this may have suggested that the 20m bones would have had a higher level of fragmentation, the statistical analysis described in Chapter 4.1 shows that this is not the case.

5.4 Comparison with Spanish civil war case studies

Butterfly (both false and double) patterns were common in this study. The prevalence of this pattern follows the expectations given by the literature presented in Chapter 1.2. This pattern has also been seen in upper and lower limb bones in Spanish civil war excavations. Polo Cerdá et al (2012) describe a humerus and femur recovered from a civil war mass grave which present with comminuted fractures attributed to ballistic trauma. Though the bones have not been reconstructed in the paper, when looking at the fragments present in the images there appear to be triangular-shaped fragments which create the butterfly or false butterfly patterns. This was also seen in a humerus from a burial site in “Castillo Argallén” with Mauser ammunition located nearby (Domínguez et al., 2017), showing that this type of fracture can be caused by the Mauser ammunition in the humanitarian context.

The rectangular skimming defect seen in this study has also been seen in crania that have been exhumed as part of the Spanish civil war excavations such as the mass burial site at Guadalajara (Owens, 2021). During the excavation a skull was discovered presenting with a rectangular defect which appears to have been caused by a bullet skimming across the superior portions of the left and right parietal bones, creating semi-circular defects at the entrance and exit of the wound. This was also seen in a skull from Alcalá de Henares (Madrid) where it was referred to as a keyhole defect (Dorado Fernandez et al., 2012). It follows that the presentation of this type of bullet impact appears in the long bones in a similar way as in the cranium, and so the methods used to determine the directionality of the bullet in cranial trauma may also be used when examining the long bones. Identifying this type of trauma prior to reconstruction would be relatively simple as elongated transverse fracture edges would be visible on the resulting fragments, such morphology was not seen on the fragments of any other femora in this study and so could be considered as an individuating feature.

The complete fracture described in bone 2/6 has a similar morphology to fractures seen in both humeri of individual 2 from a burial site in Lluçmajor, Mallorca (Aranzadi, 2019). These fractures also showed sections of transverse and

oblique fracturing with the possibility of a wedge-shaped morphology if more oblique fractures were present. The report suggested that they could be caused by BFT from a fall, though this couldn't be definitively concluded. This is a strong example of how similarities between BFT and indirect ballistic trauma may present in humanitarian examinations and the need for comparison studies to be conducted for definitive conclusions to be made.

5.5 Limitations

This study is limited by a relatively small sample size as only three femora were used for each shot variation. While this can be large enough to visualise patterns that occur, the consequence of this limitation is visible when combined with a further limitation of this study, the aiming inaccuracies. With the majority of the indirect impact samples accidentally experiencing a bullet-to-bone impact the study was left with only two true indirect samples to examine. In order to mitigate this issue, the sample sizes should have been larger, allowing more room for error and, in all likelihood, resulting in more true indirect samples to examine.

As mentioned in Chapter 2.1 the exact conditions of the source of the femora cannot be guaranteed. The level of calcium in the diet of growing pigs significantly affects bone strength with pigs on a calcium-deficient diet experiencing significantly reduced failure loads (Eklou-Kalonji et al., 1999). If the pigs used in this study had been fed varying levels of calcium this may have had an impact on how fractures propagated through the femora and therefore creating a variable which could not be controlled.

It should be noted that this study was also limited by resources as only two bones were able to be scanned using micro-CT limiting the conclusions that could be drawn from this data. Without comparisons to the direct impact bones, this study was only able to comment that microfractures were present on the two indirect impact bones without the ability to comment on the significance of this.

6 Conclusion

This study aimed to view the variations in fracture patterns between direct and indirect trauma and the distances at which they were shot. The method managed to produce an indirect fracture that was comparable to the current literature. From this, a comparison could be made to visualise the differences from direct ballistic trauma including the level of fragmentation and extent of fracturing. An indirect fracture will not produce the high level of comminuted fractures seen in direct ballistic trauma. Though the same types of fracture lines are present in both traumas, indirect trauma will create much simpler patterns with some fracturing only visible at the microscopic level. Direct trauma, by contrast, creates complex patterns with identifiable false and double butterfly shapes. The shot distances seem to show variation in the size of fragments and number of fractures created, though more study is needed to determine the extent of this.

An unexpected result of the study was the presentation of skimming impacts to the edge of the femoral diaphysis creating an elongated rectangular wound. The formation of this wound gives clear evidence to the mechanism of trauma which can be easily differentiated from the direct impacts. This trauma is a good example of the importance of fragment analysis in humanitarian investigations due to its individuating transverse fracture edges. For direct impacts, the examination of fragments should focus on the identification of circular defects indicative of a bullet wound. From here the shape of the fragment can be used to estimate the resulting fracture pattern, for example, a wide triangular shape could indicate a butterfly formation. Each of the patterns seen in this study can be compared to those seen in remains examined from the Spanish civil war and the following Francoist regime. Some of these trauma patterns have not been definitively attributed to a trauma mechanism, though this study has presented anthropological methods that could be used in such situations.

6.1 Recommendations for Future Work

There is a wide range of opportunities for future work on this topic. This could simply begin with an improvement on this study by increasing the number of

femora used and improving the accuracies for aiming the indirect impacts. This should include micro-CT scanning of all samples. This would then create a base to begin to widen the scope of the study. This could include using more types of long bones to assess the variation between upper and lower limbs. Other variation that could be examined includes that between types of ammunition and distances. Distances in this context would mean both how far away the target is from the firearm and how far away the bullet trajectory and impact site are from the bone surface. The most important comparison that should be examined in further study is that with other types of trauma, especially BFT due to its similarities in fracture patterns with indirect ballistic trauma.

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APPENDICES

Appendix A Ethical Approval Letter



7 June 2023

Dear Miss Essam ,

Reference: CURES/19217/2023

Project ID: 21149

Title: A comparison of direct and indirect ballistic trauma to pig femora using WW2 and Spanish Civil War rifles

Thank you for your application to the Cranfield University Research Ethics System (CURES).

We are pleased to inform you your CURES application, reference CURES/19217/2023 has been reviewed. You may now proceed with the research activities you have sought approval for.

If you have any queries, please contact CURES Support.

We wish you every success with your project.

Regards,

CURES Team

Appendix B Glossary

Deposition	The placing or burial of remains
Analogues	Comparative models for human tissue
Synbone®	Synthetic models made to simulate human bone
Peri-mortem	Occurs around the time of death
Ante-mortem	Occurs before the time of death
Post-mortem	Occurs after the time of death
Bone remodelling	Process of new bone formation
Morphology	Shape or visual appearance
Permanent cavity	The space left by the passage of the projectile
Temporary cavity	Expansion of tissue during the projectile's passage
Fracture initiation	The formation of fractures in bone
Fracture propagation	The progression and termination of fractures in bone
Bullet yaw	Deviation of the tip of the bullet from its line of flight
Maceration	Process of removing soft tissue
Diaphysis	Midsection (shaft) of a long bone
Cortical flaking	Fracturing of the outer layer of bone
Bullet wipe	Grey-black coloured soot residue