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Factors affecting Early Stone Age cut mark cross-sectional size: implications from actualistic butchery trials

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ABSTRACT

Early Stone Age cut marks are byproducts of hominins' tool-assisted animal carcass consumption and provide a potential avenue of inference into the paleoecology of hominin carnivory. If diagnostic cut mark characteristics can be linked to flake and core tool use or the completion of distinct butchery actions, it may be possible to infer ancient tool preferences, reconstruct the consumption of specific muscular tissues, and illuminate landscape-scale stone resource use. Recently, diagnostic morphological criteria including cut mark width and depth have been used to identify marks made by different classes of experimental and archaeological stone tools (Bello, S.M., Parfitt, S.A., Stringer, C., 2009. Quantitative micromorphological analyses of cut marks produced by ancient and modern handaxes. *Journal of Archaeological Science* 36: 1869–1880; de Juana, S., Galan, A.B., Dominguez-Rodrigo, M., 2010. Taphonomic identification of cut marks made with lithic handaxes: an experimental study. *Journal of Archaeological Science* 37: 1841–1850; Dominguez-Rodrigo, M., de Juana, S., Galan, A. B., Rodriguez, M., 2009. A new protocol to differentiate trampling marks from butchery cut marks. *Journal of Archaeological Science* 36: 2643–2654). The work presented here adds to this experimental butchery database by using measurements of cut mark cross-section taken from bone surface molds to investigate how stone tool characteristics including flake versus core tool type, edge angle, and tool weight, influence cut mark width and depth, ultimately testing whether cut mark size is a useful indicator of tool identity. Additionally, these experiments investigate the influence of contextual factors, including butchery action, carcass size, and bone density on cut mark size. An experienced butcher used replicated Oldowan flakes and bifacial core tools in experimental trials that isolated skinning, bulk and scrap muscle defleshing, and element disarticulation cut marks on goat and cow skeletons. This sample explores cut mark traces generated under realistic butchery scenarios and suggests the following results: 1) Core and flake tools were equally efficient at completing all butchery tasks in size 1 and 3 bovid carcasses. 2) Samples of cut mark width and depth produced by core and flake tools were similar and cut marks could not be accurately classified to a known tool type. 3) Skinning and disarticulation activities produced significantly wider and deeper marks than defleshing activities. 4) Cut marks on cows tended to be wider and deeper than those on goats. 5) Cut mark width is negatively correlated with bone density when carcass size and bone portion are taken into consideration. These results suggest that a general quantitative model for inferring tool type or edge characteristics from archaeological cut mark size is not warranted.

1. Introduction

Bone surface modifications created by stone tools during butchery encode information about the role of technology in the paleoecology of human carnivory (Binford, 1981; Bunn, 1981; Capaldo, 1997; Dominguez-Rodrigo, 1997; Dominguez-Rodrigo et al., 2005, 2010; Lupo, 1994; Lyman, 2005; McPherron et al., 2010; Nilssen, 2000; Potts and Shipman, 1981; Selvaggio, 1994, 1998; Shipman and Rose, 1983), and recent publications claim that cross-sectional size and morphology can be used to distinguish cut marks experimentally produced by different classes of Early Stone Age (ESA) tools including handaxes, retouched flakes and unmodified flakes (Bello et al., 2009; de Juana et al., 2010; Dominguez-Rodrigo et al., 2009; Greenfield, 2006). Applying these experimental results to identify archaeological flake and core tool use would shed light on whether ESA hominins utilized certain tools for processing large or small animal carcasses or for completing different butchery tasks (Bello et al., 2009; Jones, 1980;

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Pobiner and Braun, 2005; Toth, 1985; Wilson, 1982). Likewise, detecting flake and core butchery in different paleogeographic settings would help resolve whether cores were transported across ancient landscapes as multi-purpose butchery tools, or as portable raw material sources for flake production (Blumenschine and Peters, 1998; Blumenschine et al., 2008; Braun et al., 2008a; Bunn, 1981, 1994; Potts, 1991; Rogers et al., 1994). These higher-range paleoanthropological conclusions depend on accurate archaeological diagnoses of flake and core butchery traces, which in turn require a clear inferential connection between experimental cut mark morphology and its causal factors (Binford, 1981; Gifford-Gonzalez, 1991).

Experiments using replicated ESA tools to intentionally incise wooden boards or defleshed ungulate limb bones report morphological criteria, including cross-sectional size, that distinguish narrow and deep flake cut marks from wide and shallow core tool marks (Bello and Soligo, 2008; Greenfield, 2006; Walker and Long, 1977). Other studies successfully discriminate flake and core cut mark morphology when relatively inexperienced butchers completely process (i.e. skin, disarticulate and deflesh) carcasses or limb segments with replicated ESA tools (Bello et al., 2009; de Juana et al., 2010; Dominguez-Rodrigo et al., 2009). To date, experimental butchery studies describe cut mark morphology in relation to tool attributes, but have not thoroughly explored how potential confounding factors introduced during the butchery process affect cut mark size and shape or considered whether skeletal location impacts cut mark morphology.

It is hypothesized that in addition to stone tool type, cut mark size may be influenced by the increased effort necessary to butcher large animals, as well as the slicing mechanics involved in completing different butchery tasks like skinning, disarticulation and defleshing that target distinct soft tissues and incise different bone portions. Assessing whether cut mark size is a reliable signal of tool type in light of the potential variation in cut mark morphology introduced by these factors is necessary to create a causal link between classes of ESA effectors and cut mark morphology. The actualistic butchery study presented here explores the influence of ESA tool type on cut mark size while considering carcass size, butchery action, and the density of the bone portions where cut marks occur.

2. Materials and methods

2.1. Experimental design

Butchery trials consisted of half-carcass replications of fore- and hindlimb musculo-skeletal units without phalanges. Cut marks made by different tools were examined across butchery action (skinning, element disarticulation, bulk muscle defleshing, scrap

Table 1
Experimental butchery trial treatment information and summary statistics.[a]

Trial	Side	Size	Action	Tool ID	Tool Type	Raw Material	Edge Angle	Tool Weight	Cut Mark Count	Time	Mean Width	Median Width	STD Width	Mean Depth	Median Depth	STD Depth
IB12	R	cow	bulk	C40	core	chert	50	453.0	565	39	0.2649	0.2188	0.2057	0.0601	0.0625	0.0345
IB15	R	cow	bulk	C41	core	chert	60	96.5	228	38	0.2248	0.1875	0.1089	0.0561	0.0625	0.0257
IB12	L	cow	bulk	F50-9	flake	chert	42	26.1	415	52	0.2061	0.1875	0.1084	0.0523	0.0625	0.0271
IB15	L	cow	bulk	F40-4	flake	chert	38	39.9	212	46	0.2272	0.1875	0.1023	0.0597	0.0625	0.0334
IB13	L	cow	scrap	C37	core	chert	45	731.1	581	28	0.2378	0.2188	0.1053	0.0602	0.0625	0.0326
IB16	L	cow	scrap	C42	core	chert	56	102.8	270	31	0.2324	0.1875	0.2381	0.0512	0.0625	0.0241
IB13	R	cow	scrap	F83	flake	chert	32	5.2	233	31	0.2122	0.1875	0.1128	0.0506	0.0313	0.0288
IB16	R	cow	scrap	F70-1	flake	chert	67	38.8	270	26	0.2403	0.1875	0.1988	0.0543	0.0625	0.0380
IB7	R	goat	bulk	C29	core	chert	43	24.5	198	25	0.1870	0.1563	0.0907	0.0379	0.0313	0.0139
Tr3	R	goat	bulk	Tr3-r	core	phonolite	–	–	23	20	0.1811	0.1563	0.0612	0.0408	0.0313	0.0147
DB1	L	goat	bulk	DB1-l	flake	–	–	–	310	25	0.2113	0.1563	0.1452	0.0451	0.0313	0.0255
Tr3	L	goat	bulk	Tr3-l	flake	phonolite	–	–	64	20	0.1948	0.1563	0.0799	0.0464	0.0313	0.0243
IB10	R	goat	scrap	C35	core	chalcedonay	45	50.9	291	14	0.1823	0.1563	0.1010	0.0454	0.0313	0.0248
IB9	L	goat	scrap	C34	core	chalcedonay	65	27.9	418	13	0.1734	0.1563	0.0700	0.0464	0.0313	0.0209
IB10	L	goat	scrap	F92	flake	phonolite	36	65.1	272	15	0.1918	0.1563	0.1023	0.0507	0.0313	0.0267
IB9	R	goat	scrap	F71	flake	ignimbrite	16	8.8	331	19	0.1890	0.1563	0.1714	0.0458	0.0313	0.0232
IB11	L	cow	skinning	C36	core	chalcedonay	70	53.8	0	2	–	–	–	–	–	–
IB14	R	cow	skinning	C30	core	ignimbrite	63	514.6	3	6	0.4792	0.4688	0.2658	0.1458	0.0938	0.0902
IB11	R	cow	skinning	F50-11	flake	chert	35	58.4	4	2	0.5000	0.4688	0.2932	0.2109	0.2188	0.1260
IB14	L	cow	skinning	F40-1	flake	chert	56	129.0	3	4	0.4688	0.4688	0.0313	0.1979	0.1875	0.0786
IB11	R	cow	disarticulation	C36	core	chalcedonay	70	53.8	82	11	0.3589	0.3125	0.2312	0.0972	0.0781	0.0638
IB14	R	cow	disarticulation	C30	core	ignimbrite	63	514.6	32	36	0.5083	0.3326	0.4434	0.1484	0.0938	0.1609
IB11	L	cow	disarticulation	F50-2	flake	phonolite	50	193.7	53	13	0.5188	0.4375	0.3111	0.1297	0.0938	0.1046
IB14	L	cow	disarticulation	F40-1	flake	chert	56	129.0	49	17	0.3829	0.3215	0.2286	0.1122	0.0938	0.0802
IB2	R	goat	skinning	C1	core	ignimbrite	75	704.4	18	7	0.2847	0.2188	0.1226	0.0816	0.0781	0.0306
IB3	R	goat	skinning	C22	core	phonolite	70	357.0	9	2	0.4965	0.3750	0.2105	0.1389	0.1250	0.0627
IB2	L	goat	skinning	F34	flake	chert	53	7.6	2	6	0.3906	0.3906	0.3315	0.1094	0.1094	0.0663
Tr1	R	goat	skinning	Tr1-r	flake	phonolite	–	–	6	2	0.2917	0.2344	0.1393	0.0781	0.0781	0.0171
IB3[b]	R	goat	disarticulation – fore	C15	core	quartizte	52	103.3	7	2	0.3482	0.1414	0.0893	0.0893	0.0938	0.0420
IB3[b]	R	goat	disarticulation – hind	C13	core	quartizte	55	215.2	10	10	0.5813	0.2413	0.1781	0.1781	0.1406	0.1660
IB4[b]	R	goat	disarticulation – fore	C7	core	ignimbrite	52	115.1	16	3	0.4375	0.2914	0.1367	0.1367	0.0938	0.1057
IB4[b]	R	goat	disarticulation – hind	C14	core	chert	50	240.9	40	6	0.3958	0.1429	0.1052	0.1052	0.0938	0.0362
IB3[b]	L	goat	disarticulation – fore	F26	flake	chalcedonay	17	6.8	9	2	0.2465	0.1254	0.1007	0.1007	0.1250	0.0304
IB3[b]	L	goat	disarticulation – hind	F37	flake	chert	5	16.1	43	4	0.2246	0.1090	0.0770	0.0770	0.0625	0.0417
IB4[b]	L	goat	disarticulation – fore	F23	flake	ignimbrite	38	25.7	14	2	0.2969	0.1750	0.0915	0.0915	0.0625	0.0740
IB4[b]	L	goat	disarticulation – hind	F32	flake	chert	22	15.4	24	5	0.3893	0.2549	0.1289	0.1289	0.0938	0.1015

[a] Tool edge angle is recorded in degrees, tool weight is in grams, butchery time is in minutes, and the mean, median and standard deviation of cut mark size are in millimeters. Core trials are shaded in grey and flake trials are unshaded.

[b] In goat trials, a different tool was used to disarticulate the forelimb and hindlimb.

muscle defleshing), carcass size (mammalian size class 1 (goat) and 3 (cow)), and long bone portion (proximal epiphysis, proximal near-epiphysis, midshaft, distal near-epiphysis and distal epiphysis) categories. The sample of 32 butchery trials follows a full factorial design with two half-carcass replications of each tool type/action/size treatment (Table 1). Merritt (2011) includes a more detailed description of the experimental methodology that is described below.

2.2. Hypotheses tested

It is hypothesized that cut mark size is influenced by butchery action, bone portion, animal size class, and tool type. The effect of these factors on cut mark size is used to construct an experimental sub-sample where the relationship between cut mark width, depth and tool attributes can be explored with minimal confounding influence.

Butchery trials were conducted to test the following hypotheses:

1. Flakes and cores are equally effective at accomplishing the same butchery action within an animal size class.
2. Flakes make narrower and deeper cut marks than cores.
3. Tool edge angle correlates positively with cut mark width and negatively with depth.
4. Tool weight correlates positively with cut mark width and depth.
5. Cut mark width and depth are similar across animal size classes.
6. Skinning and disarticulation produce wider, deeper cut marks than defleshing large muscles or scraps of tissue.
7. Wider and deeper cut marks occur on less dense long bone end portions (epiphyses and near-epiphyses) than midshafts.
8. Average defleshing cut mark width per portion negatively correlates with bone density.

In these experiments, a single tool was used in each butchery trial, and it produced a number of cut marks on the skeleton. Every mark incised by one tool during a butchery trial is a repeated measurement of the relationship between the tool and cut mark size, not an independent observation, which violates an assumption of most inferential statistical tests (see Hurlbert, 1984 for a discussion of pseudoreplication and independence). Still, each tool is expected to produce cut marks that differ in size, and this variation may be influenced by other factors like slicing angle and pressure or bone density per portion, which may be masked as cut mark measurements are summarized per tool. The total sample of cut marks was analyzed to explore patterning in cut mark size distributions, but since these results have less inferential power, they are compared with summaries of cut mark size per tool.

2.3. Experimental butchery procedure

Cow and goat carcasses from animals greater than 2 years of age were purchased from Dassanech pastoralists near the town of Ileret, Northern Marsabit District, Kenya, and after butchery, the meat was donated to local community members. A Dassanech man experienced in livestock butchery conducted all experimental trials to eliminate idiosyncratic variability in cut mark production. He was offered a choice of replicated Oldowan unmodified cortical and non-cortical flakes and bifacially flaked cores knapped by the author from raw materials that occur archaeologically at Koobi Fora, including chert, chalcedony, phonolite, ignimbrite and quartzite. He was asked to select a flake or core of any material, and to perform each butchery action as efficiently as possible. The butcher was naïve about the analysis of cut mark size. Tools were never retouched during butchery and in most cases a single tool was used on both the fore- and hindlimb in each half-carcass trial. Butchery trials were recorded on video and timed to the nearest minute.

Tool edge angle was measured with a goniometer at the most obtuse point along the cutting edge, and tool weight was measured to the nearest gram with a digital scale. In four pilot butchery trials included in this study, tools were discarded before edge angle and weight were recorded. Non-parametric Kruskal–Wallis tests were used to confirm that tool edge angle and weight were evenly distributed across experimental trials. The core sample has a significantly wider median edge angle than the flake sample ($X^2 = 10.70$, d.f. $= 1$, $p < 0.001$), but tools of similar edge angle were used to butcher cows and goats ($X^2 = 1.95$, d.f. $= 1$, $p = 0.163$), and to accomplish different butchery actions ($X^2 = 5.06$, d.f. $= 3$, $p = 0.167$). Compared to the modified needle-point caliper method, a goniometer is less accurate, particularly when measuring narrow-edged tools (Dibble and Bernard, 1980), therefore experimental flake edge angle may include more measurement error. However, this inaccuracy is random and present in all experimental factor categories because both flakes and cores include wide and narrow examples, and both tool types were used to process large and small carcasses and complete different butchery actions. Cores were significantly heavier than flakes ($X^2 = 10.70$, d.f. $= 1$, $p < 0.001$), but goat and cow trials and butchery action trials were conducted with tools of similar weight ($X^2 = 2.16, 5.06$, d.f. $= 1, 3$, $p = 0.142, 0.163$, respectively).

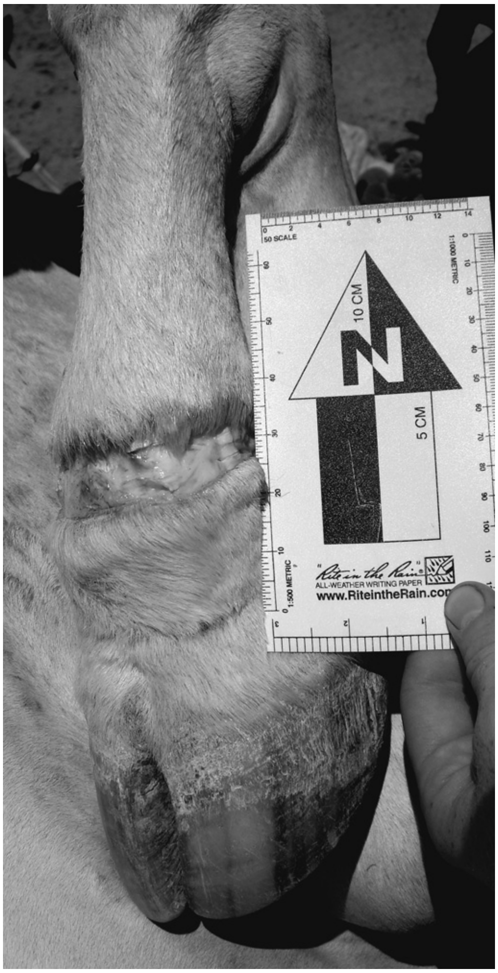

Fig. 1. A transverse skinning incision made with a stone tool on a cow distal metapodial. The north arrow is 10 cm long from point to base.

The lithic raw material used in each trial was an aspect of the butcher's tool selection, and was not systematically controlled in order to examine how tool type influences cut mark size regardless of raw material. However, experimental flakes and cores made from glassier materials (chert and chalcedony) were not significantly wider or heavier than the corresponding tool made from coarser materials (phonolite, ignimbrite and quartzite) (ANOVA with interaction of tool type and material texture category: $F = 0.77, 1.22$, d.f. = 1, 1, $p = 0.388, 0.279$, for edge angle and weight respectively).

To examine how cut mark morphology varies with butchery action, a single action that targeted mutually exclusive soft-tissues was conducted per trial. Skinning included transverse slices around the distal near-epiphyses of the metapodials and medial incisions running superiorly up each leg (Fig. 1). In a pilot study, contact between the stone tool and bone during skinning was limited to the transverse incision that severed the hide and cut through subcutaneous tissue into the bone surface. Therefore after the initial incision, skinning was completed with a metal knife and the hands. The time recorded for skinning trials represents only the transverse incision made with stone tools.

Disarticulation trials investigate cut marks produced by disarticulating limb elements, excluding the phalanges. Preparation for disarticulation involved flesh removal with a metal knife, which was completed with care to prevent contact with bone and left a small amount of muscle tissue surrounding the joints. A search with a 10× handlens identified a few metal knife preparation marks on shaft portions, which were not measured. These marks were easily distinguished from stone tool cut marks based on their length and deep, acute V-shaped cross section (Blumenschine et al., 1996).

Bulk muscle defleshing targeted the large muscle groups of the forelimbs and hindlimbs including the scapula and innominate. The metapodials and phalanges were not defleshed since they are encased in tendon. The butcher was asked to remove as much flesh as necessary, without disarticulating the bones, to expose the majority of the shaft so that fragmentation with a hammerstone and anvil would be possible. Typically, this resulted in adhering flesh scraps around joints and muscle attachment sites. The periosteum was not removed.

Scrap defleshing targeted flesh that remained after bulk defleshing, but these trials were conducted separately (Fig. 2). Goat and cow limbs typically yielded between 250 and 500, and 500–1000 g of muscle scraps respectively, which were concentrated on the scapular basins, ilium, and around joints. Bulk muscles were removed carefully with a metal knife and this process was observed closely and video-recorded to exclude metal knife preparation marks from analysis.

2.4. Experimental cut mark identification, molding and measurement

Bones were boiled in saline-alkaline water from lake Turkana, adhering soft tissue was removed by hand, and boiling episodes continued until fatty residues no longer covered the dry bone surface.

Each element was examined under strong, low-incidence light from at least two directions using a 10× handlens to identify cut marks (Blumenschine et al., 1996; Bunn, 1981; Potts and Shipman, 1981). Cut mark location was recorded on a bone portion scale following Blumenschine (1995) and Lyman (1994), where proximal epiphyses (PEPI) and distal epiphyses (DEPI) contain articular and non-articular bone and are bounded by the metaphysis. Proximal near-epiphyses (PNEF) and distal near-epiphyses (DNEF) contain cancellous medullary surfaces, and include the area from the metaphysis to the beginning of the midshaft diameter. These portions typically contain muscle attachments like the deltoid and radial tuberosities, lesser trochanter and the tibial crest, and in sub-adult domesticates may possess a roughened cortical texture, particularly in DNEF. Midshaft (MSH) portions occur between PNEF and DNEF portions and have smooth cortical and medullary surfaces.

A cluster of slices is counted as a single cut mark by some authors (de Juana et al., 2010; Johnson and Bement, 2009; Lyman, 2005), but this study counts each distinct V-shaped striation with

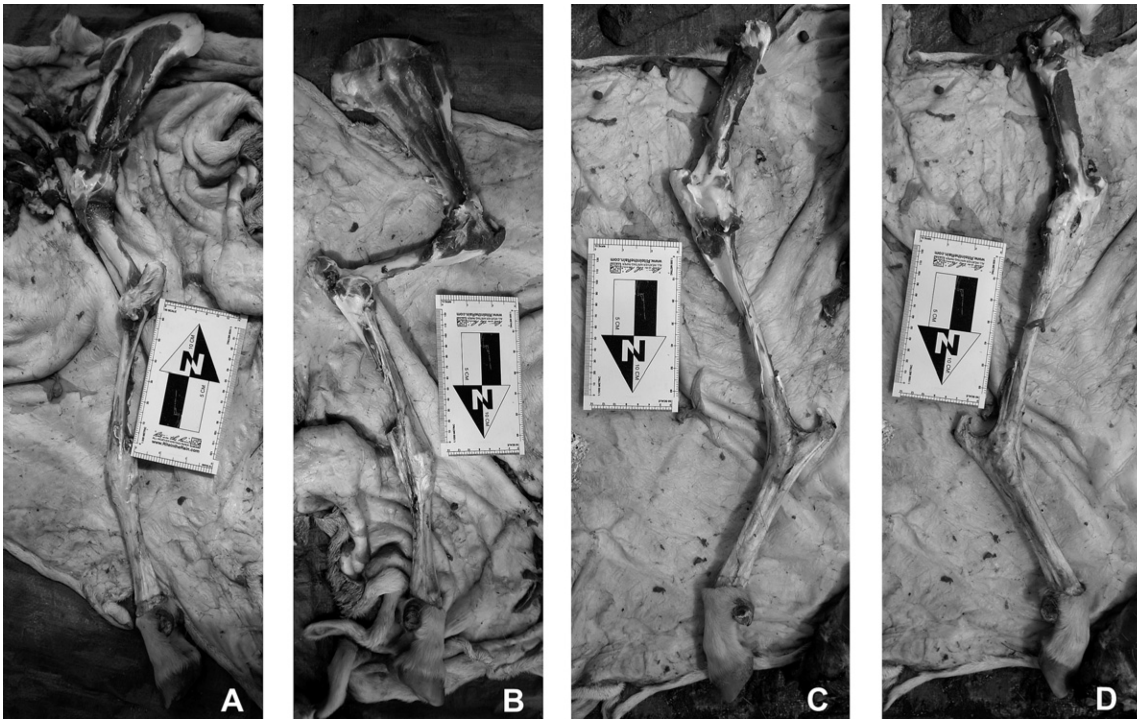

Fig. 2. Typical flesh amount and location on goat limbs at the end of bulk muscle defleshing trials and the beginning of muscle scrap defleshing trials. The north arrow is 10 cm long from point to base. A) Left forelimb, lateral view. B) Left forelimb, medial view. C) Left hindlimb, lateral view. D) Left hindlimb, medial view.

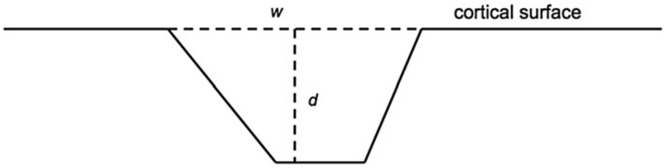

Fig. 3. Schematic of cut mark cross section. Width (w) is the distance from each edge of the incision into cortical bone, and includes all sub-parallel internal striae associated with an incision. Depth (d) is the perpendicular distance from the deepest point of a cut mark's floor to the estimated cortical surface, which is modeled as a straight line between the mark's edges.

internal microstriae as a single cut mark (Bunn, 1981). Each cluster of cut marks was drawn, and each mark was given a number. Cut mark clusters were molded with 3M Express Bite Registration putty. With reference to the bone and cluster drawing, each numbered mark was identified on the mold and cross-sectioned at its widest point. Cut mark width, defined as the distance across the incision into the cortical surface, and depth, defined as the perpendicular distance from the cortical surface to the mark's floor, were measured using a binocular microscope at 32× magnification with a micrometer disc precise to 0.03125 mm (Fig. 3). Every cut mark was molded and measured.

To test reproducibility, the width and depth of 36 randomly selected cut marks was re-measured. The average percent difference between initial and re-measured values was 23.6%, but 93% of the 72 width and depth measurements are less than 0.09 mm from their initial value.

3. Results

3.1. *Flake versus core butchery time*

Butchery trial time is similar when a paired *t*-test is used to compare flake and core trials of the same animal size class and butchery action ($t = 0.075$, $p = 0.941$). This result is supported by the Wilcoxon Rank Sum test ($Z = 0.189$, $p = 0.850$). An ANOVA with interaction effects that examines defleshing trial time finds that cows took significantly longer to deflesh ($F = 22.6$, d.f. $= 1$, $p < 0.001$), but neither tool type was quicker in the entire sample ($F = 42.3$, d.f. $= 1$, $p = 0.405$), or in goat or cow trials ($F = 0.16$, d.f. $= 1$, $p = 0.698$). Trial time data are not distributed normally, but both ANOVA on logarithmically transformed time and the Kruskal–Wallis test on untransformed data ($X^2 = 18.3$, d.f. $= 1$, $p < 0.001$) find significant differences only between goat and cow trials.

3.2. *Median cut mark size differences across single-factor categories*

Box and whisker plots are used to visualize the distributions of cut mark size for each tool type, carcass size, and butchery action category. When all cut marks are examined, the most apparent difference occurs between wide and deep skinning and disarticulation marks versus narrow and shallow bulk and scrap defleshing marks (Fig. 4).

The median flake and core cut marks' width is equal (0.1875 mm), and their right-skewed distributions are nearly identical with equivalent interquartile ranges. Interestingly, the Kruskal–Wallis test finds a significantly larger median cut mark in the core tool sample ($X^2 = 15.2$, d.f. $= 1$, $p < 0.001$). This result is influenced by measurement precision, which resulted in a large number of cut marks with the same width value. This suggests that core marks are wider than flake marks, but the similarity of each tool type's cut mark size distribution is corroborated by the histogram of cut mark width (Fig. 5). Likewise, the median core cut mark's depth (0.0625 mm) is significantly deeper than the median flake mark (0.0312 mm) ($X^2 = 11.5$, d.f. $= 1$, $p < 0.001$), but the interquartile ranges of both tools' marks overlap completely (Fig. 6).

The median cut mark width and depth in the cow sample is significantly larger than in the goat sample ($X^2 = 220.8$, d.f. $= 1$, $p < 0.001$, for width; $X^2 = 182.4$, d.f. $= 1$, $p < 0.001$, for depth). The

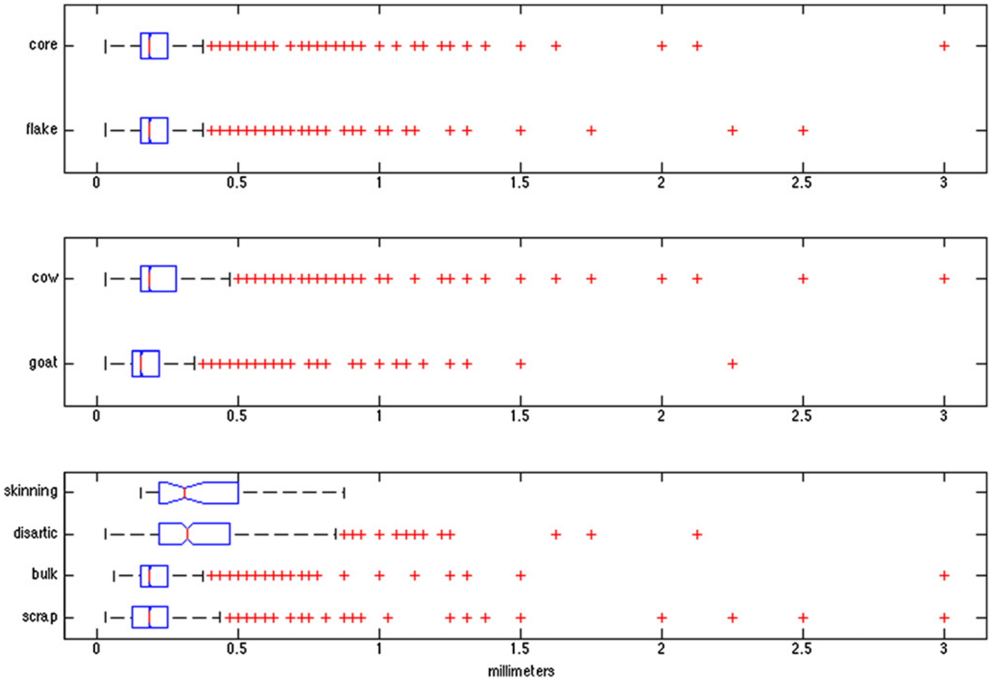

Fig. 4. Box and whisker plots show the distribution of cut mark width across tool type, animal size class, and butchery action categories. The box represents the interquartile range, (the values that include the middle 50% of observations), the whiskers extend to +/− 1.5 times the IQR, and outlying values are represented with '+' symbols. The notch around the median line is a visual assessment of the Kruskal–Wallis test for different medians. When notches do not overlap in a plot, medians are significantly different at $p = 0.05$.

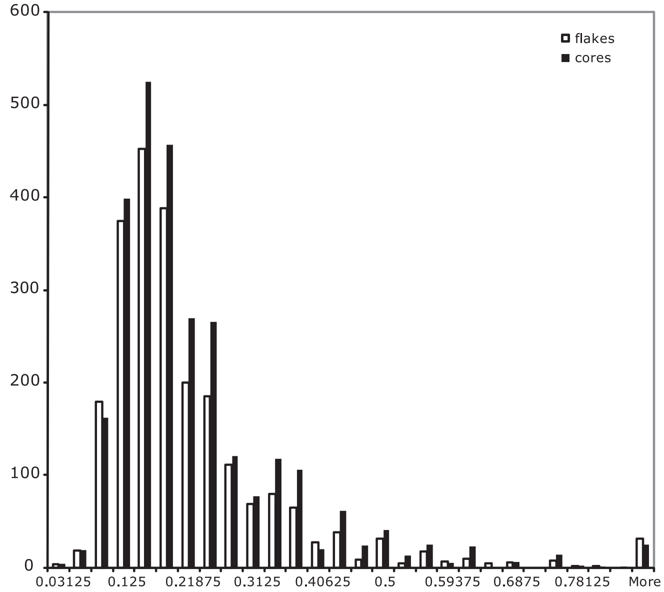

Fig. 5. Distribution of width measurements (millimeters) for every cut mark in the experimental sample.

interquartile range of cut mark width in cows includes higher values than in goats, but cut mark depth has an identical range across carcass size categories.

Skinning and disarticulation marks have equivalent median width and depth, but are significantly wider and deeper than the median bulk and scrap defleshing marks ($X^2 = 370.2$, d.f. $= 3$, $p < 0.001$, for width; $X^2 = 524.1$, d.f. $= 3$, $p < 0.001$, for depth). Bulk and scrap defleshing marks have equal median widths, different median depths, and an equivalent interquartile range.

When all defleshing marks on goat and cow long bones are considered, the median MSH mark is indistinguishable from the median PNEF mark, but significantly narrower than the median DNEF and EPI marks ($X^2 = 53.4$, d.f. $= 4$, $p < 0.001$) (Fig. 7). Cut mark depth occupies a much narrower range of values across long bone portions in defleshing trials, but the median MSH and PNEF are equivalent and shallower than the median DNEF and EPI cut marks ($X^2 = 108.5$, d.f. $= 4$, $p < 0.001$) (Fig. 8).

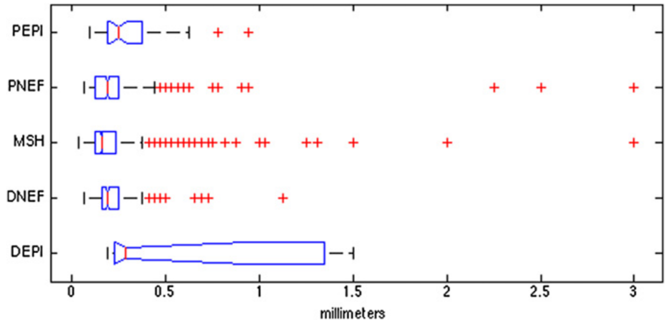

Fig. 7. Box and whisker plots show the distribution of defleshing cut mark width across long bone portion categories. Cut marks on the scapula and innominate are not included.

3.3. *Cut mark size differences per tool*

Although cut mark distributions tend to be right-skewed and kurtotic, mean cut mark width and depth are calculated per tool because the sample of marks is large in defleshing trials, and the greater width and depth of skinning and disarticulation marks is confirmed by the Kruskal–Wallis test on the total mark sample. ANOVA on log-transformed average mark width and depth per tool indicates that skinning and disarticulation trials produced wider and deeper cut marks compared to defleshing trials ($F = 25.56$, d.f. $= 3$, $p < 0.001$, for width; $F = 46.37$, d.f. $= 3$, $p < 0.001$, for depth), which is supported by the Kruskal–Wallis test ($X^2 = 19.89$, d.f. $= 3$, $p < 0.001$, for width; $X^2 = 22.81$, d.f. $= 3$, $p < 0.001$, for depth). This analysis also indicates that cow trials contained wider and deeper

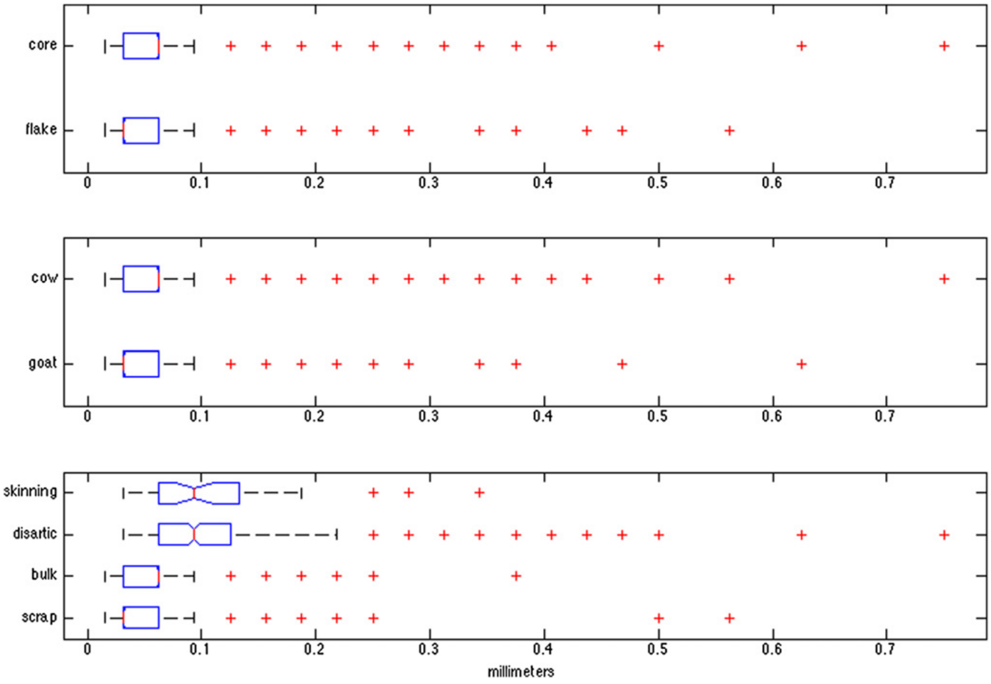

Fig. 6. Box and whisker plots show the distribution of cut mark depth across tool type, animal size class, and butchery action categories.

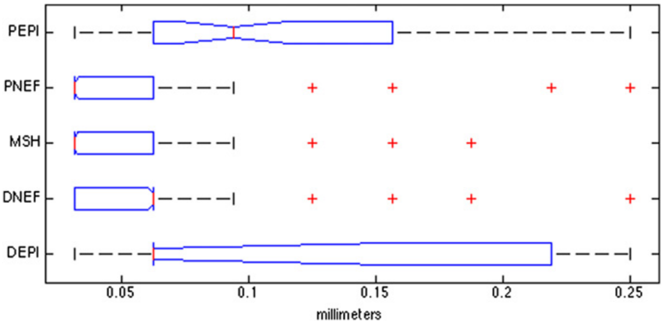

Fig. 8. Box and whisker plots show the distribution of defleshing cut mark depth across long bone portion categories. Cut marks on the scapula and innominate are not included.

cut marks than goat trials, but this result is not supported by the Kruskal–Wallis test (X^2 = 0.62, d.f. = 1, p = 0.429, for width; X^2 = 0.3516, d.f. = 1, p = 0.553, for depth). Flake and core trials produced similar size cut marks per tool (F = 1.55, d.f. = 1, p = 0.223, for width; F = 0.03, d.f. = 1, p = 0.862, for depth), which is supported by the Kruskal–Wallis test (X^2 = 0.16, d.f. = 1, p = 0.693, for width; X^2 = 0.014, d.f. = 1, p = 0.906, for depth).

A scatter plot matrix shows the relationship between tool edge angle and weight against average cut mark width and depth per tool, separated into carcass size and tool type categories (Fig. 9). In both goat and cow trials, tools of similar edge angle or weight tend to produce wider and deeper cut marks when used for skinning or disarticulation versus defleshing. Within butchery action and carcass size categories no clear pattern describes the relationship between cut mark size and tool variables.

Correlation analyses were carried out in goat and cow trials to examine the relationship between average cut mark size and tool edge angle and weight regardless of tool type (Table 2). Skinning and disarticulation trials were considered separately from defleshing trials, which only include marks on MSH portions. Lilliefors tests indicate that tool attributes and cut mark size were distributed normally within all sub-samples once a base-10 logarithmic transformation of tool weight reduced its skewness and kurtosis. Pearson's and Spearman's analyses show the weak correlation between tool edge angle or weight and average cut mark width or depth in the skinning and disarticulation sub-sample. In the defleshing sub-sample, average MSH cut mark width is positively correlated with log-transformed tool weight in cow trials, and average MSH cut mark depth is positively correlated with log-transformed tool weight in goat trials. With such loose relationships between tool attributes and average cut mark size, and inconsistencies across carcass size and butchery action categories, regression analysis cannot explain a large proportion of variance in cut mark dimensions.

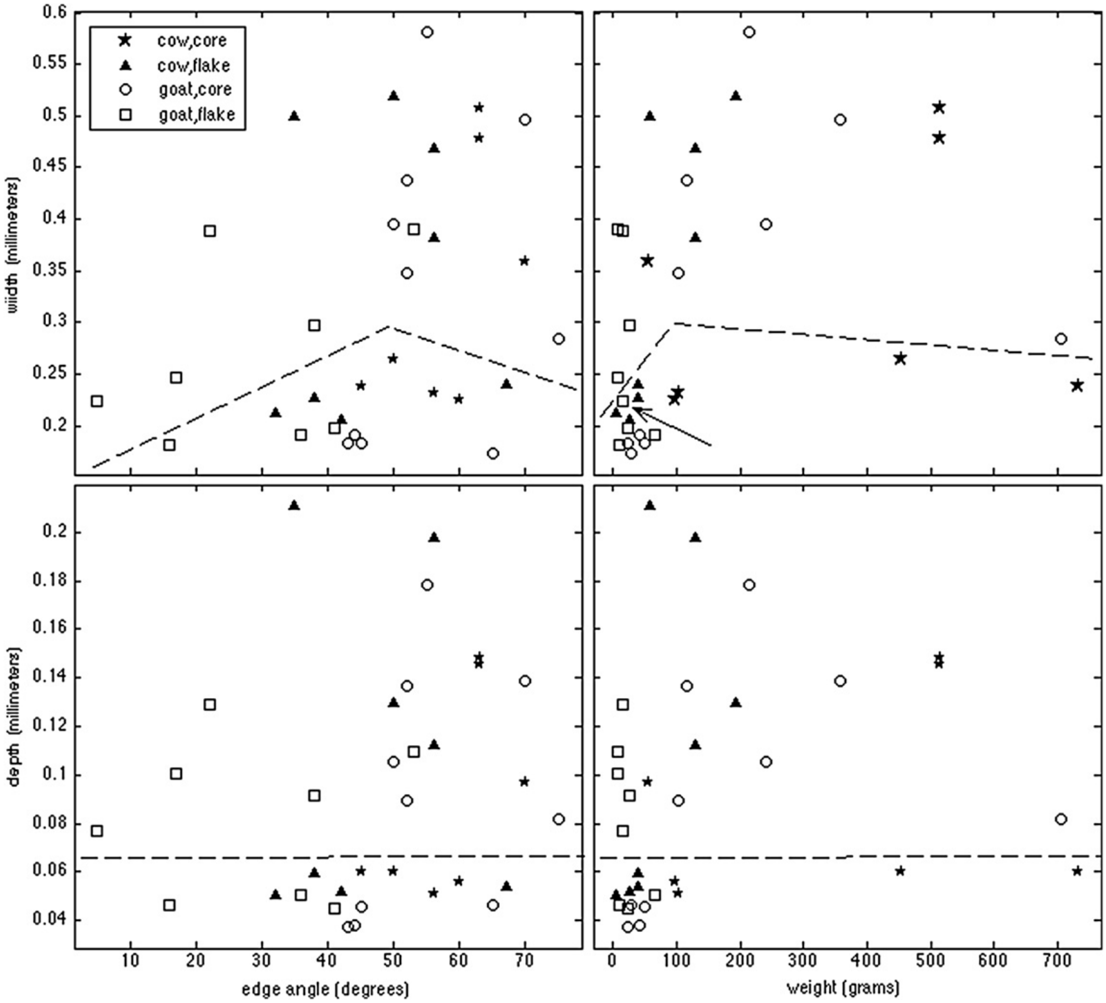

Fig. 9. Scatter plot matrix of tool variables versus average cut mark size per tool. Points above the dashed lines in each plot are skinning and disarticulation trials. Defleshing trials occur below the line. An outlying disarticulation trial in the tool weight vs. cut mark width plot is indicated by an arrow.

Table 2
Correlation between tool variables and average cut mark size per tool in samples stratified by animal size class and butchery action[a].

Correlation of edge angle and average cut mark width					Correlation of edge angle and average cut mark depth				
	Skinning and disarticulation		Defleshing MSH			Skinning and disarticulation		Defleshing MSH	
	Cow	Goat	Cow	Goat		Cow	Goat	Cow	Goat
Pearson									
r	−0.497	0.539	0.249	0.724	*r*	−0.676	0.279	0.149	0.477
p	0.257	0.087	0.553	0.166	*p*	0.096	0.406	0.725	0.417
Spearman									
r	−0.491	0.565	0.333	0.700	*r*	−0.527	0.365	0.143	0.300
p	0.265	0.070	0.428	0.233	*p*	0.237	0.271	0.752	0.684
Correlation of log tool weight[b] and average mark width					Correlation of log tool weight[b] and average cut mark depth				
Pearson									
r	0.501	0.457	0.769	0.701	*r*	−0.072	0.245	0.360	0.928
p	0.252	0.158	**0.026**	0.188	*p*	0.879	0.468	0.381	**0.023**
Spearman									
r	0.600	0.436	0.857	0.300	*r*	0.164	0.146	0.429	1.000
p	0.173	0.183	**0.011**	0.684	*p*	0.724	0.673	0.299	**0.017**

[a] Boldface type indicates a significant correlation.
[b] Base 10 logarithmic transformation.

3.4. Discrimination of known flake and core tool marks

When cut mark size is averaged per tool in the defleshing MSH sub-sample (Table 3), ANOVA tests on log-transformed average mark width and depth indicate that flake and core trials produced similar size marks within goat and cow sub-samples ($F = 2.9$, d.f. $= 1$, $p = 0.115$; $F = 0.3$, d.f. $= 1$, $p = 0.619$; differences related to tool type in width and depth respectively), but wider and deeper cut marks tend to occur in cow trials regardless of tool type ($F = 26.8$, d.f. $= 1$, $p < 0.001$; $F = 32.8$, d.f. $= 1$, $p < 0.001$; differences related to size class in width and depth respectively). The similarity of flake and core cut mark size is corroborated by Kruskal–Wallis tests for different median average cut mark size per trial (Figs. 10 and 11).

Linear discriminant function analysis (DFA) is used to describe the multivariate width and depth distributions of flake and core marks. Each cut mark is classified to a tool type according to its width and depth, and the percentage of correctly classified cases is recorded. If classification is typically successful, tool type may be confidently inferred from cut mark size.

DFA examines cut mark size on two scales: individual cut marks, which inform about the distribution of flake and core cut mark size, but are not independent observations, and average cut mark size per tool, which meets the assumption of statistical independence and multivariate normality. Cow and goat cut marks were considered separately, and only cut marks on midshaft portions from defleshing trials were included to minimize confounding effects introduced by different butchery actions or bone portion densities. Individual cut mark width and depth samples were adjusted with a base-10 logarithmic transformation. This does not produce multivariate normal samples, but the large number of marks lessens the impact of outlying values.

This DFA calculates the percentage of marks or trials classified as the correct tool type, weighted by the prior probabilities of group membership based on group sample sizes. The result is compared to the proportional chance criterion (Morrison, 1969 in McGarigal et al., 2000) to evaluate classification success against random assignment of cases to flake and core categories based on their frequency in the known sample (Kovarovic et al., 2011).

In the cow sample 62.9% of marks were correctly classified using log-transformed width and depth, but this is only 9.6% better than classification into flake or core categories if marks were randomly assigned to a tool type. Goat cut marks were correctly classified 56.6% of the time, which is only 5.7% better than random assignment (Table 4). Average cut mark size per tool leads to a correct classification rate of 62.5% in both cow and goat trials, which is only 12.5% better than random assignment.

Table 3
Midshaft defleshing cut mark size per tool (millimeters)[a].

Size	Tool Type	Tool	Cut Mark Count	Mean Width	Mean Depth
Cow	core	C37	129	0.2379	0.0584
Cow	core	C40	163	0.2255	0.0548
Cow	core	C41	45	0.2254	0.0604
Cow	core	C42	106	0.2023	0.0451
Cow	flake	F40-4	50	0.2196	0.0550
Cow	flake	F50-9	119	0.2019	0.0475
Cow	flake	F70-1	43	0.2182	0.0545
Cow	flake	F83	49	0.2015	0.0523
Goat	core	C29	81	0.1670	0.0359
Goat	core	C34	124	0.1633	0.0408
Goat	core	C35	60	0.1802	0.0427
Goat	core	Tr3R	9	0.1989	0.0417
Goat	flake	F71	67	0.1297	0.0341
Goat	flake	F92	74	0.1537	0.0443
Goat	flake	Tr3L	16	0.1660	0.0391
Goat	flake	DB1L	202	0.1888	0.0421

[a] Core trials are shaded in grey and flake trials are unshaded.

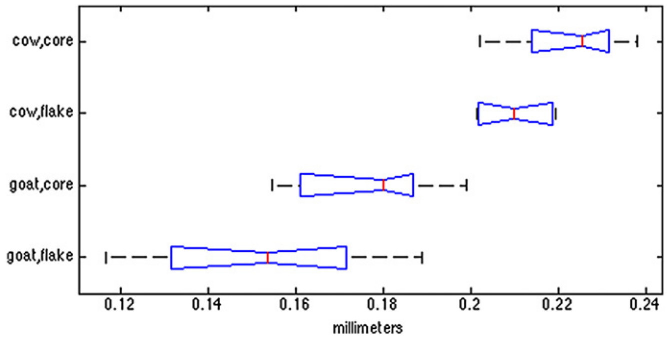

Fig. 10. Box and whisker plots show the distribution of average cut mark width per tool on MSH portions of defleshing trials. Flake and core trials produced marks with similar average width, but wider marks tend to occur in cow trials (Kruskal–Wallis test: $X^2 = 13.9$, d.f. $= 3$, $p < 0.004$).

3.5. Cut mark size across bone portions of different density

Bone mineral density (BMD) data for different anatomical regions of the *Connochaetes taurinus* skeleton (Lam et al., 1999) are used to examine the relationship between average cut mark width per portion and bone density in goat and cow defleshing sub-

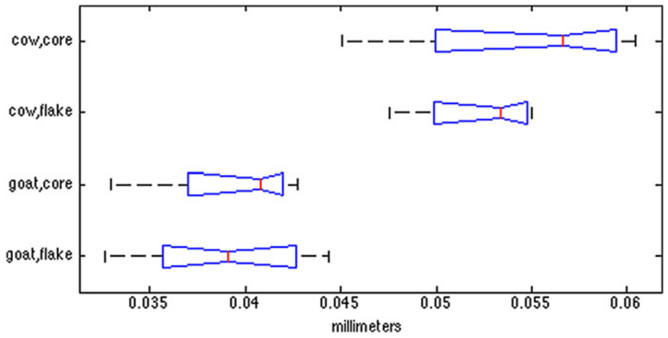

Fig. 11. Box and whisker plots show the distribution of average cut mark depth per tool on MSH portions of defleshing trials. Flake and core trials produced marks with similar average depth, but wider marks tend to occur in cow trials (Kruskal–Wallis test: $X^2 = 12.8$, d.f. $= 3$, $p < 0.006$).

Table 4
Classification success for MSH defleshing cut marks.

	Number of marks	Classification success	C_{pro}[a]	Number of trials	Classification success	C_{pro}[a]
Cow						
Core	261	62.9%	53.3%	4	62.5%	50.0%
Flake	443			4		
Goat						
Core	274	56.6%	50.9%	4	62.5%	50.0%
Flake	359			4		

[a] Proportional chance criterion $= p^2 + (1 - p)$, where p is the proportion of cases in the first group (Morrison, 1969).

Table 5
Bone portion density values and mean cut mark width per portion in millimeters.

Element	Portion	Portion code	BMD *C. taurinus*[a]	Mean cut mark surface width	
				Cow	Goat
Scap	glenoid and tubercle	SP1	1.02	0.344	n/a
Scap	neck	SP2	1.01	0.234	0.197
Scap	ant border and basin	SP3	0.73	0.199	0.198
Scap	post border and basin	SP4	0.98	0.223	0.200
Scap	distal blade	SP5	0.50	n/a	n/a
Hum	PEPI	HU1	0.32	0.333	0.219
Hum	PNEF	HU2	0.49	0.216	0.205
Hum	MSH	HU3	1.10	0.248	0.172
Hum	DNEF	HU4	1.03	0.237	0.178
Hum	DEPI	HU5	0.51	0.363	0.188
Rad	PEPI	RA1	0.51	0.313	0.281
Rad	PNEF	RA2	1.02	0.228	0.158
Rad	MSH	RA3	1.07	0.221	0.161
Rad	DNEF	RA4	0.96	0.510	0.172
Rad	DEPI	RA5	0.47	1.500	n/a
Ulna	olceranon	UL1	0.46	0.278	0.193
Ulna	semi-lunar notch	UL2	0.85	n/a	n/a
Ilium	blade	IL1	0.39	0.212	0.257
Ilium	ramus	IL2	0.96	0.265	0.195
Acetabulum	acetabulum	AC1	0.64	n/a	0.297
Pubis	ramus	PU1	0.40	0.312	0.225
Pubis	symphysis	PU2	0.56	0.328	n/a
Ischium	superior to acetabulum	IS1	0.92	0.222	0.336
Ischium	tuberosity	IS2	0.31	0.219	0.202
Fem	PEPI	FE1	0.41	n/a	n/a
Fem	greater trochanter	FE7	0.31	0.453	0.303
Fem	PNEF	FE2	0.51	0.218	0.187
Fem	MSH	FE4	1.16	0.210	0.166
Fem	DNEF	FE5	0.66	0.207	0.186
Fem	DEPI	FE6	0.38	n/a	n/a
Tib	PEPI	TI1	0.42	0.281	0.250
Tib	PNEF	TI2	0.91	0.286	0.172
Tib	MSH	TI3	1.12	0.222	0.183
Tib	DNEF	TI4	1.09	0.242	0.344
Tib	DEPI	TI5	0.59	n/a	n/a

[a] BMD values from Lam et al. (1999).

samples (Table 5). When the scapula and innominate are included, the goat sample shows a significant negative rank-order correlation between per-portion cut mark width and BMD (Spearman's $r = -0.547$, $p = 0.003$), although the cow sample does not (Spearman's $r = -0.233$, $p = 0.224$). When only long bone portions are considered, both cow and goat samples show significant negative rank-order correlations between average mark width and BMD (Spearman's $r = -0.475$, $p = 0.047$, for cows; $r = -0.613$, $p = 0.009$, for goats).

4. Discussion

The results of these experiments suggest that cut mark size changes more with butchery action, carcass size, and bone density than tool type, weight, and edge angle. Despite significant differences in edge angle and weight among tool classes, flake and core cut mark size is similar when individual mark distributions are compared and when average cut mark size per tool is examined. Skinning and disarticulation produce wider and deeper samples of cut marks compared to defleshing, but these actions primarily target less dense epiphyseal and near-epiphyseal bone portions. Exploring the relationship of bone density and cut mark size in defleshing trials shows that wider and deeper cut marks occur on less dense long bone portions, suggesting that "variation in slicing mark morphology is influenced by the properties of bone" (Bromage and Boyde, 1984: 366). Therefore, examining MSH cut marks from defleshing trials minimizes the confounding effects of butchery action and bone density on mark size, but even in this experimental sub-sample flakes and cores create marks with similar width and depth distributions.

Wider and deeper cut marks tend to occur on larger animals in this study. The median cut mark in cow trials was significantly wider and deeper than in goat trials, and average cut mark width was larger in nearly all cow bone portions. Since cows were not typically butchered with wider-edged, heavier tools, the difference in average defleshing mark width per portion may reflect the increased effort of butchering large animal carcasses.

Although cow and goat samples both display significant negative rank-order correlations between BMD and cut mark width across skeletal portions, average cut mark width values per portion are not correlated in goats and cows (Pearson's $r = 0.131$, $p = 0.525$). Animal size is not assumed to influence bone density values per portion (Lam et al., 1999), so the intertaxonomic differences in defleshing cut mark width may be an artifact of averaging cut mark width per portion for different trials. Regardless, the relationship between bone density and cut mark size is significant in both animal size classes.

Overall, the results of this study contradict the majority of previous butchery experiments that successfully discriminate flake and core marks, most likely because they focused primarily on the relationship between tool attributes and cut mark size or shape, and excluded contextual factors that affect cut mark morphology like bone density, animal size, and the mechanics of completing different butchery actions. By intentionally incising cut marks onto defleshed bone or flat wooden boards (Bello and Soligo, 2008; de Juana et al., 2010; Greenfield, 1999, 2006; Walker and Long, 1977), and butchering limbs "with the intention of imparting marks on bone surfaces" (de Juana et al., 2010: 1842), previous studies may have under-represented the range of cut mark sizes created during flake and core butchery. The experiments presented here replicate cut mark creation as an incidental effect of completing different butchery tasks, not the intended goal of carcass processing (Fisher, 1995; Shipman and Rose, 1983), and quantify flake and core tool marks in light of contextual factors that influence cut mark size. Therefore this investigation, which examines the skeletal traces of distinct butchery behaviors across different parts of the skeleton in large and small animals, is a realistic model of cut mark size variability created by flakes and cores.

5. Conclusion

These butchery trials model ancient traces of carcass processing by using replicated Oldowan bifacial cores and flakes to complete a variety of tasks, and indicate that butchery action, bone density, and carcass size affect cut mark width and depth. Even when these confounding effects are controlled, as in the MSH sample of defleshing cut marks that is separated into animal size classes, flake and core cut mark cross-sectional size cannot be reliably discriminated. Documenting these confounding factors is analogous to identifying equifinalities amongst the causes of cut mark size (Gifford-Gonzalez, 1991). Without a robust discrimination of flake and core mark size in an experimental context where causal factors are controlled, inferences about the tool that created an archaeological cut mark will be plagued by uncertainty.

For example, one zooarchaeological interpretation of ESA hominin foraging suggests that bifacially flaked core tools were transported across the ancient landscape during the Okote Member (1.6 Ma) at Koobi Fora because they were preferred for large animal butchery (Bunn, 1981, 1994). Core tool butchery is inferred from the wide, shallow cut marks that occur on large animal specimens, but as the results of this work show, flakes can also produce wide cut marks, and wider marks tend to occur on larger animals regardless of tool type. Therefore, while core tool butchery may have occurred, additional lines of evidence beyond cut mark size are necessary to support this claim.

Despite the inability to discriminate flake and core tool butchery using cut mark cross-sectional size, this work sheds light on the debate surrounding the utility and effectiveness of ESA flakes and cores for different butchery tasks (Jones, 1980; Toth, 1985). Time per trial was similar when flakes and cores were used to skin, disarticulate and deflesh goat and cow carcasses, which suggests both tool types are equally effective at completing different butchery tasks. In this study, the butcher, who had previously used sharp stone when metal knives were not available, reported a preference for the straighter, longer edge of a flake versus the sinuous arrangement of shorter cutting edges on a bifacial tool. Likewise, the butcher's choice of tools does not indicate that heavier tools are preferred for processing larger animals. The butcher had no investment in proving the utility of either tool type, and as a pastoralist, was experienced with butchering larger mammals, therefore these experiments provide a realistic analog for evaluating flake and core utility. Given the similar effectiveness of flakes and cores, and since a core's cutting edge becomes more sinuous and irregular as it is retouched (Blumenschine et al., 2008; Braun et al., 2008b), knapping a core to generate a series of flakes seems like a more conservative strategy for producing useful butchery tools when raw material is limited.

In conclusion, these experiments refine inferential connections between cut mark traces and causal taphonomic factors including stone tool effectors and butchery behaviors, and identify equifinalities that linger in archaeological interpretations of cut mark morphology (Gifford-Gonzalez, 1991). While the results do not allow diagnosis of ESA tool type from cut mark size, they highlight the importance of including contextual factors like cut mark location and animal size in zooarchaeological interpretations of butchery behavior (Dominguez-Rodrigo et al., 2010).

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