

ORIGINAL PAPER

Anthropology

Ballistic impact of hollow-point ammunition on porcine bone

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Abstract

Identifying failure mechanisms in skeletal tissue allows a deeper understanding of the effects of specific projectile impacts on bone. While ballistic trauma in flat bones is largely researched, knowledge of how long bones react to gunshot impacts is limited in the literature. The impacts of deforming ammunition appear to produce higher levels of fragmentation; however, these have not been studied in depth. This study compares the damage to femora bone by HP 0.357 and 9 mm projectiles constructed with both full and semi-metal jackets. Impact experiments were undertaken on a single-stage light gas gun involving the use of a high-speed video camera and full reconstruction of the bones to ascertain fracture patterns occurring in the femora. Higher degrees of fragmentation are likened to the presence of semi-jacketed HP projectiles than jacketed HP projectiles. The observations of external facing beveled edges are believed to be associated with the increased separation of the jacket and lead core of projectiles. Additionally, experimentation has shown that the amount of kinetic energy lost postimpact is likely related to the presence or the absence of a metal jacket on an HP projectile. The observed data, therefore, suggest that the composition, rather than the configuration, of a projectile affects the type and extent of the damage.

KEYWORDS

ballistic trauma, bone trauma, firearms, fracture analysis, hollow point, jacketed bullet

Highlights

- First investigation of bone damage characterization from HP bullets.
- Comparison between HP impact to bone and that of jacketed or soft-point bullets.
- Damage to femora has a higher degree of fragmentation from HP than jacketed bullets.

1 | INTRODUCTION

Gunshot wounds in soft tissue are well researched [1], however, ballistic trauma in bone is not covered in any depth in scientific research. In the present literature, ballistic trauma is researched more

so in flat bones such as those comprising the cranium, and the scapulae [2, 3], as well as the rib cage [4, 5]. Current research has shown that researchers have focused on the areas of the skeleton which are most likely to cause fatality. In contrast, both in conflict and on battlefields, trauma centers encounter injuries to the extremities more

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frequently [6, 7]. A bullet traveling through easily disrupted organs such as the brain is generally fatal in head trauma versus extremities which are often more tolerant to impact. The neurovascular structure of the extremities may avoid damage from the bullet's path but remain susceptible to functional failure [6]. Vascular injuries, such as to the femoral vein, will ultimately cause complications such as major blood loss which can lead to fatality [7, 8]. These factors highlight a need for researching ballistic trauma in extremities, specifically the fracturing of bone tissue.

Bone trauma created by high-velocity gunshot wounds causes fracture patterns which could help investigators establish bullet types [2]. Research has shown that while calibers and bullet types affect the degree of wounding, the construction of the bullet also influences damage. The construction of a bullet can be characterized by the absence or the presence of a metal jacket, whether full or partial. Identified fracture patterns in bone have led to the identification of both bullet types and calibers [9, 10]. The minimum diameter of entrance wounds in bone has been used for caliber estimation [10]. Additional research has shown that bullets of the same physical size, a 9 mm and 0.38 caliber bullet, produce indistinguishable entrance wound minimum diameters, whereas a 0.22 caliber bullet creates an evidently smaller entrance wound [9]. However, it should be stated that only broad caliber estimations can be made based on the diameter of the entrance wound.

Full metal jacket (FMJ) bullets have been shown to create more fragmentation in impacted femora than lead bullets because the metal jacket absorbs minimal impact energy due to its mass and density, so it is dispersed into the bone [9]. Soft-point (SP) and hollow-point (HP) rifle bullets, which both deform on impact, display the same amount of kinetic energy loss at lower firearm velocities [2]. Figure 1 illustrates the three aforementioned bullet types.

While HP ammunition remains legal and commonly used by civilians and police, they are known to create considerable damage on impact [1]. HP bullets are distinguishable by the cavity in the nose designed to aid the expansion or deformation of the bullet on impact. Due to the expansion, the core is often stripped from its jacket. These bullets are recognized for their extensive damage to soft tissue causing larger wound cavities [12]. Due to the deformation of an expanding projectile, its caliber becomes less influential in the

damage done. Additionally, both the bullet's velocity and the presence of a metal jacket will affect its deformation and questionably, the type of fracturing mechanisms seen in impacted bone [1]. This study will focus on the physical damage of HP ammunition and its wounding capacity to long bone.

When a soft- or hollow-point bullet impacts a soft homogeneous medium, the pressure of the impact is imparted on the exposed lead causing deformation and increasing energy transfer [13]. This phenomenon does not occur with an FMJ hollow-point bullet, which behaves like FMJ round nose bullets unless the target medium is able to penetrate the hollowed tip [13]. The construction of a bullet, regarding the presence of a metal jacket covering the lead core, has been shown to cause a higher degree of fragmentation in long bones [9]. It has also been documented that soft-point bullets have created linear and larger fractures in bone compared with those impacted by FMJ projectiles [14].

The fractures caused by the semi-jacketed hollow-point (SJHP) projectiles used in this study are anticipated to be comparable to fractures caused by SP round nose bullets. The lead point of the SJHP projectiles is effectively the same composition as the soft point of a lead round nose bullet, the difference lies in the hollowed point of the projectiles. This difference is shown in Figure 2. It appears the HP directly impacts the *amount* of damage observed to the bone, while the presence of a jacket is shown to affect the *type* of damage.

Bullet mass is one of the main characteristics worth considering during the interpretation of ballistic damage as two different bullets may be the same type and caliber but possess different masses. However, the bullet size, or caliber, has been shown to influence energy expenditure more so than bullet mass at given velocities [15]. Harger and Heulke (1970) conclude nonetheless that as a bullet's impact velocity increases, the dispersion of energy is affected, and damage will increase regardless of the bullet's features [15]. It must be noted that in this study, Harger and Heulke conducted their experiments using steel balls, therefore not considering the deformation factor of HP ammunition.

Bone is a viscoelastic tissue with properties that allow it to deform and return to its original shape [1]. Long bones provide stability to the human body as they possess cylindrical medullary cavities surrounded by cortical bone, with less dense trabecular bone in

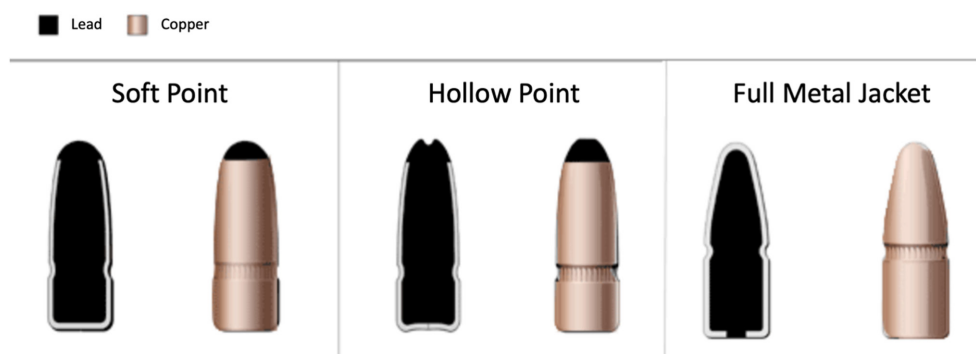


FIGURE 1 An illustration of 9 mm full metal jacket (FMJ) bullets, 9 mm HP (HP) bullets, and 7.62 SP bullets [11].



FIGURE 2 An HP bullet (left) and SJHP bullet (right) (image authors own).

the epiphyses [3, 16, 17]. The macrostructure and the microstructure are structurally different between flat bones and long bones and consequently influence the failure mechanisms following high-velocity impacts [4, 16, 17]. The differences in microstructure suggest that fracture lines do not propagate on the surface of the end of long bones, versus the femoral diaphysis which does not contain the porous trabecular bone. The strength of the bone tissue leads to significant energy transfer and fragmentation when impacted by bullets [6]. The energy transfers from a handgun bullet to bone remain significant, whereas full metal jackets and deforming bullets specifically carry less energy than rifle bullets. Consequently, the energy transfer to the bone would be less [13].

When the bullet's kinetic energy transfers to the bone and travels through the medullary cavity, fracturing occurs in all directions. Information on the types of fracture lines occurring in long bones from impact has been outlined in literature [18, 19]. Reconstruction of a fractured bone is often necessary for proper analysis, where it helps display evidence of a projectile's travel and characteristics [1, 4, 9].

"Comminution" is identified as bone which fragments into more than two pieces. Comminuted fractures that occur in long bones, typically occur in the diaphysis which is comprised of cortical bone [18]. This type of fragmentation has been shown to occur due to several types of traumas, including ballistic trauma [8]. Typical in femoral gunshot wounds, the bone will absorb the energy of the projectile and cause comminution. The presence of comminuted fractures has not been exclusively linked to the damage of certain projectile types nor especially observed in long bones [3, 20]. The termination of the oblique and longitudinal fractures may be explained by the ability of the bullet's kinetic energy to dissipate in the trabecular bone within the ends of the long bone more easily than in the cortical bone. Trabecular bone is less dense than the cortical bone and consequently less rigid under strain. It is also more porous in comparison and able to withstand the stress that is applied to the articular surface of a long bone [8, 21].

Beveled margins of entrance and exit wounds are a result of a disruption of the inner and outer tables of bone, appearing as internal and external beveling. Most often observed in gunshot trauma to the skull, the shape of internal beveling can help identify the entrance wound while external beveling helps differentiate the entrance wound from the exit wound [22]. External beveling of entrance wounds has shown to be most valuable in determining extrinsic factors of the projectile. The external beveling of an entrance wound helps indicate the directionality of a projectile's impact on bone [23]. Typically, external beveling is categorized as either a "key-hole" defect from a tangential strike, or as a perpendicular strike to the surface of the bone, typical of contact handgun wounds [22–24]. DiMaio suggests that beveling of skeletal entrance defects is more common from contact, rather than distant, gunshot wounds [1, 25]. The experimental conditions of this study imitate handgun close-range firing distances. Coe stated that the mechanisms that influence this type of external beveling are not well understood, while other studies have proposed that the defect is owed to the return of gases through the bullet hole or the twisting of the bullet, especially for contact handgun wounds [23, 26]. The experimental results from Coe showed that a relatively small-caliber, low-velocity bullet could not produce substantial backward pressure within a skull to create the beveled margins of an entrance wound [23]. External beveling of entrance wounds has not been explicitly linked to bullet types, but rather compared with gunshot wounds of specific firearms, directionalities, and distances.

The outward flaking of the cortical layer of bone occurs when a great amount of energy, such as a high-velocity impact, is released through the layers of bone tissue. Specifically, the energy propagates through the microstructure of the bone causing cortical flaking on the surface [9]. This fracture characteristic is likened to bone weathering, or skeletal decomposition, where either the outermost concentric layers of bone or fracture edges separate and cause chipping or flaking [27]. Cortical flaking has been reported in entrance defects of bone impacted by high-velocity projectiles, indicative of the range of firing and bullet-type categorization [9, 25]. This feature has been shown to be present in long bones struck by FMJ ammunition, yet absent when impacted by lead bullets [9]. The impact of FMJ bullets has additionally been proven to create delamination of bone, where the bone fractures into layers [14]. The chipping and flaking of the boundaries of the entrance wound is indicative of a near contact shot [25]. Results observed from FMJ bullet damage which created flaking of the cortical bone around entrance wounds were absent in damage from lead bullets [12]. The reasoning suggests that the full metal jacket of a projectile cannot absorb kinetic impact energy and it is left to disperse within the bone, causing tension and disruption of the bone layers.

The whitening of both trabecular and cortical bone, an effect observed when bone is subject to instantaneous impact has been studied due to stress and strain failure [28, 29]. Quantitative measurements have indicated that whitening is a definitive indicator of microdamage of bone tissue [28]. Cortical bone, which is a more brittle tissue than trabecular bone, revealed a lower strain failure

rate in comparison to trabecular bone [28]. The latter study utilized the distal portion of a bovine femoral shaft, representative of the specimens in this study. Yet, it is important to consider the great amount of kinetic energy imparted on the bone from a high-velocity projectile in comparison with the loading force that was applied to test strain failure. Thurner et al. indicated that whitening in trabecular bone faded after unloading [28]. In this study, any bone whitening will be observed to support previous work and note any differences or similarities when using HP ammunition.

There is a clear gap in the literature regarding ballistic trauma to the bone from HP ammunition. This study aims to begin to fill that gap by investigating the topics outlined above; namely projectile energy loss (the amount of kinetic energy of the projectile lost postimpact), bone fragmentation patterns (the postimpact damage of the bone, including fragment shape, distribution, and crack mapping), beveling (a cone-shaped erosion in the direction of the bullet path), cortical flaking (outward flaking of the surface cortical layer of bone upon high-velocity impact) and bone whitening (the phenomena noted when the bone becomes more white postimpact).

2 | MATERIALS

2.1 | Sample description

Twenty mature porcine (*Sus scrofa*) femora were selected for ballistic impact as an analog for human long bones due to their similarities in microstructure to human bone [13]. The commonalities of the cortical bone histology are of main importance as the chosen impact location in the samples was the center of the femoral diaphysis. The average length of the bones was 159 mm (SD=1 mm). The femora were disarticulated prior to our possession, and there was some soft tissue remaining. As much soft tissue as possible was removed, without causing damage to the bone by the tools. The bare bones were kept frozen prefiring in a freezer at -15°C and allowed to thaw to room temperature before impact. Postfiring, the bones, and their associative fragments were stored back in the freezer in labeled bags.

In addition to the 20 bare bones impacted, four porcine femora were encased in a 10%, 4°C ballistic gel to simulate the effects soft tissue will have during impact. The comparison of gel simulants allowed the identification of any potential differences in impact mechanisms and kinetic energy dispersion and loss while focusing on the fracture mechanisms occurring in the femora.

An additional four empty gel molds were impacted by the projectile types as control samples.

2.2 | Ammunition

Two projectile types, a 9 mm jacketed HP (JHP) Sierra® projectile and a 0.357 JHP XTP® projectile, were chosen for the impacts. Each projectile type had a 100% lead core, and either a >95% Cu jacket (Hornady XTP®) or a 95% Cu/5% Zn jacket (Sierra®). To create semi-jacket HP projectiles (SJHP) of each bullet caliber, six of each were machined in a lathe to expose the lead core. The masses of the final projectiles are included in the caption of Figure 3, which shows each type of ammunition used.

Projectiles were mounted in 3D printed polylactic acid (PLA) 2-piece discarding sabots, of a 21.6 mm diameter and 15.0 mm length, to allow the loading and firing of the subcaliber rounds in the gas gun. These sabots, which ensure the projectile is in the correct position, were stripped upon exiting the muzzle of the gun. Although some debris was witnessed on the high-speed video footage, there was no damage to the femora by the sabot.

3 | EXPERIMENTAL PROCEDURES

3.1 | Impact experiments

A single-stage light gas gun with a 21.6 mm caliber smooth bore barrel was used for the experimental shooting. A smooth bore was used to eliminate the influence of spin on the impact, in an effort to isolate the effect of the HP. The gas gun is an impact system that is powered by the rapid release of compressed air or helium gas and is capable



FIGURE 3 From left to right, a 0.357 JHP Hornady XTP® (10.2 g [30]), a 0.357 SJHP Hornady XTP® (9.8 g), a 9 mm JHP Sierra® (8.1 g [31]), and a 9 mm SJHP Sierra® (7.9 g) projectile.

of replicating handgun velocities. The propelling gas is released via a fast-acting valve mechanism, remotely operated by a solenoid.

Velocities of 1092–1200 ft/s were achieved by using air as a driving gas held at 30 bar pressure prefiring. The velocities were chosen to reflect the muzzle velocities for the selected rounds. The variation occurs due to natural differences in the way the gas gun was filled (how quickly fired after filling and slight differences in pressure due to manual filling). Each femur was fixed at the base using a specially constructed ballistic stand and positioned inside the target chamber on a stand, positioned in an anatomical position so that the projectile would impact the anterior side of the femoral shaft. The bones not encased by gel were kept in place using plasticine around the distal end (Figure 4). For those encased in gelatine, the flat base allowed for the samples to rest on the stand unsupported. An optical laser was used to confirm the location of impact. The distance between the sabot stripper and the target was approximately 150 mm. After firing, every identifiable fragment of the bone was collected and placed in a labeled, plastic resealable bag. The target chamber was cleared of remaining debris between targets.

3.2 | Sample assessment

Five bare femora were shot once with each type of projectile; 9 mm JHP, 9 mm SHJP, 0.357 JHP, and 9 mm SHJP. These femora without gel are intended to simulate a bullet wound to the anterior aspect of a long bone such as the tibia, where there is often very little soft



FIGURE 4 The experimental set-up of an individual femur on a stand inside of the gas gun target chamber in front of the muzzle of the gas gun, located on the right. The specially constructed ballistic stand is shown holding the femur upright in place.

tissue present for the bullet to deform in. Additionally, the four gel-encased samples were shot once by each of the projectile types. The gel in these samples acts as the layer of soft tissue reminiscent of the posterior aspect of the tibia or surrounding the femur. The fragments were kept frozen after firing in a freezer until they could be cleaned for reconstruction. It is important to note that a single cycle of freezing and thawing has shown to have minimal effect on bone properties (such as bone mineral density) and that additional freeze-thaw cycles do not cause the bone to become more susceptible to fracture than natural degradation [32, 33]. Before reconstruction, the fragments were placed in a Tergazyme® solution and heated to approximately 90°C for 3–4 h to loosen the remaining tissue, which was then removed by hand. The fragments were left to dry for approximately 1 week. All 24 samples sustained damage from the firing and were reconstructed using white craft glue. The number of fragments was counted postreconstruction to provide quantitative analysis on the different damage inflicted by the two types of projectiles. The reconstructed bones were kept in a dry cabinet at an average ambient temperature of 23°C. An example of a reconstructed femur is shown in Figure 5. In all cases, some bone fragments were not recovered due to size from both the entry and the exit sides.

To record high-speed video of each impact, a Phantom V1212 high-speed camera was used, operating with a resolution of 512×352 pixels, 40,000 frames/second, and 5 μs exposure. The Phantom Camera Control© software measured the speed and angle at which the projectile impacted and exited the targets. The data allowed a calculation of the loss of kinetic energy for each target.

To match the kinetic energies of the two different rounds, we have adjusted the muzzle velocity to compensate. This allows for a more direct comparison of the impact energy and the damage done to the bone.

The kinetic energy loss of the projectiles was analyzed using the Sapiro-Wilks test for normality, Levene's test for equal variances, and a one-way analysis of variance (ANOVA), run by the R Project for Statistical Computing software [34].

An analysis of the ballistic gel's reaction to the projectile impacts, as well as an observation of the energy transfer, was also obtainable through the high-speed camera video recordings.

4 | RESULTS AND DISCUSSION

4.1 | Projectile energy loss

The kinetic energy lost by each projectile in all 20 of the porcine femora samples was calculated for comparison between projectile types, determined through the differences in kinetic energy of the projectiles pre- and postimpact. For the four samples with no gel, the calculated values were verified for normality using the Sapiro-Wilk test and tested to observe if variances were homogenous using the Levene's test. The values displayed normality, and the variances were homogenous. A one-way parametric ANOVA was conducted at

a significance level of 0.05. Table 1 displays the data which did not provide any significant differences.

The kinetic energy lost by each projectile when impacting the femora encased in gel differed from those with no gel, where more energy was lost when the bone was encased in gel. This was to be expected and allows a better comparison with a true gunshot wound, where skin, musculature, and fatty tissues would be present. However, the fracture patterns per ammunition composition remained consistent. This indicates that while the energy loss is greater, the failure mechanism of the bone does not change due to the presence of ballistic gel.

4.2 | Kinetic energy at the time of impact

The muzzle velocity of the projectiles was recorded during firings preimpact with the target bone, ranging between 1131 and 1200 ft/s, depending on the weight of the projectile. Although the mass of the 0.357 projectiles is greater than the 9 mm, and the JHP is heavier than the SJHP projectiles of the same caliber, they affect the attained velocity in the gas gun. Nonetheless, the velocity of the projectiles will influence the amount of energy on impact more so than the projectile's mass [2].

The kinetic energy loss was plotted against the muzzle velocity of each projectile (Figure 6). Figure 6 highlights the difference between the 0.375 HP projectile and the 9 mm HP projectile. This

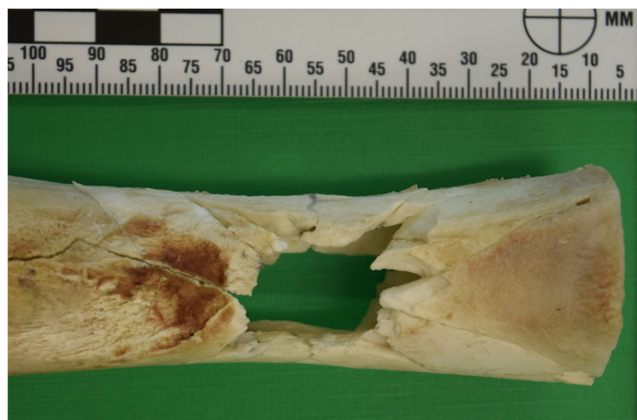


FIGURE 5 A sample of a reconstructed femur using white craft glue, demonstrating both bevelling and chipping around the margins.

Projectile model	n	Mean	SD	Total sum Sq.	p Value
0.357 Jacketed Projectile	4	34.76	17.25	827.6	0.215
0.357 Semi-Jacketed Projectile	3	39.03	5.50		
9 mm Jacketed Projectile	3	36.66	13.82		
9 mm Semi-Jacketed Projectile	4	5ja3.31	8.53		

Note: The *p* value of 0.215, above the significance level of 0.05. High-speed video failed in six captures, resulting in only 14 viable high-speed measurements.

graph additionally displays the variances in muzzle velocities in each group or each projectile type. The individual samples from the 0.357 JHP and 0.357 SJHP projectile groups attained similar muzzle velocities, whereas the samples in the 9 mm JHP and 9 mm SJHP projectile groups tend to vary. This can be linked to nonideal gas pressures being used in the gas gun for the lighter 9 mm projectiles. Error bars show the standard deviation among the sample sets. The error bars among the samples from the 0.357 JHP, 0.357 SJHP, and 9 mm SJHP projectile groups tend to overlap, indicative that the differences are not statistically different within that projectile type's sample set. The error bars for the 9 mm JHP projectile group do not overlap, indicative of statistical differences in the sample set.

These observations can be explained by the lighter masses of the 9 mm projectiles, which will ultimately affect the speed of the projectile and its kinetic energy upon impact. While Figure 6 displays differences in energy loss between the four different projectile types, the loss of kinetic energy is better illustrated in Figure 7. The bar graph demonstrates higher mean energy losses from the SJHP projectiles than the JHP projectiles. A second observation lies in the higher energy loss from the 9 mm SJHP versus the 0.357 SJHP projectiles. Error bars show the standard error, whereas the error bars for each projectile type overlap, suggesting that the mean loss energies from each projectile group are not statistically different. This observation is supported by the results in Table 1.

Ultimately, the observations in Figure 7 can be attributed to the weight differences between the two different calibers, and consequently, the higher muzzle velocities attained by the lighter 9 mm SJHP projectiles. While the mass of the projectiles may present as an evident factor in the difference of velocity and subsequently energy loss, comparable results would be expected due to the apparent effect seen from the presence of a semi-metal jacket. Conclusively, while the differences are not significant, the insignificant variances can be attributed to the different damage mechanisms occurring in the bones from the different projectile types, regardless of their weights. The energy loss observations correlate with levels of bone fragmentation, based on projectile types.

4.3 | Projectile configuration, construction, and caliber

Table 2 outlines the statistical results of the comparison of kinetic energy loss between projectile types.

TABLE 1 Comparison of kinetic energy loss in different projectile types: projectiles were classified into four groups according to their construction. The means, sample size, standard deviation, sum of square, and *p* value via a one-way ANOVA were calculated to determine if there was a significant difference.

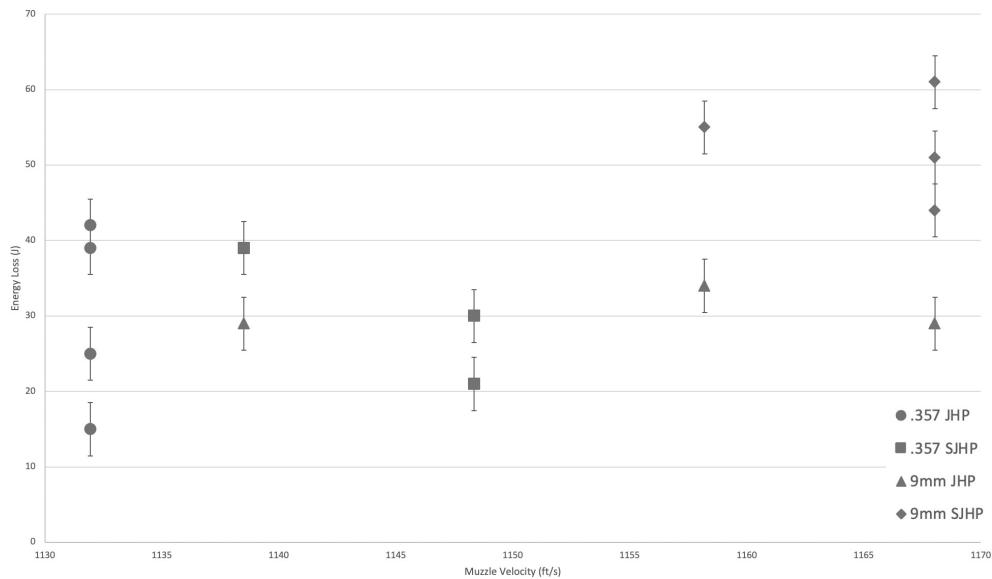


FIGURE 6 The relationship between energy loss and muzzle velocity of each sample is displayed for each projectile group, as per the key.

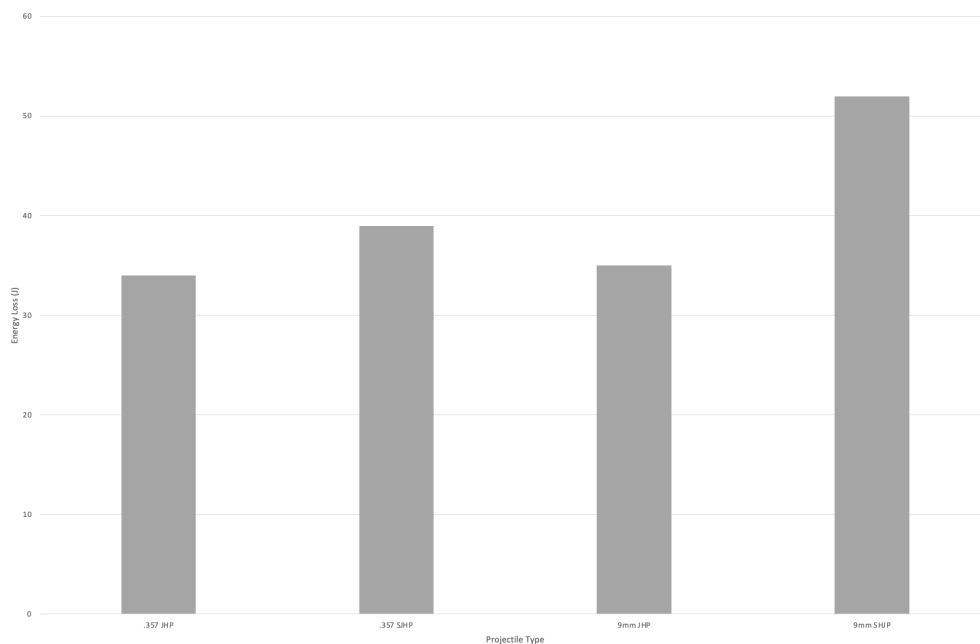


FIGURE 7 Mean energy loss in different projectile types, as per the key. An anomalous value was excluded from the 0.357 JHP projectiles data set. There are absent data points in the 0.357 SJHP, 9 mm JHP, and 9 mm SJHP projectile groups due to erroneous readings of exit velocities from the HSV analysis.

Although the statistical results in Table 2 display insignificant differences between the energy loss from each projectile type, and Figure 7 demonstrates minor differences in mean energy losses, the amount of energy loss that is occurring must still be linked to the observed failure mechanisms in the bones. The results support the assumption that the configuration of the projectiles, their hollowed points, continues to play a part in the damage, regardless of the weight of the projectiles. Consequently, when the deformation of a projectile occurs, the shape and the caliber will decrease in importance [2]. Though it is clear that a hollowed point affects the

amount of damage occurring in the bone, the presence of a metal jacket does affect the amount of kinetic energy that is imparted onto the bone as well as its loss postimpact. Subsequently, this affects the type of damage that has been observed in the femora. The construction of the projectiles becomes one of the most influencing factors of the observed impact mechanisms and the energy transfers on impact.

Although the mean loss energy from each bullet type is not significantly different, ($p=0.215$, Table 2), the differences have created important variances in femoral fragmentation patterns which must

Projectile model	n	Mean	SD	Total sum Sq.	p Value
0.357 Jacketed projectile	4	34.76	17.25	827.6	0.215
0.357 Semi-jacketed projectile	3	39.03	5.50		
9 mm Jacketed projectile	3	36.66	13.82		
9 mm Semi-jacketed projectile	4	53.31	8.53		

Note: The *p* value of 0.215, above the significance level of 0.05. Significant difference ($<\alpha$).

TABLE 2 Comparison of kinetic energy loss in different projectile types: projectiles were classified into four groups according to their construction. The means, sample size, standard deviation, sum of square, and *p* value via a one-way ANOVA were calculated to determine if there was a significant difference.

be considered. These qualitative differences in fracture patterns will be discussed further in this paper. The short amount of time in which the high-velocity impact occurs is a moment often disregarded, though the minimal changes occurring from jacketed and semi-jacketed HP projectiles are suggestive of bullet-type categorization.

4.4 | Fracture patterns

All 20 bare femora targets in this portion of the study resulted in fracturing which required reconstruction for qualitative observations. The propagation of fractures through the femora and levels of fragmentation were compared for each projectile type. The different construction of each projectile influenced the damage that occurred in each femur.

Among the targets, secondary longitudinal and oblique fracture lines were observed as incomplete fractures around the circumference of the proximal end of the femora, in all samples. These lines are propagations of the primary radiating fractures originating from the impact sites but do not result in additional fragments.

A main observation in all 20 targets is the creation of polygonal fragments of varying sizes. These fragments are observed anteriorly among all targets. The creation of polygonal fragments occurs due to a combination of fracture lines, indicative of the failure mechanism occurring in the bone. Figure 8 shows these polygonal-shaped fragments. These particular fragments, created by oblique fracture lines propagating through the bone, may be attributed to the impact of an HP projectile. On the anterior side of the bone where the bullet impacted, the polygonal fragments were larger when impacted by a JHP. More oblique secondary fractures caused smaller fragments when an SHJP was used.

The observed degree of comminution occurring in the damaged bones was similar across the four projectile types, suggesting once again that the deformation of the HP projectiles on impact is likely affecting the amount of damage occurring in the bone, but not necessarily the type of the damage or directionality of the fracture lines.

Elevated levels of fragmentation can create minute fragments that cannot be recovered. Loss of bone is typically observed in the shaft of a femur comprised of cortical bone [22]. This level of fragmentation can be referred to as "bone dust" [27]. The recorded amount of bone loss was higher in the targets impacted by 0.357 SJHP projectiles, in direct comparison to the 0.357 JHP projectiles. The level of bone loss is not substantial from the 9 mm SJHP projectiles, compared with the jacketed versions. The higher levels of

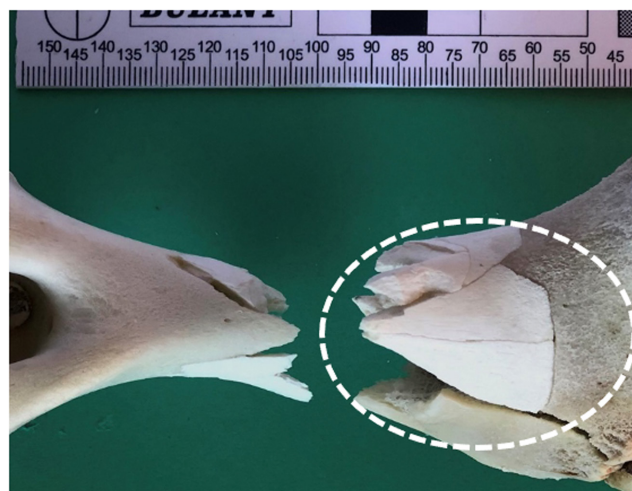


FIGURE 8 A *Sus scrofa* (porcine) femur exhibiting polygonal fragments, created between two oblique fracture lines, due to impact from a 0.357 SJHP projectile. Note the triangular shape of the fragments indicated by the dashed circle.

bone loss in targets impacted by the 0.357 SJHP projectiles could be associated with the higher level of the projectile's deformation on impact, causing more localized trauma on the surface. Yet, the results do not propose significant differences in this conclusion. Due to the anomalies with the bone loss, the authors were unable to quantify the amount of loss, however, have noted that there is a clear difference between the number of fragments. The femora impacted with an HP projectile was noticeably more fragmented than those impacted with a jacketed bullet.

In the four femora encased in gel, only three projectiles made physical contact with the bone. The fourth projectile traveled through the gel and missed the bone, however, the shock traveling through from the temporary cavity did cause fractures to the bone. From all three configurations of ammunition that did hit the bone, the primary fractures radiated from a circular entrance defect terminating at the cut ends of the bone, creating wedge-shaped fragments. The main difference seen between the JHP and SHJP impact lies in the number of secondary fragments, irrespective of the presence or the absence of ballistic gel. In both SJHP impacts, multiple oblique secondary fractures radiating nearly 90° from the primary fractures created more small, square fragments close to the entrance. These differences are highlighted in Figures 9 and 10.



FIGURE 9 Left: a fractured femur impacted by a 0.357 JHP projectile in gel. Right: a fractured femur impacted by a 9 mm SJHP projectile in gel.

4.5 | Beveling and chipping

In this study, the margins of entrance wounds in femora impacted by the JHP projectiles display the presence of both external beveling and chipping. Chipping is defined as occurring on the entrance side of impact and stresses on the opposite wall will cause fracturing propagation into the outer wall, causing a large area of beveling. The bevel is a cone-shaped erosion in the direction of the bullet path (24). Based on these definitions, in addition to previous literature focused on concentric heave-out fractures, the literature suggests that these heave-out fractures are predominantly studied in skull impacts [35]. However, as this research is focused on a long bone, we ascertain that we are observing beveling and chipping, as these are more commonly observed in long bone research as opposed to concentric heave-out fractures. Figure 5 (above), 10, and 11 highlight these features in the margins of the wound. These features occur more in femora impacted by the JHP compared to the SJHP projectiles. The 9 mm SJHP projectiles have created similar amounts of external beveling and chipping of the entrance wounds as the 9 mm JHP projectiles.

The results from this study suggest that the presence of a full metal jacket may affect the number of beveled and chipped edges occurring in the entrance defect. It is not possible to consider that the impact velocities of the JHP projectiles are affecting the amount of pressure building up in the femoral shaft's marrow, as the SJHP projectiles possessed higher impact velocities in comparison. Though, there remain insignificant findings of beveling in the femora samples to support these conclusions.

Chipped edges have been recorded on the lateral sides of the femoral shafts in all samples, regardless of being encased in gel or not. These can be seen in Figures 10 and 11. There are more prominent beveled edges found in femora impacted by SJHP projectiles and minimally in those impacted by JHP projectiles. There are edges that are more steeply sloped than others among all femora.

The beveled edges, which occurred on the lateral sides of the femoral shafts in this study, explicitly not at the entrance or exit site, indicate that they are likely not produced by the conoidal

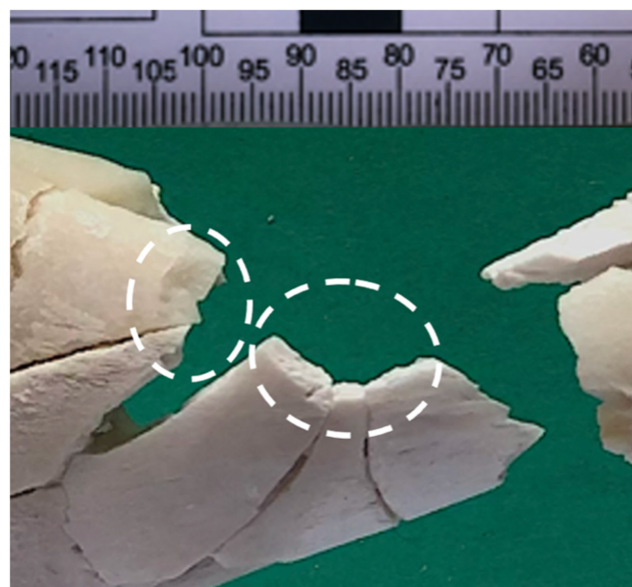


FIGURE 10 A partial margin of an entrance defect exhibiting chipping in a femur impacted by a 9 mm jacketed HP projectile. The chipped edges are indicated by dashed circles.

crack. It is, however, impossible that fragments of the deforming bullets or of the bone are causing these features. The beveled edges might suggest that portions of the bone failed in tension from the medullary cavity outwards as this would create an externally facing beveled edge, as observed among the sample set. The temporary cavity that forms in femoral shafts due to gunshot trauma generates a hydraulic bursting effect that applies tension to the inner surface of the cortical shaft [32]. The sloped edges occurring on the lateral sides of the femora in this study could be attributed to this mechanism. Similar mechanisms were observed in the cranium, where expanding gases from the wound channel presumably penetrate the marrow cavity and shift the outer tables of bone [28]. A two-part study from Huelke et al. (1968) concluded that temporary

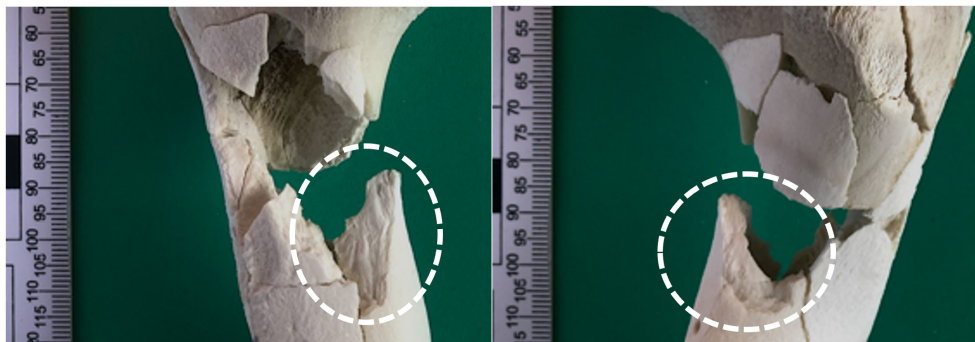


FIGURE 11 Left: an external facing beveled edge on the right lateral side of a femur impacted by a 0.357 SJHP projectile, as highlighted. Right: an external facing beveled edge on the left lateral side of the same femur. Note the location of the sloped edges, not associated with the entrance or exit wounds, as highlighted.

cavitation in the marrow of human femora had the effect on the epiphysis but not the diaphysis, yet additional research proposed that the cavitation is in fact operative in the diaphysis of long bone [16, 17, 19]. While the SJHP projectiles are causing considerably more angulated edges in the bone postimpact than the JHP projectiles, it is important to consider the behavior of deforming and fragmenting bullets. Kneubuehl (2008) states that both semi-jacketed and HP bullets behave uniquely in the medullary cavity of the bone, as they will create temporary cavities immediately upon impact. With an FMJ bullet, the temporary cavity will form after penetration, even when they fragment upon a perpendicular impact [19]. The SJHP projectiles in this study, which deform and fragment more than the JHP projectiles, which have created the temporary cavitation earlier, which influences the bursting effects in the marrow and subsequently causes the beveled edges in the femoral shaft. The hollowed point of the JHP projectiles, although considered FMJ, will deform to a certain degree and seemingly cause the same effect in the marrow cavity, but to a lesser extent.

4.6 | Circular entrance defect

The presence of a circular entrance defect was noted in the majority of the femora postimpact, irrespective of the presence of gel. Figure 12 shows this type of damage. This lends to the failure of the bone not being dependent on the gel.

There is a tendency in the targets impacted by JHP projectiles to present circular defects versus the incomplete entrance wounds noted in targets impacted by the SJHP projectiles. The presence of a circular defect, where the entrance wound displays a more rounded lesion in the bone, is attributed to both the configuration and the construction of a full metal jacket bullet [3, 17], however, is not typical of expanding ammunition [3].

The tendency for the entrance wounds of the femora impacted by JHP projectiles to present circular defects is likened to the increased capability of the full metal jacket to enclose the lead core pre- and postimpact in comparison with the SJHP projectiles which deform sooner. Notably, as opposed to previous evidence highlighted by Fragkouli et al. [2018], there are in fact

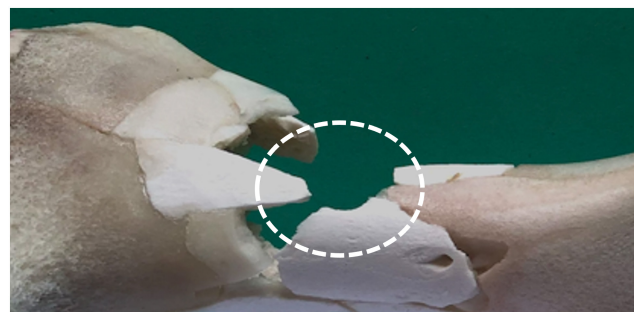


FIGURE 12 A partial circular defect indicating the location of an entrance wound in a femur impacted by a 0.357 jacketed HP projectile, as highlighted.

circular defects occurring in bone impacted by expanding projectiles in this study [3]. Nonetheless, HP projectiles are less likely to create circular entrance wounds due to their deformation upon impact, whereas factors such as range and velocity must still be considered.

4.7 | Cortical flaking

Flaking of the outer layer of cortical bone is observed in a few of the recovered fragments among the five sample groups in this study and not on the margins of entrance wounds. Additionally, of the femora which have circular defects present, they have not presented flaking of the margins. There is no significant presence of cortical flaking from a given projectile type.

These results may indicate that the configuration of a projectile, the hollowed point, influences the presence of flaking. The HP projectiles are dispersing a substantial amount of energy on impact due to their deformation which is subsequently traveling through the layers of bone and causing the flaking effect on comminuted fragments. It is important to note that an intermediate range implicated in this study, differentiates from the experimental conditions of Amadasi et al. [25]. Different firing distances have not been shown to create differences in fragmentation patterns from FMJ

bullets in scapulae and mandibles, whereas the bullet type itself had an evident effect on damage [3]. It appears the type of ammunition, specifically full metal jacket and HP projectile types, creates cortical flaking in bone, but not exclusively on the margins of entrance wounds. The presence of cortical flaking is due to the yielding nature of the type of projectile used.

4.8 | Bone whitening

Among the targets that have undergone reconstruction, there is evident whitening of some of the reconstructed fragments. This is seen in the polygonal fragments that were separated from the femur following impact. In Figure 13, the whitening of the impact area and the femur's reconstructed fragments can be clearly seen. The observation of permanent whitening of the recovered fragments can indicate a significant level of microdamage that could not be reversed. It must be noted that fragments closer to the impact site show higher levels of visual whitening than those further away from the entrance defect [28, 29]. Further research is required to determine whether the amount of microdamage and whitening could be used to determine the amount of kinetic impact energy that was imparted on the bone. Indication of the extrinsic factors of a ballistic interpretation could follow. The whitening of fragments that has occurred in this study's specimen is indicative of microdamage in the tissue but cannot provide any specific information regarding external factors of the ballistic trauma.

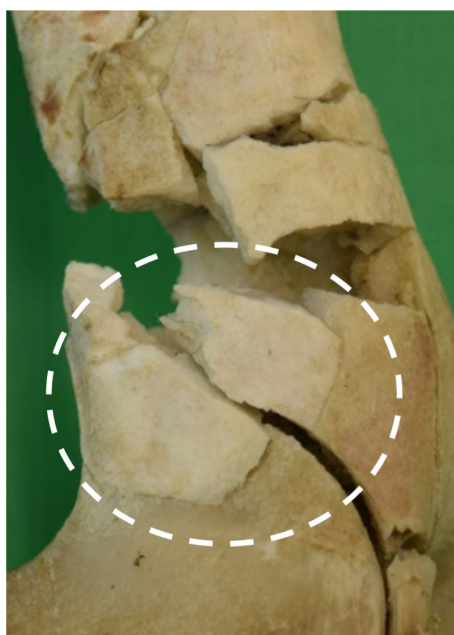


FIGURE 13 Bone whitening is heightened in the circled fragments, compared with the surrounding fragments, which were further away from the impact site.

5 | CONCLUSION

Ballistic impacts on porcine femora were conducted on a single-stage light gas gun to determine if categorizations of bullet configuration and construction could be established from trauma caused by full metal jacket and semi-metal jacket HP projectiles. The analysis of femoral fracture patterns, failure mechanisms, and projectiles' energy loss allowed a better understanding of how a long bone reacts to a high-energy impact from a certain type of HP projectile. The findings of this study support the identification of variances between four types of HP projectiles:

1. A partial jacket on an HP projectile will ultimately affect its loss of kinetic energy postimpact, associated with the ability of the exposed lead core to absorb impact energy, and disperse energy in different directions following separation from the jacket.
2. The presence of gel surrounding the femora did not change the fracture pattern, presence of bevelling, presence of cortical flaking, or bone whitening; this suggests the gel does not change the failure mechanism of the bone.
3. SJHP projectiles cause a higher degree of bone fragmentation than JHP projectiles, resulting in smaller polygonal fragments, compared with the larger fragments produced by a JHP impact.
4. The presence of circular defects, chipping, and beveling of the entrance wounds, as well as cortical flaking are not indicative of a full metal jacket or semi-metal jacket HP projectile.

Overall, this paper has shown that while the HP configuration of a projectile will affect the amount of damage that occurs in an impacted femur, the presence of a metal jacket will affect the morphology of damage. These observations allow the categorization of bullet construction from ballistic impacts to femora as well as a better understanding of the type of damage mechanism observed in the femora from these types of impacts. The conclusions drawn from this research cannot be generalized to all bullets until future work can be conducted and expand on this selection. Future experiments should additionally include the comparison of femoral impacts from full metal jacket and soft-point round nose projectiles, to explicitly highlight the general effect of an HP configuration. Future considerations should also include the use of a slightly lower pressure on the gas gun to allow equivalent impact velocities amongst the four projectile types.

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CONFLICT OF INTEREST STATEMENT

The authors have no conflict of interest to declare.

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