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High-Tech Models for Simulating the Wounding Effects of Projectiles of Small Calibres: Benefits for Security Management

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Abstract

The aim of this study is to analyse the effects of projectiles of small calibres on the human femur using an innovative indirect identification method. A heterogeneous physical model was developed that combines ballistic gelatine for soft tissues and porcine femur as an analogue for human bone to simulate gunshot injuries under ethical and economic conditions. The study evaluated three types of ammunition: 9 mm Luger pistol cartridges and two micro-calibre rifle cartridges, 5.56×45 mm (SS 109) and 5.45×39 mm (7H6). Ballistic testing measured impact and exit velocities, assessed bone tissue destruction, soft tissue damage, and the temporary cavity created by projectiles. The findings reveal that micro-calibre rifle projectiles cause up to twice the bone destruction and more extensive soft tissue damage compared to pistol ammunition. The study also highlights the significant role of liquid structures in the medullary cavity in amplifying bone damage. These results improve ballistic testing methodologies, offering valuable insights for crisis management, security operations, and the development of protective equipment. The proposed model serves as a critical tool for understanding the effects on human tissues, aiding in forensic analysis, and advancing experimental ballistics. This research opens new opportunities for applications in the security and health disciplines.

Keywords: Physical Model; Ballistic Experiment; Complex Gunshot Injury; Indirect Identification Method; Projectiles of Small Calibres; Live Tissue Substitution; Wounding Effect of a Projectile; Wounding Potential of a Projectile.

1. Introduction

In the available scientific literature, there remains a significant lack of rigorous information regarding the direct effects of projectiles of small calibres, both of traditional and modern design, on human bone tissues. Current knowledge about bone-related gunshot injuries is based primarily on analysis of real-world cases, such as accidents, suicides, or violent crimes involving firearms [1]. These incidents often include head wounds with varying degrees of soft tissue damage and the formation of gunshot fractures in the flat bones of the skull surrounding the projectile channel [2, 3]. To better understand the specific phenomena that occur during the penetration of projectiles into rigid bone tissues, the energy dynamics of weapon systems of small calibres, and the impact of gunshot bone injuries on the overall extent of tissue damage, ballistic experiments have been conducted. These experiments focus on the direct effects of projectiles of small calibres on the femur (thigh bone), resulting in gunshot fractures in the long bones of human limbs [4].

Previous experimental studies in the field of wound ballistics have mainly focused on homogeneous physical models simulating human soft tissues [5]. Early works by Di Maio [6] highlighted the utility of ballistic gelatine for evaluating

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soft tissue injuries but underscored its limitations in simulating heterogeneous body structures. Tong et al. [7] emphasised the critical role of bone and fluid-filled structures in mediating projectile-induced injuries. Similarly, MacPherson [8] noted the need for improved models to explore the interplay of soft and rigid tissues under dynamic conditions.

Modern heterogeneous models have sought to bridge this gap by combining synthetic substitutes for soft tissues, such as ballistic gelatine, with biological tissues, such as porcine femurs, which serve as analogues for human bones. This approach improves realism while respecting ethical considerations and resource constraints. Previous studies have further advanced these models, incorporating interdisciplinary insights and refining methodologies for experimental validation. However, these models do not sufficiently represent the interaction of projectiles with heterogeneous body structures, such as bones or combinations of soft and rigid tissues [9, 10]. Modern heterogeneous models combine synthetic substitutes for soft tissues, such as ballistic gelatine, with biological tissues, thus increasing their realism [11, 12]. Although economic and more importantly, ethical considerations [13] have shifted the focus to synthetic substitutes in the preparation of these models, the use of biological tissues in ballistic experiments remains indispensable in justified cases [14].

A critical gap in the literature lies in the insufficient understanding of the interaction between modern projectiles of small calibres and bone tissue under dynamic conditions that closely simulate real-life impacts. Despite advancements in the field of wound ballistics, existing research still lacks comprehensive insight into how the energy parameters of projectiles correlate with the extent and type of tissue damage, particularly in the complex interplay between soft and hard tissues, such as muscle and bone. This limitation hinders the development of reliable predictive models for injury outcomes and complicates the optimisation of protective equipment design.

Recent studies have made significant strides in the advancement of numerical modelling and simulation techniques, providing a deeper understanding of biomechanical responses under ballistic loading. Sun et al. [10] employed finite element modelling to evaluate the dynamic response of bone to ballistic impacts, while MacPherson [8] highlighted the need for more accurate representations of projectile energy dissipation within heterogeneous tissues. Sangeetha et al. [9] demonstrated the utility of combining synthetic and biological components in ballistic models, but their findings emphasised the ethical and logistical challenges of such approaches. Similarly, Sun et al. [10] reviewed existing methods and identified limitations in current modelling techniques, particularly the inability to replicate complex fracture patterns observed in vivo.

Experimental studies have also progressed, such as Shen et al. [15], which analysed bone damage caused by high-velocity projectiles in controlled environments, but these studies often neglect the broader energy-tissue interactions. Furthermore, Yi-Chia et al. [16] and Sangeetha et al. [9] underscored the importance of energy transfer mechanisms but did not adequately explore their role in heterogeneous structures involving bone. Maroušek et al. [17] focused on protective applications but lacked data on the direct interaction of modern projectiles with bone tissues. The numerical models developed in previous studies aimed to bridge this gap by incorporating dynamic fracture mechanics into their simulations [18, 19]; however, the experimental validation of these models remains incomplete. Furthermore, Zhao et al. [20] evaluated bone injury mechanisms but mainly focused on soft tissue interactions, leaving bone-specific dynamics underexplored.

The overarching challenge lies in the limited experimental validation of advanced simulations and the scarcity of studies that address the combined effects of projectile design, velocity, and target material composition [21, 22]. These gaps underscore the need for further research to integrate experimental and computational methods, enabling the development of robust predictive models that accurately reflect real-world injury scenarios. By addressing these deficiencies, future research can significantly improve our understanding of projectile-bone interactions and inform the development of more effective protective measures and forensic analysis protocols.

The primary objective of this article is to analyse and comprehensively describe the wounding effects of projectiles of small calibres on the human femur through the application of an innovative heterogeneous physical model. This research introduces a multidisciplinary approach to experimental ballistics, offering valuable insights for forensic analysis of gunshot injuries and advances in protective technologies. The proposed model integrates synthetic and biological components, specifically ballistic gelatine to simulate soft tissues and an animal femur as an analogue for human bone. This combination allows for a highly realistic simulation of complex gunshot injuries under controlled experimental conditions.

The study focusses on the mechanisms of bone tissue damage resulting from projectile impact, evaluating critical factors such as energy transfer, fracture patterns, and the extent of soft tissue destruction. These findings are intended to address existing gaps in the understanding of projectile interactions with heterogeneous body structures, particularly bone tissue, under dynamic conditions that mimic real-life impacts.

The results of this research have significant implications for crisis management and security operations, particularly in the development and improvement of ballistic protective equipment. By providing a detailed framework for assessing the effects of projectiles of small calibres, this study contributes to the broader field of experimental ballistics and offers practical applications in forensic science and the design of advanced injury mitigation systems.

In connection with this objective, the following key question was formulated.

KQ: What are the direct effects of projectiles of small calibres on a heterogeneous physical model simulating the human femur and how can the resulting data be applied to predict injuries under real biological conditions?

The article employs a combination of experimental, analytical, visualisation, and comparative methods to evaluate the wounding effects of projectiles of small calibres. The study began with experimental research using the heterogeneous physical model, which combines 20% ballistic gelatine to simulate soft tissues and an animal femur to represent the human femur. To ensure an adequate and comparable reaction of the human femur and soft tissues to a penetrating projectile, the heterogeneity of the physical model was achieved based on the analysis of our own experience with the gradual introduction of substitute materials for living tissues during the design and preparation of physical models for ballistic testing. The development evolved from synthetic models to combined models that incorporate synthetic and biological substitutes. The use of a porcine femur embedded in 20% ballistic gelatine yielded the best results. Detailing this gradual development, which we have undertaken, would involve mapping approximately 30 years of our scientific work published for example in [23, 24]. Shooting tests were conducted using three types of ammunition: 9 mm Luger; 5.56×45 SS 109; 5.45×39 7H6.

During the experiments, the impact and exit velocities of the projectiles were measured, the wound channel was analysed, and the extent of the temporary cavity created by the projectile was assessed. For analytical evaluation, the kinetic energy transferred by the projectiles to the target medium was calculated and the destructive effects on bone and soft tissues were analysed, including fragmentation of the projectile and its impact on surrounding tissues. X-ray and digital photographs were used to visually document and archive the morphology and fractures. The longitudinal sections of the gelatine blocks provided a detailed analysis of the affected structures.

To obtain a complete overview, a comparative analysis of the effects of various types of projectiles was performed, evaluating the correlation between the type of projectile, its kinetic energy, and the extent of tissue damage. This interdisciplinary approach integrated knowledge from biomechanics, forensic medicine, and ballistics, allowing a thorough analysis of projectile effects and providing valuable information for the development of protective equipment and crisis management. The methodology was complemented by an ethical framework and practical implications for applications in the security and healthcare sectors.

2. Material and Methods

Figure 1 illustrates the key steps of the research methodology, from experimental setup to data collection and analysis.

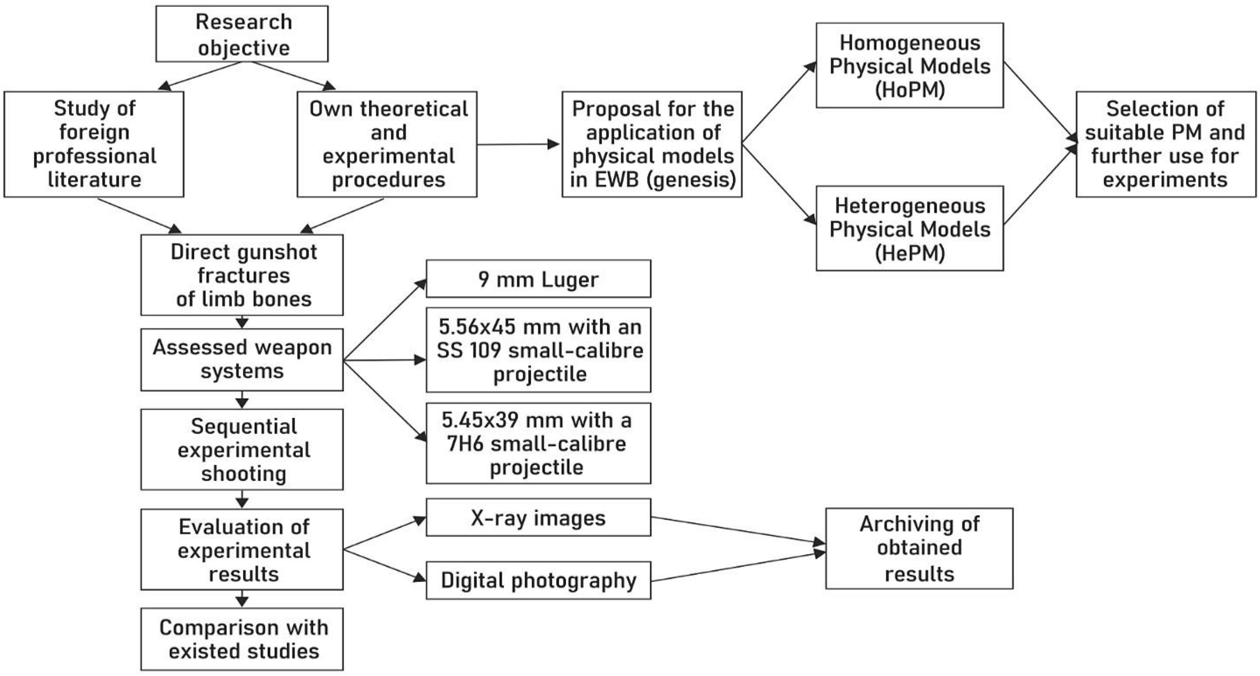


Figure 1. The Methodological process flowchart

2.1. Ballistic Simulation of Direct Effects of Projectiles of Small Calibres on the Human Femur

To simulate the effects of projectiles of small calibres on soft biological tissues (soft "homogeneous" structures), we previously utilised proprietary homogeneous physical models made from synthetic substitute materials. Among these, ballistic gelatine cast onto test blocks proved to be the most effective. The shooting experiment was conducted using indirect identification on a newly designed heterogeneous physical model. The model was successively shot using three weapon systems of small calibres of varying ballistic performance, representing selected modern pistol and rifle calibres. In all cases, impacts on bone substitutes were assumed to occur at perpendicular projectile impacts on the heterogeneous substitute model.

The use of actual animal tissues, representing human biological tissues within a heterogeneous physical model, has been shown in practice to be a highly effective method to create a realistic biological environment for the development and evaluation of the wounding effects of projectiles of small calibres. A critical prerequisite for ensuring the accurate reproduction of ballistic experiment results and their translation to real human tissues is the careful selection of the animal donor.

2.1.1. Objectives of the Experiment

In addition to the primary objective of verifying the functionality of the proposed physical model and the suitability of the measurement system for impact and exit velocities of projectiles, the following specific objectives were defined:

- Assess the feasibility of accurately aiming and hitting the bone embedded in a gelatine block at a predetermined distance.
- Evaluate the behaviour of bone tissue substitute and its response to projectile penetration, including its influence on the projectile's subsequent movement immediately after penetration.
- Demonstrate the relationship between the parameters of the wound channel created in the bone and the amount of kinetic energy (E_{pr}) transferred by the projectile, as well as the effect of the resulting temporary cavity (if present) on the extent (volume) of the damage to the impacted bone structures.
- Analyse wound channel profiles obtained through longitudinal sections of gelatine blocks at the wound site and predict their effects on the femur and surrounding soft tissues (muscle and blood vessels) in humans.
- Recover the projectiles in a cotton block for a subsequent evaluation of possible shape (or mass) changes.

The ballistic experiment aimed to simulate a complex gunshot injury in which a projectile penetrates both soft tissues and the femur in the diaphysis region. The selected heterogeneous physical model, composed of a 20% gelatine block, included a porcine femur as a biological substitute representing the human femur. The shooting tests used weapon systems chambered for:

- 9 mm Luger (Sellier & Bellot, Czech Republic);
- 5.56×45 mm (Sellier & Bellot, Czech Republic) with an SS 109 micro-calibre projectile;
- 5.45×39 mm (Tula, Russia) with a 7H6 micro-calibre projectile.

These systems formed a limited sample of typical representatives of modern military rifle ammunition of small calibres, along with the most commonly used standard calibre pistol cartridge.

2.1.2. Arrangement of the Physical Model

A physical model was designed for the shooting tests, consisting of the following components:

- ***Gelatine block***: A cube-shaped block of 20% ballistic gelatine with an edge length of 15 cm, containing a central segment of a porcine femur. Each end of the femur segment was fitted with cylindrical nylon caps.
- ***Frame***: Constructed from two square PVC plates, each 15 mm thick and measuring 20 cm on each side, joined at the corners by four steel bolts with a diameter of 8 mm and a length of 180 mm. The inner (opposing) faces of the plates were equipped with centrally positioned cylindrical recesses, 5 mm deep and 50 mm in diameter.

The use of a porcine femur in the heterogeneous physical model was carefully considered and scientifically justified based on biomechanical parameters. Key properties such as the density, elasticity, and viscoelasticity of the porcine femur and ballistic gelatine were measured and compared with both animal and human tissues to ensure the realism of the model. Beyond these parameters, additional characteristics, including the apparent density of bone tissue and its modulus of elasticity, were determined to further validate the suitability of these substitutes.

These measurements, calculations, and the subsequent verification of the model's behaviour in ballistic experiments were documented and analysed in our previous publications, e.g. [24-27].. This groundwork provided a solid foundation for the current study, confirming that the mechanical responses of the porcine femur, when combined with 20% ballistic gelatine, closely replicate those of human femurs and soft tissues under dynamic conditions. The femora of three animal donors were processed by removing the proximal epiphyses (hip joint heads) and distal epiphyses (knee joint heads) through frontal cuts, resulting in three diaphyseal segments with the marrow cavity and its liquid content intact. This prepared femoral diaphysis was fitted with cylindrical nylon caps, each with a diameter of 50 mm, a height of 15 mm, an inner cylindrical cavity 40 mm in diameter, and a depth of 5 mm. The secure connection between the bone and the nylon caps was achieved using a two-component adhesive ("Dentacryl").

The arrangement of the prepared bone assembly is shown in Figure 2 (left). Three of the prepared bone segments were embedded in 20% gelatine inside a metal mould to the height of the bone samples (Figure 2, right).

Figure 2. Preparation of heterogeneous physical models for experimental shooting; Left: Assembly of the diaphyseal segment of the porcine femur before embedding in gelatine; Right: A block of 20% gelatine containing three bone samples (overview)

The preparation conditions for the ballistic gelatine (ambient temperature, ambient temperature and relative humidity) were monitored using a universal measuring device, GMH 3350. The gelatine block was cut into three separate blocks (Figure 3, right), designated B_1, B_2, and B_3.

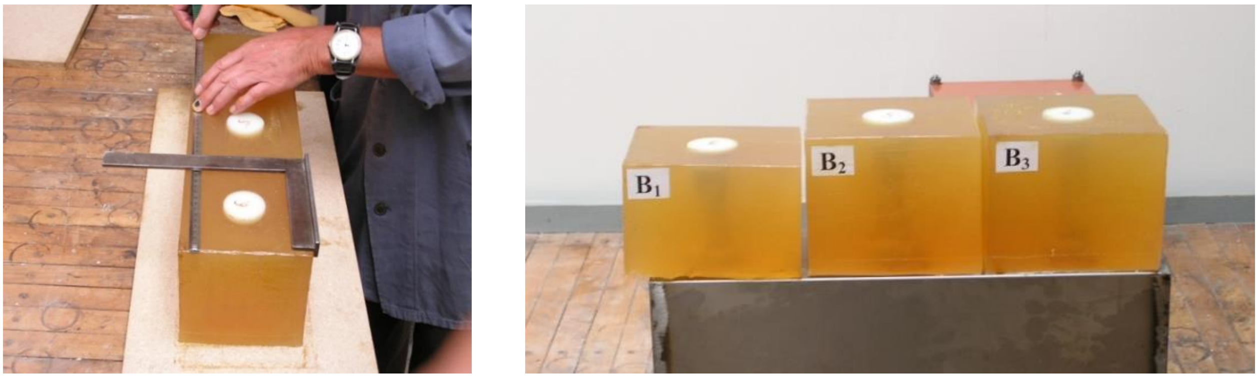


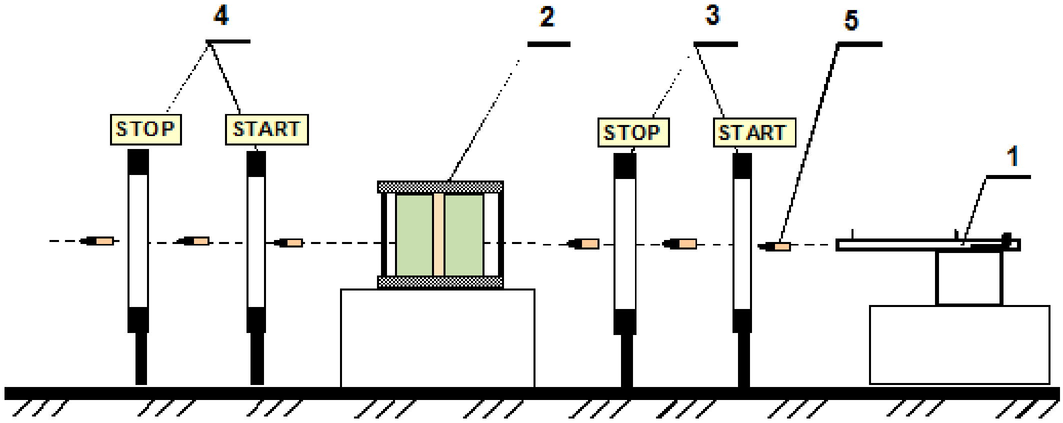
Figure 3. Processing of the compact gelatine block immediately after removal from the metal mold: Left: Measurement and marking of dividing planes; Right: General view of the individual blocks (B_1, B_2, and B_3)

By placing the gelatine block into the frame and inserting the nylon caps into the central recesses of the PVC plates, while simultaneously tightening the bolts of the corner connectors, the desired boundary and initial conditions for the proper functionality of the physical model in the ballistic experiment were achieved. The elasticity of the nylon caps partially mimicked the cartilage of the removed joint connections, while the deformation of the gelatine block (ΔL=10 mm, ϵ=6.7%) of its height simulated, to some extent, the intramuscular tension of the soft biological tissues surrounding the femur.

2.1.3. Ballistic Characteristics of the Experiment

The frame containing the test gelatine block with the embedded bone was placed on a table at a distance of X=4.5m from the muzzle of the ballistic test barrel and secured to prevent rearward displacement upon penetration of the projectile. The aim point (a white square target, 1 cm×1 cm) was precisely in the centre of the front face of the block, directly opposite the bone substitute. Accurate targeting of the ballistic barrel was performed using a muzzle-mounted optical sight with direct illumination of the rear side of the target block. The objective was to ensure that all projectiles from the tested cartridges unequivocally struck the bone substitute within the block, capturing the entire trajectory of the projectile, including any development of the temporary cavity within the gelatine block. For each shot, the projectile velocity v_2 (measured 2 metres in front of the ballistic test barrel muzzle) was recorded using intelligent LS 04 gates. This velocity was considered the impact velocity v_v relative to the block's position. Furthermore, the velocity v_6 (measured 6 metres in front of the test barrel muzzle) was recorded and treated as the exit velocity v_e of the projectile.

These velocity measurements aligned with the initial assumption that projectiles would penetrate individual blocks with surplus kinetic energy, achieving complete perforation of the test blocks. The arrangement of the shooting (measurement) station is illustrated in Figure 4.



1. **Ballistic test barrel**: Used for shooting the test ammunition with precise control and alignment.
2. **Physical model of the thigh segment**: The prepared gelatine block containing bone samples simulating part of a thigh.
3. **LS 04 gates for measuring projectile velocity** v_2**)**: Positioned 2 meters in front of the test barrel muzzle to record the projectile's impact velocity relative to the block.
4. **LS 04 gates for measuring projectile velocity** v_v**)**: Positioned 6 meters in front of the test barrel muzzle to capture the projectile's exit velocity.
5. **Projectile trajectory**: The direct path taken by the projectile from the ballistic test barrel, passing through the gelatine block and exiting on the opposite side, with measurements capturing both the impact and exit velocities.

Figure 4. Diagram of the shooting station (measurement) (Shooting tunnel by Prototypa-ZM, s.r.o., Brno)

2.1.4 Ammunition Used in the Wound Ballistics Simulation

9 mm Luger with a full metal jacket (FMJ) projectile*:* Manufactured by Sellier & Bellot, Vlašim, Czech Republic. This cartridge was originally developed in 1902 by DWM for Georg Luger's military pistol, which was initially designed for the 7.65 mm Parabellum calibre. The 9mm Luger cartridge has been produced and remains in production in many countries in a variety of configurations, including military, defensive, and sporting ammunition. The manufacturer specifies an initial velocity of the projectile v_0 of approximately 390 m.s^{-1}, with a mass of the projectile of 7.5 g, resulting in a corresponding kinetic energy of E_0 = 570 J.

5.56×45 mm (hunting equivalent: .223 Remington) with a full metal jacket (FMJ) projectile*:* This micro-calibre rifle cartridge was introduced alongside the M16A1 automatic rifle into the US Army's arsenal and was first deployed during the Vietnam War. For the purposes of the ballistic experiment, a military-grade 5.56×45 mm cartridge manufactured by Sellier & Bellot was used, featuring an FMJ projectile mass m_q=4.0 g. The manufacturer states an initial projectile velocity v_0, of approximately 945 ms^{-1}, which yields a kinetic energy of E_0 = 1 786 J. The projectile design, which includes a steel core in its forward section, significantly enhances penetration capability while maintaining considerable wounding potential.

5.45×39 mm Soviet (Russian) infantry cartridge*:* This micro-calibre cartridge was introduced in 1974 for the modernised Kalashnikov assault rifle (AK-74) and the RPK-74 machine gun. The FMJ projectile of this micro-calibre cartridge is highly sophisticated, offering exceptional accuracy and penetration. For the experiment, a cartridge with a basic 7H6 projectile was used, featuring a tombak-plated steel jacket, a long and soft steel core encased in a steel sleeve, and an air gap in the forward section. With a projectile mass of m_q=3.42g, the initial velocity v_0 is approximately 880 m.s^{-1}, resulting in a kinetic energy of E_0 = 1 336 J.

The fundamental design and ballistic parameters of the ammunition used in the experiment are summarised in Table 1. The cartridges were shot sequentially from the ballistic test barrels in prepared test blocks (heterogeneous physical models) made of surrogate biological tissue encased in a rigid frame. Before shooting, the barrel axis was aligned with the aim point located at the centre of the front (impact) surface of the test block. The key design and ballistic parameters of the ballistic test barrels used in the shooting experiment are presented in Table 2.

Table 1. Basic design and ballistic data of the ammunition used in the ballistic experiment (values as specified by the ammunition manufacturers)

Cartridge		Projectile					Propellant		Velocity	KE
Designation	**Manufacturer**	**Type**	**Core I**	**Core II**	**Jacket**	m_q	**Type**	ω	v_0	E_0
[1]	[1]	[1]	[1]	[1]	[1]	[g]	[1]	[g]	[m.s^{-1}]	[J]
9 mm Luger	S&B; Vlašim	FMJ	-	PbSb0,5	CuZn30	7.5	D-032 spherical	0.33	390	570
5.56×45	S&B; Vlašim	FMJ	Steel	PbSb3	CuZn10	4.0	tubural	1.63	945	1786
5.45×39	Tula, Rusko	FMJ	Soft steel	PbSb3	CuZn10	3.42	spherical	1.41	880	1324

Table 2. Design and ballistic parameters of ballistic barrels (Provided by Prototypa-ZM, s.r.o., Brno)

Test ballistic barrels		d [1)]	L_{HL} [2)]			Number of grooves	Groove twist rate		
Calibre	Number	[mm]	[mm]	[in]	[calibre]	[1]	[mm]	[in]	[calibre]
R 9 mm Parabellum	H 028	8.82	201	7.87	22,7	6	250.0	9.85	28.34
R 5.56×45 NATO	H 027	5.56	508	20.0	91,4	6	177.8	6.97	31.98
R 5.45×39	H 7891	5.40	385	15.16	71,3	4	255.0	10.03	47.22

Notes: 1) The diameter (d) of the ballistic test barrel is measured between opposite lands; 2) The rifled length of the ballistic test barrel.

3. Literature Review

The experimental representation of a real object, such as a human body, by a physical model that closely mimics its physical and mechanical properties and geometric configuration forms the basis of the indirect identification method. This approach is critical to studying the wounding effects of ammunition of small calibres on living organisms. In the early development of wound ballistics, the primary method of assessing the wounding effects of ammunition of small calibres involved simulating its impact on vital biological tissues. Experimental animals, their isolated organs, or, less frequently, human cadavers were used for this purpose [28]. The use of animals presents challenges when extrapolating results to human conditions. To achieve relevant results, it is necessary to select an animal species that closely approximates humans in size, tissue structure, and the distribution of vital organs. In the Czech Republic, the experimental use of animals is regulated by Act No. 246/1992 Coll. on the Protection of Animals Against Cruelty [29]. Over time, these methods were complemented by the use of physical models that simulate the anatomical structures of the human body through their configuration and ballistic properties.

Initially, homogeneous physical models were used, but have gradually been replaced by heterogeneous models that better simulate complex gunshot injuries, where projectiles interact with soft tissues and bones or with major blood vessels [30]. Today, various substitute materials such as ballistic gelatine, soap, or mixtures of petrolatum and paraffin are used to replicate the mechanical properties of biological tissues [31]. These materials facilitate standardised tests and comparisons of results without the ethical dilemmas associated with using living organisms [32]. Accurate assessment of wounding potential requires quantified methods that consider factors such as the kinetic energy of the projectile after impact, the penetration depth, the maximum width of the temporary cavity, and the momentum of the projectile. These parameters provide a comprehensive understanding of the capacity of a projectile to cause tissue and organ damage [33].

In recent years, research has also focused on the effect of shooting distance on wounding potential, especially for airguns. Studies show that as the shooting distance increases, the projectile velocity decreases, thus reducing its kinetic energy and its ability to inflict injury [34]. These findings are crucial for forensic analyses and the development of safety standards [35]. Another significant aspect is the design and material composition of the projectile, as well as its ability to deform upon tissue penetration. Certain modern projectiles are designed to deform or fragment upon impact, significantly increasing their wounding effect [36]. However, such designs can conflict with international humanitarian law, which prohibits the use of ammunition that causes excessive suffering [37].

Ethical and legal considerations play a pivotal role in the development and testing of new types of ammunition [38]. International treaties such as the Hague and Geneva Conventions set rules for the use of weapons and ammunition to minimise unnecessary suffering. These standards impact not only military operations, but also the civilian sector, where the use of certain types of ammunition is heavily restricted or completely banned [39]. In the field of experimental wound ballistics, it is crucial to continuously update and refine methods to assess the wounding potential of projectiles [40]. This includes the development of novel surrogate materials, advanced modelling techniques, and standardised testing protocols [41]. The objective is to achieve the most accurate and reproducible results possible, which can be applied in medicine, forensic sciences, and the development of ballistic protective equipment for humans [42].

The evaluation of the wounding potential of projectiles of small calibres is a complex discipline that requires an interdisciplinary approach that encompasses physics, biomechanics, medicine, and ethics. Advances in this field contribute to a deeper understanding of the mechanisms of gunshot injuries and to the development of more effective protective and therapeutic strategies [43].

4. Results & Discussion

The evaluation of the results of the shooting experiment focused on the following aspects:

- ***Measured impact and exit velocities***: The velocity values achieved by individual projectiles were recorded. The difference between these measured velocities enables the determination of the kinetic energy transferred $E_{PŘ}$ by the projectile to the target medium, which reflects the extent of expected changes in the affected tissues.
- ***Shape and position of the projectile channel (permanent cavity):*** The assessment included the shape and position of the permanent cavity and, in the case of temporary cavity formation (presence of radial cracks), its size (volume).
- ***Extensive extent of bone tissue damage:*** The degree of damage to the femur caused by the penetrating projectile was evaluated, including the characteristics of the resulting ballistic fractures.
- ***Presence of bone fractures and projectile fragments***: The study considered the occurrence of bone fragments and projectile fragments (secondary projectiles) around the projectile channel and their impact on the extent of soft tissue damage within the temporary cavity region.

To quantitatively assess the effects of each projectile subjected to wound ballistic investigation, predictions were made regarding the development of two types of gunshot injuries to the human lower limb (thigh) involving the femur after direct impact:

1. **Complex gunshot injury to the human thigh with direct femur impact by a slow pistol projectile**: A pistol cartridge projectile that penetrates the lower extremity at subsonic velocity.
2. **Complex gunshot injury to the human thigh involving the femur caused by a high-speed micro-calibre rifle projectile:** A rifle cartridge projectile traversing the affected limb at a distinctly supersonic velocity. The wounding action of the projectile is accompanied by extensive destruction of bone structures and surrounding soft tissues due to the formation of a temporary cavity and secondary projectiles.

4.1. 9 mm Luger with a Full Metal Jacket (FMJ) Projectile: Manufactured by Sellier & Bellot, Vlašim, Czech Republic

The projectile impacted the front surface of the block with a velocity of v_d = 381,4 m.s^{-1} (E_d = 545,5 J), penetrated the block stably, and exited the gelatine block after passing through the bone with a exit velocity of v_v = 66,1 m.s^{-1} (E_v = 16,4 J). From the measured values, the kinetic energy transferred to the penetrated medium was analytically calculated as $E_{PŘ}$ = 529 J. The projectile channel was narrow, closed, and featured a small temporary cavity that maintained the direction of the shot. As the projectile progressed through the block, it lost energy evenly, except during the bone penetration phase. The ballistic experiment demonstrated the limited penetration ability of the 7.5 g projectile when a bone obstructs its path. During its penetration, the projectile lost a substantial portion of its impact energy (approximately 97%). The recovered projectile remained unchanged in mass after penetration, with deformation limited to flattening of the parabolic nose (Figure 5).

Figure 5. Shape of the FMJ projectile of the 9 mm Luger pistol cartridge (Sellier & Bellot, Vlašim, Czech Republic): Left: Before impact on the gelatine block; Right: After penetrating the gelatine block with the embedded bone substitute

Following the shooting, the gelatine block was removed from the frame and transported to the Department of Forensic Medicine in Brno, where X-ray of the compact physical model block containing the perforated bone were taken (see Figure 6). A simple gunshot wound to the thigh (affecting only soft tissues) will probably become complicated if the femur is impacted by the projectile. X-ray and digital photographs (Figures 6 and 7) reveal the formation of a gunshot fracture in the femur. The X-ray clearly displays the entry wound and the lines of a comminuted gunshot fracture.

The fracture is complex and characterised by the formation of complex fracture lines and numerous small bone fragments. These fragments may contribute to additional damage to surrounding muscle tissues or blood vessels located near the affected bone.

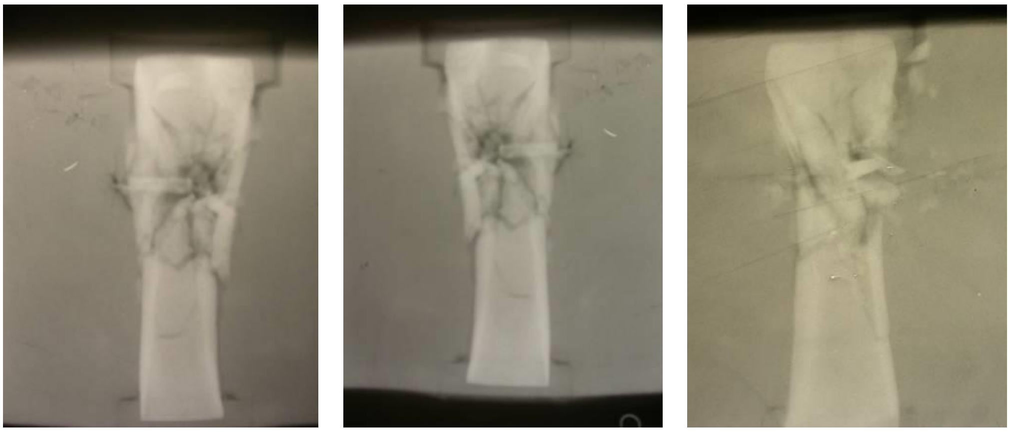


Figure 6. X-ray images of the compact gelatine block with a femur perforation by a full metal jacket (FMJ) projectile from a 9 mm Luger pistol cartridge (Sellier & Bellot, Vlašim, Czech Republic): Left: Anteroposterior X-ray image; Centre: Posteroanterior X-ray image: Right: Lateral X-ray projection.

Given that the injury involves a perforation (an open projectile channel), the overall clinical condition of the injured individual is likely to be further complicated by the onset of sepsis. This may result from the suction of debris and contaminated water vapours from the external environment as a result of the pulsations of the temporary cavity.

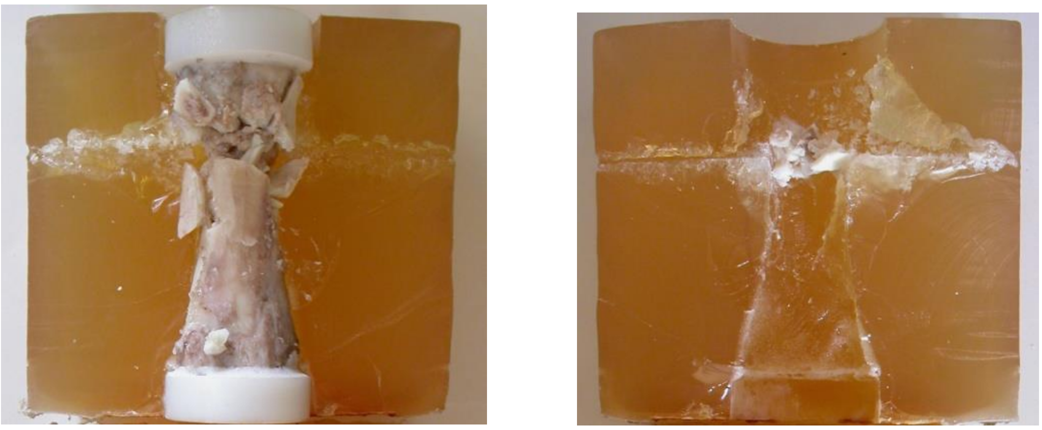


Figure 7. Longitudinal section of the bone gelatine block along the longitudinal axis of the projectile channel (the figure reveals an extensive comminuted fracture of the femur, located just below the head of the proximal epiphysis)

4.2. 5.56×45 mm (Hunting Equivalent: 0.223 Remington) with a Full Metal Jacket (FMJ) Projectile

The SS 109 projectile, developed by the Belgian company F. N. HERSTAL, features a specific construction with a steel core in the front section and a lead filling in the rear section. It is a component of modern micro-calibre ammunition designed for use with the upgraded M16 A2 automatic assault rifle. The rifle's barrel has a progressive rifling twist with a shorter twist rate (6.97 inches), ensuring excellent projectile stability and high penetration capability. The projectile of the experimentally used cartridge achieved an impact velocity of v_d = 938 m.s^{-1} (E_d = 1 760 J) when striking the gelatine block (B_2). The initial segment of the projectile channel within the gelatine, located before the bone, was narrow and straight.

Upon impact with the bone, the projectile produced an explosive effect, resulting in the complete destruction of the bone substitute and severe damage to the gelatine block. This impact led to the disintegration of the unsupported upper plate of the frame into four pieces and the bending of all steel bolts. However, the lower PVC plate that forms the base of the physical model frame remained intact (see Figure 8). The results of the experiment indicate a high probability of extensive destruction of bone tissues and surrounding muscle tissues in a thigh with bone involvement when struck by this projectile. The extent of damage correlates with the dimensions of the temporary cavity. In this case, the loss of the femur substitute spanned 90 mm of its length, with all bone fragments located within the projectile channel (temporary cavity).

This assessment highlights the significant influence of the temporary cavity on the extent of tissue damage to the femur, which, at the moment of impact by the high-speed micro-calibre projectile, was located within the cavity. Conditions for the development of the temporary cavity were highly favourable, given the presence of liquid structures (bone marrow) within the narrow cavity of the femur substitute. This allowed for the full development of the explosive effect upon direct bone impact, where the bone acted as a piston within a hydraulic system.

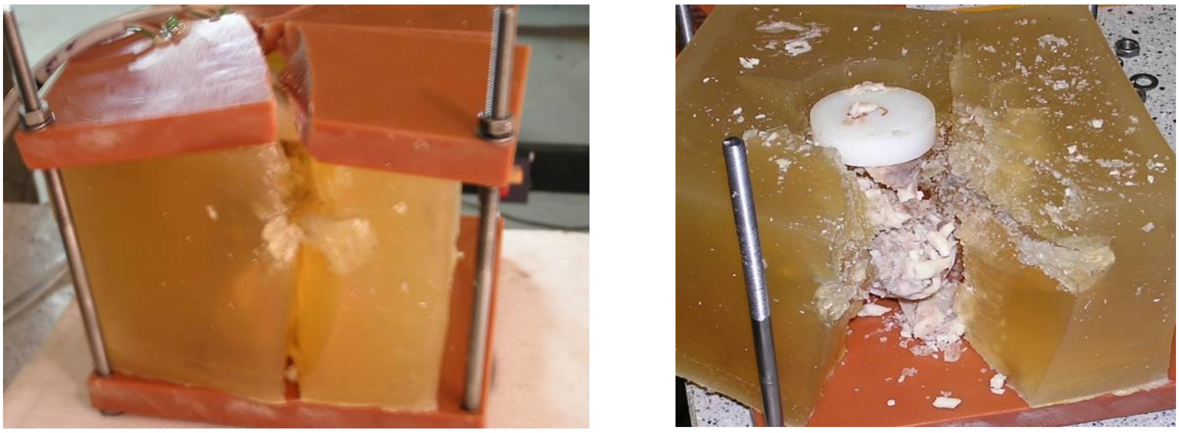


Figure 8. Physical model of the thigh with bone substitution immediately after perforation with the SS 109 micro-calibre cartridge (5.56×45 mm, Sellier & Bellot, Vlašim, Czech Republic): Left: View of the front surface of the gelatine block in the physical model; Right: Gelatine block with the upper frame plate removed, showing extensive destruction of the femur substitute.

4.3. Micro-Calibre 7H6 Projectile from the 5.45×39 mm Rifle Cartridge (Tula, Russia)

Although it had a lower mass and initial velocity (and therefore lower initial kinetic energy) compared to the SS 109 projectile of the 5.56×45 mm cartridge with a similar ballistic performance class, the effects of the 7H6 projectile on the biological target were comparable, if not superior. The 7H6 projectile, with a mass of m_q=3.42, impacted the front surface of the gelatine block at v_d = 902,2 m.s^{-1} (E_d = 1 392 J) and struck the bone in the proximal metaphysis region while traversing the physical model. Although the projectile had a slightly lower mass (by 0.08 g) and impact energy (by approximately 400 J) compared to the SS 109 projectile, its effect on bone tissues was comparable to that of the American cartridge.

A distinctive feature of this projectile's effect is the significant extent of the temporary cavity, as demonstrated by its size (length) and the density of radial cracks in the gelatine block. The temporary cavity occupied more than 50% of the total volume of the gelatine block. The impact of the cavity, combined with the unique structural characteristics of the projectile (longer overall length and long soft steel core), resulted in extensive destruction of bone tissues comparable to the effects of the previously evaluated SS 109 projectile (see Figure 9).

Figure 9. Cross section of a gelatine block with bone substitute at the site of the gunshot channel caused by a 7H6 rifle cartridge projectile, calibre 5.45×39 (Tula, Russia)

Upon removing the gelatine block from the frame, numerous bone fragments were observed on both opposing surfaces, having been expelled from the internal area around the nylon cups. Additionally, some fragments of bone tissue were forced out of the block in the direction of the shot due to the pressure exerted by the advancing projectile. These fragments were found on the substrate behind the physical model. An evaluation of the effects of micro-calibre projectiles from both rifle cartridges reveals their comparable wounding effects on the bone substitute and surrounding soft tissues. However, these effects were achieved through different projectile mechanisms upon impact with the target.

Although the SS 109 projectile acts as a cohesive projectile on the gelatine block only during the initial penetration phase (until the projectile impacts the rigid bone), the 7H6 projectile remains mass-stable throughout its penetration of the physical model. The temporary cavity in the block did not contain any fragments of the 7H6 projectile body (see Figure 8). The ballistic experiment showed that the SS 109 projectile fractured immediately after impacting the bone, splitting into two halves just behind the steel core. The front part of the projectile (the tip with the core) continued independently and deviated noticeably from the shooting direction after penetrating the entire block. The rear portion of the projectile (the lead core), which makes up almost 60% of its total mass, was fragmented into small pieces that were evenly distributed within the gunshot channel and its immediate vicinity.

The ballistic experiment, which focused on simulating the direct effects of projectiles of small calibres on a femur using a heterogeneous physical model, provided significant insight into the mechanisms of bone tissue and surrounding soft tissue damage. The results demonstrated that tissue devastation is significantly influenced by the type and construction of the projectile.

A 9 mm Luger handgun projectile exhibited limited wounding effects, with a narrow gunshot channel and minimal temporary cavity volume. On the contrary, micro-calibre rifle projectiles, specifically 5.56×45 (SS 109) and 5.45×39 (7H6), caused substantially more extensive tissue devastation, including significant bone fragmentation and the formation of extensive temporary cavities. This effect was particularly pronounced with the 5.56×45 projectile, which achieved a high impact kinetic energy and fragmented when hitting the substitution model, thus significantly increasing the extent of tissue damage.

A key finding was the impact of the presence of liquid structures within the marrow cavity of the femur on the extent of its damage. The liquid content within the bone acted as a medium for kinetic energy transfer, leading to a hydrodynamic effect and subsequent devastation of the bone tissue. This phenomenon corroborates previous studies that highlight the importance of the temporary cavity in gunshot wounds [42, 43].

The results of this study confirm that the type and construction of a projectile significantly influence the mechanisms of damage to both bone and soft tissue. A direct comparison of the effects of small-calibre pistol projectile and micro-calibre projectiles clearly demonstrates that the higher kinetic energy and specific design of ammunition of small calibres result in more extensive tissue devastation. Although the 9 mm Luger pistol projectile caused limited tissue destruction with a narrow gunshot channel and a small temporary cavity, micro-projectiles 5.56×45 SS 109 and 5.45×39 7H6 created significantly larger temporary cavities and extensive comminuted bone fractures.

4.4. Mechanisms of Destruction and Their Interpretation

High-velocity supersonic projectiles use the transfer of kinetic energy to create a pronounced temporary cavity, formed by the rapid expansion of surrounding tissues as the projectile penetrates. This expansion generates pressure waves that cause secondary damage to both soft and hard tissues [22]. The presence of liquid content in the medullary cavity significantly contributes to the hydrodynamic effect, amplifying the devastation of bone tissue. This mechanism is corroborated by Kneubuehl et al. [42], who describe fluid pressure transfer as a key factor in comminuted fractures.

The 5.56×45 SS 109 projectile is characterised by significant fragmentation of its body, which increases the general extent of tissue damage. Sellier et al. [5] emphasises that projectile fragmentation has a critical impact on secondary projectiles, thus broadening the scope of damage to surrounding tissues.

In contrast, the 5.45×39 7H6 projectile remained mass-stable, leading to a different mechanism of destruction, effectively using a longer temporary cavity and energy transfer to a larger tissue volume. Moravanský et al. [44] also highlight the differences in projectile effects on tissues depending on their fragmentation properties.

The factors contributing to the "twice as much" destruction of bone tissue caused by micro-calibre projectiles, compared to small-calibre pistol ammunition, extend beyond their impact kinetic energy. The pronounced effects of micro-calibre projectiles on dense bone tissue are amplified by two critical stability-related mechanisms: mass instability and motion instability.

The SS 109 micro-calibre projectile exhibits mass instability due to its tendency to fragment upon impact. This fragmentation generates secondary projectiles that spread within the bone tissue and surrounding areas, significantly expanding the damage zone. However, the 7H6 micro-calibre projectile demonstrates motion instability, as it deviates substantially from its velocity vector upon penetration of the tissue. This tumbling effect causes an irregular energy distribution within the bone, amplifying mechanical damage by generating additional shear forces and unpredictable fracture patterns.

The magnitude of kinetic energy at the moment of impact is a crucial determinant of the mechanical effect on bone. For micro-calibre projectiles, their high impact velocities - markedly supersonic - allow them to transfer substantial energy to the tissue in a short time frame, creating extensive damage zones. The rapid release of energy also contributes to the formation of a temporary cavity in the surrounding tissue, a phenomenon that exerts significant pressure waves and further intensifies the destruction of bone and soft tissues.

In contrast, the 9 mm Luger pistol small-calibre projectile, with its full metal jacket design, is relatively slower, with an impact velocity close to the sound velocity in air (342 m/s). This projectile maintains stability in terms of mass, shape, and motion during penetration, leading to a significantly smaller mechanical effect on both soft and hard tissues. Its relatively slow velocity limits the formation of a temporary cavity and results in a more localised and less destructive injury pattern. The combination of mass fragmentation and motion instability in micro-calibre projectiles, along with their high kinetic energy, underscores their devastating effects on bone tissue. This knowledge is critical to advance ballistic models, improving protective technologies, and improve the understanding of gunshot wound mechanisms in medical and forensic applications.

4.5. Comparison with Homogeneous Substituent Models

The use of a heterogeneous physical model in this study represents a significant advancement in realistic simulation of the effects of projectiles on human tissues, including the formation of complex injuries. Homogeneous models, such as ballistic gelatine without bone substitutes, provide only limited information about the interaction of projectiles with rigid tissues. Lavrov et al. [30] demonstrated that homogeneous models often overestimate the extent of the temporary cavity because they do not account for the structural strength of the bones and their influence on the propagation of pressure waves.

4.6. Comparison with Previous Studies

Comparison of this study with previous research confirms that heterogeneous substitute models are better suited to replicate the real-world conditions of complex gunshot injuries. Zaseck et al. [22] found that the presence of bone in models significantly affects the mechanisms of propagation of pressure waves and the formation of temporary cavities. Study [4] described that high-velocity (markedly supersonic) projectiles with body fragmentation result in a larger volume of tissue damage, aligning with the findings of this study.

The results revealed significantly greater tissue destruction when micro-calibre rifle projectiles (SS 109 and 7H6) were used compared to the 9 mm Luger pistol small-calibre projectile. This increased destruction was primarily due to the higher impact kinetic energy of micro-calibre projectiles and their ability to generate extensive temporary cavities. The temporary cavity is a critical phenomenon that influences the extent of injury, as it affects the surrounding tissues through pressure waves and generates secondary projectiles in the form of bone fragments and projectile debris. These findings are consistent with studies [42, 45-47], which highlight the importance of energy parameters and their impact on injury severity.

Furthermore, similar results were published by Moravanský et al. [46]. The authors noted that cavity size and energy transfer are directly correlated with projectile velocity and material composition. Babich et al. [48] and Chu et al. [49] emphasised the importance of material interactions, particularly in cases involving heterogeneous models, as the bone rigidity and marrow cavity amplify hydrodynamic effects. The presence of liquid structures in the bone marrow cavity was a significant factor that amplified the effects of the temporary cavity, contributing to comminuted fractures. This hydrodynamic effect, in which fluids transfer the kinetic energy to surrounding structures, was also confirmed in previous studies [19, 22, 43]. Similar findings published by Du et al. [50] and Valeika et al. [51] corroborated the role of liquid mediums in amplifying energy transfer, showing that injuries are significantly more severe in models containing fluid-filled cavities.

The fragmentary properties of the SS 109 and 7H6 projectiles demonstrated different damage mechanisms. SS 109 exhibited pronounced fragmentation, while 7H6 remained mass stable but lost its stability during penetration, resulting in varying damage distributions. This observation aligns with observations published by Igansi et al. [52] and Sekar et al. [53]. Authors of these studies explored projectile stability as a factor in heterogeneous damage distributions.

Despite the valuable results, the study had certain limitations, including a small number of test samples and a limited range of projectiles used. These constraints could be addressed in future research by incorporating a broader spectrum of ammunition and a larger number of experimental samples. Supplementing experiments with high-speed cameras and numerical simulations could enable a more detailed analysis of the dynamics of the projectile channel and pressure waves, contributing to a deeper understanding of biomechanical damage mechanisms. Expanding upon these parameters could further validate the relevance of the findings and ensure the model's applicability in forensic and medical contexts.

5. Conclusions

Ballistic experiment using a heterogeneous physical model to simulate the wounding effects of projectiles of small calibres has provided significant advances in understanding the biomechanics of projectile impacts. The study successfully validated the model's ability to replicate realistic interactions between projectiles and bone-soft tissue composites under dynamic conditions, enhancing its utility for experimental wound ballistics. Key findings of the research include the identification of significant differences in tissue and bone damage between pistol and micro-calibre rifle projectiles. Micro-calibre projectiles, such as the 5.56×45 mm SS 109 and 5.45×39 mm 7H6, exhibited superior tissue destruction capabilities compared to the 9 mm Luger pistol ammunition, primarily due to their higher kinetic energy and ability to create extensive temporary cavities. This phenomenon emphasises the role of projectile energy and design in determining the severity of gunshot injuries.

Furthermore, the study highlighted the hydrodynamic effects of liquid structures within the medullary cavity of bones, demonstrating their critical role in amplifying the extent of tissue and bone destruction. These findings corroborate earlier research on the dynamics of temporary cavities and extend our understanding of the interaction between ballistic energy and biological tissues. The implications of this research are multifaceted. In forensic science, the model provides a reliable tool for reconstructing shooting incidents and assessing wound patterns. For the security and healthcare sectors, insights into projectile effects are invaluable for designing advanced protective equipment and developing injury mitigation strategies.

Despite its contributions, the study acknowledges limitations, including a restricted variety of projectiles and sample sizes. Future research should integrate a broader range of ammunition, advanced numerical simulations, and high-speed imaging to deepen the understanding of ballistic impacts. Expanding the experimental framework to include additional biomechanical parameters will further enhance the applicability in interdisciplinary contexts.

This study underscores the potential of innovative physical models to bridge the gaps between experimental data and real-world applications, marking a significant step forward in the fields of experimental ballistics, forensic analysis, and protective equipment development.

6. Declarations

6.1. Author Contributions

Conceptualization, L.J., K.P., D.M., and O.V.; methodology, L.J. and K.P.; investigation, D.M. and O.V.; writing—original draft preparation, L.J., K.P., D.M., and O.V.; writing—review and editing, L.J., K.P., D.M., and O.V. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

6.3. Funding

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6.5. Ethical Considerations

Ethical aspects are another critical point of discussion. The use of biological substitutes combined with ballistic gelatine allows the minimisation of experiments on live animals, which is in line with current legislation and ethical principles [29, 46]. This approach is further supported by Maiden [38]. Authors emphasise the importance of ethical and practical solutions in wound ballistics.

6.6. Informed Consent Statement

Informed consent was obtained from all subjects involved in the study.

6.7. Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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