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An Experimental Investigation of Cutmark Analysis of Sharp Force Trauma in the Bronze Age

Authors: Rebecca L.J. Strong[1], Linda Fibiger[2]

Affiliations: [1]School of Health and Life Sciences, Teesside University, UK. [2]School of History, Classics and Archaeology, University of Edinburgh, UK.

Corresponding author: Rebecca Strong (r.strong@tees.ac.uk)

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Highlights:

- There is a lack of research observing osteological evidence related to BA weapon use and trauma in combat contexts.
- The aim of this research is to evaluate cutmark morphologies of a Late Bronze Age (BA) sword and dirk to observe any distinguishing characteristics between the two wound patterns.
- Macroscopically, microscopically, metrically no distinguishing characteristics between the BA sword and dirk.
- This suggests the current standards for identification of weapon class are not appropriate for BA weaponry and the BA dirk and sword were being used in similar ways.
- Further research should aim to provide a more suited classification system for diagnosing weapon class specifically for distinguishing the BA sword and dirk.

Abstract

Many studies of Bronze Age weaponry have focused on demonstrating the capability and effectiveness of weapons in a combat context, with little or no observation of the osteological evidence for weapon use and trauma. Downing and Fibiger (2017) is the only study to have taken into consideration cutmark analysis of trauma sustained by Bronze Age weapons. The results of their study demonstrated a need for further research to distinguish between cutmarks sustained by Bronze Age swords and dirks, as the two weapons produced cutmarks with similar macroscopic morphologies. The aim of the current study is to re-evaluate the macroscopic and microscopic morphologies of a Late Bronze Age sword and Late Bronze Age dirk to identify characteristics to distinguish wound patterns from these weapons. A total of 13 strikes were performed by the weapons against two Synbone® cylinders and three *Sus scrofa* forelimbs. The cutmarks produced were analysed macroscopically, microscopically and metrically to observe distinguishing morphologies and discern between the cutmarks sustained by the two weapons. Results showed cutmarks sustained by the Bronze Age sword and dirk exhibited no distinguishing morphologies. Both weapons produced cutmarks characteristic of both knife and sword weapon classes demonstrating that current standards for identification of weapon class are not appropriate for Bronze Age weaponry. Further research should aim to provide a more suited classification system for diagnosing weapon class specifically for distinguishing the Bronze Age sword and dirk.

1. Introduction

Within the history of studying violence and conflict, the Bronze Age (BA) is considered a significant period. The weapons found from this period have been designed specifically to cause harm other individual's (Fyllingen, 2006; Molloy, 2007), leading the BA to be described as the first 'arms race' (Osgood, 2000; Harding, 2007). In the last two decades, research has demonstrated the weapons present in the BA were efficient and functional for combat situations (Kristiansen, 2002; Molloy, 2011, 2004, 2007, 2008; Anderson, 2011; O'Flaherty, Gilchrist and Cowie, 2011; Dolfini and Crellin, 2016; Faulkner-Jones, 2016; Downing and Fibiger, 2017; Gentile and van Gijn, 2019; Hermann *et al.*, 2020). The osteological record further supports this notion with evidence of healed and unhealed trauma in skeletal material, indicative of interpersonal violence (Table 1).

While research has successfully demonstrated the efficiency of BA weapons, interpretation of skeletal trauma is difficult. Researchers are often unable to identify what specific type of weapon caused the injury in question. Unless evidence such as embedded weapons are found within the skeletal remains (Erdal, 2012), the skeletal trauma described could be attributed to several weapon types found in the archaeological record. This is particularly true of skeletal trauma associated with sharp force trauma (SFT).

Table 1: Examples of Trauma Evidenced across the Bronze Age (based upon Horn, 2022)

Site	Date	Findings	Number of individuals	Interpretation	Reference
Granhammar, Sweden	Late BA	Multiple Sharp force	1	Murder, Combat	Lindstrom, 2009[1]
Krakeroy, Norway	Early BA	Multiple Sharp force, attempted beheading	1	Murder, Combat	Holck, 1987[1]
Over Vindinge, Denmark	Early BA	Sharp force trauma, spearhead embedded in pelvis	1	Combat, Ambush	Kjaer, 1912[1]
Sund, Norway	Early BA	Multiple sharp and blunt force including antemortem injuries	22	Massacre	Fyllingen, 2003, 2006
Tollense Valley, Germany	Early BA	Multiple sharp and blunt force including antemortem injuries. Several embedded arrowheads	Over 100	Battlefield	Jantzen *et al.*, 2011; Flohr *et al.*, 2015
Titriş Höyük, Anatolia	Late BA	Multiple sharp and projectile injuries. Evidence of antemortem blunt force trauma.	19	Massacre	Erdal, 2012; Erdal and Erdal, 2012
Mogou Site, China	Early BA	Sharp and blunt force trauma including evidence of antemortem injuries.	361	Combat	Dittmar *et al.*, 2019
Ust-Isa I Cemetery, Siberia	Early BA	Embedded projectile point	1	Assault	Lieverse *et al.*, 2014
Ballabio, Italy	Early BA	Potential projectile or sharp force injuries to cranium	27	Murder	Pasini *et al.*, 2019
Bakheri Chala, Armenia	Late BA	Sharp and blunt force injuries, with evidence of decapitation.	32	Violence[2], assault	Khudaverdyan and Hobossyan, 2017
Sevan Region, Armenia	Late BA	Sharp force injuries associated with decapitation	2	Ritual	Khudaverdyan, 2014
Makó and Érd, Hungary	Middle BA	Blunt and sharp injuries present. Evidence of dismemberment and decapitation	70	Ritual Violence	Szeverényi *et al.*, 2020
South-East Iberian Peninsula	Late BA	Blunt trauma and depressed fractures	221	Conflict	Jiménez-Brobeil, Du Souich and Al Oumaoui, 2009

Table 1 Continued.

Site	Date	Findings	Number of Individuals	Interpretation	Reference
Baderna/Mompaderno, Croatian Istria	Early BA	Sharp Trauma and depressed fracture	1	Interpersonal Violence	Vincenti *et al.*, 2021
Mesopotamia, Iraq	Early BA	Healed sharp and blunt injuries	1278	Accidents and Inter-group violence	Sołtysiak, 2017
Landjik, Kaps, Black Fortress, Armenia	Early BA Late BA	Healed blunt injuries and fractures	26	Military and Labour	Khudaverdyan, 2012
Lu’an, Anhui Province, China	475-221BC	Sharp force injuries	1	Conflict, decapitation	Zhou *et al.*, 2020
Buckinghamshire, United Kingdom	Early BA	Healed antemortem fractures	1	Accident	Anderson, 2002
Helmsdorf, Germany	Early BA	Sharp force injuries	1	Conflict, Assault	Nicklisch *et al.*, 2022
Junggouzi Cemetery, China	550BCE	Blunt, sharp and projectile injuries with evidence of two embedded projectiles.	153	Interpopulation conflict	Zhang *et al.*, 2019
Montilla del Azuer, Spain	Late BA	Healed fracture to hyoid	1	Accident or intentional aggression	Jiménez-Brobeil *et al.*, 2011
	Late BA	Healed and unhealed fractures and sharp injuries	107	Accident and intentional violence. One case of potential homicide/interpersonal violence	Jiménez-Brobeil *et al.*, 2014
Nong Nur, Ban Lum Khao, Ban Na Di, Thailand	Late BA	Blunt trauma (fractures)	343	Accidental and interpersonal violence	Domett and Tayles, 2006
Tomarton, United Kingdom	Middle BA	Multiple projectile injuries. Two spearheads found embedded in the remains of one individual.	4-5	Skirmish	Osgood, 2006

[1] Information for these sites are sourced from Horn (2022)

[2] The authors also cite murder and execution as a cause for the decapitation case.

The analysis of SFT in a combat context has primarily focussed on the recording and interpretation of cutmarks made by weapon classes (Lewis, 2008). In both forensic and archaeological framework, analyses have concentrated on cutmarks sustained in homicide (Shaw *et al.*, 2011; Baiker-Sørensen and Herlaar, 2022), dismemberment (Lynn and Fairgrieve, 2009; Delabarde and Lundes, 2010), butchery (Bello and Soligo, 2008; Okaluk and Greenfield, 2022) and ritual settings (Klaus, Centuri and Curo, 2010; Baustian *et al.*, 2012). What this research has demonstrated is there are discernible differences between cutmarks created by sword classes and knife classes (Table 1).

Very little research, however, has been conducted examining cutmarks sustained by BA weapons in a combat context (Downing and Fibiger, 2017). The analysis of SFT cutmarks in combat contexts has focussed on Neolithic, Medieval or modern weapons (Novak, 2000; Donnellan, Chatzinikolaou and Kranioti, 2013; Boucherie, Marie and Smith, 2017; Constantinescu *et al.*, 2017; Dyer and Fibiger, 2017; Forsom and Smith, 2017). Downing and Fibiger (2017) is the only study to date to have analysed cutmarks experimentally from BA weapons used in a combat context. Employing three replica BA weapons, macroscopic and microscopic analysis of the cutmarks were performed after striking analogues simulating human skeletal tissues (Downing and Fibiger, 2017). The study found current methodologies for analysing skeletal SFT, such as those applied in forensic contexts (Lewis, 2008), could be applied to cutmarks sustained by BA weapons. Their results further demonstrated that, macroscopically, the BA sword produce very similar cutmarks to those produced by knives. Unfortunately, due to the failure of the BA dirk, a short bladed weapon similar to a dagger or knife (Osgood and Monks, 2000), during experimentation a microscopic comparison could not take place to establish any morphological differences to aid in diagnosing weapon class of BA trauma (Downing, 2015; Downing and Fibiger, 2017). There is, therefore, a need to re-evaluate the morphologies of the BA sword and dirk to identify characteristics for distinguishing the two wound patterns.

The aim of this study is to re-evaluate the macroscopic and microscopic morphologies of both the BA sword and the BA dirk to determine if any characteristics to distinguish the two wound patterns. The hypothesis, therefore, is there will be distinguishable morphological and metrical features to differentiate cutmarks created by the BA sword and BA dirk.

Table 2: Observable differences between specific traits associated with sword and knife cutmarks. Based upon findings from Lewis (2008).

Trait	Sword Cutmarks	Knife Cutmarks
Shape	Elliptical	Line or triangle shape.
Floor	Narrow and V-Shaped or broader rectangle shaped with a flat bottom.	V-Shaped
Cross Section Shape	V- or U-shaped	V-shaped
Walls	One smooth, vertically curved wall and one rough vertically straight wall.	Cutmark walls are small and straight.
Damage	Shows higher amount of damage.	Little to no damage observed.

2. Materials and Methodology

Two Synbone® cylinders[1] were used to simulate human skeletal long bones, specifically the humerus due to research demonstrating the upper arm to be majority affected by SFT (Novak, 2000; Harde, 2006; Modlinger, 2011). Synbone® is a synthetic bone substitute comprised of polyurethane materials covered in a latex skin to mimic the properties and biomechanics of natural bone (Smith *et al.*, 2015). The Synbone® cylinders were filled with type three porcine ballistic gelatine, using a ratio of 11.25 grammes of gelatine to 100 millilitres of water (Jussila, 2004; Downing and Fibiger, 2017). The gelatine and latex skin act to simulate the internal structure and periosteum of the bone, respectively. Three fleshed porcine (*Sus scrofa)* forelimbs sourced from a local butcher were used as a second analogue for human remains. The forelimbs were approximately 45 centimetres in length and weighed 2.76, 2.83 and 2.90 kilogrammes. Porcine forelimbs were chosen as a second analogue, as the skin is the traditional model for human skin (Pounder *et al.*, 2011) and has been used in many studies of trauma both forensic and archaeological in context (Lynn and Fairgrieve, 2009; Shaw *et al.*, 2011; Donnellan, Chatzinikolaou and Kranioti, 2013; Faulkner-Jones, 2016).

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[1] The cylinders employed in this study can be purchased via the Synbone website: https://www.synbone.com/product/ifg-002013/?shop_currency=CHF Accessed: 28th September 2022

A replica Late Bronze Age dirk (c.1000-800 BCE) (Figure 1A) and Late Bronze Age sword (c.1100 BCE) (Figure 1B) created by Neil Burridge, a Bronze Age craftsman (http://www.bronze-age-craft.com/), were employed to strike the analogies. The weapons can be created using silicon or sand moulds followed by a single or multiple cycles of hammering, dependent on the weapon created. Measurements of the weapons were taken prior to the experiment following terminology and descriptions set forth by Lewis (2008) and Cerutti *et al.* (2014). Measurements were obtained using a tape measure, digital callipers and a digital scale. All weapons specifications are found in Table 2.

Figure 1: Replica Bronze Age weapons. (A) Late Bronze Age Dirk (c.1000-800 BCE) and (B) Late Bronze Age Sword (c.1100 BCE) (Photographed by author).

Table 3: Metrical Analysis of the Replica BA Weapons

Weapons	**Dirk**	**Sword**
Total length* (mm)	378	567
Blade length* (mm)	259	456
Weight (inc. handle) (g)	392	570
Maximum blade width⁎ (medial-lateral) (mm)	57.3	38.5
Maximum blade thickness⁎ (superior-inferior) (mm)	11	7.1
Thickness of cutting edge⁎ (mm)	≈0.4	≈0.9
Handedness	1	1
Blade composition	12% tin, copper, bronze	2% lead, 9% tin, 89% copper

** Measurements taken with tape measure*

⁎Measurement taken with digital callipers

The experimental set up was designed to replicate an authentic face to face combat situation between two right-handed opponents. One ‘attacker’ executed the strikes, a right-handed male (Height 180 cm; Weight 77.6 kg) experienced in handling historical weapons, specifically Viking weaponry. A total of 13 strikes were performed by the attacker; six strikes were performed with the BA dirk and seven by the BA sword (Table 3). The strikes delivered as a slashing strike, used the blade edge drawn along the target producing an incision and laceration cut (Molloy, 2007). The thrusting strike propels the lateral edge of the blade forward towards the target (Molloy, 2007). A range of motions for performing each strike were employed to introduce variation that would have occurred during a combat situation (see Supplementary Information).

The pig forelimbs were suspended using a hoist, to the shoulder height of the attacker and held in tension, using a 15 kg sandbag and rope to secure the forelimb, to stimulate mobility and resistance encountered by a living opponent (Molloy, 2007) (Figure 2A). This experimental setup was chosen to allow some mobility because if the analogue were fixed, it could potentially damage the weapons should the attacker miss (O’Flaherty, 2007). The Synbone® cylinders were affixed to the torso of a mannequin at the glenohumeral joint (Figure 2B). The cylinders were secured to the torso by a ball of string and tape, simulating the humeral head and associate muscles at the joint. A small piece of foam was placed on the surface of the humeral head equivalent and surface of the torso to simulate the joint capsule, providing mobility and elasticity naturally seen in the glenohumeral joint of a living opponent. The torso was stabilised and secured to a table, at a height of 147.5 centimetres, to ensure accurate simulation of a face-to-face conflict situation between two individuals of similar height. The impact of each strike for each trial was recorded by SockWatch 2 impact indicators[2], placed superiorly on each analogue. The indicators are set to activate in the event the G-force of the impact exceeded a threshold of 50. For this research activated indicators were noted when the indicator turned red, meaning the force exceeded 50G. When strikes did not exceed 50G, the indicators did not turn red and were noted as failed.

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[2] For more information regarding ShockWatch visit: http://shockwatch.com/products/impact-and-tilt/impact-indicators Accessed: 28th September 2022

Table 4: List of strikes

Weapon Type	Analogue Type	Strike					
		Strike Number	Type	Angle/Movement	Skeletal Impact Location	Attacker Force Rating	ShockWatch Indicator Activation
Dirk	*Sus scrofa* A	1	Slash	Downward motion from left shoulder	Missed	Moderate	Failed
Dirk	*Sus scrofa* A	2	Slash	Downward motion from left shoulder	Ulna, midshaft diaphysis, lateral surface	Moderate/High	Failed
Dirk	*Sus scrofa* A	3	Thrust	Right to left motion at chest height with slight upward trajectory	Radius, midshaft diaphysis, medial surface	Moderate	Failed
Sword	*Sus scrofa* B	4	Slash	Downward motion from left shoulder	Ulna, proximal diaphysis, caudal surface	Low/Moderate	Failed
Sword	*Sus scrofa* B	5	Slash	Downward motion from left shoulder	Ulna, midshaft diaphysis, lateral surface	Moderate/High	Failed
Sword	*Sus scrofa* B	6	Slash	Downward motion from right shoulder	Radius, proximal diaphysis, medial surface	Moderate/High	Failed
Dirk	*Sus scrofa* C	7	Thrust	Right to left horizontal motion at chest height	Ulna, mid-diaphysis, caudal surface	High	Failed
Sword	*Sus scrofa* C	8	Slash	Upward motion from left hip	Missed	Moderate	Failed
Sword	*Sus scrofa* C	9	Slash	Upward motion from left hip	Radius, proximal diaphysis, cranial surface	High	Failed
Dirk	Synbone® A	10	Slash	Downward motion from left shoulder	Midshaft diaphysis, lateral surface	Moderate	Activated
Dirk	Synbone® A	11	Slash	Downward motion from left shoulder	Proximal diaphysis, lateral surface	Moderate	Activated
Sword	Synbone® B	12	Slash	Downward motion from left shoulder	Proximal diaphysis, lateral surface	Moderate	Activated
Sword	Synbone® B	13	Slash	Downward motion from left shoulder	Midshaft diaphysis, lateral surface	Moderate/High	Activated

Figure 2: Experimental set up for each human skeletal tissue analogue. (A) Animal analogue and (B) Synbone® cylinders (Photographed by author).

Osteological analysis of the cutmarks, was documented, identified and described using standard terminology for cutmark features (Figure 3) (Bartelink, Wiersema and Demaree, 2001; Byers, 2005; Kimmerle and Baraybar, 2008; Lewis, 2008; Downing, 2015). Both macroscopic and microscopic analyses were performed including metric and morphological assessment of the cutmarks. Morphological evaluation of the cutmarks followed standards developed by Lewis (2008) and Byers (2005), with metrical analysis following Lewis (2008). Analytical assessment and documentation of the cutmarks were conducted before and after soft tissue removal. Soft tissue removal was achieved through de-fleshing and maceration. De-fleshing was achieved through gross dissection, with maceration by water, heated to 85 degree Celsius, and biological washing powder. The Synbone® cylinders required little processing, removing the gelatine with hot water and latex skin by hand.

Microscopic analysis of the bone surface, margins, walls and floor of each cutmark was conducted using a Dino-Lite Pro (HR AD7013MZT) polarising digital microscope. Casts of the cutmarks were created following recommendations set out in Downing (2015) to facilitate further analysis.

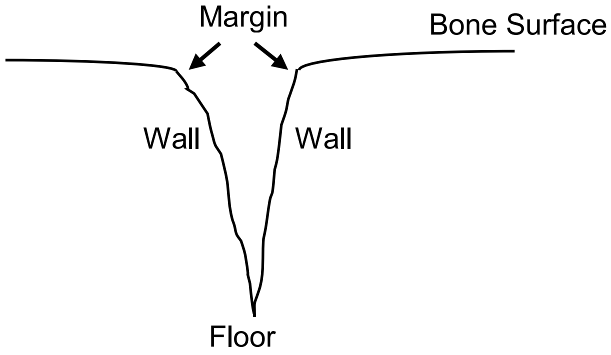

Figure 3: Cutmark terminology used to describe the cutmark features (adapted from Downing, 2015; Downing and Fibiger, 2017).

3. Results

Of the 13 strikes employed, 11 strikes produced skeletal damage. Strike 1 and strike 8 are considered 'missed' strikes as no skeletal damage was sustained; these strikes were not included in any further analysis.

3.1. Macroscopic Analysis

All strikes in this study created incision cutmarks to the soft tissue producing several features in the criteria developed by Byers (2005) for identification of SFT. All strikes produced a V-shape cross section and a length-width ratio consistent with incision type cutmarks. The depth of the cutmarks were characterised as shallow as all metric assessments of depth were under one centimetre. Vertical striations were observed in five of the 13 cutmarks produced. No hinge fractures were present typical of incision cutmarks; however, three strikes produced hairline fracture lines which can occur but are rare (Byers, 2005; Lewis, 2008). Wastage is defined as the fragments that can become detached from the main bone, three strikes produced no wastage, four strikes produced minimal wastage and four produced significant wastage.

The strikes performed in this study produced cutmarks characteristic of several weapon classes developed by Lewis (2008) including class I (Katana), class III (Broadsword) and class VI (Knife). Of the 13 strikes, elliptical shapes were produced in eight of the strikes typical of class III with the remaining three producing line shapes, typical of class VI. Unilateral flaking, where a piece of bone next to the cutmark breaks off, was a feature present in nine strikes with two strikes displaying no flaking, a typical feature of class I (Lewis, 2008). Additional features such as feathering (n=0), cracking (n=0), breakage (n=1) and shards (n=4) were present in a small number of cutmarks.

3.2. Microscopic Analysis

Microscopically, six of the strikes produced similar cutmarks, with straight defined floors, proximal walls and margins, and undefined irregular distal walls. Microscopically, strikes 3, 9 and 13 all produced straight defined floors, walls and margins with a smooth topography. Strikes 10 and 11 produced cutmarks with some distinctive morphology; the proximal wall of strike 10 produced an irregularity and strike 11 produced a curved distal wall.

3.3. Metrical Analysis

The measurements taken using the Dino-Lite software are indicated within table 4. The cutmarks sustained in this study were similar in length for both weapons, with some considerable overlap. The dirk produced both the longest cutmark at 17.6 mm and smallest cutmark at 3.4 mm. Cutmarks created by the sword were within the range of the dirk length measurements, with the longest cutmark measuring at 14 mm and the smallest at 7.9 mm. The remaining measurements, the width between the margins, the width of the floor and the depth were all very similar between both weapons with negligible differences in the measurement.

Table 5: Metrical Analysis of the cutmarks

Trait	**Strike 2**	**Strike 3**	**Strike 4**	**Strike 5**	**Strike 6**	**Strike 7**	**Strike 9**	**Strike 10**	**Strike 11**	**Strike 12**	**Strike 13**
Length	17.6	3.4*	10.2	12.4	7.9	4.9*	7.9	13.9	12.8	14.0	12.8
Width: Kerf Floor*	0.04	N/A	0.05 (min) 0.8 (max)	0.1 (min) 0.2 (max)	0.09 (min) 0.1 (max)	0.2	0.05 (min) 0.1 (max)	0.07 (min) 0.08 (max)	0.07 (min) 0.4 (max)	0.1	0.06 (min) 0.2 (max)
Width: Margins*	1.8 (min) 3.3 (max)	0.1 (min) 0.2 (max)	3.2	1.3 (min) 3.8 (max)	3.1 (min) 3.6 (max)	2.5 (min) 6.8 (max)	1.5 (min) 2.0 (max)	3.1 (min) 6.0 (max)	3.0 (min) 3.7 (max)	2.8 (min) 5.9 (max)	0.2 (min) 0.3 (max)
Depth	1.7	N/A	2.6	2.1	1.4	0.8	N/A	2.4	2.3	1.9	N/A

**Measurements taken with Dino-Lite*

4. Discussion

The aim of this study was to observe any distinguishing morphologies and metrical differences between the cutmarks sustained by the BA sword and BA dirk. Due to the failure of the dirk during previous studies, a comparative analysis between the two weapons has not been conducted in other studies (Faulkner-Jones, 2016; Downing and Fibiger, 2017). The macroscopic, microscopic and metrical analysis from this study demonstrates the BA sword and the BA dirk cannot be distinguished.

4.1. Experimental Set-up

The primary aims of this study was to observe the macroscopic and microscopic differences of the cutmarks sustained by the BA weapons. In this study, the suitability of the two human skeletal analogues, was examined to reproduce a replicable experimental set-up suitable for examining SFT in a combat context. Numerous studies utilise mechanisms for delivering the blows, these mechanisms are constructed to hold sharp force implements and control the movement of the weapon by producing the impulsive force and energy needed to produce SFT (e.g. Alunni-Perret et al 2005; Lynn and Fairgrieve 2009; Bartelink et al 2001; Shaw et al 2011; Cerutti et al 2014). These studies allow for precise examination of the angle and force used to produce the cutmarks. A number of studies, however, have utilised real life or an actualistic set up to produce SFT (e.g. Molloy 2007; Lewis 2008; Donnellan et al 2013; Faulkner-Jones 2016). Unlike studies employing mechanisms to create SFT, studies utilising human agency allow for observation of variability and variation of factors such as angle and force found in real combat situations (Anderson, 2011). In previous studies, the experience attackers have with historical weapons has varied, with few authors trained specifically in the weapons used in their research (e.g. Molloy 2004, 2007). Many authors have the knowledge of how these weapons may have been used but realistically have little to no practical experience in handling the weapons themselves (e.g. Faulkner-Jones 2016; Downing and Fibiger 2017). For this reason, this study chose to employ an attacker experienced in handling historical weapons to ensure not only the variability of SFT injuries observed in the BA was replicated in the present study, but the weapons were used accurately. The angle and force of the strike in this experiment, therefore, was recorded using a camera, a ShockWatch indicator and a rating provided by the attacker.

While a measurement of force is not utilised in the identification of SFT and therefore not a primary source of data, a reading was still taken as an additional source of data to observe if the force of the attack influenced the morphologies between the BA sword and dirk. The measurement of force in this study, as stated, was measured using a ShockWatch indicator, a device predominantly used in monitoring packages in transport. The ShockWatch was chosen chiefly for its simplicity of use, despite only providing a minimum and maximum rating of force. While easy in application, this method of measuring force was only applicable during strikes on the Synbone analogues, as the indicators failed during strikes performed against the *Sus scrofa* materials. This is potentially due to the amount of soft tissue present on the *Sus scrofa* remains compared to the Synbone cylinders. The malfunction of the ShockWatch in the *Sus scrofa* trails should not be unexpected as the ShockWatch is designed to monitor mishandling of packages, not as a measurement of force in experimental weapons testing. Therefore, an alternative method of measuring force should be implemented in future SFT research using an animal analogue, such as an impact force measurement system suitably modified for the experiment set up.

The experimental set up of the *Sus scrofa* trials involved hoisting the analogue to approximate shoulder height of the attacker, securing the material to the floor to introduce tension and resistance seen naturally in a living individual. While this set up allowed for some natural movement of the *Sus scrofa* materials and allowed for the compliance to health and safety standards, it did not replicate complete natural movement and resistance seen in an individual. The experimental set up for the Synbone trials differed significantly from the *Sus scrofa* trials. While this experimental set up is more anatomically correct, there are some discrepancies that may affect the SFT injuries sustained. For example, the Synbone did not include any soft tissue analogue, only the latex skin representing the periosteum. In previous studies utilising Synbone, artificial skin has been utilised to improve reproduction of ballistic and BFT wound morphology (Thali *et al.*, 2002; Thali, Kneubuehl and Dirnhofer, 2002). Moreover, soft tissue models have been utilised in previous SFT research, for example Downing and Fibiger (2017) utilised towels to simulate soft tissue of the tibia. The lack of soft tissue therefore may have influenced the morphology of the SFT sustained. Furthermore, while the biomechanics of the glenohumeral joint was replicated during experimentation, the diameter of the simulated humeral head was bigger than normal human variation (Bass, 1995). This would not have influenced the SFT sustained during the experiment, but future research should endeavour to ensure accurate simulation of the glenohumeral joint utilising an appropriate analogue with an appropriate diameter measurement.

Overall, both experimental designs can be replicated, as all the materials utilised during the experiment such as the sandbag, rope, tape (packing and specialist), the ball of string, mannequin torso and ShockWatch indicators can be easily obtained for little expense. The *Sus scrofa* analogues were obtained from a local butcher for a small fee with Synbone purchased online.

4.2. Weapon Classification

Weapons can be classified depending on the similarity of morphological characteristics (Houck, 1998; Alunni-Perret *et al.*, 2005; Lewis, 2008). The BA sword used in this experiment can be classified into Lewis' (2008) class III as it is most similar in shape to a broadsword and class IV based on the similarity in sword's size to the Samburu. The dirk, on the other hand, is classified in class VI the knife class (Lewis, 2008). In previous research, cutmarks produced by the sword classes should produce cutmarks morphologically different to those sustained from knife classes. BA swords, however, have exhibited cutmarks that are identified as characteristic of the knife class (Lewis, 2008; Downing and Fibiger, 2017). Macroscopically, the results of this study support the findings from Downing and Fibiger (2017), that the BA sword can produce cutmarks characteristic of the knife class. Furthermore, this study demonstrate that the BA dirk can exhibit the cutmarks characteristic of sword classes. From macroscopic observation in the present study, it is clear there are two types of cutmarks present; those that are characteristic of sword class and those that are characteristic of the knife class (Figure 4). The results from this study have demonstrated that both the dirk and sword can produce cutmarks from both class types, regardless of which type of strike was employed. Upon microscopic observation, regardless of the weapon class, the cutmarks did not exhibit any distinguishable morphologies to differentiate between cutmarks sustained by the BA sword and BA dirk (Table 5).

When compared to cutmarks observed from BA sites in the archaeological record, the cutmarks created in the current study exhibited similar morphological features. For example, the cutmarks described found at the Early BA Mogou site are described as linear incisions, having a narrow V-shaped cross section and very little damage (Dittmar *et al.*, 2019). Of the 11 cutmarks produced in the current study, three cutmarks also produce these features. Dittmar and colleagues hypothesise that the cutmarks from Mogou were likely created by a thin bladed weapon such as a sword or dagger, which is supported by the results of this study. Similarly, at the Early BA site Tollense Valley in Germany, the skeletal injuries here also exhibit these features (Brinker *et al.*, 2017). It is possible that the cutmarks present at Mogou and Tollense Valley, were produced by a thin sharp instrument used in a slashing motion to create these incised cutmarks. Further evidence is observed at the Tollense Valley site of weapons being used in a downward slashing action, as one sword injury visible on the scapula of one of the individuals demonstrated the cutmark had one curved wall and one smooth wall (Brinker *et al.*, 2017). These features were also present in strike 11 of this study, which was produced by the MBA dirk, demonstrating that weapons such as swords and dirks can be utilised in the same way.

Skeletal SFT present at other BA sites such as Titriş Höyük (Erdal, 2012) and Ballabio (Pasini *et al.*, 2019) demonstrate that SFT produced by bladed weapons are variable. For example, the SFT present at Titriş Höyük are characteristic of cleft and puncture injuries, likely produced by weapons such as metal battle axes, daggers and spears (Erdal, 2012). The punctured wounds are likely the produce of weapons such as the spears and daggers used in a stabbing motion, producing elliptical or oval shapes. While the majority of the cutmark in this study exhibited elliptical shapes, these shapes are likely due to the additional damage sustained to the cutmark such as flaking. The sharp force injuries witnessed at Ballabio, exhibited square shaped injuries with straight margins and a lack of additional damage (Pasini *et al.*, 2019). The authors suggest this wound was created by a perforating weapon or a weapon-like object with sharp edges such an axe or heavy sword. This indicates that force is a key factor in the morphology produced.

It is evident there are metrical changes between the BA sword and dirk used in this experiment. The BA sword is longer, heavier and thinner in both the medially-laterally and superiorly-inferiorly aspects in comparison to the dirk which is shorter in length, lighter and wider. Despite these metrical differences, this was not replicated in the cutmarks. There is significant overlap in both measurements of length and width. These results are to be expected as previous studies demonstrated that weapons cannot be identified on metric analysis alone due to other influencing factors such as the angle of the blade (Bartelink, Wiersema and Demaree, 2001; Cerutti *et al.*, 2014).

In comparison to cutmarks found in the BA archaeological record, the cutmarks created in this study are considerably smaller. For example, the SFT associated with skeletal remains from Titriş Höyük, Anatolia, averaged almost twice the length and width than those created in this study (Erdal, 2012). Despite the cutmarks in this study being created manually by an ‘attacker’, the force may not be synonymous to real-world situations as there were concerns that the weapons under experimentation would become irreparably damaged if too much force was implemented by the ‘attacker’. Such irreparable damage would have potential halted any further investigation. Another possible explanation for the difference in cutmark sizes between those found in the archaeological record and those created experimentally is that the cutmarks were likely created by swords as these would have been broader and able to cause deeper wounds in both the soft tissue and skeletal tissue than the dirks.

Table 6: Observable macroscopic and microscopic differences between specific traits associated with sword and dirk cutmarks.

Trait	BA Sword Cutmarks	BA Dirk Cutmarks
Shape	Ellipses and line	Ellipses and line
Floor	Straight, narrow and V-shaped	Straight, narrow and V-shaped
Cross Section Shape	V-shaped cross section	V-shaped cross section
Walls	Walls are small and straight, producing. One wall exhibits smooth topography the other is irregular.	Walls are small and straight, producing. One wall exhibits smooth topography the other is irregular.
Damage	One side of the bone surface can show a higher amount of damage than the other, dependent on the shape produced.	One side of the bone surface can show a higher amount of damage than the other, dependent on the shape produced.

4.4. Weapon Capabilities

It is evident that, despite differences in the blade length and width of these weapons; both the dirk and sword blades are morphologically similar. Both weapons have a double edge blade with no serrations. Moreover, the thickness of the cutting edge is very similar with only 0.5mm difference between the sword and dirk. The only morphological difference between the weapons was a prominent raised ridge extending the midline of the entire length of the dirk blade. The fact that both weapons can create cutmarks that are macroscopically and microscopically very similar suggests both weapons could have been utilised in the same manner during conflict, capable of producing skeletal damage without sustaining irreparable damage (Faulkner-Jones, 2016; Downing and Fibiger, 2017).

Replica dirks in previous studies have sustained damage to the dirk blade and the hafting plate following a stabbing blow and splintering damage to the butt of the hilt following a blunt force blow (Faulkner-Jones, 2016; Downing and Fibiger, 2017). The damage sustained on the model dirks replicated damage observed on the original artefact, suggesting BA dirks were not capable of inflicting fatal injury by SFT (Faulkner-Jones, 2016). In the current study, however, damage was sustained but it did not impede further strikes being conducted during the experiment, hence demonstrating BA dirks are capable of not only inflicting potentially fatal skeletal SFT without sustaining damage, but potentially fatal injuries to the soft tissue.

Therefore, the lack of damage sustained to the dirk from the strikes supports the argument that the dirk can be a functional and efficient weapon in BA combat. This was the reason porcine materials were used alongside the synthetic Synbone® anlaogues. As while the bone structure of pigs differs from human skeletal tissue at the microscopic level (Schotsmans *et al.*, 2014) the analogues provided additional data should the Synbone® analogues had caused damage to the weapons the dirk, potentially halting the experiment and limiting data collection.

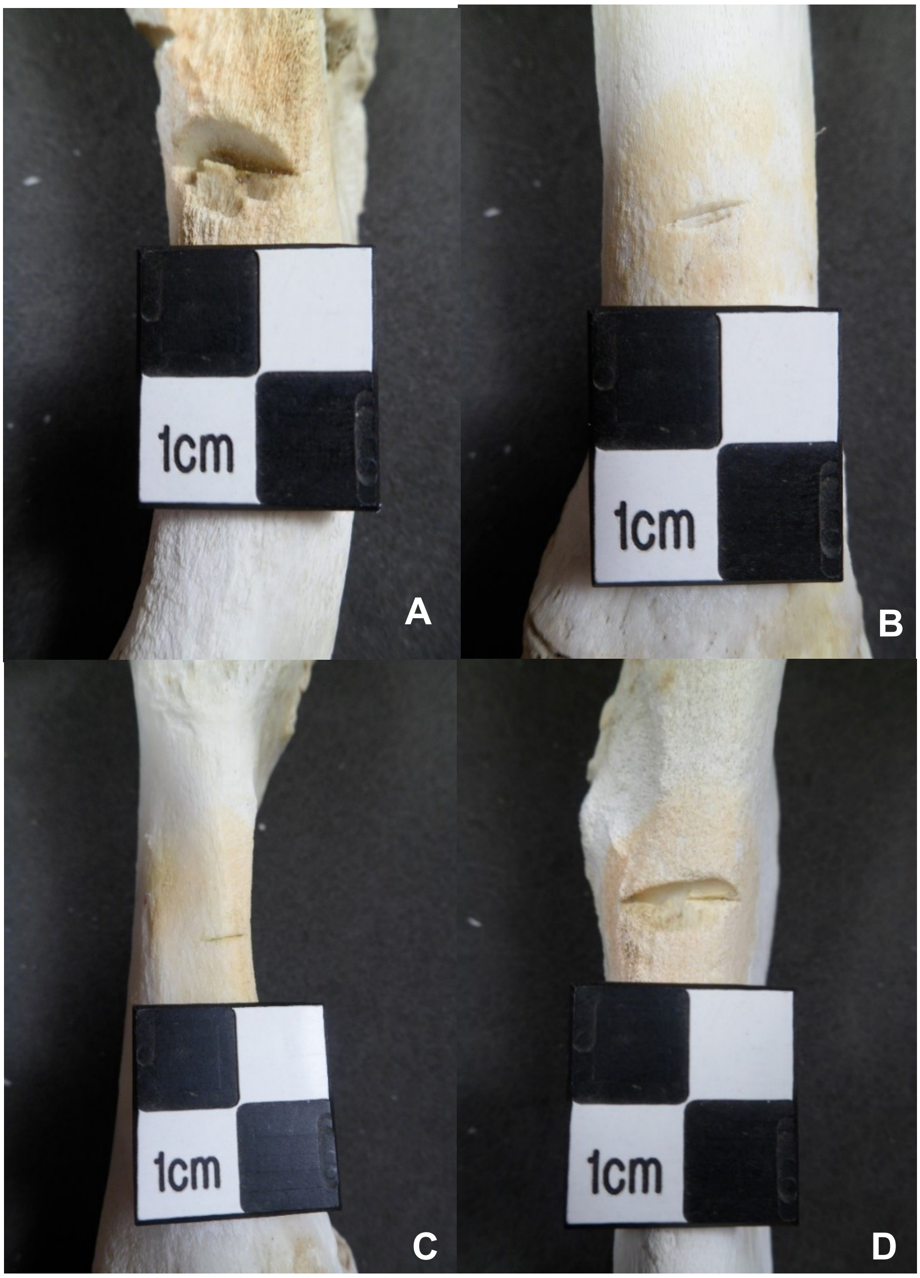

Figure 4: Cutmarks sustained by BA Sword. (A) Strike 5 demonstrating typical sword trauma and (B) Strike 9 demonstrating typical knife trauma. Cutmarks sustained by BA Dirk. (C) Strike 3 demonstrating typical knife trauma and (D) Strike 7 demonstrating typical sword trauma

4.4. Recommendations for further study

This study provides a crucial step in experimental BA research, by demonstrating current methods of weapon class identification may not be appropriate for identification of SFT caused by BA swords and dirks. Further research investigating SFT of BA weapons, especially the BA sword and dirk, should focus on using more strikes to not only allow for performance of statistical analysis but for observation of any variation produced in the cutmark morphology that can allow for differentiation of cutmarks produced. By increasing the number of strikes, evaluation of atypical cutmark morphology can be more easily identified. The results can be used to produce standards for identification and interpretation of SFT sustained by BA weapons. Furthermore, employing additional microscopic methods for analysis of microscopic morphologies such as computed tomography (CT), scanning electron microscopy (SEM) and 3D microscopy should be implemented (Alunni-Perret *et al.*, 2005; Bello and Soligo, 2008). The higher magnification power may allow for some additional details that were not observed during this study.

In addition to further experimenal research desigined to identify morphological differences between the BA sword and dirk, an additional line of research should include the creation of a centralised database. This centralised database should aim to collate all known BA cutmarks found not only in the archaeological record but within experimental research. The database should contain all information pertaining to the morphological features present, both at the macroscopic and microscopic level, and metrics of the cutmark. This will allow for standardisation of terminology, permitting researchers to directly and critically compare cutmark morphology. Furthermore, the database will provide researchers with the ability to identify existing and new diagnostic features for identifying BA weapons from skeletal SFT with ease across a large sample, formulating new and improved classification systems. In the future the database should include a repository for photographs and visualisations (e.g. 3-dimensional models) which would not only aid in visualisation of cutmark morphology but in time could be used for geometric morphometric analysis. Geometric morphometrics is a statistical analysis that uses landmarks to quantify shape (Zelditch *et al.*, 2012). This has already been used in archaeological research to analyse cutmark morphology and it stands to reason that it can be applied to cutmarks sustained by Bronze Age weapons (Mate-González *et al.*, 2015; Courtenay *et al.*, 2019)

5. Conclusion

Cutmark analysis of BA weaponry is a topic that is relatively unexplored in the literature. In previous research, macroscopic and microscopic cutmark analysis has demonstrated the BA sword can produce morphologies similar to that of knife class weapons (Downing and Fibiger, 2017). Moreover, due to damage sustained in experimentation macroscopic and microscopic analysis of cutmarks sustained by the BA dirk has been prevented (Faulkner-Jones, 2016; Downing and Fibiger, 2017). Analysis has further demonstrated Synbone®, may not be a suitable analogue for examination of SFT, with Synbone® not displaying all microscopic features for identification of the type of SFT sustained (Byers, 2005; Downing and Fibiger, 2017). Thus, the purpose of this study was to observe if cutmarks sustained by the BA sword and dirk could be distinguished macroscopically and microscopically. The analysis of cutmarks sustained by the BA sword in the present study support previous research, that the BA sword can produce cutmarks similar in morphology to cutmarks sustained by a knife class weapon in previous studies. Additionally, the cutmarks sustained by the BA dirk in the present study demonstrate the dirk can produce morphologies similar to cutmarks sustained by sword class weapons. Microscopically, analysis of both the BA sword and BA dirk cutmarks exhibited no distinguishing morphologies. Furthermore, there is considerable overlap in the metrical analysis of the cutmarks sustained by both weapons, in length, depth and width. It is therefore clear cutmarks sustained by the BA sword and dirk cannot be distinguished macroscopically, microscopically or metrically. The results from this present study demonstrate current standards for identification of weapon class (Lewis, 2008) are not appropriate for BA weaponry. Further research should aim to provide a more suited classification system for diagnosing weapon class specifically for distinguishing the BA sword and dirk.

CRediT authorship contribution statement

Rebecca L.J. Strong: Conceptualisation, Methodology Investigation, Writing – Original Draft.

Linda Fibiger: Conceptualisation, Writing – Review and Editing, Supervision**.**

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Statements and Declarations

The authors declare no conflict of interests. All guidance and governance for use of animal material was followed. Ethical approval was given by History, Classics and Archaeology Department, Edinburgh University.

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