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Identifying sword marks on bone: criteria for distinguishing between cut marks made by different classes of bladed weapons

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Abstract

Swords have been one of the major weapons used in violent conflicts for much of human history. Certain archaeological situations, especially those dealing with the recovery and analysis of battle casualties, may raise questions about what type(s) of bladed weapon was used in a particular conflict (e.g., the battle of Kamakura, Japan, AD 1333; the battle of Wisby, Sweden, AD 1361; the battle of Towton, England, AD 1461). Little work has been done, however, on developing criteria to differentiate sword cut marks from other types of cut marks, or to distinguish between marks created by different sword types. To develop such criteria, bovine tibiae ($n = 7$) were struck using six different types of bladed weapon and the resulting marks ($n = 92$) were analyzed. Eight traits describing the morphology of the cut mark – such as shape, the presence and unilateral/bilateral state of flaking and feathering, the presence of bone shards, associated breaks, etc. – are defined and related to blade type used. Sword marks were found to be easily distinguishable from knife marks. The variation in marks made by different sword types is significantly correlated with differences in blade weight ($p < 0.0001$), grip ($p < 0.0113$), and sharpness ($p \leq 0.0179$). The criteria and analyses developed and implemented in this study will be of use to researchers in forensics and osteoarchaeology who want to infer bladed weapon type from marks on bones.

Keywords: Sword; Cut mark; Knife; Taphonomy; Forensics; Warfare

1. Introduction

Most studies of cut marks on bones have focused on those made by small tools, such as stone or metal knives (Bromage and Boyde, 1984; Greenfield, 1999; Houck, 1998; Lyman, 1987; Toth, 1989). Marks made by larger tools, such as swords, are relatively understudied (but see Karasulas, 2004; Shackley, 1986; Wenham, 1989), even though swords are fundamentally a different type of tool from knives: they are longer, heavier, and are wielded in a different manner in inter-human confrontations. Thus it is unclear whether cut marks made by swords differ systematically from those made by knives, and whether specifics of those marks could be used to infer the category of sword used (e.g., an 'Arabian scimitar' versus a 'European broadsword' versus 'Japanese katana').

Certain archaeological situations, especially the recovery and analysis of battle casualties (Carman, 1997), may raise questions as to what type(s) of bladed weapon(s) was used and how. Examples include the remains recovered from the battle of Kamakura (Japan, AD 1333), the battle of Wisby (Gotland, Sweden, AD 1361) and the battle of Towton (Yorkshire, England, AD 1461) as well as of specific historical figures such as Spanish conquistador Francisco Pizzaro (Karasulas, 2004 and references therein). However, no clear criteria exist for inferring bladed weapon type used based on the marks left on bones.

The first goal of this study is to discern to what extent perimortem sword wounds on bones can be differentiated from metal knife marks. The second goal is to evaluate whether different classes (i.e. different shapes and sizes) of swords leave different kinds of marks, and whether criteria exist that allow

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the reliable inference of sword type from the morphology of the mark. These questions were addressed via experimentation by generating sword and knife marks on bovine ("cow") tibiae.

There are effectively two kinds of weapon-mark investigations available in the literature: specific case studies and general experimental studies. In specific case studies, a weapon is recovered that (based on other lines of evidence) is suspected to have made the marks on a particular victim. This circumstance is rare in forensic or archaeological situations (see Supplementary Text). To interpret marks on bones where no suspected weapon is present, experimental studies are needed to identify characteristics of marks that may be diagnostic of the general kind of weapon used. Much work has focused on knife marks (see Supplementary Text and references therein). Two studies have tried to develop criteria for differentiating sword marks on bones from other types of wounds via experimentation. Wenham (1989) attempts to distinguish sword (type unspecified, but presumably a European broadsword) from axe marks in a sample of six archaeological skeletons with 38 marks, and suggests criteria for making that distinction. These criteria are said to have been "tested by experimental cutting of bone by a variety of blades and were found to be valid" (Wenham, 1989, p. 127), but no details regarding the experimentation are given and the illustrations are limited (three photos of axe marks, one SEM of a sword mark). Wenham attempted to associate characteristics of the sword and axe marks with weapon properties, but only at a superficial level and by comparison with archaeological specimens. This work is a good first step, but more controlled experiments need to be performed using a wider range of weapon types.

More recently, Karasulas (2004) performed an experimental study to try to address what happened at the battle of Kamakura (Japan, AD 1333). The 65 sword marks on 26 out of 275 (9%) of the victims' crania were originally interpreted as indicating the use of light swords by combatants closely following the traditional warrior code of honor (Shackley, 1986). In order to develop criteria to use in predicting sword type from those cut marks, Karasulas (2004) struck cow pelves from standing and horse-mounted positions using three different katanas. Based on the results, it was instead argued that the Kamakura victims were poorly armed and generally dispatched by horse-mounted personnel with long pole arms (*naginata*), not necessarily following the traditional warrior code (Karasulas, 2004). Little specific information about the marks was reported by Karasulas (2004), and no general criteria were developed for distinguishing sword marks.

Some recent forensic work has focused on large bladed weapons, but as used for dismemberment rather than combat. Humphrey and Hutchinson (2001) describe analyzes of bone 'hacking' trauma made by a machete, a cleaver, and an axe on partially fleshed porcine limb segments ($n = 58$ marks on 28 bones). Their results indicate that the three different classes of 'hacking' tool marks could be differentiated based on size, shape, and presence of breakage associated with the different classes' cut marks (Humphrey and Hutchinson, 2001). Subsequent work on the same cut mark surfaces using SEM showed that the weapons used to make the marks can be identified to class and possibly individual (Tucker et al., 2001). Alunni-Perret et al. (2005) compared experimental knife marks ($n = 15$) to axe marks ($n = 15$) on defleshed human bone. They describe in detail how axe marks are a combination of smooth cut mark walls indicative of a sharp blade, as well as lateral pushing back of adjacent bone and other irregularities indicative of a blunt force mechanism (Alunni-Perret et al., 2005), but it is unclear how the absence of flesh on the bones may have influenced the results. These studies provide useful data regarding dismemberment, but fall short of addressing questions of inferring sword type from mark morphology: they did not actually investigate swords per se or consider combat/attack marks.

2. Materials and methods

This study used six different bladed weapons (Fig. S1): a Japanese-style katana, an Arabian-style scimitar, a "kris-blade" (wavy blade) broadsword, a Samburu short sword, a machete, and a hunting knife. All weapons were purchased commercially in the United States except the Samburu sword, which was bought from a traditional blacksmith in Maralal, Kenya.

Measurements and indices describing weapon morphology, such as blade length and height, weight, curvature index, and sharpness index are defined and described in the Supplementary Text, illustrated in Figs. S2 and S3, and listed in

Table 1
Weapon characteristics

Representative	Class I Katana	Class II Scimitar	Class III Broadsword	Class IV Samburu short	Class V Machete	Class VI Knife
Total length	96.5	88.9	85.1	50.8	57.2	22.4
Blade length	73.6	60.9	67.3	34.3	45.7	11.4
Blade height	2.59	11.75	3.67	3.83	5.74	2.5
Edge height	0.265	0.65	0.14	0.15	0.16	0.1
Sup. edge width	0.17	0.3	0.17	0.25	0.2	0.1
Weight	0.8	2.8	1.3	0.35	0.41	0.14
Curvature index	0.04	0.14	0.01	0.055	0.056	0.14
Sharpness index	1.56	2.17	0.82	0.6	0.8	1
Handedness	2	2	2	1	1	1

All linear measurements in centimeters, all weights in kilograms. See Supplementary Text for definition of measurements.

Table 1. Each weapon used in this study is considered to represent an overall class of weapons that share its basic morphology (Table 1). For example, though the word katana refers to a specific type of sword produced by a particular culture and area, it is used here to represent all swords that are lightly curved, thinly bladed, gripped with two hands, etc. For this reason the class names are capitalized, as they refer not to individual weapons but to the range of weapons within that particular class.

The hindlimbs of domestic cattle (*Bos taurus*) were used as a proxy for human bone and cartilage (Fig. S4). The sample consisted of seven hindlimb segments, from seven adult/subadult individuals of unknown sex. These elements were chosen to approximate human limbs, which are highly likely to be struck with a sword in inter-human confrontation. Between 1 and 2 cm of flesh was present on the bone surfaces struck during modification, in an attempt to accurately represent the impact of a sword on a living organism. The potential for differences between human and bovine bones to affect the applicability of results is limited given general bone microstructure similarity across taxa (Houck, 1998, p. 421) and the use of bovine bone or other proxies for human bone is common (Houck, 1998; Humphrey and Hutchinson, 2001; Karasulas, 2004; Tucker et al., 2001; Wenham, 1989; White, 1992).

The hindlimbs were positioned on a shock-absorbing cushion and immobilized with a cord (Fig. S5), so that the specimen would be stable yet still somewhat mobile, as would the limb of a living person. Every effort was made to strike the specimens in a uniform fashion regardless of weapon type (See Supplementary Text for more detailed description of striking procedure.). An average of 15 marks (range: 10–24) were made on each specimen (total of 92). If a bone broke during modification, no further modification was made after breakage. After striking, the hindlimbs were defleshed by boiling (Tucker et al., 2001), and air-dried under full sun for 8 h. Digital photographs were taken of each modification using the methods of Gilbert and Richards (2000).

Standard terms for cut mark morphology are identified here and used throughout the following descriptions. As a blade damages a bone, it contacts the surface, passes through the bone tissue, and comes to rest at a particular depth. The linear indentation of the blades' final depth can be identified as the 'kerf', or 'floor' of the cut mark (Fig. 1). The bone tissue between the kerf and the exterior surface of the bone can be identified as the walls of a cut mark (Fig. 1). It is on this wall surface that the lamellar rings of bone are exposed, and upon which microscopic scratches and indentations are left. The area on the exterior surface of the bone adjacent to the kerf and walls can be identified as the sides of a cut mark (Fig. 1).

Metric and non-metric observations were made on all cut marks in the form of eight traits developed for this study, which are cut mark Length (Trait 1) and Shape (Trait 2); the presence of bone Feathering (Trait 3) and Flaking (Trait 4) damage to the sides of a mark; Cracking (Trait 5) of the bone through the mark; Breakage (Trait 6) of the bone itself; the presence of bone Shards (Trait 7) in the mark; and the Aspect (Trait 8), or angle of entry of the weapon into the bone surface. A detailed key was created that describes and illustrates all of the traits and their possible states, and provides specific instructions for their scoring. This key, as well as all of the raw data (in database form), is included in the Supplementary Material.

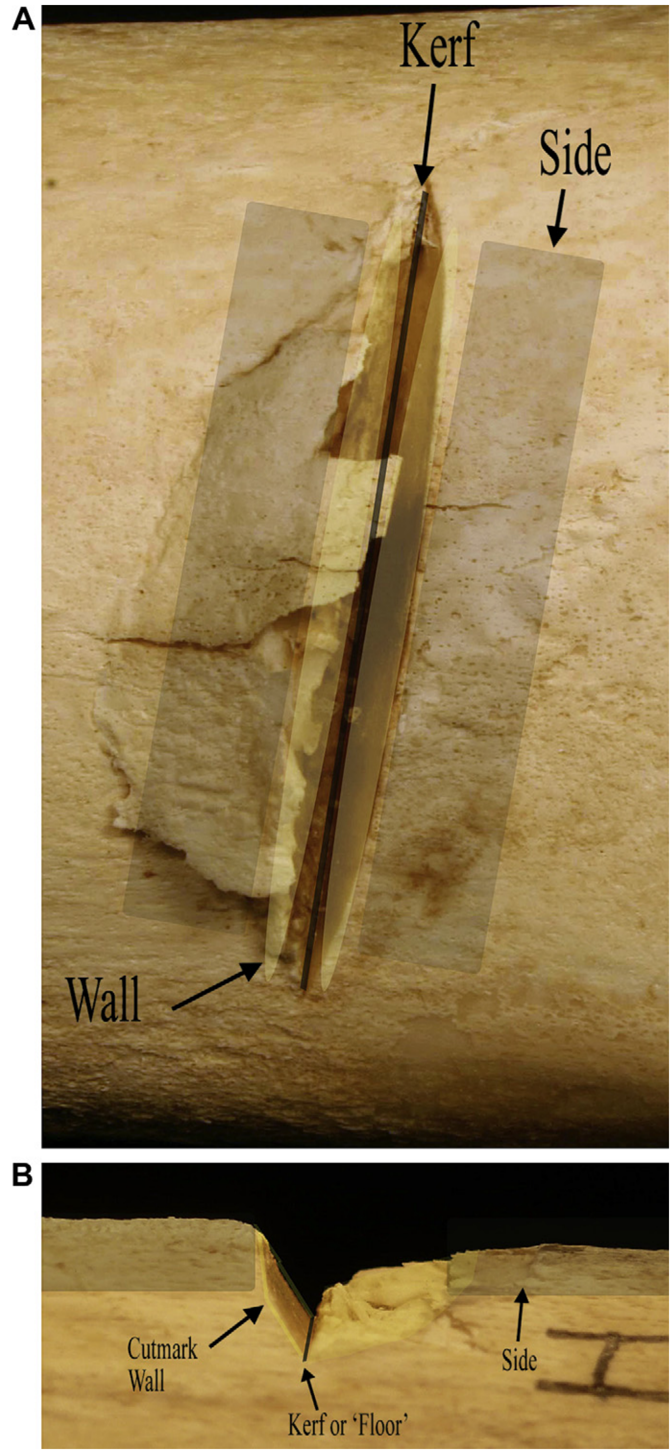

Fig. 1. Katana marks in superior (A) and lateral (B) views showing cut mark terms.

The analytical procedure followed here is a combination of general morphological description of cut mark morphology, followed by the more detailed recording of the specific character states for each abovementioned trait. Each specimen was examined with the naked eye, or at low magnification when necessary, under harsh incandescent illumination. Cut marks, and especially sword marks, are large enough to be seen in great detail with a hand lens, not requiring the use of SEM or other methods (Blumenschine et al., 1996; White, 1992). This procedure was used in order to strike a balance between describing as much of the context and specific details associated with each cut mark, and creating a set of repeatable observations upon which statistical analysis and future comparisons with other studies can be based (White, 1992, p. 108–109). This is useful for comparing complex configurations of two- and three-dimensional characters like sword and knife marks. For example, both kinds of marks can display feathering of bone on one side of a cut mark, but the feathering of a knife mark can look completely different from a sword mark. By performing only general description *or* trait counts, the potential to miss important opportunities for comparison and analysis is created.

Both intra- and interobserver errors were quantified to evaluate how repeatably these variables could be scored (cf. Blumenschine et al., 1996). Intra- and interobserver error methods are described in the Supplementary Text, and consistencies for each trait can be found in Tables S1 and S2, respectively. Intraobserver consistency was 88% (range of 71–99%), and interobserver consistency was 76% (range of 40–98%). Some traits, such as Shape, Feathering, and Shards, were not scored very consistently between observers, which suggested that improved descriptions were needed. This motivated the development of the detailed Key (online Supplementary Material), so it is hoped that the interobserver consistencies reported in Table S2 are minimums, as they were done without benefit of the Key. The second round of observations were used only for error calculations; all data reported below were from the first bout of observations.

Statistical tests were performed with JMP v. 5.0 for Macintosh. Sword and cut mark characteristics were statistically compared via χ^2 analysis and cluster analysis. When possible, Fisher's exact probabilities are reported; otherwise the normal chi square probability is given. Because the data violated the assumptions of parametric statistical analysis, the medians of the sword mark character counts were used for the cluster analysis instead of the mean.

3. Results

3.1. Distinguishing sword marks from knife marks

A qualitative comparison was made between the 68 sword marks and the 24 knife marks. A number of criteria were identified that clearly distinguish marks made by swords from marks made by a knife. The average mark length is relatively consistent across sword classes (22.9–24.2 mm), while knife marks are much shorter (mean of 12.7 mm). This suggests that amongst sword marks, the length of the mark is not diagnostic of weapon class used, and perhaps is instead related to the diameter of the bone. The sword marks were wide, deep, and displayed large amounts of damage to the sides of the mark, and the kerfs were straight. The cut was either deep and narrow or deep and wide depending on the nature of the sword blade. Some sword classes with a low sharpness index (e.g., Samburu sword or Machete) created marks with a flat-bottomed, ⊔-shaped profile (c.f. Greenfield, 1999).

Fig. 2. Typical knife mark.

Sword marks in cross-section most often display one curved, smooth wall and one straighter, sometimes roughened wall (Fig. 1), in contrast to the consistent ‘V’ shape of most metal knife marks (Greenfield, 1999). Wenham (1989) referred to the smooth, curved wall as the ‘obtuse angled’ side, and the other as the ‘acute angled’ side. This apparently unique cross-sectional shape of sword marks is most likely due to the downward direction of the force from a sword strike, as compared to the forward, slashing motion of a knife strike. This situation is analogous to cutting through a block of cheese: the resistance of the cheese block to the blade slowly pushes the blade towards the outside of the block, so that the slice of cheese is much thinner at the bottom than the top.

In sword marks, the wall and side opposite from the smooth, curved wall was more likely to contain traces of damage such as flaking or feathering. This conforms to observations by Wenham (1989: p. 131), in which he describes the

Table 2
Scoring of marks by type of weapon used

Trait	State	Katana Class I	Scimitar Class II	Broadsword Class III	Samburu short sword Class IV	Machete Class V	Knife Class VI
1. Length	n/a	23.7	24.2	24.0	22.9	22.9	12.7
2. Shape	Pentagon	1 (6%)				1 (7%)	
	Circle	1 (6%)	1 (7%)	2 (20%)	1 (8%)	5 (36%)	
	Triangle	2 (11%)	1 (7%)	1 (10%)	1 (8%)	2 (14%)	5 (21%)
	Line	1 (6%)	3 (21%)		2 (17%)	1 (7%)	18 (75%)
	Ellipse	13 (72%)	7 (50%)	5 (50%)	5 (42%)	3 (21%)	1 (4%)
	Square						
	Rectangle		2 (14%)	1 (10%)		1 (7%)	
	Rhombus				2 (17%)	1 (7%)	
	Trapezoid			1 (10%)	1 (8%)		
3. Feathering	Unilateral	11 (61%)	4 (29%)	1 (10%)	6 (50%)	5 (36%)	5 (21%)
	Bilateral	2 (11%)	4 (29%)	5 (50%)	6 (50%)	5 (36%)	
4. Flaking	Unilateral	15 (83%)	7 (50%)	4 (40%)	7 (58%)	10 (71%)	
	Bilateral		5 (36%)	5 (50%)	5 (42%)	4 (29%)	5 (21%)
5. Cracking		4 (22%)	10 (71%)	1 (10%)	6 (50%)	2 (14%)	
6. Breakage			6 (43%)	3 (30%)			
7. Shards			3 (21%)				
8. Aspect	Glancing	3 (17%)	2 (14%)	4 (40%)	2 (17%)	5 (36%)	1 (4%)
	Perpendicular	15 (83%)	12 (86%)	6 (60%)	10 (83%)	9 (64%)	23 (96%)
Total	# Of marks	18	14	10	12	14	24

Length is in millimeters.
Note: Class VI cut mark length is an average of both linear (average 14.6 mm) and puncture (average 3.0 mm) knife marks.

detachment of bone flakes from the acute angled side (the opposite side of the smooth, curved wall). The similarity between Wenham's (1989) observations, made on cranial sword marks, and those of the present study, using diaphyseal sword marks, suggest that sword mark morphology is consistent across different skeletal elements.

The knife marks (Fig. 2) produced in this study, on the other hand, are long and narrow, with little damage to the sides of the cut mark, and can display a meandering of the kerf. The meandering kerf of the knife is due to the fact that these blades are crossing the surface of the bone laterally, by a stabbing or cutting motion, and therefore are free to change direction during the course of the cut. Close inspection of the knife marks reveals small, 'whispy' damage to the surface of the sides of the cut mark, which was classified as Feathering, and is usually unilaterally present. This 'feathering' is qualitatively different than sword mark Feathering, as it is the result of a stabbing motion and therefore sweeps laterally in the direction of the cut mark (Fig. S7). This feature is therefore useful in determining the directionality of the stab. Otherwise, the knife marks created here are similar to those described elsewhere (Greenfield, 1999) and are dissimilar to sword marks. The observed differences between sword marks and knife marks can be summarized as follows: (a) swords produce cut marks that are deep, wide, with a straight kerf and damage on the sides of the mark, whereas knives produce shallow, narrow and often meandering kerfs and relatively little damage to the sides of the mark; (b) the kerf floor of sword marks can be either narrow and V-shaped or broader, ⊔ shaped with a flat bottom, whereas knife mark kerf floors are always V-shaped; (c) sword marks, when viewed in profile, tend to have one smooth, vertically curved wall, and one rough, vertically straight wall, forming a combined 'V' and 'U' shaped cross-section, whereas knife mark walls are small and V-shaped; (d) sword marks show damage (or higher amounts of damage) on the side of the cut mark opposite to the smooth, curved wall.

In sum, based solely on macroscopic visual comparison, it appears to be generally possible to distinguish cut marks created by large bladed weapons used in a hacking or chopping

Table 3
Diagnostic cut mark features for each weapon class

	Class I Katana	Class II Scimitar	Class III Broadsword	Class IV Samburu short	Class V Machete	Class VI Knife
Shape	Long, narrow ellipse	Shorter, wider ellipse	Often elliptical, can be variable	Irregularly shaped	Circular	Long, very thin lines and small triangles
Damage	Smooth walls	Broke bone	Broke bone	Cracking and other blunt force damage	Conchoidal flaking	
Other	Unilateral damage	Shards in mark		Unclean walls		

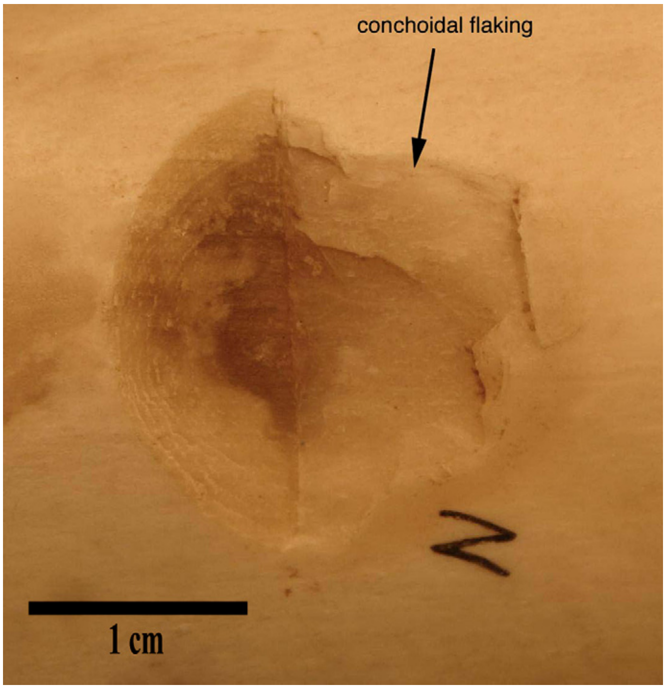

Fig. 3. Machete mark showing conchoidal flaking.

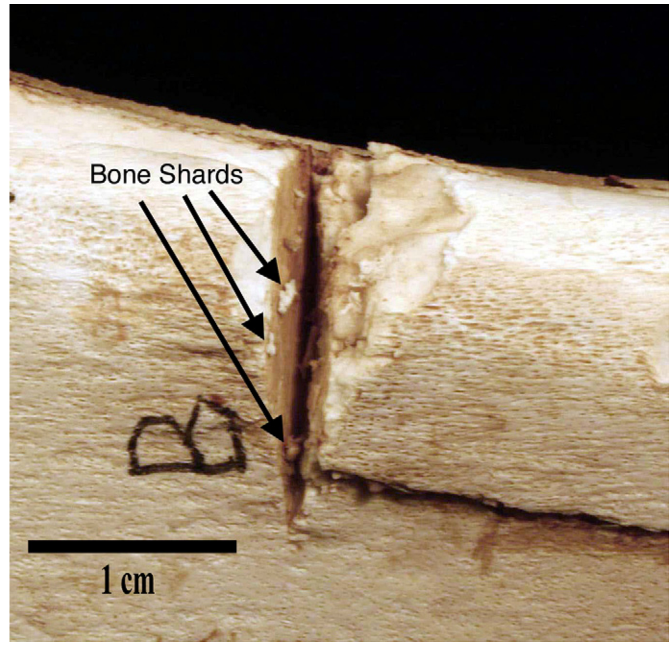

Fig. 4. Scimitar mark showing presence of bone shards in mark.

motion from cut marks created by smaller bladed weapons used in a slicing or stabbing motion.

3.2. Identifying marks from different classes of swords

In order to address the issue of inferring sword class from cut marks, eight variables (see Section 2 and Supplementary Text) were scored on 68 sword marks and 24 knife marks. The attributes of the cut marks made by the different weapon classes are shown in Table 2. Variation among mark features appears correlated with sword type, as discussed in detail for each class of weapon in the Supplementary Text and summarized in Table 3.

Based on macroscopic visual comparison, it is generally possible to distinguish cut marks created by different large bladed weapon classes used in a chopping motion from one another. Some classes, like the Machete or Scimitar, leave very specific types of damage such as the production of conchoidal flaking (Fig. 3) and bone shards (Fig. 4), respectively. Other classes, like the Broadsword or Katana, can display a wider range of morphologies, but are nonetheless distinguishable from other classes.

3.3. Relationship between mark characters and weapon attributes

In order to go from cut mark characterization to weapon class predictions, the relationship between cut mark characters and weapon morphology must be analyzed. Weapon classes were grouped based on blade morphology and χ^2 tests relating these morphologies to cut mark character states were performed. Statistically significant relationships are shown in Table 4 and discussed in more detail in the Supplementary Text. From these results it can be seen that differences in weapon weight, grip, and sharpness are significantly correlated with the presence of particular cut mark character states.

In order to determine which weapons, and which corresponding sets of cut marks, were more similar to one another, a cluster analysis was performed on the medians of both the weapon characters from Table 1, and on the medians of the cut mark character counts from Table 2 (including Shape designations). The resulting 'tree' for the weapons themselves cluster together the Katana and Broadsword, the Machete and the Samburu sword, the Scimitar as a sister sword to the Machete and Samburu sword, and the Knife as an outgroup (Fig. 5). The 'tree' for the cut marks is very similar, except that the Scimitar and the Knife switch positions. The similarity between the weapon tree and the cut mark tree supports the hypothesis that cut mark morphology is driven by weapon morphology.

4. Discussion

The sword and knife cut mark morphology described here is in general agreement with other small and large bladed weapon marks described in the literature (see Supplementary

Table 4
Results of chi square analyzes between blade characteristics (Table 1) and cut mark characteristics (Table 2)

Weapon attribute	Attribute state	Cut mark trait	Trait state	Probability (p)	χ^2
Weight	>1 kg	Breakage	Present	<0.0001	26.031
Sharpness index	> or = 1	Aspect	Perpendicular	=0.0179	5.605
Sharpness index	> or = 1	Feathering	Unilateral	<0.0003	15.921
Sharpness index	> or = 1	Flaking	Unilateral	<0.0001	22.570
Handedness	2	Flaking	Unilateral	<0.0113	8.974

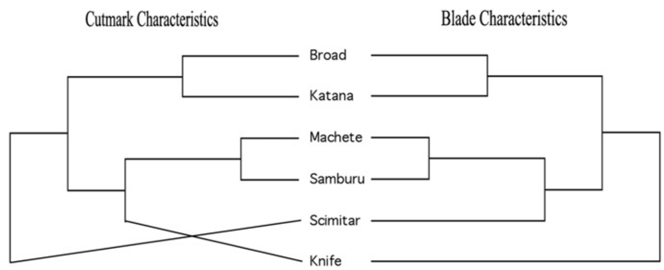

Fig. 5. Cluster analysis of blade characteristics (attributes given in Table 1; shown on right side) and cut mark characteristics (traits given in Table 2; shown on left side).

Text) (Alunni-Perret et al., 2005; Greenfield, 1999; Humphrey and Hutchinson, 2001; Wenham, 1989). Sword marks tend to display features associated with the sharp, cutting blade of a knife, such as smooth walls, as well as aspects of heavy weapon blunt force trauma, such as lateral pushing back, cracking, breakage, and other irregularities identified by Alunni-Perret et al. (2005). Variation between marks made by different swords is due to their being more or less blunt force versus sharp cutting instruments.

In order to make a sword class prediction from cut marks of unknown origin, one must first score the marks for the eight traits described here. Other observations may be useful as well (e.g., conchoidal flaking for the Machete), so the attributes considered should not necessarily be limited to the eight traits defined here. The sword class designation would then be inferred by tabulating the relative frequencies of cut mark characteristics, and relating them to both the "known" frequencies produced by different sword classes and the sword attributes as established by the statistically significant relationships described above. In implementing the traits described here, attention should be paid to that trait's observer error – which suggests, for example, that Shape not be given much weight – as well as overlap in the trait frequencies between sword classes.

The way in which both the formal traits and the relationships between sword attributes and mark attributes can be combined to infer the sword type(s) used is illustrated here via a hypothetical example. Take the example of an archaeological assemblage of battle graves that was analyzed and found to exhibit two main types of cut marks on the remains: one group displayed breakage of the bone, a preponderance of perpendicular marks, and unilateral flaking and feathering; the other group displayed no breakage of the bone, a somewhat equal if not higher amount of glancing marks than perpendicular ones, and a somewhat equal if not higher amount of bilateral feathering and flaking than unilateral. The first group of cut marks could confidently be attributed to a Scimitar-type weapon, as this is the only class that contains weapons that are greater than 1 kg (breaking the bone), have a sharpness index greater than 1 (causing unilateral damage), and is wielded with two hands (also associated with unilateral damage). The finding of shards in any of the cut marks would be a further indication of the causal weapon belonging to this class. The second group of cut marks could either be associated with a Samburu-type weapon or a Machete-type weapon, as they are both less than 1 kg (not breaking the bone), have a sharpness index less than 1 (causing bilateral damage) and are wielded with one hand (also associated with bilateral damage). The difference between these two classes is that the Machete produces a particular type of conchoidal cut mark, whereas the Samburu short sword produces marks that vary in size, shape, and the laterality of flaking. If none of the marks in the second grouping display conchoidal fracture, then they could be confidently associated with a Samburu-type weapon.

5. Conclusions

Cow hindlimbs were struck with six different kinds of bladed weapon, and the 92 resulting marks analyzed to determine if mark attributes could be used to infer the general weapon type used. Based upon the experimentation and previous work, it is possible to identify a readily observable set of diagnostic criteria for distinguishing sword marks from knife marks. This study confirmed some of what has already been observed (e.g., Humphrey and Hutchinson, 2001; Wenham, 1989), but allowed the first comprehensive identification of sword mark features. In general, the results suggest that swords produce marks that are clearly different from those produced by knives. Certain classes of swords also produced relatively diagnostic marks (e.g., the bone shards of the Scimitar). If a sufficient number of marks are present (circa 10), it is possible to reliably infer the class of sword used. Most distinct are the Machete and Scimitar, based on conchoidal flaking and bone shards, respectively. The Katana and Scimitar produce marks that are quite similar. Similar blades can produce different kinds of marks, however, such as for the Machete versus the Samburu short sword. The Broadsword produces the largest diversity of mark types. Cut mark characteristics are related to blade attributes, as demonstrated statistically here.

In forensic and archaeological cases, there is sometimes external evidence as to the possible range of weapons employed (e.g., the battle of Kamakura graves), which could be combined with an analysis of the marks using the criteria developed here to produce a relatively specific weapon identification. Future work could potentially improve these criteria by increasing the sample size, and broadening it beyond cow hindlimbs. Future research may develop and implement methods to accurately and precisely quantify many more aspects of cut mark morphology, such as overall depth, channel angle, and possibly shape. These data could then be used to more rigorously predict sword class from marks, perhaps in combination with statistical techniques such as discriminant function analysis or canonical variance analysis.

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Appendix. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jas.2008.01.016.

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