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Quantitative micromorphological analyses of cut marks produced by ancient and modern handaxes

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ABSTRACT

In this study, we analyse the three-dimensional micromorphology of cut marks on fossil mammal remains from a ~0.5 million year old Acheulean butchery site at Boxgrove (West Sussex, southern England), and make comparisons with cut marks inflicted during the experimental butchery of a roe deer (*Capreolus caproelus*) using a replica handaxe. Morphological attributes of the cut marks were measured using an Alicona imaging microscope, a novel optical technique that generates three-dimensional virtual reconstructions of surface features. The study shows that high-resolution measurements of cut marks can shed light on aspects of butchery techniques, tool use and the behavioural repertoire of Lower Palaeolithic hominins. Differences between the experimental cut marks and those on the Boxgrove large mammal bones suggest variation in the angle of the cuts and greater forces used in the butchery of the larger (rhinoceros-sized) carcasses at Boxgrove. Tool-edge characteristics may account for some of these differences, but the greater robusticity of the Boxgrove hominins (attributed to *Homo heidelbergensis*) may be a factor in the greater forces indicated by some of the cut marks on the Boxgrove specimens.

1. Introduction

Cut marks on fossil bones and teeth are an important source of evidence in the reconstruction of prehistoric butchery practices and have a direct bearing on subsistence strategies and the behavioural repertoire of early humans (e.g. Binford, 1981; Blumenschine et al., 1994; Dominguez-Rodrigo and Pickering, 2003; Shipman, 1986). Many such studies have focussed on the interpretation of the microscopic morphology of cut marks (Bartelink et al., 2001; Choi and Driwantoro, 2007; Gilbert and Richards, 2000; Greenfield, 1999, 2004, 2006a, b; Saidel et al., 2006; Shipman, 1981; Villa et al., 1986; Walker, 1978; Walker and Long, 1977; White, 1992), but with rare exceptions (e.g. Walker and Long, 1977; Potts and Shipman, 1981; Shipman, 1983; During and Nilsson, 1991; Bartelink et al., 2001; Kaiser and Katterwe, 2001) these have been qualitative in nature. In recent years, there have been a number of advances in optical microscopy that enable high-resolution three-dimensional images of bone surfaces to be made. Features of the micro-topography of bone surfaces can now be measured that were previously unobtainable using more conventional techniques (e.g. scanning electron microscopy). Recently, this approach was applied to cut marks by Bello and Soligo (2008), who used an Alicona imaging microscope to quantify characters such as cross-sectional shape, depth and shoulder heights. They were also able to infer details of the cutting-edge morphology as well as characteristics such as the inclination of the tool and by inference the tool user's hand during cutting. While experimental work on slicing cut marks (*sensu* Greenfield, 1999) produced directly on bone has already been reported (Bello and Soligo, 2008), the technique has not been applied to the analyses of slicing cut marks produced during butchery and only preliminary analyses have been undertaken on fossil material (Bello et al., 2007).

In this paper, we demonstrate that this methodology using an Alicona 3D InfiniteFocus imaging microscope can be applied to the study of ancient slicing cut marks on bones from an Acheulean butchery site at Boxgrove, UK. We compared these cut marks to slicing cut marks produced during the experimental butchery of a roe deer using a replica handaxe. Comparisons of cut marks parameters, such as sharpness, depth of cut and inclination, have led to new insights into patterns of carcass-processing and the behaviour of early hominins.

2. Materials

2.1. The site

The Boxgrove Acheulean site, near Chichester in southern England, has yielded some of the oldest human remains in northern

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Europe and one of the richest early Middle Pleistocene artefact and humanly modified bone assemblages yet known (Roberts and Parfitt, 1999). Today, the site is situated 10 km inland of the current shoreline of the English Channel, but during the early Middle Pleistocene it was located on the coast. Subsequent tectonic activity was responsible for raising the marine deposits ca 30 m above present-day sea level (Preece et al., 1990; Bates et al., 1997). The Lower Palaeolithic land surface associated with the marine deposits has been traced in an embayment for a distance of ∼26 km, but extensive archaeological excavations have only been possible where sand and gravel extraction has removed the overburden. At Boxgrove, quarrying has exposed a succession of near-shore marine and terrestrial interglacial deposits overlain by cold stage colluvium. Archaeological research at Boxgrove, led by Mark Roberts, has resulted in the recovery of extensive archaeological assemblages from the marine beach deposits and throughout the terrestrial sequence, with the main concentration occurring in an extensive palaeosol formed within the upper part of the marine sediments (Roberts and Parfitt, 1999). The distribution of archaeological material through the sequence suggests that human occupation at the site spanned a substantial part of the interglacial cycle and parts of the ensuing cold stage. Biostratigraphical evidence places the interglacial deposits in the early Middle Pleistocene, probably towards the end of the 'Cromerian Complex', with an age of about 0.5 Ma (Roberts and Parfitt, 1999).

In 1993, a largely complete hominin left tibial diaphysis was recovered from calcareous colluvial sediments at a site designated Q1/B (Roberts et al., 1994; Stringer, 1996; Stringer et al., 1998; Trinkaus et al., 1999; Streeter et al., 2001). Subsequently, excavations in 1995–1996 recovered two incisors from freshwater deposits directly underlying the colluvium; these sediments are broadly coeval with the palaeosol horizon. The Boxgrove hominid specimens have been assigned to *Homo heidelbergensis* and the size of the tibia suggests a robust individual at least 175 cm in height (Trinkaus et al., 1999). The hominin remains were found in association with abundant remains of butchered large mammals and an artefact assemblage dominated by finely-flaked ovate and limande handaxes and the waste from their manufacture (Pope, 2002). Elsewhere at Boxgrove, the fine-grained sediments have preserved small clusters of refitting debitage (Austin, 1994; Roberts and Parfitt, 1999) often associated with the butchered remains of a single large mammal carcass (e.g. GTP 17, the Horse Butchery Site. Pope and Roberts, 2005), but at Q1/B a wide range of mammalian species with evidence of butchery are represented. These mammals were probably attracted to the freshwater pools, which were fed by springs that emanated from the chalk cliff. The site was also a focus for carnivore activity. Bear (*Ursus deningeri*), spotted hyaena (*Crocuta crocuta*), lion (*Panthera leo*) and wolf (*Canis lupus*) are all represented in the faunal assemblage, but the patterns of damage suggest that humans had primary access to the large mammal carcasses.

The handaxes were made from good-quality nodular flint obtained from the chalk cliff and talus some 50 m to the north of Q1/B. The handaxes are typically between 80 and 150 mm long, flaked on both faces and knapped to maximise cutting edges. During the final stages of knapping, bone or antler hammers were used to thin and finish the tool and the tips of many of the handaxes are characterised by the removal of a sharpening ('tranchet') flake from their tip (Bergman and Roberts, 1988; Bergman et al., 1990). The thin 'blade-like' cutting edge produced by the tranchet removal contrasts with the 'zig-zag' morphology resulting from alternating flaking around the edges and base of the handaxe (Fig. 1). Retouched flakes and scrapers were extremely rare at the site and this supports the hypothesis that acheulean handaxes functioned primarily as butchery tools.

Microwear analysis of a sample of the ∼400 handaxes from Q1/B has identified use traces resulting from butchery tasks (Mitchell, 1997). Significantly, these traces, together with the morphology of the cut marks, indicate that the handaxes were used with a slicing action to process large mammal carcasses. Although use traces have been found along the edges of the Boxgrove handaxes, the tranchet tip was the focus of re-sharpening thus implying that the maintenance of this cutting edge was of primary importance.

The research at Boxgrove was designed to place the human activity in an accurate chronological and environmental context and to provide interpretations of human behaviour at different temporal and geographical scales. An important aspect of the research has been a programme of experimental studies, including flint knapping, butchery and the replication of tool microwear, which have made important contributions to the interpretation of the archaeological record at the site (e.g. Wenban-Smith, 1989; Mitchell, 1995, 1997; Smith, 2003).

2.2. The fossil sample

During the 1985–1986 excavations at Boxgrove, about 1050 humanly modified large mammal bones were recovered from a small area of the quarry immediately to the south of the buried cliff. These remains include a wide spectrum of taxa, ranging in size from European beaver (*Castor fiber*) to rhinoceros (*Stephanorhinus hunsdheimensis* and *Stephanorhinus megarhinus*). Although many of the bones are fragmentary, they were buried in fine-grained highly calcareous sediments and show little or no alteration resulting from trampling or high-energy taphonomic processes. Other post-depositional processes, such as weathering and diagenesis have had a negligible effect on cut mark morphology, which typically show the characteristic features of incisions produced by a sharp flint edge used with a slicing, scraping or chopping motion. The cut marks show a patterned distribution consistent with a range of butchery tasks, including skinning, dismembering, disarticulation and filleting. Intentional fracturing of limb elements indicates that marrow-bone processing was also undertaken at the site. Specimens were inspected first by light microscopy to determine the suitability for micromorphological analysis. We then selected 13 cut-marked specimens, each with at least one complete un-truncated cut mark, for analysis using the Alicona imaging microscope. A total of 44 slicing cut marks has been scanned. These include specimens representing a range of skeletal elements and extremes of body size (i.e. roe deer, ∼59 kg and rhinoceros, ∼2000 kg). Details of the specimens are given in Table 1 and Fig. 2. The maximum size of the specimens examined (<120 mm) was constrained by the height of the Alicona microscope mounting.

2.3. The experimental sample

A comparative sample of cut marks produced during the experimental butchery of a roe deer using flint replicas of Boxgrove handaxes was analysed to serve as a baseline for interpreting the Boxgrove cut marks. The butchery experiments are described in detail by Mitchell (1995), with the principal aim being the efficient removal of the meat from the carcass. Initial stages of carcass preparation involved gutting and skinning, followed by careful boning and jointing of the limbs to remove the meat. These experiments showed that handaxes are effective butchery tools, with the long curved edges of the handaxe being particularly effective when used with a gentle slicing motion. Most of the cuts were made using the length of the handaxe edge from the butt to tip, with the tip being used for shorter 'filleting' cuts during the final stages of meat removal. In this way, the bones were marked by both the razor-sharp flake edge of the tranchet removal as well as

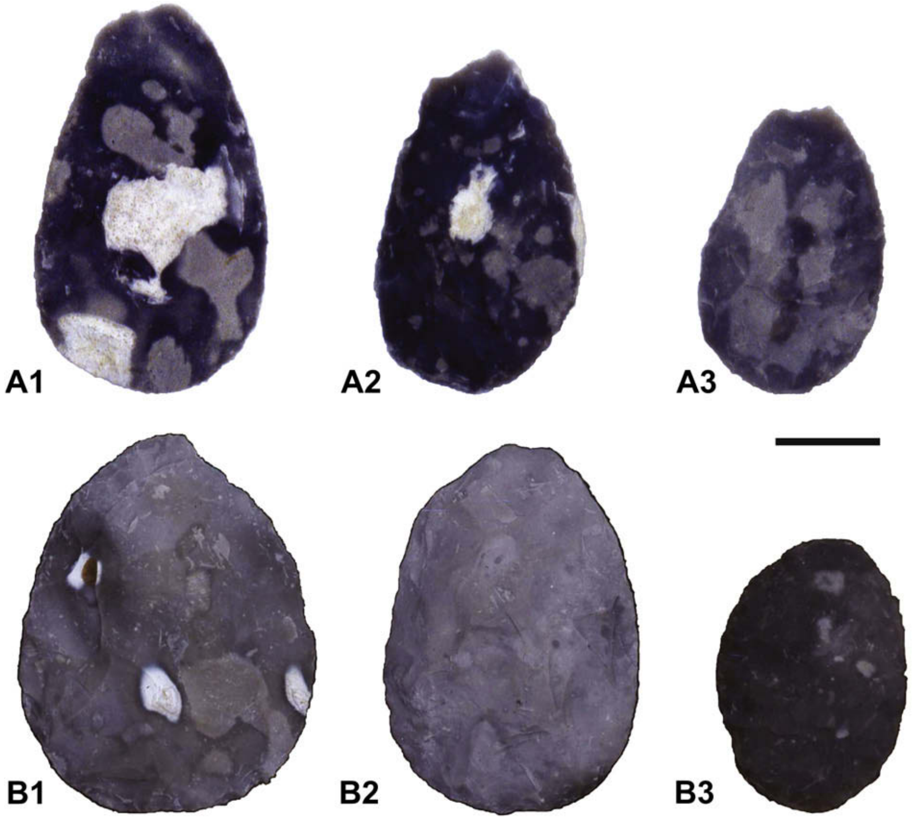

Fig. 1. Handaxes found in association with butchered bones at Boxgrove site Q1/B (A1, A2 and A3) and replica handaxes used in the butchery experiment (B1, B2 and B3).

the 'zig-zag' edge along remainder of the sides and butt of the handaxe (Fig. 1).

A selection of the bones was then prepared for microscopic analysis by gently boiling them in water to remove any remaining flesh and periosteum. In the final stages of this process, washing powder was added to remove any remaining fatty residues and the bones were whitened using a dilute solution of hydrogen peroxide. The comparative experimental cut marks were selected to include marks with a range of characteristics and anatomical locations. We scanned 76 of the experimental slicing cut marks from 15 specimens; details are given in Table 2 and Fig. 2.

3. Methods

Images of each cut mark were captured using an Alicona 3D InfiniteFocus imaging microscope, using a 5× objective lens at a vertical resolution of $4\ \mu m < z < 5.292\ \mu m$ and a lateral resolution of $1.75\ \mu m \times 1.75\ \mu m$. In most cases, the cut marks were scanned in their entirety. In their paper, Bello and Soligo (2008) analysed seven regularly-spaced points along each cut mark, with the first profile at 0.5 mm from the starting point and ending at 0.5 mm from the finishing point of the cut mark (Soligo and Bello, 2008; Fig. 3). In this study, we have been unable to adopt this approach because it was not always possible to identify directionality and thus the starting and ending point of the cut mark. To circumvent this problem, we analysed profile cross-sections perpendicular to the length of the cut only at its mid-point.

A linear regression model (R) was fitted to each profile to model the position of the intact bone surface and to serve as a reference against which cut mark parameters were recorded. According to Bello and Soligo (2008), measurements that extend above this reference line are referred to as 'heights', and measurements that extend below it as 'depths'. Further linear regression models are fitted to each slope (S_1 and S_2) of the cross-section profile.

The following parameters were recorded (for a graphical representation of these parameters, refer to Bello and Soligo, 2008; Fig. 4):

1. *Opening angle* of the cut mark (δ) is the angle between the slopes S_1 and S_2 ($\delta = 180^\circ - [\sigma_1 + \sigma_2]$) (Bello and Soligo, 2008; Fig. 4b). In Bello and Soligo (2008), the slope angles (σ_1 and σ_2) are the angles between the slopes S_1 [left] and S_2 [right] of the cut mark and the unaffected bone surface [R] bordering the cut. In their study, Bello and Soligo were able to determine left and right sides of the cuts in relation to its starting point. In this study, we were often unable to recognise the starting and ending points, and therefore a 'left' and 'right' side of the cut. However, this does not affect the evaluation of the opening of the angle, because this is the result of $\sigma_1 + \sigma_2$.
2. *Angle of the Tool Impact Index (ATI Index)*: according to Bello and Soligo (2008), the bisector angle of a cut mark (BAC) is equal to $\sigma_2 + (180^\circ - [\sigma_1 + \sigma_2])/2$), σ_1 and σ_2 being the angles between the slopes S_1 [left] and S_2 [right] of the cut mark and the unaffected bone surface [R]. Because we are unable to determine a 'left' and 'right' side of the cut, we suggest an alternative way to measure the inclination of the tool by mean of the 'Angle of the Tool Impact Index' (ATI Index):

$$\left[\text{ATI Index}\right] = \frac{[90^\circ - \sigma_1] - [90^\circ - \sigma_2]}{[90^\circ - \sigma_1] + [90^\circ - \sigma_2]}$$

Theoretically, the absolute value of the index can range from 0 (when the inclination of the tool is perpendicular (at 90° to the bone surface) to 1 (when the inclination of the tool is parallel (0°) to the bone surface).

Table 1
Anatomical distribution and characteristics of scanned cutmarks on early Middle Pleistocene large mammal remains from Boxgrove.

Specimen number	Cut mark number	Taxon	Anatomical element	Position	Cut mark length (mm)
6626	1	Rhinoceros (*Stephanorhinus* sp.)	Tibia	Midshaft	10.52
	2				10.61
7483	3	Rhinoceros (*Stephanorhinus* sp.)	Pisiform		4.63
	4				2.54
1746	5	Rhino-sized large mammal	Long bone fragment	Midshaft	10.14
	6				7.23
5448	7	Rhino-sized large mammal	Rib		6.36
30073	8	Rhinoceros (*Stephanorhinus* sp.)	Rib		6.51
	9				6.01
	10				4.04
30138	11	Rhino-sized large mammal	Rib		5.37
	12				5.45
	13				4.33
2008	14	Rhino-sized large mammal	Long bone		6.04
	15				4.22
30396	16	Indet. large mammal	Long bone?		4.91
30962	17	Red deer-sized large mammal	Rib		0.81
	18				3.88
	19				2.16
30117	20	?Rhino-sized large mammal	Rib		10.02
6322	21	Roe deer (*Capreolus capreolus*)	Femur		2.98
	22				3.49
	23				2.85
	24				3.38
7545	25	Roe deer (*Capreolus capreolus*)	Tibia		2.22
	26				14.42
	27				7.19
4898	28	Roe deer (*Capreolus capreolus*)	Scapula	Blade	21.42
	29				27.83
	30				44.61
	31				20.66
	32				14.38
	33				11.89
	35				1.90
	36			Neck	4.26
	37				4.39
	38				9.53
	39				2.42
	40				2.73
	41				1.21
	42				1.56
	43				0.97
	44				2.67
	45				0.79

3. *Shoulder Height Index (SH Index)*: according to Bello and Soligo (2008), the height of the shoulders formed on either side of the cut ($SH_1 = \sin\beta_1 \times L_1$; $SH_2 = \sin\beta_2 \times L_2$, where L_1 and L_2 are the distances from the tip of the shoulder to the corresponding intersection between the cut mark profile and regression line R, and where β_1 is the angle between L_1 and R and β_2 is the angle between L_2 and R). L_1, L_2, $\beta_1$and β_2 are determined accordingly to S_1 [left] and S_2 [right] of the cut mark (Bello and Soligo, 2008; Fig. 4c). Once again, because we are unable to determine 'left' and 'right' side of the cut, we calculated a 'Shoulder Height Index' (SH Index) as[1]:

$$\left[\text{SH Index}\right] = \frac{S_1 - S_2}{S_1 + S_2}$$

The absolute value of the indexes can range from 0 (when the two shoulders have equal height) to 1 (when only one shoulder is present).

4. *Depth of cut (DC)*: the perpendicular depth of the cut relative to the unaffected bone surface ($DC = \sin\alpha \times H$; where H is the distance from the lowest point of the cut mark profile, point A, to the intersection between S_1 and the regression line R, point B, and where α is the angle between H and R; Bello and Soligo, 2008; Fig. 4d).
5. *Floor radius*: the radius of a circle fitted to the floor of the cut mark profile, with the floor defined as lying between the two points where the profiles of the slopes start to converge (i.e., where the cut mark profiles start to diverge from the regression models S_1 and S_2; Bello and Soligo, 2008; Fig. 4c).

4. Results

Results are presented according to the specimen on which analyses were conducted: fossil material (Fossil roe deer, Frd; Fossil large mammals, Flm) and Experimental roe deer (Erd). A distinction has also been made according to the anatomical distribution of the cut marks: long bones (e.g. tibia, fibula), ribs and scapula. Finally, a distinction was made according to the position of cut marks on an anatomical element: either on the midshaft or in proximity to (or on) the articular surface.

4.1. Opening angle

The mean value of the opening of the angle of cut marks observed on the fossil roe deer was 148.2°, compared with 134.2° for other fossil large mammals and 120.7° for the experimental cut marks produced by the replica handaxe (Fig. 3).

The opening angle of experimentally produced cut marks can be statistically differentiated from that observed on the fossil material, both when exclusively compared to the fossil roe deer ($W = 1804.5$, $p \leq 1.704e{-}06$), and when compared to the total of fossil specimens ($W = 3448.5$, $p \leq 1.821e{-}05$). Similarly, the differences between the opening of the angle of cut marks observed on fossil roe deer and other fossil large mammal are statistically significant ($W = 355$, $p \leq 0.026$). This seems to indicate variability in the degree of the opening of angle of cut marks according to the faunal species on which they were found. When considering the different anatomical elements, only in the case of long bones was it possible to statistically differentiate experimentally produced cut marks from fossil cut marks ($W = 426$, $p \leq 0.035$).

On the experimental material, it was possible to observe a pattern in the opening of the angle according to the anatomical position of cut marks along the shaft or in proximity to the articulation of long bones. Cut marks close to (or on) an articulation of long bones were generally more acute (mean 80.17°, standard deviation (STDEV) of 29.07) than those observed along the shaft (mean 124.8°, STDEV 23.25; Wilcoxon two sample test, $W = 21$, $p \leq 0.0056$). Cut marks analysed on the fossil sample had been exclusively found along diaphysis. By comparing the experimental sample and the fossil sample (mean 139.2°, STDEV 25.96) and excluding in the case of the experimental sample cut marks found in proximity of the articulation, we eliminate the difference between the two samples (Wilcoxon two sample test, $W = 374$, $p \leq 0.085$).

Similarly, on the experimental material, a pattern was observed on the ribs according to the anatomical position of cut marks along the shaft (average 126.59°, STDEV 25.76) or in proximity to the vertebral articulation (mean 101.11°, STDEV 21.45, Wilcoxon two

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[1] In this case, 1 and 2 have no lateral meaning, but indicate the two opposing slopes of the cut mark.

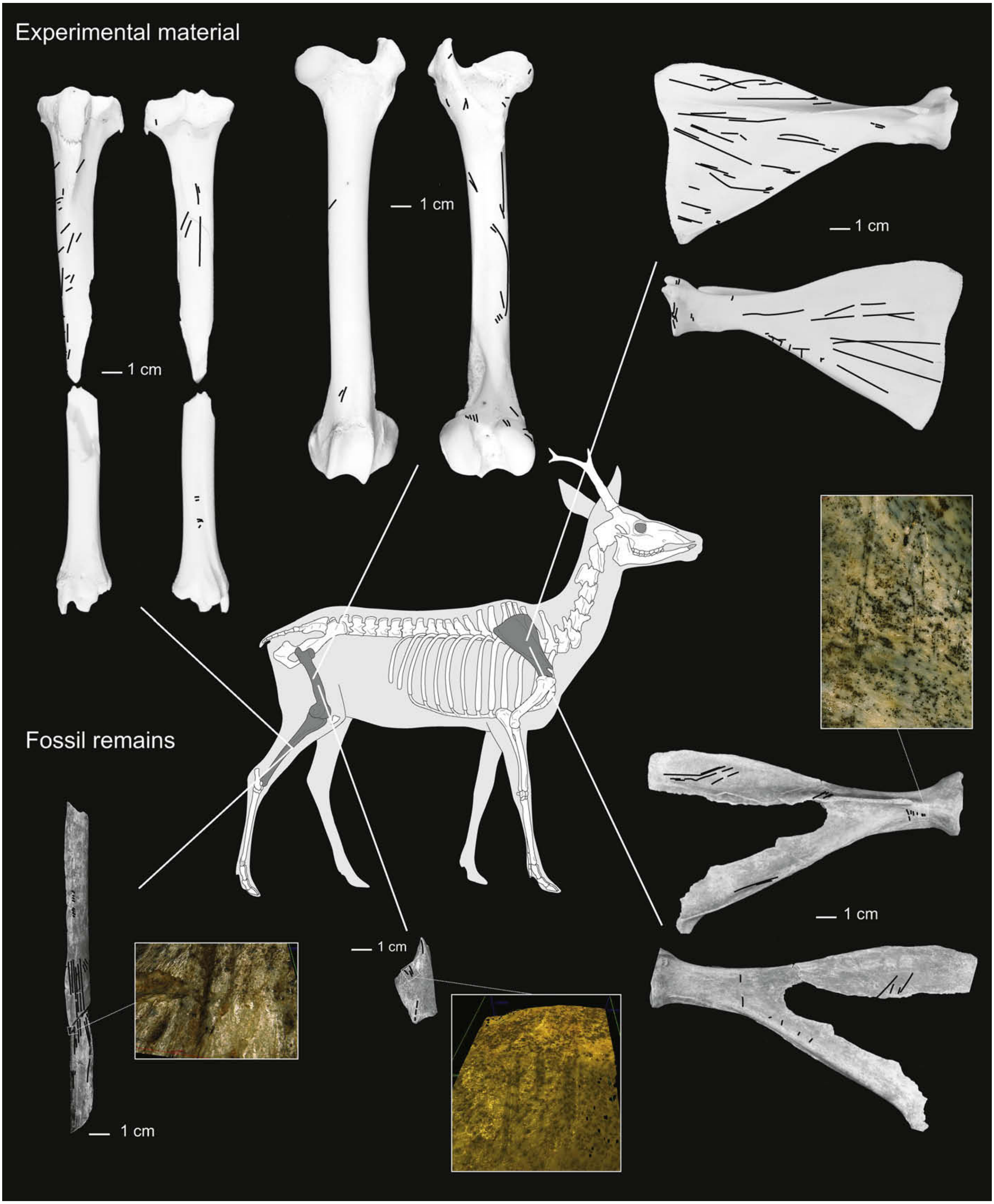


Fig. 2. Anatomical distribution of cutmarks on fossil (bottom) and modern (top) roe deer on scapulae, femurs and tibiae with examples of Alicona images of cutmarks.

Table 2
Anatomical distribution and characteristics of scanned cutmarks experimentally produced during the butchering a roe deer using a replica of a Boxgrove handaxe.

Specimen	Cut mark	Anatomical element	Position	Cut mark length (mm)
1	1	Rib	Shaft (middle)	7.26
2	2	Rib	Shaft (middle)	2.21
3	3	Rib	Shaft (middle)	1.98
4	5	Rib	Shaft (middle)	3.64
	6			6.78
	7			3.70
	8			3.94
	9			1.95
	10			1.95
	11			2.00
5	12	Rib	Shaft (middle)	2.51
	13			6.01
	14			2.48
6	15	Rib	Shaft (middle)	5.75
7	16	Rib	Shaft (middle)	12.36
8	17	Rib	Vertebral extremity, between the costal groove and the tubercle	2.99
	18			4.88
	19			2.33
	20			2.55
	21			1.45
	22			2.87
	23			3.91
	24			4.01
	25			2.61
9	26	Rib	Shaft (costal groove region)	2.35
	27			1.37
	28			0.89
	29			4.41
	30		Vertebral extremity, between the costal groove and the tubercle	2.6
	31			1.68
	32			1.99
	33			3.64
10	34	Tibia	Proximal shaft (lateral surface of the tibia)	8.73
	35			10.42
	36		Midshaft	11.54
	37			3.15
	38			1.76
11	39	Radius	Midshaft	10.11
	40			2.02
12	41	Ulna	Proximal extremity Shaft	28.87
	42			2.46
	43			6.17
	44			1.54
	45			2.17
	46			0.92
	47			3.92
	48			3.7
	49			2.09
	50			2.07
	51			1.45
	52			1.15
	53			1.17
	54			1.86
	55			2.59
	56			2.96
	57			2.08
	58			1.82
13	59	Femur	Prox. epihysis (neck)	4.73
	60			5.09
	61			3.55
14	62	Femur	Midshaft	5.05
	63			40.51
	64			9.70
	65			28.78
15	66	Scapula	Blade	6.07
	67			17.87
	68			9.76
	69			23.37
	70			11.73
	71			16.83
	72		Neck	2.6
	73			3.48
	74			1.53
	75			4.00
	76			2.04

sample test, $W = 165$, $p \leq 0.041$). Cut marks analysed on the fossil sample had been exclusively found along the rib shaft. Although no statistical difference has been observed between the opening angle of cut marks on fossil and modern ribs, these values become even closer by excluding cut marks found in proximity to the vertebral articulation.

4.2. *Angle of Tool Impact Index (ATI Index)*

The mean value of the ATI Index was 0.065 for cut marks on the fossil roe deer, 0.096 for cut marks observed on other fossilised large mammals and 0.153 for the experimental cut marks (Fig. 4).

The values are generally low, indicating that the tools were held almost perpendicular to the unaffected bone surface. Cut marks observed on experimental material have slightly higher values, an indication that the tool and the hand of the tools' user were more inclined toward the unaffected bone surface.

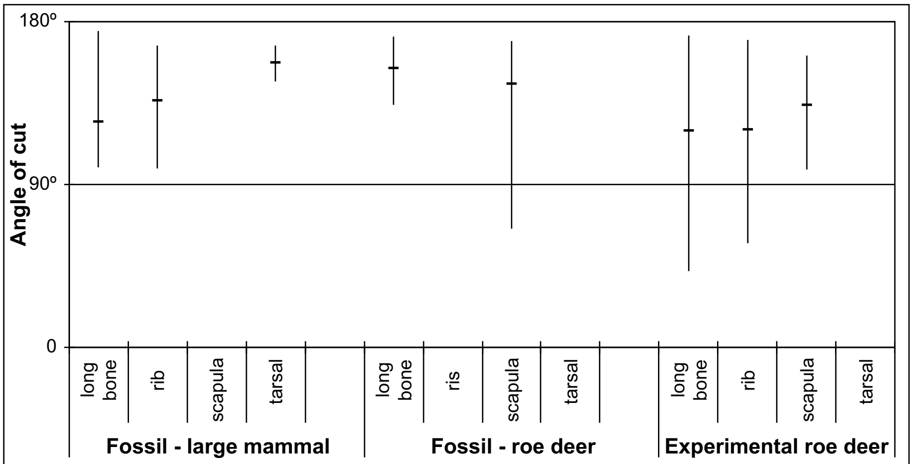
The ATI Index of the experimentally produced cut marks can be statistically differentiated from the ATI Index of cut marks observed on the fossil material, both when compared to the fossil roe deer only ($W = 908$, $p \leq 0.0142$), and when compared to the total of fossil specimens ($W = 2175$, $p \leq 0.008$). No differences were observed according to the anatomical element considered. No statistical differences were observed between the inclination of the tool adopted in producing cut marks on fossil roe deer and the other large mammal remains ($W = 462$, $p \leq 0.768$).

Cut marks close to (or on) long bone articulations were characterised by greater inclination of the tool toward the unaffected surface (mean 0.25, STDEV 0.29) than those observed along the shaft (mean 0.16, STDEV 0.16), but this difference is not statistically significant. Similarly on ribs, the tool had a greater inclination toward the unaffected surface in the case of cut marks located in proximity to the vertebral articulation (mean 0.18, STDEV 0.17) than in cut marks found along the shaft on the ribs (mean 0.10, STDEV 0.11, the difference is not statistically significant).

4.3. *Shoulder Height Index (SH Index)*

The mean value of the SH Index was 0.532 for cut marks on the fossil roe deer, 0.679 for cut marks on other fossil large mammals and 0.502 for the experimental cut marks (Fig. 5).

The variability of the index is extreme in all samples analysed. It appears, however, that the SH index values are generally lower for cut marks observed on the experimental material. The SH Index of experimentally produced cut marks cannot be statistically differentiated from the SH Index of cut marks observed on fossil material, both when compared to fossil roe deer ($W = 1258.5$, $p \leq 0.70$) and when compared to all fossils specimens ($W = 2909$, $p \leq 0.18$). Similarly, it is not possible to distinguish the inclination of the tool

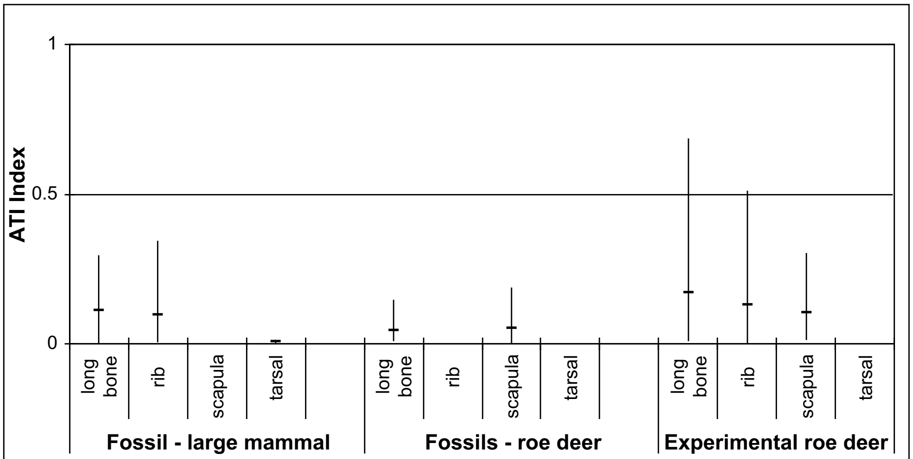


	Flm		Frd		Total fossils		Erd	
	Mean	STDEV.	Mean	STDEV.	Mean	STDEV.	Mean	STDEV.
LB	124.49°	27.46°	153.95°	14.14°	139.22°	25.96°	119.40°	27.77°
Rib	136.15°	19.31°			136.15°	19.31°	120.10°	25.17°
Scapula			145.78°	24.38°	145.78°	24.38°	133.87°	21.80°
Tarsal	156.97°	13.42°			156.97°	13.42°		

Fig. 3. Opening angles of cutmarks observed on Boxgrove fossil material and on the experimental material according to the distribution of cutmarks on the anatomical elements. (Frd, Fossil roe deer; Flm, Fossil large mammals and Erd, Experimental roe deer).

adopted in producing cut marks on fossil roe deer and other fossil large mammal ($W = 477$, $p \leq 0.14$).

No statistically significant differences in the SH Index were observed according to the anatomical elements on which cut marks have been found. However, differences in the SH Index have been observed on the experimental material according to the anatomical position of cut marks along the shaft or their proximity to the articulation of long bones. Cut marks in close proximity to long bone articulations were characterised by shoulders with more asymmetrical heights (SH index, mean 0.67, STDEV 0.24), while cut marks observed along the shaft of long bones were characterised by more symmetrical shoulder heights (mean 0.48, STDEV 0.33; the



	Flm		Frd		Total fossils		Erd	
	Mean	STDEV.	Mean	STDEV.	Mean	STDEV.	Mean	STDEV.
LB	0.139	0.119	0.066	0.044	0.103	0.094	0.170	0.178
Rib	0.085	0.097			0.085	0.097	0.131	0.137
Scapula			0.064	0.055	0.064	0.055	0.102	0.080
Tarsal	0.007	0.006			0.007	0.006		

Fig. 4. Angle of Tool Impact Index (ATI Index) observed on Boxgrove fossil material and on the experimental material according to the distribution of cutmarks on the anatomical elements. (Frd, Fossil roe deer; Flm, Fossil large mammals and Erd, Experimental roe deer).

difference is not statistically significant). Similarly on ribs, the cut marks found in proximity to the vertebral articulation were characterised by more asymmetrical shoulder heights (mean 0.70, STDEV 0.27) than the ones found along the shaft on the ribs (mean 0.47, STDEV 0.32; Wilcoxon two sample test, $W = 275$, $p \leq 0.04$). These results were consistent with observations by Bello and Soligo (2008), who demonstrated that the inclination of the tool and the relative heights of the shoulders are correlated. A stronger inclination of the tool to the unaffected bone surface (here expressed by ATI Index close to 1) is correlated with a higher asymmetry in shoulder heights (here expressed by high SH Index close to 1). Therefore, the ATI and SH Index values seem to indicate that tools were held with a less perpendicular angle to the unaffected bone surface when in proximity to an articulation.

4.4. Depth of cut

The mean value of the depth was 56.82 μm for cut marks observed on the fossil roe deer, 70.44 μm for cut marks on other fossil large mammals and 54.08 μm for the experimental cut marks (Fig. 6).

The depth of the experimental cut mark was not statistically different from the depth of cut marks observed on the fossil roe deer ($W = 1369.5$, $p \leq 0.20$). However, statistically significant differences were observed in the case of the depth of experimental cut marks when compared to the total of fossils specimens ($W = 3031.5$, $p \leq 0.04$). No statistically significant difference has been observed between cut marks on the fossil roe deer and any of the other fossil large mammal remains ($W = 489$, $p \leq 0.23$).

When considering different anatomical elements, the differences in the depth of cut between experimentally produced and fossil cut marks were statistically significant in the case of long bones and scapulae (long bones, $W = 432$, $p \leq 0.02$; ribs, $W = 296$, $p \leq 0.18$; scapulae, $W = 179$, $p \leq 0.047$).

On the experimental material, it was possible to observe a clear pattern in the depth of cut marks according to their anatomical position. Cut marks close to (or on) long bone articulations were generally deeper (mean 132.33 μm, STDEV 106.60) than those observed along the shaft (mean 34.10 μm, STDEV 34.92; Wilcoxon two sample test, $W = 104$, $p \leq 0.047$). Similarly on ribs, the cut marks found in proximity to the vertebral articulation were slightly deeper (mean 51.39, STDEV 25.72) than those found along the shaft on the ribs (mean 39.46, STDEV 40.47; this difference is not statistically significant).

4.5. Floor radius

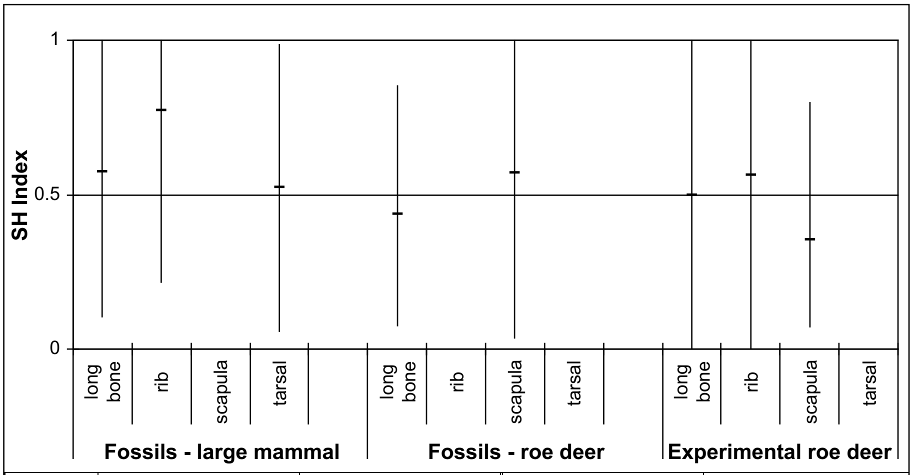
The mean value of the floor radius was 253.18 μm for cut marks on the fossil roe deer, 333.37 μm for cut marks observed on other fossil large mammals and 129.29 μm for the experimental cut marks (Fig. 7).

In general, cut marks observed on the experimentally butchered material have shorter radii regardless of their anatomical distribution. This is indicative of narrower cut marks (Bello and Soligo, 2008).

The length of the radius of experimentally produced cut mark can be statistically differentiated from the length of the radius of cut marks observed on fossil material, when exclusively compared to the fossil roe deer ($W = 1832$, $p \leq 1.205\mathrm{e}{-06}$) as well as when compared to the total of fossil specimens ($W = 3639$, $p \leq 2.632{-07}$). No statistically significant difference has been observed between cut marks on fossil roe deer and other fossil large mammal remains ($W = 422$, $p \leq 0.52$).

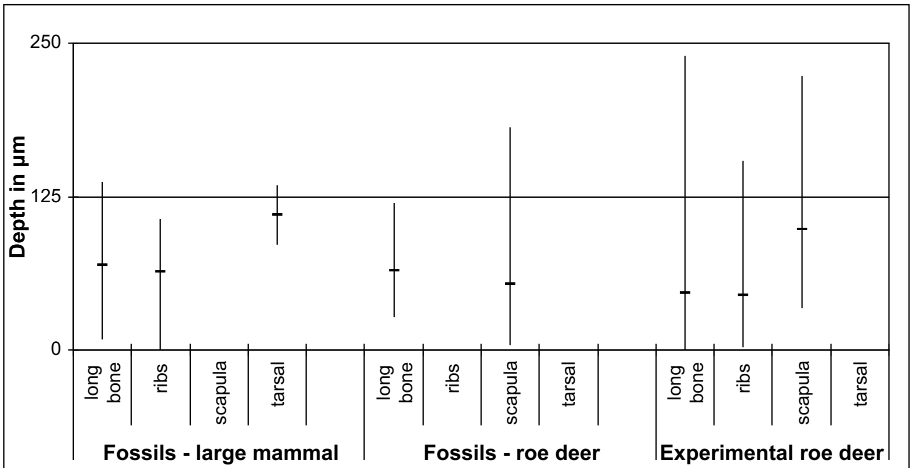
The differences in the floor radius between experimental and fossil cut marks were also statistically significant in the case of long bones and ribs (long bones, $W = 722$, $p \leq 7.01\mathrm{e}{-05}$; ribs, $W = 341$, $p \leq 0.01$; scapula, $W = 113$, $p \leq 0.18$).

On the experimental material, it was not possible to statistically differentiate the floor radii of cut marks according to their anatomical



	Flm		Frd		Total fossils		Erd	
	Mean	STDEV.	Mean	STDEV.	Mean	STDEV.	Mean	STDEV.
LB	0.574	0.410	0.436	0.264	0.505	0.339	0.500	0.325
Rib	0.774	0.315			0.774	0.315	0.564	0.317
Scapula			0.572	0.313	0.572	0.313	0.355	0.251
Tarsal	0.522	0.656			0.522	0.656	0.056	

Fig. 5. Shoulder Height Index (SH Index) observed on Boxgrove fossil material and on the experimental material according to the distribution of cutmarks on the anatomical elements. (Frd, Fossil roe deer; Flm, Fossil large mammals and Erd, Experimental roe deer).



	Flm		Frd		Total fossils		Erd	
	Mean	STDEV.	Mean	STDEV.	Mean	STDEV.	Mean	STDEV.
LB	69.65	51.07	64.69	31.86	67.02	40.96	46.01	56.50
Rib	63.97	40.42			63.97	40.42	44.16	35.43
Scapula			53.58	44.74	53.58	44.74	97.88	62.56
Tarsal	109.85	33.06			109.85	33.06		

Fig. 6. Depth of cut observed on Boxgrove fossil material and on the experimental material according to the distribution of cutmarks on the anatomical elements. Measurements in µm (Frd, Fossil roe deer; Flm, Fossil large mammals and Erd, Experimental roe deer).

position. Cut marks close to (or on) the articulation of long bones were slightly narrower (mean 141.54 µm, STDEV 75.95) than those observed on the midshaft (mean 199.1 µm, STDEV 582). However, this difference is due to a single cut mark located on the midshaft with a floor radius of 3166.1 µm. If we exclude this value (new mean 93.14 µm, STDEV 119.62), the result is inverted with broader cut marks close to (or on) an articulation of long bones.

On ribs, the cut marks found in proximity to the vertebral articulation were slightly broader (average 65.05 µm, STDEV 55.69) than the ones found along the shaft on the ribs (average 60.08 µm, STDEV 49.04).

5. Discussion

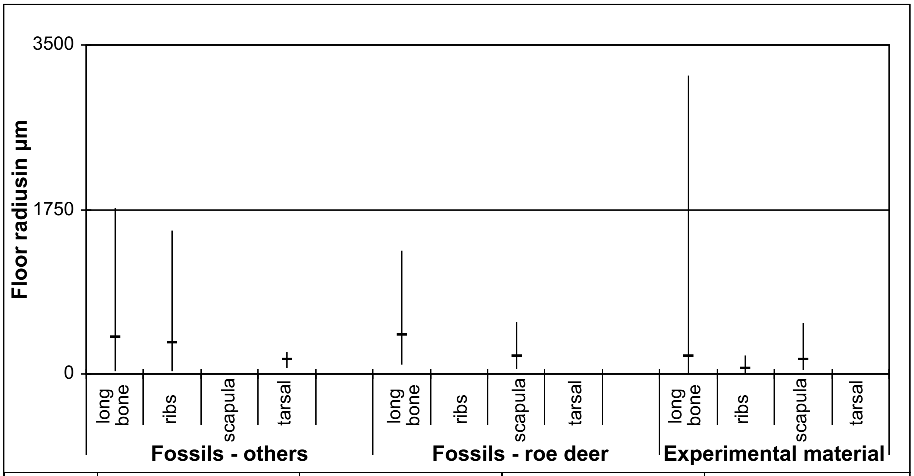
Alicona images of the fossil and modern cut marks display microscopic criteria consistent with incisions made by a stone tool edge. These features include, internal micro-striations, lateral striations or shoulder effects, Herzian cones and raised 'shoulders' along one or both edges (e.g.: Walker and Long, 1977; Eickhoff and Herrmann, 1985; Blumenschine and Selvaggio, 1988; Blumenschine et al., 1996; Fig. 8). Modifications to the method proposed by Bello and Soligo (2008) were necessary because it was not always possible to identify features, such as smears, oblique faulting and chipping used by Bromage and Boyde (1984) as directional indicators. In other cases, these features could not being distinguished with sufficient clarity to identify directionality of the cut marks. In most of the cut marks examined, the margin of error was too high to confidently determine directionality and consequently we are not able to identify the starting and ending point. In order to overcome this problem, analysis of profile characteristics have been conducted exclusively at the mid-point of the incision. Also, we suggest that the inclination of the tool (which is related to directionality; Bromage and Boyde, 1984; Bello and Soligo, 2008) can be defined by two new indices: the 'Angle of the Tool Impact Index' (ATI Index) and the 'Shoulder Height Index' (SH Index), which are independent of directionality.

In comparison, the experimental slicing cut marks examined by Bello and Soligo (2008) were less variable than slicing cut marks produced either experimentally during butchery or in the fossil sample. The experimental and fossil slicing cut marks produced by handaxes also show greater variation in width, and frequently comprise sub-parallel incisions that overlap, intersect and bifurcate along a sinuous path.

Cut marks experimentally produced on a modern specimen using a replica Boxgrove handaxe presented several differences from cut marks found on fossil material. Cut marks observed on the experimentally butchered material generally have a more acute cross-sectional angle, a smaller floor radius and were shallower (Fig. 9).

The narrower cut marks observed on the experimental material may suggest that the replicas of Boxgrove handaxe had a sharper cutting-edge than that of the Acheulean handaxes found at Boxgrove. However, examination of the Boxgrove handaxe edges shows that there are no discernable differences when compared to the replica handaxes.

Alternatively, the broader cross-section of fossil cut marks could be the result of taphonomic processes. For example, the fossil cut marks could have been progressively eroded thus leading to an exaggeration of their initial characteristics. Few observations have been made on the effect of corrosion, weathering and exfoliation on cut marks (Lyman, 2005). A recent study on tooth marks produced by the extinct beaver *Dipoides* sp. showed that tooth marks tend to become deeper with increasing weathering, which results in alteration and widening of the grooves (Rybczynski, 2008). However, the Boxgrove fossil specimens were buried in fine-grained, highly calcareous sediments and they exhibit little or no alteration resulting from taphonomic processes. Further studies should be conducted to better understand the effect of taphonomic processes on the micromorphology of cut marks.



	Flm		Frd		Total fossils		Erd	
	Mean	STDEV.	Mean	STDEV.	Mean	STDEV.	Mean	STDEV.
LB	388.28	615.85	414.30	407.56	401.29	501.89	192.12	545.80
Rib	331.76	441.82			331.76	441.82	62.04	50.96
Scapula			186.84	133.24	186.84	133.24	154.47	149.55
Tarsal	150.04	111.67			150.04	111.67		

Fig. 7. Length of the floor radius of cut observed on Boxgrove fossil material and on the experimental material according to the distribution of cutmarks on the anatomical elements. Measurements in μm.

Another possible explanation for the greater width of Boxgrove cut marks could relate to repeated use of the Acheulean handaxes causing a progressive 'blunting' of the cutting edge. Bello and Soligo (2008) in their experiment observed that the average radius increased noticeably as a function of the number of times a flake was used. According to this observation, the broader cut marks observed on the fossil material could be the result of repeated use of the same handaxe without any re-sharpening of the handaxe cutting edge. However, a recent study (Braun et al., 2008) appears to show that there is no statistical support for the assumption that repeated cutting causes significant dulling of stone tool edges, although further experimental work using different type of tools and raw materials needs to be undertaken to confirm this observation.

Finally, the deeper and wider incisions could be due to greater forces employed during butchery of the carcasses at Boxgrove. To date, only preliminary studies have been undertaken in an attempt

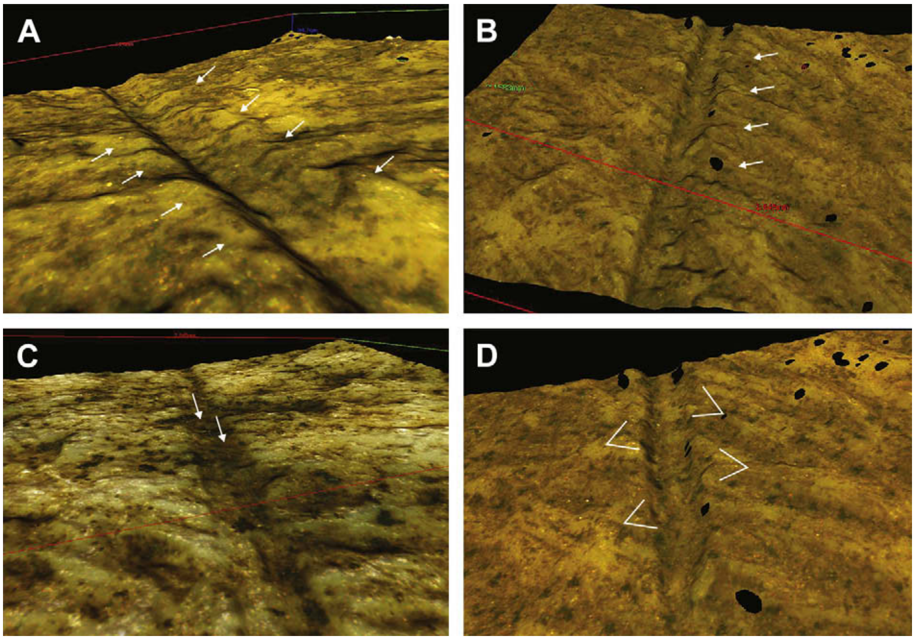


Fig. 8. Alicona images of fossil cutmarks displaying microscopic criteria consistent with incisions made by a stone tool edge: A, raised 'shoulders' along both edges; B, raised 'shoulders' along one edge; C, internal micro-striations; D, Herzian cones.

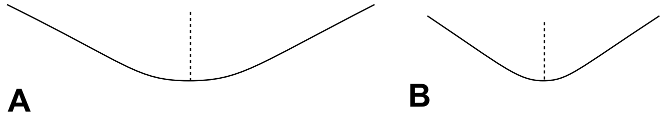


Fig. 9. Representation of the mean values of the opening of the angle of cut, radius and depth of cutmarks on fossil (A) and experimentally butchered specimens (B).

to observe effects of increase force on the morphology of cut marks. These preliminary studies indicate a correlation between body robusticity, force exerted and depth of cut marks (Potter, 2005). The human tibia found at Boxgrove has been described as robust, similar to those of Neanderthals, but more robust than those of modern humans (Roberts et al., 1994; Stringer et al., 1998; Trinkaus et al., 1999), with a morphology interpreted as an adaptation to greater activity and the relatively harsh climatic conditions in Northern Europe during an interglacial that was probably cooler than the Holocene (Stringer et al., 1998; Stringer and Trinkaus, 1999). It is therefore plausible to infer that biologically stronger *H. heidelbergensis* applied more strength to their butchering action, resulting in the production of wider and deeper cut marks. However, the indication of use of greater force could have other explanations. Other factors may include the weight of the tool or condition of the carcass at the time of butchery. The importance of carcass condition has been discussed by Dewbury and Russell (2007), who have shown that ‘stiffness’ of the carcass due to *rigor mortis* or freezing can increase cut mark frequency because a stronger action is required. It is likely that difference in the state of decomposition of a carcass may also determine differences in the micromorphology of cut marks (Binford, 1984).

It is also possible, that the differences in cut mark morphology are a result of specific ways in which the handaxes were manipulated during different butchery task. From the anatomical location and orientation of cut marks, it has been predicted that specific cut marks can be linked to specific kind of butchery tasks, such as skinning, cutting, boning and dismembering (Binford, 1981, 1984; Bunn, 2001). The results obtained by the analyses of cut marks according to their anatomical position on the experimental material show a clear pattern when comparisons are made between cut marks located on the midshaft and cut marks located in proximity to the articulation. Cut marks close to (or on) an articulation were typically broader, deeper and have a greater inclination. These characteristics may be associated with disarticulation/dismembering process that require more force. Very few studies have described differences in the morphology of cut marks associated with differences in the butchery process (Binford, 1978, 1981, 1984). We suggest that the quantitative analysis of cut marks micromorphology using the Alicona technology could enhance this field of research by quantify cut marks profile parameters that can be associated with specific butchering actions.

Finally, cut marks parameters measured on roe deer and other large mammals fossils present some differences that could also be linked to different patterns of carcass-processing. Cut marks on large mammal fossils were typically broader, deeper and have a greater inclination when compared to cut marks observed on fossil roe deer. This result may suggest that a greater force was used in the butchery of larger (rhinoceros-sized) carcasses at Boxgrove. There is no agreement on the influence of carcass size on the frequency and morphology of cut marks. Some studies have reported differences in the frequency of butchering cut marks as a function of variation in carcass size (Lyman, 2002); some have suggested there is no simple relationship between cut mark frequency and amount of meat present (Lyman, 2005), and others have proposed that cut mark frequency is directly proportional to the strength of muscle attachments (Bunn, 2001; Potter, 2005). Further analyses should be undertaken to better understand the effect of carcass size on the butchering processes.

6. Conclusions

In this paper, we demonstrate that the analyses of cut mark micromorphology using the Alicona imaging microscope can be applied to the study of ancient and modern butchery slicing cut marks. The methodology proposed by Bello and Soligo (2008) can be equally applied to the study of experimentally produced cut marks and fossil cut marks with only minor modifications. These include profile analyses taken at the mid point of the cut and the use of two new indices (the Angle of the Tool Impact Index and the Shoulder Height Index).

The analyses of cut marks micromorphologies reveal specific patterns of butchery processing. Differences in the micromorphology characteristics of cut marks have been observed according to their anatomical position, which indicate different actions (i.e. dismembering *vs* filleting). The size of the carcasses also appears to have a significant influence on cut mark micromorphology (e.g. cut marks on rhinoceros bones were typically broader, deeper and have a greater inclination). Particularly noticeable are the differences between fossil and experimental slicing cut marks, with cut marks found on fossil material being generally broader and deeper. Although we suggested several possible interpretations, the most likely explanation relates to the use of different forces. We suggest that the biologically stronger *H. heidelbergensis* applied more strength during butchery. So far, the temporal trend in robusticity in *Homo* has been documented through osteometric cross-sectional analyses of post-cranial bones (e.g. Ruff et al., 1993, 1994; Stock and Shaw, 2007; Trinkaus, 1997). No association had been made, so far, between cut marks micromorphology and robusticity. This observation is the first attempt to associate the by-product of human activity to biological descriptions and may open new field of research on the behavioural repertoire and anatomical characteristics of Lower Palaeolithic hominins.

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