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# A comparison of penetration and damage caused by different types of arrowheads on loose and tight fit clothing

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ABSTRACT

Bows and arrows are used more for recreation, sport and hunting in the Western world and tend not to be as popular a weapon as firearms or knives. Yet there are still injuries and fatalities caused by these low-velocity weapons due to their availability to the public and that a licence is not required to own them. This study aimed to highlight the penetration capabilities of aluminium arrows into soft tissue and bones in the presence of clothing. Further from that, how the type and fit of clothing as well as arrowhead type contribute to penetration capacity. In this study ballistic gelatine blocks (non-clothed and loose fit or tight fit clothed) were shot using a 24 lb weight draw recurve bow and aluminium arrows accompanied by four different arrowheads (bullet, judo, blunt and broadhead).

The penetration capability of aluminium arrows was examined, and the depth of penetration was found to be dependent on the type of arrowhead used as well as by the type and fit or lack thereof of the clothing covering the block. Loose fit clothing reduced penetration with half of the samples, reducing penetration capacity by percentages between 0% and 98.33%, at a range of 10 m. While the remaining half of the samples covered with tight clothing led to reductions in penetration of between 14.06% and 94.12%.

The damage to the clothing and the gelatine (puncturing, cutting and tearing) was affected by the shape of the arrowhead, with the least damaged caused by the blunt arrowheads and the most by the broadhead arrows. Clothing fibres were also at times found within the projectile tract within the gelatine showing potential for subsequent infection of an individual with an arrow wound.

Ribs, femur bones and spinal columns encased in some of the gelatine blocks all showed varying levels of damage, with the most and obvious damage being exhibited by the ribs and spinal column.

The information gleaned from the damage to clothing, gelatine blocks and bones could potentially be useful for forensic investigators, for example, when a body has been discovered with no weapons or gunshot residue present.

## 1. Introduction

A penetration injury is generally a result of sudden and forceful pressure in a small area, causing the tissues to be stretched or crushed by a projectile, such as a bullet, knife or, in the case of this study, an arrow [1]. It is estimated that archery has been used as a means of hunting and protection since the late Palaeolithic period, however interest in archery as a means of protection declined by the late 1700s later being revived, but for sport rather than protection [2]. Now in the 21st century; firearms have become increasingly popular as the weapon of choice, in warfare and law enforcement as well as crime. As a result, archery is used in the modern world for sport and recreation but is no longer used primarily for hunting and warfare with the exception of indigenous groups, such as Australian Aborigines [3]. However, it is not unheard of for a bow and arrow to be used as a weapon in place of a firearm or knife either to injure oneself or another. Cina et al. [4] describe a case of suicide, where a 17-year-old man used a compound bow held in his hands and drawn by his left foot to shoot a broadhead arrow into his chest. While Erikson et al. [5] describe a case of murder, here a foreman was found dead at his place of work with three arrows in his chest. In this case, the man had been shot by a co-worker who decided to kill someone after watching videos containing murders and purchased arrows specifically to kill the first person to enter the building after him. More recently in India Devchand and Singh [6] describe a case of a non-fatal arrow shooting following an argument between two brothers resulting in one of them being shot in the chest. Despite the fact that firearms are taking over as a weapon used in criminal activities, projectile trauma is readily observed, therefore investigators may

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**Fig. 1.** Left to right: bullet, blunt, judo and broadhead arrowheads used during the project.

come across a crime where a bow and arrow has been used be they cases of suicide, murder, assault or accidental as described by Paučić-Kirinčić et al. [7]. This case involved two children (aged 9 and 17) who were playing outside with a toy bow and arrow when the arrow broke and a part struck the younger boy in his left eye. Though the boy survived this injury he lost his left eye and was left with brain damage causing weakness down the right-hand side of his body.

Although arrows can be purchased with pre-set arrowheads, many arrows are designed in such a way that the arrowheads can be interchanged. These arrowheads include but are not limited to, broadhead, judo, blunts and bullet [Fig. 1]. Broadheads are used in bow-hunting and consist of two or more blades radiating from the body of the shaft beneath a conical tip. The blades are designed to cut and tear the tissue and organs of the animal hunted [8]. The judo is designed with four spring-action arms that open out during flight; then catch onto grass or tree stumps preventing the arrow from being lost during target practice. The blunt is designed so that the tip is flat and is used mainly for field practice and stump shooting, but can also be used in bowhunting to stun smaller prey. Bullet points are mainly used for target shooting and their tip looks like that of a bullet typically fired from a firearm [9].

Arrows can cause damage to a human by puncturing, stabbing, tearing, cutting or a combination of these mechanisms depending on the arrowhead used. In the Handbook of Forensic Medicine [10], it is stated that the wounding potential of an arrow is primarily dependent on the shape of the arrowhead. For example, puncture wounds being caused by pointed or rounded tips and cuts caused by a sharp tip being forced into the body. It also states that the penetration mechanism of soft tissues uses a combination of cutting and stabbing – resulting in a deep penetration of tissues. This penetrative arrow trauma is also dependent on the draw weight of the bow, the distance the arrow is shot from and the type of tissue encountered [11]. For example, considering Newton's 2nd Law of Motion, a bow with a 20 lb draw weight will supply an arrow with less acceleration than a 24 lb. bow resulting in a lesser penetrative force applied at impact thus potentially causing less penetrative damage than that of the 24 lb bow shot over the same distance. Also, the area of injury and the type of tissue encountered are of great importance as it is usually proportional to the severity of the injury. For example, a thoracic arrow injury may result in the damage to major blood vessels or the heart (which could potentially result in death) whereas an injury to the arm can lead to a treatable bone fracture [12].

Arrows will certainly come into contact with soft tissues and are likely come into contact with bone; the damage caused will be dependent on the type of bone impacted. The arrow will impact tightly in thick bones, such as the femur, essentially penetrating deep enough into the bone to become embedded making extraction of the arrows difficult. However, with flat bones such as ribs or scapula, the arrows may perforate or fracture the bones [9]. Though skin is the most resistant of the body's soft tissues once penetrated less force is needed to penetrate further into the body [13]. Therefore once the skin is overcome the internal organs, especially those in the abdominal region, are easily incised and damaged.

Although most arrow injuries are survivable, they can potentially lead to death, such as a case reported by Hain [14] where an arrow travelled through the right bicep of the individual and entering the right side of their chest, causing rapidly fatal injuries. In some instances, death is not directly caused by the arrow injury but from a subsequent infection, such as blood loss, septicaemia, pneumonia or hypotension [12].

When arrow wounds are encountered by investigators in crime scenes, depending on the arrowhead used, the injury may be misinterpreted as a potential stab wound or gunshot wound. Randall and Newby [15] carried out a wound ballistic study observing that field tipped arrow wounds have a high resemblance to gunshot wounds both morphological and the reddish-brown abrasion rings of burned skin, surrounding the entrance wound. Therefore, in cases where no gunshot residue is detected or bullet fragments recovered, field-tip arrows could be considered as a potential murder weapon. In these types of situations, the individual will most likely be clothed; therefore ballistics studies have been carried out using ballistics ordnance gelatine covered with clothing to determine the impact of the clothing. Vennemann et al. [16] conducted an investigation into how textile fibres can be distributed along the path of a bullet into the human body. They used soft-tissue simulants including gelatine and the belly region of slaughtered pigs covered in a layer of textile material and shot at from a distance of 2 m. The study demonstrated that textile fibres from the entrance and exit areas were transferred into the bullet tract in both an anterograde and retrograde fashion – however, the distribution pattern was determined by the bullet path and the extension of the temporary cavity.

Fabric damage can occur in many different ways depending on the weapons used, such as tearing where the pulling force on the fabric causing the threads to stretch and/or break, or cutting where the fibres are forcefully severed. According to Robertson and Grieve [17], puncture damage to clothing is produced by pointed instruments without cutting edges and penetration is dependent on the shape of the tip and the force applied. Several studies have been carried out with regards to penetration capacity in firearms, air weapons and even bladed weapons. The Wightman et al. [18] study found that clothing that was in contact with the gelatine provided a reduced penetration capacity of various types of air rifle pellets, however, a greater relative standard deviation was found when the clothing was loosely wrapped around the gelatine. In the same study, it was also noted that any damage caused to clothing was dependent on the pellet shape, with the pointed pellets causing the least damage and the domed pellets causing the most damage. They also noted that the type of clothing affected the penetration capacity with jeans providing the most protection from the pellets and the T-shirt providing the least. Cuts caused by knives were examined by Johnson [19] who found that the tip of the blade engaged with the fabric, pushing into or between a yarn eventually causing the yarn to fail, resulting in cutting or tearing. The penetration capability of the blade was influenced by several factors, including blade thickness and tip radius and/or sharpness. Finding that the blunter the tip, the more difficult penetration was, resulting in more fabric distortion and frayed yarns rather than cut yarns.

This study investigated the impact and penetration of aluminium arrows, in the presence of clothing, into ballistic gelatine, to simulate soft-tissue. Four different arrowheads were used: broadhead, judo, blunt and bullet, with two clothing types tested, jeans and T-shirts. Both of the clothing types were either being loosely draped over or tightly wrapped around the gelatine in a way that a human may wear the clothing and therefore allowing to determine whether the fit of clothing contributes to penetration capacity. Bones were also added to some of the blocks to determine the impact on bones and injury caused by broadhead arrows.

It was hypothesised that loose fit clothing would provide greater resistance to arrow penetration as it would absorb energy thus reducing the speed and kinetic energy of the arrow; that the jeans would provide greater resistance to penetration due to the tensile strength and failure strain of the fabric being harder to overcome than the weft knit of the T-shirt; and that bullet arrowheads would allow for the greatest penetration capacity and blunt arrowheads the smallest penetration capacity due to the bullet's more aerodynamic design allowing for greater velocity and, therefore, greater force applied to the gelatine during impact and with the opposite being true of the blunt.

## 2. Materials and methodology

### 2.1. Gelatine

The gelatine (FLUKA, 270-310G bloom strength) was prepared using the Fackler and Malinowski method [20] – 100 g gelatine powder added to 900 mL cold tap water in a conical flask with the solution being stirred for 3 min; then incubated in a water bath at 37.4 °C for 90 min, stirring for 3 min every 20 min; then after 90 min a single drop of cinnamon oil added and the solution stirred once more for 3 min. The solution was then poured into plastic rectangular gelatine moulds and stored at 2–4 °C for 24 h. The bones (Bovine: scapula, rib, femur or spinal column), if used, were placed in the gelatine at this time. If, after 24 h, the gelatine was clear and free from bubbles when removed from the mould it was wrapped in clear cling film ready to be used.

### 2.2. Archery equipment

A 24 lb draw weight recurve Rolan bow was used to shoot aluminium arrows (Easton) with 4 different arrowheads [Fig. 1]: bullet points (23.2634 g, Easton); rubber blunt points (26.3526 g, Bear Paw); judo points (28.1228 g, Zwicky); broadhead points (26.4329 g, Fosse) [21].

### 2.3. Clothing

Commonly worn clothing was used in the study: T-shirt (95% cotton and 5% elastane, weft knit) and jeans (65% cotton, 33% polyester and 2% elastane, plain weave) or (99% cotton and 1% elastane, plain weave). The gelatine blocks were placed inside the clothing, which was either draped loosely or stretched tightly across the surface to simulate different clothing fits. A set of gelatine blocks with no clothing was also used to allow for a comparison of penetration capacities of the arrowheads without the consideration of clothing.

### 2.4. Shooting arrangement

The gelatine blocks were placed on a purpose-built stand in front of a boss (Merlin Archery) and safety net (Longshot). Each arrowhead type was shot into each clothing type (including both fits) twice from a distance of 10 m. All shots were conducted by one archer to allow for consistency throughout the investigation. The archer had undergone training prior to the study to evaluate their draw strength, accuracy and ability to hit the required area on the gelatine samples, which in turn helped reduce variation and errors during the study.

### 2.5. Result collections

All gelatines, arrows and clothing were photographed in situ with a Nikon D60 camera and an iPad (5Megapixel camera) – to show penetration capacity and damage caused to the clothing. Close up photographs of gelatine and clothing damage were taken with a Discovery VMS-001 USB microscope (200 × Magnification). The penetration capacity was measured from the gelatine surface entry hole to the tip of the arrowhead.

### 2.6. CT scans

The HMX-225 microtomography scanning system scanned the bones pre and post shooting to compare the structure and any abnormalities of the bones prior to shooting to damage caused by the arrow impact. All bones were scanned with an energy of 84 kV, current of 83 μA, a 0.1 mm aluminium filter, to reduce beam hardening and 1500 angular projections (1500 slices scanned as the sample was rotated). After scanning the CT profiles were reconstructed recording the outer cortical layer, length and width of the bones, along with the depth for rib bones. All measurements were consistently taken from the halfway point of each bone.

### 2.7. 3D imaging

The CT scanner images were converted from volumetric files into 16-bit greyscale image stacks using the VG studio max v2.2 programme to produce 3D images. These 3D images were manipulated to show all angles of the sample and the extent of any external damage.

## 3. Results and discussion

### 3.1. Penetration capacity of non-clothed blocks

The penetration capacity of each of the arrowheads without external interference from clothing provided a reference point to clothed blocks and revealed that the broadhead arrowhead penetrated an average of 20.9 cm into the gelatine, the bullet an average of 19.2 cm, the judo an average of 10.2 cm and the blunt an average of 0.6 cm. This variation in penetration capacity can be attributed to the design of the arrowhead, both surface area of the arrowhead tip and aerodynamics.

#### 3.1.1. Damage to gelatine surface

When an arrowhead impacts gelatine [Fig. 2], the pressure applied to gelatine surface is dependent on the surface area and force of the arrowhead coming into contact with it. The smaller the surface area of the object impacting the target's surface, the greater the pressure applied and vice versa with a larger surface area [22]. For example, the bullet penetrated the surface layer of the gelatine leaving a slit whereas the blunt left a circular impression in the gelatine's surface. This is illustrated further by the flat ended blunt tip which did not penetrate deeply into the gelatine but did leave some damage [Fig. 2 A & B]. Then with the judo tip, the spring-action arms dug into the gelatine as well as

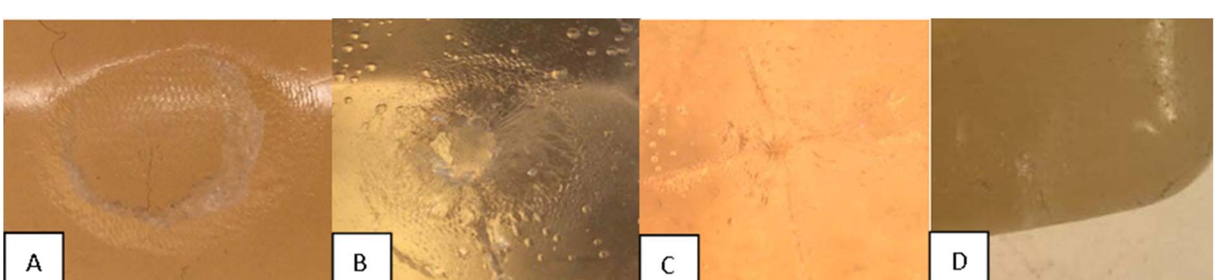


**Fig. 2.** Gelatine damage caused by blunt arrowhead: tight fit T-shirt (A), loose fit T-shirt (B), damage caused by judo arrowhead: tight fit T-shirt (C) and loose fit T-shirt (D).

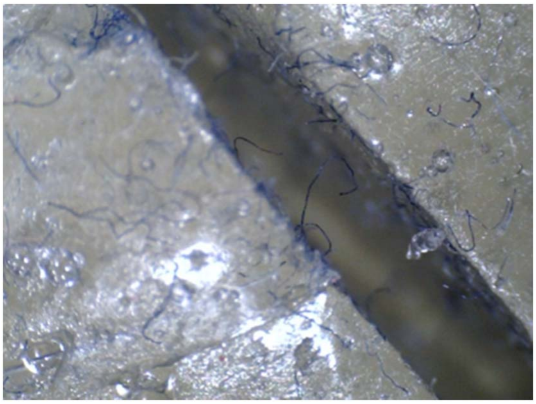

**Fig. 3.** Fibres present in broadhead cavity in gelatine block covered with 99% cotton and 1% elastane jeans.

the body of the tip [Fig. 2 C & D]. Both of which could be translated into bruising on a person.

Upon entering the body an arrow can inflict damage by creating a permanent and/or temporary cavity, as well as infection resulting from foreign material, such as fibres from clothing entering the wound. The presence of fibres was observed in the majority of the arrow cavities in this study [Fig. 3] and such fibres and possible foreign microorganisms would need to be considered in wound treatment.

### 3.2. Effect of clothing on penetration capacity

When the blocks were covered with clothing it was observed that there was a reduction in penetration of all arrowheads with the exception of the blunt, which was 0.6 cm for both non-clothed and the tight T-shirt [Table 1 and Table 2]. There were also variations in the penetration capacity of the arrowheads, such as the judo arrowhead penetrated an average of 3.3 cm into the gelatine covered with the tight fit T-shirt [Table 2], whereas the broadhead penetrated an average of 13.1 cm. It was also observed that there were variations in the penetration capacity between clothing fit. In the case of the bullet tip the loose fit T-shirt material reduced penetration capacity to a greater degree when compared to the tight fit clothing; an average penetration of 17.4 cm into the gelatine covered with the tight fit T-shirt (9.38% reduction) whereas there was a reduced average penetration of 16.5 cm when the T-shirt was loosely fitted (14.06% reduction). Another observation made was the variation between clothing types, for example,

**Table 1**
Comparison of the penetration capacity of each of the arrowhead types in the non-clothed experimental series.

| Arrowhead | Non-clothed | | |
|---|---|---|---|
| | Penetration (cm) | Mean (cm) | RSD (%) |
| Bullet | 18.8 | 19.2 | 1.5 |
| | 19.3 | | |
| | 19.5 | | |
| | 19.2 | | |
| Judo | 10.2 | 10.2 | 0.8 |
| | 10.3 | | |
| | 10.1 | | |
| | 10.2 | | |
| Blunt | 0.6 | 0.6 | 8 |
| | 0.6 | | |
| | 0.6 | | |
| | 0.7 | | |
| Broadhead | 21 | 20.9 | 1.2 |
| | 21 | | |
| | 20.5 | | |
| | 21 | | |

the judo arrowhead penetrated an average of 3.3 cm into the gelatine covered with the tight fit T-shirt (67.65% reduction), whereas it only penetrated an average of 0.9 cm into the gelatine covered with the tight fit 99% cotton jeans (91.18% reduction). Therefore when considering all the clothing variants, it might be expected that clothing would reduce the penetration capacity of all the arrowheads.

#### 3.2.1. Statistical analysis of fabric type and fit

Type and fit of fabric influences the penetration of arrows into ballistic gel (10%) but the presence of and magnitude of this effect depends on the arrow used. To demonstrate this, twenty four arrows of each type were shot at ballistic gel (10%) covered in one of 3 types of fabric (65%, 95% or 99% cotton) which were fitted either tightly or loosely to the gel. Each combination of fabric and gel was tested 4 times and the tests were randomised. Two way ANOVAs (at the 5% significance level) were carried out to determine whether there were significant main effects of fabric type and fabric fit on arrow penetration for four different types of arrows [Table 3–Table 6]. In addition, the possibility of an interaction between the fabric type and fit is reported [Fig. 4].

The effect of two factors, fabric and fit of fabric (loose or tight), on the penetration of arrows into ballistic gel (10%) depends on the type of arrow used. In the case of the bullet arrowhead, both fabric and fit of fabric influence the penetration depth and in addition, there was a significant interaction between the two factors [Table 3; Fig. 4a]. The interaction indicates that the magnitude of the effect of changing the fit of the fabric on penetration depth depends on the fabric used. For example, changing the fit of the 95% cotton had very little effect on the penetration of the bullet arrow but changing the fit had a very much greater effect on penetration of gel covered with 65% and 99% cottons. When blunt or a judo arrowheads were used, the penetration depth depended on the fabric used but not the fit of the fabric; however, for both arrow types there was a significant interaction between fit and fabric [Table 4, Table 5; Fig. 4b and c]. Therefore, despite there being no main effect of fit alone, there is a crossover interaction, which is particularly noticeable for the judo arrowhead. In effect, this means that tightening the fit of the 95% and 65% cotton on the gel, increased penetration slightly (albeit not significantly) but tightening the 99% cotton on the gel reduced penetration slightly. For the broadhead arrow, the fit of the fabric significantly influenced penetration depth but fabric type had no influence [Table 6].

The assumptions of the two-way ANOVA require that the variance across groups is equal and that the residuals are normally distributed. These assumptions were tested using Levene's test (H0:equal variance across groups) and Shapiro-Wilks test (H0: groups are normally distributed). Both assumptions were satisfied for the bullet, judo and broadhead arrows but for the blunt arrow the assumptions were not satisfied however the ANOVA is robust enough to cope with some deviation from normality [23].

### 3.3. Fibre structure and level of penetration

The observation of loose fit clothing reducing the penetration capacity was similar to the results observed during the Wightman et al. [18] study with air rifle pellets. This study attributed the fact that energy from a projectile was transferred to the fabric during collision - the fibre was subjected to a compressive wave outward along the fibre's longitudinal axis and a second wave along the transverse axis at the same velocity of the projectile which increased the energy absorbed by the fibre, until projectile is stopped or the fibre strains too much and breaks [24]. It is believed that the quantity of energy clothing absorbs and level of penetration is determined by factors such as fabric structure (including yarn thickness and fabric weave), impact velocity and projectile shape [25]. The thickness of a fibre will contribute to its tensile strength and as this can be defined as force per unit width - the thicker the fibre, the greater the strength needed to pull it apart. For

**Table 2**
Comparison of the penetration capacity of each of the arrowhead types in the clothed experimental series.

| Arrowhead | Clothing fit | T-shirt (95% cotton) | | | Jeans (65% cotton) | | | Jeans (99% cotton) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Penetration (cm) | Mean (cm) | RSD (%) | Penetration (cm) | Mean (cm) | RSD (%) | Penetration (cm) | Mean (cm) | RSD (%) |
| Bullet | Tight | 17.5 | 17.4 | 1.4 | 14.5 | 14.6 | 0.9 | 15.9 | 15.7 | 1.5 |
| | | 17.6 | | | 14.4 | | | 15.4 | | |
| | | 17.1 | | | 14.6 | | | 15.9 | | |
| | | 17.2 | | | 14.7 | | | 15.7 | | |
| | Loose | 16.7 | 16.5 | 1.3 | 11.2 | 11.1 | 0.9 | 13.4 | 13.3 | 2.03 |
| | | 16.2 | | | 11 | | | 13.5 | | |
| | | 16.6 | | | 11.1 | | | 12.9 | | |
| | | 16.4 | | | 11.2 | | | 13.4 | | |
| Judo | Tight | 2.8 | 3.3 | 23.7 | 0.2 | 0.4 | 28.6 | 0.9 | 0.9 | 5.7 |
| | | 3 | | | 0.4 | | | 0.8 | | |
| | | 3 | | | 0.4 | | | 0.9 | | |
| | | 4.5 | | | 0.4 | | | 0.9 | | |
| | Loose | 4.4 | 4.2 | 11.9 | 0.8 | 0.8 | 6.5 | 0.6 | 0.6 | 8.7 |
| | | 4.7 | | | 0.8 | | | 0.5 | | |
| | | 3.9 | | | 0.7 | | | 0.6 | | |
| | | 3.6 | | | 0.8 | | | 0.6 | | |
| Blunt | Tight | 0.5 | 0.6 | 10.5 | 0.01[a] | 0.01 | 0.0 | 0.01[a] | 0.01 | 0.0 |
| | | 0.6 | | | 0.01[a] | | | 0.01[a] | | |
| | | 0.5 | | | 0.01[a] | | | 0.01[a] | | |
| | | 0.6 | | | 0.01[a] | | | 0.01[a] | | |
| | Loose | 0.4 | 0.5 | 12.8 | 0.1 | 0.1 | 94.5 | 0.01[a] | 0.01 | 0.0 |
| | | 0.4 | | | 0.01[a] | | | 0.01[a] | | |
| | | 0.5 | | | 0.01[a] | | | 0.01[a] | | |
| | | 0.5 | | | 0.1 | | | 0.01[a] | | |
| Broadhead | Tight | 13.5 | 13.1 | 2.4 | 13.8 | 13.6 | 1.0 | 12.8 | 13.3 | 3.7 |
| | | 12.9 | | | 13.6 | | | 13.4 | | |
| | | 12.8 | | | 13.5 | | | 13 | | |
| | | 13.2 | | | 13.5 | | | 13.9 | | |
| | Loose | 13 | 13.2 | 1.3 | 13.4 | 13.1 | 2.6 | 13 | 13.0 | 1.3 |
| | | 13.3 | | | 13.2 | | | 12.9 | | |
| | | 13 | | | 13 | | | 12.8 | | |
| | | 13.3 | | | 12.6 | | | 13.2 | | |

[a] These samples when measuring did not appear to have penetrated, however there was a definite mark, so it was deemed to be < 0.1 cm.

**Table 3**
Two way ANOVA, arrow type: bullet.

| Factor | Levels | Result |
|---|---|---|
| Fabric | 95% Cotton | $F(2,18) = 772.0$; $p < 0.001$ |
| | 65% Cotton | |
| | 99% Cotton | |
| Fit | Tight | $F(1,18) = 693.6$; $p < 0.001$ |
| | Loose | |
| Fit ∗ Fabric | (Fig. 4a) | $F(2,18) = 76.0$; $p < 0.001$ |

example, a thick yarn with a sturdy weave will result in the strain and stress applied to the fabric during impact being spread to a larger area in the weave due to the mutual support from the surrounding fibres, thus greater stress must be applied for the fabric to fail [26]. Therefore, fibres possessing high tensile strengths and large failure strains can absorb considerable amounts of energy. The Lee et al. study [27] proved that the number of yarns broken correlates to the levels of impact energy absorbed – indicating fibre straining is the primary mechanism of the energy absorption in the penetration failure of textiles. Regarding the tensile strength and strain failure of the clothing during the present study, the fibres of both the 65% cotton jeans and the 99% cotton jeans are much thicker than that of the cotton T-shirt, however the tight fit jeans in the case of the broadhead did not stop the arrows as well as the tight fit T-shirt (65% jeans: 13.6 cm, 99% jeans 13.3 cm and for T-shirt 13.1 cm). This may be due to the varying percentages of elastane in their composition: the T-shirt had 5% elastane, the 65% cotton jeans had 2% elastane whereas the 99% only had 1% elastane. The level of elastane contained within the fabric can indicate how much the fabric will stretch: the greater the percentage, the greater the ability of the fabric to stretch [28]. At low velocities, the elastic strain of a fabric will keep the target material in contact with the penetrator [29]. In theory, the more the fabric stretches in the direction the "penetrator" is travelling, the longer the "penetrator" is in contact with the fabric resulting in a greater amount of energy being absorbed by said fabric – the greater the energy absorbed, the greater the reduction in force and therefore penetration capacity.

### 3.4. Aerodynamics of arrow

Aerodynamics or drag of the arrow also plays a role – drag can be reduced by reducing the friction faced during flight; this is done by designing the arrowhead to be more streamlined and aerodynamic [22]. This concept can potentially explain why the arrowheads have different penetration capacities, the blunt arrowhead's flat surface (approximately 3.0 cm in diameter) provides more drag to the arrow in flight as the air has to move up past the flat surface and then over, whereas the bullet or broadhead arrowheads have smooth edges and pointed tips (approximately 0.05 cm in diameter) resulting in the air travelling past the arrow point with more ease. The less drag on an arrowhead, the greater the speed the arrow will travel, whereas the more significant the drag the slower rate of the arrow. Therefore if the drag on the arrow is insignificant the arrow impacts the gelatine with a greater force, however, if the drag is considerable the force will be reduced and this will subsequently affect the penetration capacity in a similar fashion. Thus illustrating the fact that the smaller the surface area of the penetrating region of the arrowhead the greater the pressure applied to the gelatine and the further the arrowhead will penetrate into the gelatine resulting in the damage to the gelatine becoming deep rather than just superficial. Therefore these types of arrows would be more likely to cause damage and injury to a person's skin, internal tissues and bones.

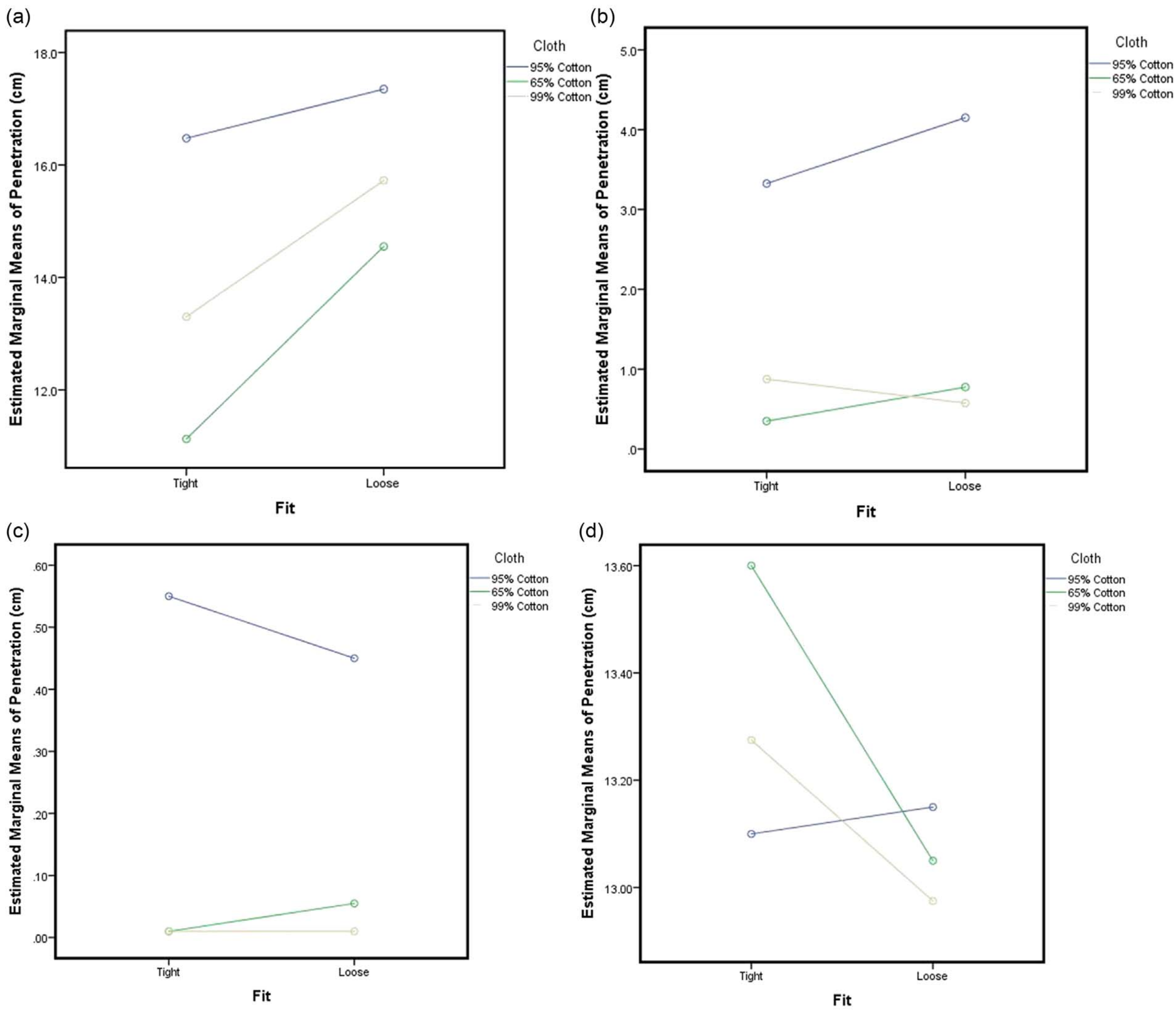


**Fig. 4.** Mean plots for arrowhead (Bullet 4a; Judo 4b; Blunt 4c; Broadhead 4d) and fabric (95% Cotton; 65% Cotton; 99% Cotton) interactions.

**Table 4**
Two way ANOVA, arrow type: judo.

| Factor | Levels | Result |
|---|---|---|
| Fabric | 95% Cotton<br>65% Cotton<br>99% Cotton | $F(2,18) = 173.7; p < 0.001$ |
| Fit | Tight<br>Loose | $F(1,18) = 4.1; p < 0.058$ |
| Fit ∗ Fabric | (Fig. 4b) | $F(2,18) = 4.4; p < 0.027$ |

**Table 5**
Two way ANOVA, arrow type: blunt.

| Factor | Levels | Result |
|---|---|---|
| Fabric | 95% Cotton<br>65% Cotton<br>99% Cotton | $F(2,18) = 392.2; p < 0.001$ |
| Fit | Tight<br>Loose | $F(1,18) = 1.3; p < 0.271$ |
| Fit ∗ Fabric | (Fig. 4c) | $F(2,18) = 7.1; p < 0.005$ |

**Table 6**
Two way ANOVA, arrow type: broadhead.

| Factor | Levels | Result |
|---|---|---|
| Fabric | 95% Cotton<br>65% Cotton<br>99% Cotton | $F(2,18) = 1.2; p < 0.323$ |
| Fit | Tight<br>Loose | $F(1,18) = 4.8; p < 0.042$ |
| Fit ∗ Fabric | (Fig. 4d) | $F(2,18) = 2.1; p < 0.158$ |

Drag can also be caused by the weight of the arrow. Lighter arrows feel the effect of drag faster than the heavier arrows resulting in the heavier arrow maintaining a greater percentage of its original speed than the lighter arrow. Therefore the greater the speed at the time of impact the greater the force applied [30]. For example, the judo point arrows were heaviest, weighing in at 28.1 g, potentially resulting in a further penetration depth, and the bullet point arrows were lightest, weighing in at 23.3 g, which suggests they should have had a lesser penetration depth. However, it can be stated that the force may not have been the same during every shot taken due to the archer's strength and draw potentially altering during the series, as illustrated by the relative standard deviations (RSD) in Table 1. It can be seen that RSD for the blunt was relatively high (non-clothed 8%, clothed 10.5–94.5% for three of the 6 combinations) suggesting that there was a greater variation between each shot taken whereas the RSD for the broadhead was relatively small (non-clothed 1.2%, clothed 1.0–3.7%) suggesting there was less variation. Although the weight of the arrow is of importance the shape of the arrowhead also needs to be considered in

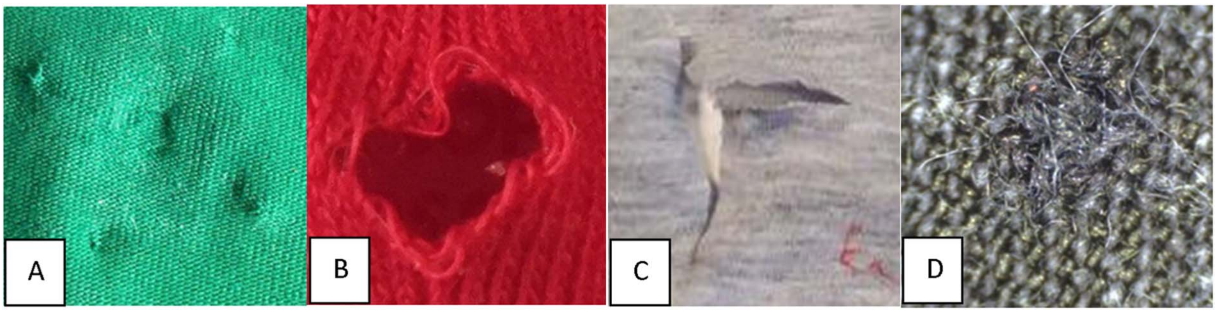


**Fig. 5.** Fabric level damage caused by judo (A), bullet (B), broadhead (C) and blunt (D).

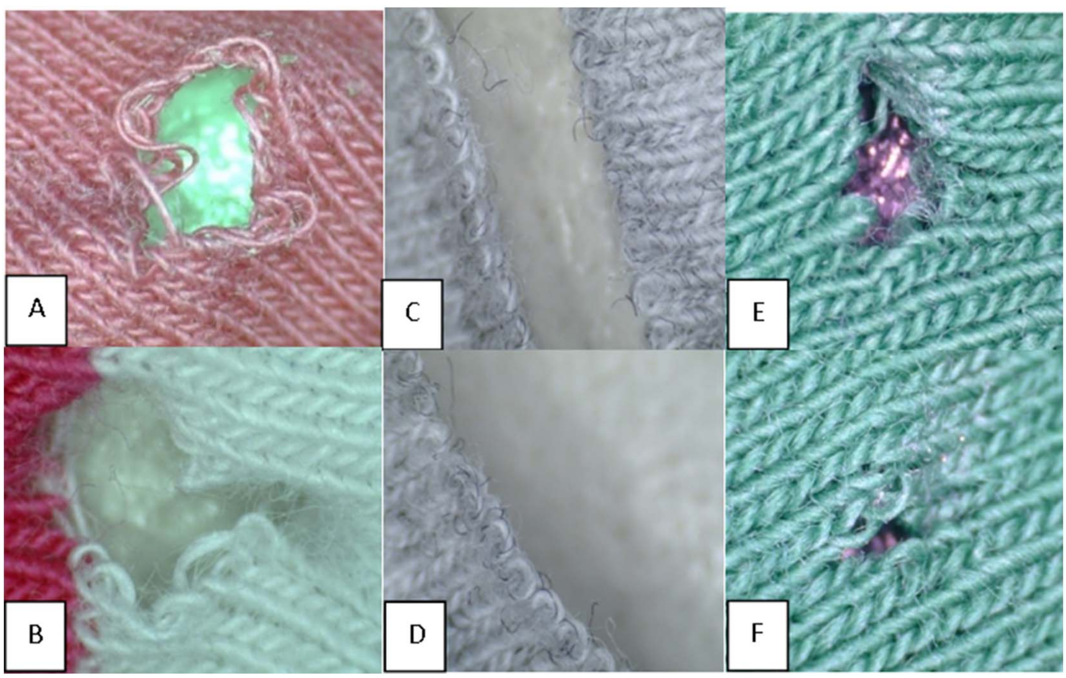


**Fig. 6.** Bullet shot loose T-shirt (A), bullet shot tight T-shirt (B), broadhead shot loose T-shirt (C), broadhead shot tight T-shirt (D), judo shot loose T-shirt (E) and judo shot tight T-shirt (F).

relation to the penetration capacity. This is demonstrated by the blunt, though heavy (26.4 g) it has a much less aerodynamic design than the other arrowhead tips due to its flat and wide tip surface (3 cm), which results in a greater amount of energy being absorbed by the fabrics – therefore resulting in a lesser penetration depth (0.6 cm, deepest penetration). Whereas, in contrast, the bullet arrowhead's impact area is minuscule, resulting in very little energy being absorbed by the resulting In contrast fibres – therefore resulting in a greater penetration depth (17.4 cm, deepest penetration). This was also observed in the Lee et al. study [27] where the larger the "penetrator" radii, the larger the quantity of energy produced. Thus the strain being shared with a greater number of surrounding yarns/fibres, resulting in more energy being absorbed slowing down the arrow and reducing its penetration depth into the gelatine.

### 3.5. Penetrative damage to clothing

In a forensic investigation any clothing under investigation must be examined at (a) the fabric level, documenting the areas of damage and the size of the damage; (b) the yarn level, the severed ends of the yarns themselves are to be noted; and (c) the fibre level, whether the fibres are stretched or distorted [31]. These levels of examination can give insight into the tool that may have damaged the clothing. For example, an investigation should consider the various mechanisms by which clothing can be damaged and that the extent of the damage depends on the fibre's tensile strength, the tightness of the weave and the nature of the impact.

The damage caused by the judo arrowhead [Fig. 5], was approximately 3 cm overall, with a 1 cm damage mark in the centre and damage caused by the spring-action arms ranging from 0.5 mm to 2 mm in diameter; while the bullet arrowhead damage was approximately 1 cm in diameter. The damage caused by the broadhead arrowhead varied in size with regards to the fit of clothing - loose fit had three cuts coming from a central point measuring 3 cm per cut whereas the tight clothing had a larger hole in the centre of the three cuts with the width of damage measuring at around 4 cm. The difference in the morphology of the broadhead damage between fits can be attributed to the fact the fabric was already stretched which would have resulted in the stretch of the fabric being easier to overcome and not returning to its original shape with ease. Finally, regarding the two pairs of jeans, the damage caused by the judo was hard to observe with the naked eye given that the damage looked like genuine wear and tear. However, the damage caused by the broadhead and the bullet were almost identical in morphology and measured at the same length when compared to the damage to the T-shirt.

Fig. 6 shows the effect of the bullet, the broadhead and the judo arrowheads on the cotton T-shirt of both fits. Although both the bullet and the broadhead were both pointed, the broadhead's tip was smaller

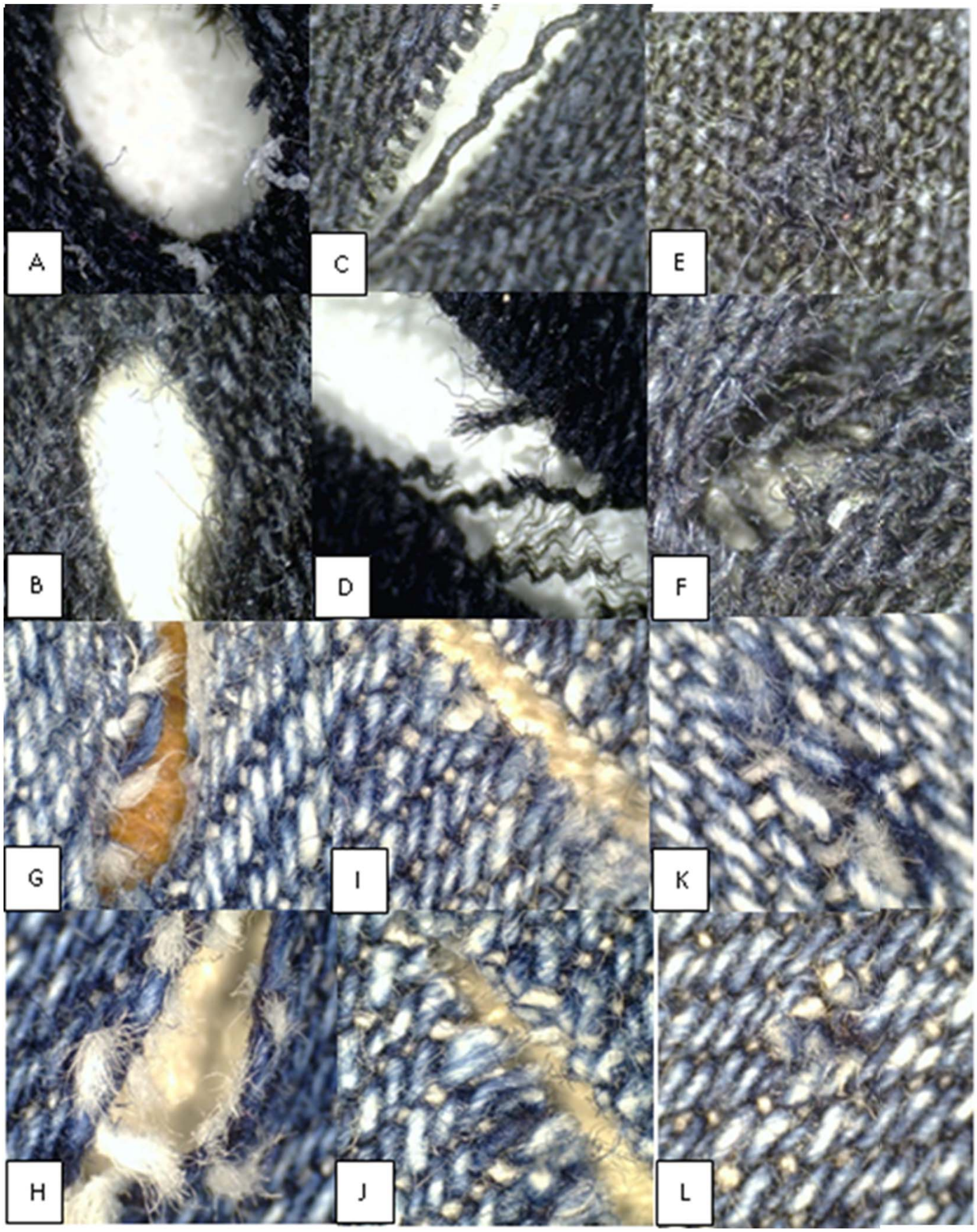


**Fig. 7.** Damage caused to tight and loose fitted 65% and 99% cotton jeans shot with bullet, broadhead and judo arrowheads. 65% jeans shot with bullet arrow – loose fitting (A), tight fitting (B); broadhead – loose fitting (C), tight fitting (D); judo – loose fitting (E), tight fitting (F); 99% jeans shot with bullet arrow – loose fitting (G), tight fitting (H); broadhead – loose fitting (I), tight fitting (J); judo – loose fitting (K), tight fitting (L).

than the bullet which could explain the variance in distortion of the fabrics between the arrowheads with the bullet producing a puncture mark and the broadhead a stabbing cut. The spring-action arms of the judo arrowhead produced small puncture marks in the fabric resulting in small circular/oval holes; however, it was difficult to match up where the broken yarns joined which can allow for a misidentification of tearing damage. They are also so small that they could be misinterpreted as general wear and tear or accidental damage.

It was observed that similarly to the cotton T-shirt, the damage to the jeans was caused by a combination of puncturing, cutting and tearing [Fig. 7]. Regarding the bullet arrowhead, there was evidence with both jean types of stretching to accommodate the arrowhead and evidence of fibres breaking unevenly under the strain; which indicates that the bullet arrowhead caused puncture damage. With the blades of the broadhead arrowhead, there was a straight severance of the fibres between the yarns, providing evidence that the fabric was cut in the way that a sharp blade would cut fabric. The spring-action arms of the judo arrowhead on the 65% cotton jeans produced tearing on tight fit jeans to such a small scale, disrupting the yarn without penetration. The loose fit jeans, however, had evidence of puncture damage with a small oval hole being produced with uneven broken yarns. Whereas the 99% cotton jeans had tearing on both the loose fit and the tight fit jeans at such a small scale there was no penetration.

Overall, it was observed that each arrowhead caused a considerable amount of damage in their own way, making it possible to differentiate the different arrowheads from one another. However, it can be seen

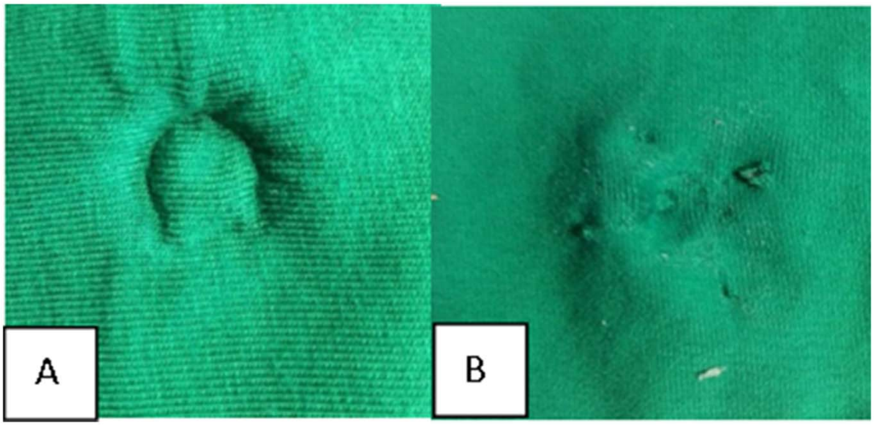


**Fig. 8.** Damage to T-shirt by blunt: tight fit (A) and judo damage to tight T-shirt (B).

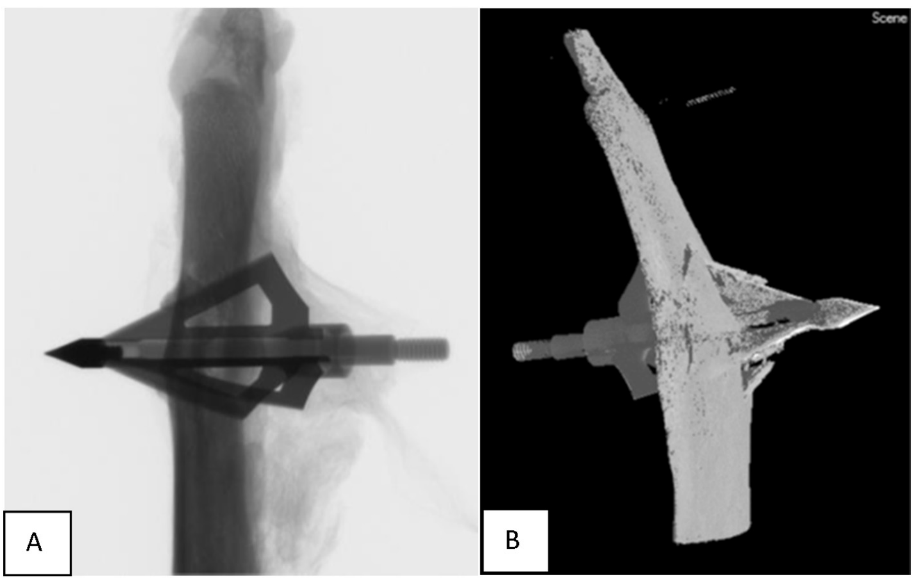


**Fig. 9.** Rib after broadhead penetration, X-ray (A) and CT image (B).

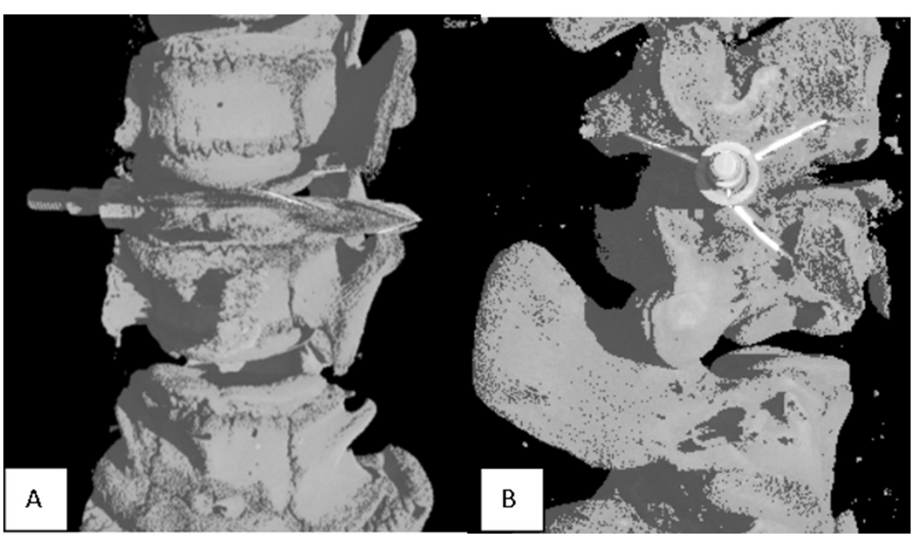


**Fig. 10.** 3D CT images of the spine with broadheads embedded.

that the broadhead caused the largest amount of damage by virtue of the size of the cuts produced.

*3.6. Non-penetrative damage of clothing*

Investigations involving the examination of clothing can also involve non-penetrative damage such as the transfer of thermal energy causing charring or the melting of fabrics.

With regards to the cotton T-shirt [Fig. 8], it can be seen that both the blunt and judo arrowheads produced a depression in the T-shirt that could not be smoothed out. This could potentially be answered by the thermal energy transferred to the fabric at from the arrow at the time of impact forcing the fabric to change shape, much in the same way as when a crease is ironed into a piece of fabric [31]. There was further

**Fig. 11.** Comparison of regular broadhead arrow (left) and broadhead arrow after impact with a femur (right).

evidence of thermal energy transfer in the T-shirts with tiny fibres separating from the yarn of the fabric. It is possible that the vegetable cotton fibres in the fabric lost mass due to the increase in temperature, the same way they would react if they were subjected to fire. Neither the 99% nor 65% cotton jeans showed any evidence of being dragged into the gelatine, however, there was evidence of thermal energy transfer.

Overall, it can be seen that both the blunt and the judo arrowheads inflicted greater damage on the cotton T-shirt in comparison with the jeans and this could be attributed to the elasticity of the clothing. The T-shirt had a greater ability to stretch, resulting in a longer contact time with the arrowhead and, therefore, a considerably larger amount of thermal energy been absorbed by the T-shirt than the less elastic jeans.

### 3.7. CT scanning of blocks containing bone

Bones have different levels of the bone matrix, namely cortical and trabeculae, therefore, were expected to behave differently upon impact with the arrows. Simply put the cortical or compound bone makes up the outer layer of the bones and provides protection as well as support to the trabeculae bone, due to its strong and rigid nature. Whereas the trabeculae bone is a sponge-like irregular lattice structure filled with bone marrow, the density of which varies depending on what bone type is examined [32,33]. Bones though seen as hard do have a degree of flexibility and can be described as "linearly elastic materials" [34] due to their ability to undergo stress and strain but retain their original shape once this has been removed. It is only when this load becomes too high or is not removed that microcracks appear in the bone and can ultimately lead to the breakage of the bone [34]. Therefore to investigate possible bone damage a number of the blocks were prepared with bones (Bovine rib, a spinal column and a femur) embedded in them to determine the impact of being shot with broadhead arrows.

#### 3.7.1. Rib penetration and damage

The X-ray and CT scan of the rib [Fig. 9] clearly shows that upon impact, the broadhead had penetrated through and had become completely lodged. The broadhead arrow tip caused fractures on the surface and internally as well as forcing shards of the cortical bone outwards from the rib in the flight direction. Due to the shape and blades of the broadhead, a large area of bone was damaged, but with less fracturing than expected due to the sharp blades rather than breaking the bone or contact simply cut through the cortical bone and trabecular material. This illustrated that the combination of the blades and speed, thus high stress, strain and load of the arrow led a catastrophic failure of the rib, thus allowing the arrow to become embedded.

#### 3.7.2. Spinal penetration and damage

With the spine [Fig. 10] these bones are designed to withstand compression loads as illustrated in the study by Evans [35] comparing different bone types. But again here the bones were not able to overcome the stresses placed upon them from the arrowhead. The tip penetrated the outer cortical layer, becoming embedded and caused damage within the inner trabecular structure, while the blades cut through the trabeculae within the bone and caused small fractures leading off from the areas cut by the blades. However, due to the denser nature and more complicated configuration of the vertebrae, the arrowhead was also damaged, with the blades becoming detached from the tip and bent outwards.

#### 3.7.3. Femur penetration and damage

The next bone tested was the harder, denser femur bone, which when shot caused a violent ricochet leaving only a small indentation and no penetration of the bone. However, in a real situation, the ricochet could damage the surrounding tissues and vessels, for example, the femoral artery leading to blood loss and possible death. The force of the impact also caused the arrow blades to detach, the tip to bend, the arrow head to be pushed back into the shaft and the aluminium to split radially around the shaft [Fig. 11].

The CT scans illustrated the internal damage [Fig. 12] not observed initially. This was due to a hole (depth 6.07 mm and diameter 3.57 mm) being formed when small shards of cortical bone split from the outer surface of the femur and a shard of bone (12.19 mm in length) split from the internal surface and was forced into the central cavity of the bone. There was also a small indentation on the right side of the

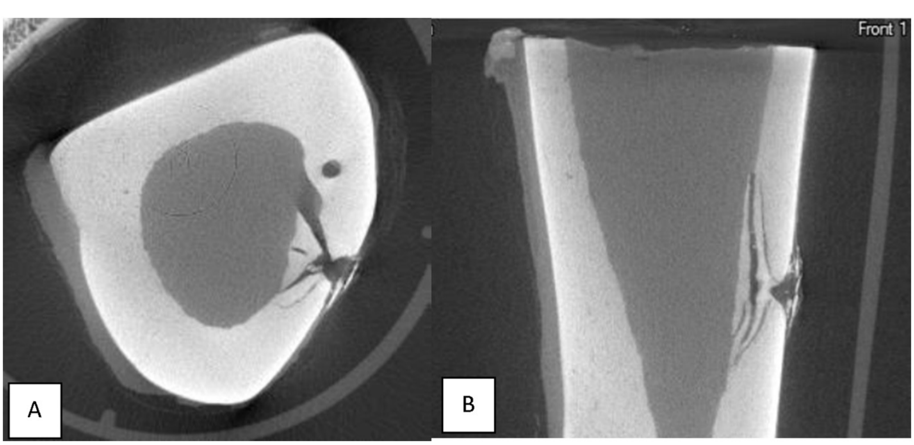


**Fig. 12.** Femur 2 Horizontal (A) and vertical (B) after impact with bullet arrowhead.

obvious damage which may show that the arrow skimmed the edge of the bone and it was this impact that caused the damage.

*3.7.4. Overview of damage*

Results from this study show that dense bones with a thicker outer layer of cortical bone surrounding a central cavity, such as femurs, are more resistant to damage by projectiles unless any internal damage or defect is present. Whereas bones with thinner layers covering an internal structure such as ribs may be more susceptible to damage, however, the small areas of space between them result in the stoppage of fracture lines continuing along the bone. The types of damage caused in this study to the ribs, spine, femur and arrows were also observed by Karger et al. in their 1998 study [3], along with similar entry wounds, such as the star like entry of the broadhead and the circular wounds of the bullet arrowheads.

Overall, it can be said that the shooting of arrows into a human body could result in extensive damage and severe bleeding both internally and externally, which could lead to shock and ultimately death. The majority of the bones in this study had some form of penetration and external fragmentation, with the greatest achieved by the arrows shot into the rib and the spinal column. This also demonstrates why the removal of the arrow should not be attempted until the person is at a hospital so the impact and position of the arrow within the body can be assessed by medical staff to prevent further injury, blood loss or infection for the individual [36].

## 4. Conclusions

This study investigated the shooting of aluminium arrows with different arrowheads into ballistics gelatine covered in clothing to determine what damage can be expected to occur to clothing, tissues and bones. It was hypothesised that the clothing would provide a degree of protection from the penetrative capability of the arrows and this was proven to an extent, as the penetrative capacity of each arrowhead was reduced, with the exception of the Blunt arrowhead on the tight T-shirt. It was also determined that the level of penetration is related to the fit and type of the clothing. Both tight and loose fit clothing provided a reduction in penetration though which was dependant on the arrowhead type used. While it was the jeans that provided the most significant resistance to penetration, with the exception of the tight T-shirt shot with the broadhead.

All of the arrow types caused damage to the gelatine, bones and clothing when present. The bladed broadhead causing the greatest damage and second overall deepest penetration, which could be translated to internal organs, muscular damage and blood loss, thus hospitalisation and possible death, as in the case detailed by Hain [14]. The blunt arrowhead caused the least damage and penetration; however, this could still lead to injuries such as bruising and even internal bleed. Regarding the penetrating broadhead arrowhead, the tight T-shirt with its greater ability to stretch provided a better stopping effect. While, with the rest of the arrowheads, it was the 99% cotton jeans with its tougher weave and stronger yarns that provided a better stopping effect. In relation to the bones used in the study, the rib and spinal column received the most obvious damage, though all of the bones including the denser femur bones were damaged. This in turn illustrated how much damage can potentially be caused by an arrow injury, thus that arrows continue to pose a large risk due to their dangerous penetrative capacities.

This information could potentially be useful for forensic investigators, for example, in a case where the arrow has been removed from the body before it was discovered. Consider the case discussed in Erikson et al. [5], what if the assailant had removed the arrows from the foreman's chest, information gleaned from the damage to the clothing as well as the skin, tissues and bones could aid in the investigators determining that arrows had been used rather than a gun or other form of projectile. With this in mind, this study which will be repeated with altered parameters, such as, more archers and modifying the gelatine recipe to resemble tissues from other areas of the body, thus determining the effect of arrow penetration into different tissues and parts of the human body can be investigated. Also whether an arrow can be identified solely on the damage caused alone, further from that whether or not the damage caused by the arrowhead can be distinguished from other potential weapons such as a screwdriver or a knife. Also the study was conducted with a 24 lb draw weight recurve bow, further studies could include recurve bows up to 40 lbs. and compound bows up to 60 lbs as well as crossbows up to 180 lbs. Finally, only common civilian clothing was tested during this project and accidents can occur during hunting, therefore, another study could investigate the damage that different arrowheads have on different types of protective hunting clothing. Thus allowing for a database of arrowhead types, damage caused to tissues, bones and clothing and penetration depths, which could be of use in cases involving arrow injuries and cases where the weapon type in unknown.

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