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Size matters. An evaluation of descriptive and metric criteria for identifying cut marks made by unmodified rocks during butchery

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ABSTRACT

One of the key concerns in human evolution studies is tracing the development of stone tool use by early hominins to acquire meat. It has been suggested that the earliest tools used for this purpose might have been unmodified, naturally sharp rocks. However, it has proven challenging to distinguish marks on bones made by hominins using humanly unmodified rocks (HURs) for butchery, from marks made by natural processes. Here we present the results of a study aimed at comparing marks made by HURs during butchery, versus marks made by the same HURs through simulated natural processes, specifically, the fluvial tumbling of bones with naturally sharp rocks (replicated here using a rock tumbler). The results of this study, in which the lithological effector is held constant while the actor is varied, confirm earlier studies suggesting that many existing categorical attributes do *not* effectively distinguish between marks made by HURs versus those made by other tools or trampling. However, we also present a novel way of measuring mark depths which shows that marks made by the human actor are much deeper and longer than those made by natural processes. The size of marks, therefore, matters. This knowledge may help us assess the likelihood that marks on bone surfaces may have been produced by natural forces, as opposed to by humans using unmodified rocks for butchery.

1. Introduction

One of the single most important behavioral adaptations in human evolution is stone tool manufacture and use. The earliest recognized stone tools, consisting of simple stone flakes struck from cores using other rocks, date to ~2.5 mya at the Kada Gona and Bouri sites in East Africa (Semaw et al. 1997; de Heinzelin et al. 1999). The appearance of these tools, which is a watershed in human evolution, surely did not happen overnight, however. The first archaeologically recognizable stone tools must represent the outcome of a long-term, increasing dependence upon stones as tools, including naturally sharp rocks, before hominins began to *modify* stones to create desirable attributes. Panger and colleagues examined this issue in detail (Panger et al. 2002), and concluded that 1) since modern chimpanzees use tools, it is likely that the common ancestor of humans and chimps used tools, 2) hominins had the anatomical capacity to use *stone* tools by 3.2 mya, and 3) hominins likely *modified* stones as tools before their earliest appearance in the archaeological record 2.6 mya. They speculate that the reason we only find stone tools after 2.6 mya is because previously invisible behaviors became archaeologically visible at this time, perhaps as a result of intensification or spatial reorganization of tool-using behaviors. They suggest that a better understanding of the origins of stone tool use and modification will be achieved when archaeologists focus on better documenting use-wear patterns on stones and cut marks on bones.

Since one of the earliest known uses of Oldowan tools is butchery, as evidenced by cut marks on bones from numerous sites (Braun et al., 2010; Bunn, 1981; Bunn and Kroll, 1986; Blumenschine, 1995; Domínguez-Rodrigo et al., 2005), it is possible, if not probable, that one of the driving forces for the development of stone tools was butchery. If such is the case, it is logical to assume that the use of modified stone tools for butchery was preceded by the use of unmodified, naturally sharp rocks for the same purpose. This issue recently came to a head when two bones associated with deposits dating to ~3.4 mya at Dikika, Ethiopia, were claimed to bear stone-tool cut marks (McPherron et al. 2010). Since these deposits are almost one million years older than the oldest documented stone tools, this claim shook the field of paleoanthropology and caused considerable debate (Domínguez-Rodrigo et al., 2010, 2011; McPherron et al. 2011). The finds have been questioned on the basis of their dates, the security of their provenience, the sedimentary context with which they were associated, and, most importantly, whether the marks were

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made by stone-tool using hominins, or by accidental trampling (Domínguez-Rodrigo et al., 2010, 2011). McPherron et al. suggested that the marks were made by hominins carrying out butchery activities using unmodified, sharp stones (McPherron et al. 2010).

This debate raised a question which has concerned taphonomists for many years, namely, how to distinguish marks made by stone tools used for butchery activities, versus those made by other factors not involving human behavior. Marks on bone surfaces are known to be caused by many factors, including carnivore teeth, trampling, fluvial action, microbial action, and stone tools (Bunn, 1981; Potts and Shipman, 1981; Behrensmeyer et al., 1986; Bunn and Kroll, 1986; Olsen and Shipman, 1988; Bunn, 1991; Gifford-Gonzalez, 1991; Blumenschine et al. 1996; Domínguez-Rodrigo et al., 2009). Distinguishing marks made by stone tools during butchery activities, versus those made by natural processes such as trampling of bones against angular sediments, has been particularly challenging. Yet, it is an important concern in paleoanthropology, since one of our key questions is documenting the development of meat-acquisition behaviors (e.g., scavenging and hunting).

Experiments have enabled researchers to develop lists of criteria to differentiate these marks. In one of the earliest experiments, Behrensmeyer et al. (1986) showed that brief trampling of bovid and equid bones in a stream by a human wearing soft-soled shoes can produce marks exhibiting the classic features of cut marks: a V-shaped cross-section and internal microstriations. This same experiment showed that cut marks on the bones were significantly altered by the trampling event, and rendered indistinguishable, in some cases, from trampling marks. It also showed that internal microstriations can be obliterated by trampling or even washing (Behrensmeyer et al. 1986). However, Eickhoff and Herrmann (1985) showed that internal microstriations are not exclusive to cut marks, and can result from gnawing by carnivores with broken teeth. Another experiment in which bovid and sheep bones were trampled in different sediment types with bare feet for two hours revealed somewhat different results (Olsen and Shipman, 1988). The marks created in this experiment were fine, shallow scratches with diverse orientations, and lacked internal microstriations. These marks could not be mistaken for butchery cut marks, according to the authors. Furthermore, the marks were not located in anatomically meaningful areas, and the trampling created a polish on all of the bones (Olsen and Shipman, 1988). Both of these classic studies emphasized that in order to evaluate marks, it is important to take into account the sedimentary context, the locations, orientations, and frequencies of the marks (Behrensmeyer et al. 1986; Olsen and Shipman, 1988), as well as their morphology, depth and association with polish (Olsen and Shipman, 1988).

Domínguez-Rodrigo et al. (2009) argued that the trampling experiments described above were unrealistically long, and designed an experiment in which they trampled small sections of deer bones using esparto grass-soled shoes for ten seconds or two minutes in five different sediment types. Unsurprisingly, they found that the largest sediment grains produced the most marks, and that longer trampling times produced more marks, as well. They concluded that the features previously described as typical characteristics of trampling marks (greater abundance, more random orientations, and a rounded base and a shoulder) are valid for intensive trampling, but not brief trampling episodes. They also argued that the bulk of trampling marks can be distinguished from butchery marks by multivariate application of microscopic criteria, such as mark shape, mark trajectory, trajectory of microstriations, location of microstriations, presence of a shoulder, and flaking on the shoulder.

Following the Dikika debate, Domínguez-Rodrigo et al. (2012) carried out an experiment involving the butchery of chicken and sheep bones using humanly unmodified rocks (HURs). They focused their analysis of the resulting cut-marks on four variables which they had previously shown to discriminate between most trampling and cut marks: cross-sectional shape of the mark, mark trajectory, incidence of shoulder effects, and incidence of flaking on the mark shoulder (Domínguez-Rodrigo et al., 2009), and an additional four variables which they found to discriminate between handaxe-inflicted marks and retouched flake-inflicted marks: presence of multiple-clustered marks, presence of forked marks, number of multiple-clustered marks, and number of forked marks (de Juana et al., 2010). The team's comparison of these variables across the sample of HUR butchery marks, and previously published samples of marks made using other effectors in their experiments – unretouched flakes, retouched flakes, and handaxes – showed the greatest contrast between marks made by unretouched flakes versus those made by HURs, and the greatest resemblance between marks made by retouched flakes and those made by HURs. In other words, the team's joint and pair-wise analyses of these eight variables across marks made by unretouched flakes, retouched flakes, handaxes, and unmodified sharp rocks showed that marks made by sharp rocks are similar to those made by retouched flakes, and very different from those made by unretouched flakes (Domínguez-Rodrigo et al., 2012).

It is unclear why Domínguez-Rodrigo et al. (2012) did not include trampling marks in their joint and pair-wise analyses of the variables; it would have been interesting to compare trampling marks versus those made by HURs, since those are the two mark effectors which are being debated in the case of Dikika. However, the authors did include trampling marks in one of the multiple correspondence analyses (MCA) that they ran on the data. The results of the MCA showed that the variables which explain most of the variability are driven by the marks made by handaxes (Domínguez-Rodrigo et al., 2012). They also concluded on the basis of a biplot of the MCA scores that the confidence interval of the sample of trampling marks overlaps strongly with that of the HUR marks (Fig. 5 in Domínguez-Rodrigo et al., 2012).

The strength of Domínguez-Rodrigo et al. (2012), as well as the previous studies upon which it is based (de Juana et al. 2010; Domínguez-Rodrigo et al., 2009), is that it shows that different lithological effectors – HURs, unretouched flakes, retouched flakes, and handaxes – produce different marks on bone. The overlap in morphology of marks made by HURs with marks made by the three other effectors (Figs. 3–5 in Domínguez-Rodrigo et al., 2012) is striking; it is probably best explained by the fact that the edge angles and other properties of the HURs' edges likely encompass the *range of edge angles and properties* of the other lithological effectors, from very thin and sharp (as in the case of unretouched flakes), to robust and irregular (as in handaxes). In future studies, the relationship between cut mark morphology and lithological effector will be better identified if the same care is given to documenting the properties of the stone tool edges used in the experiments, as is given to documenting the morphologies of the cut marks. Likewise, a more rigorous comparison of the similarities and differences between the marks created by trampling to those created by humanly unmodified rocks is necessary.

The type of data that we need to evaluate the Dikika cut marks, however, is not a comparison of marks made by handaxes, retouched flakes, unretouched flakes, and HURs. We need data that are specific to the question of what marks made by HURs used during butchery activities might look like, versus marks made by HURs during natural (taphonomic) processes. In other words, logic dictates the following possible causes of the Dikika marks: 1) natural forces resulting in contact between stones and bones, such as trampling, which has been documented at paleontological, Miocene-period sites (e.g., Behrensmeyer et al. 1989), or fluvial action, documented in archaeological assemblages such as Member

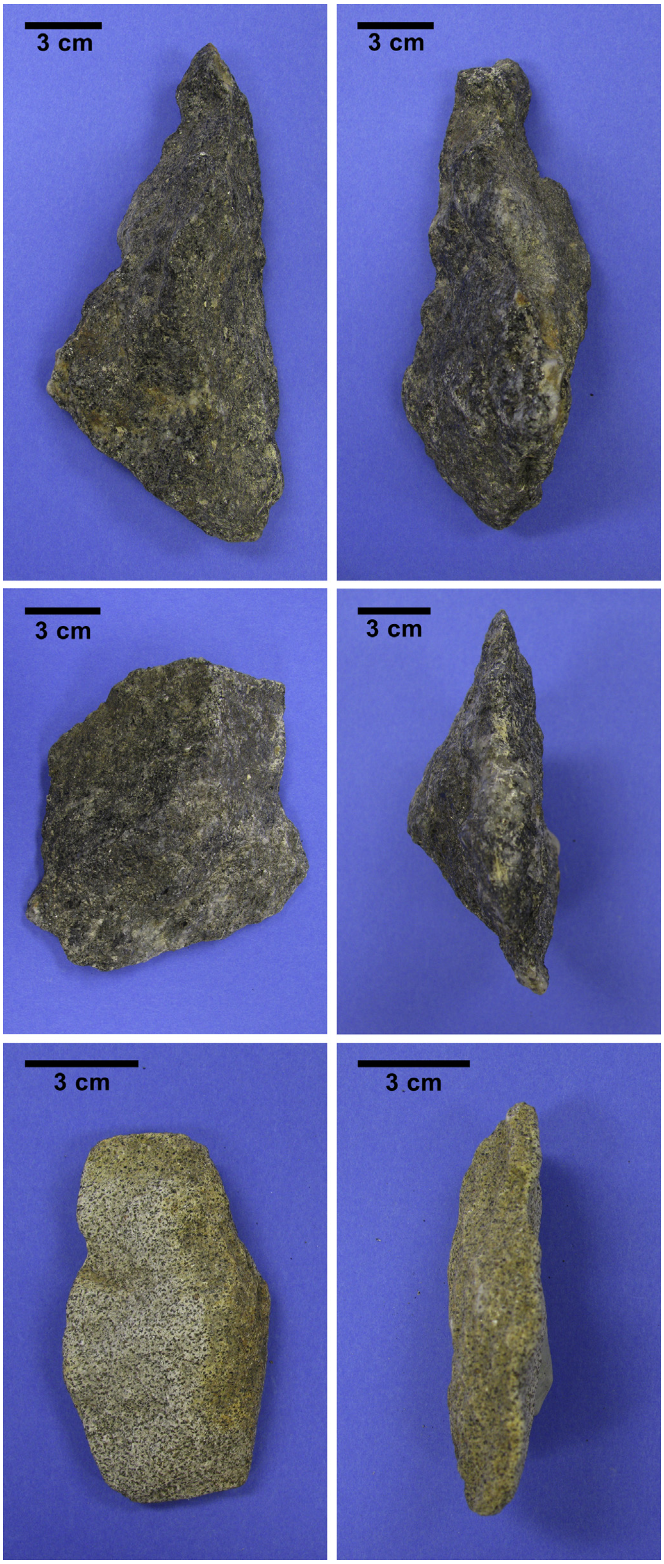

Fig. 1. The three humanly unmodified rocks (HURs) used in the experiments. From top to bottom, HUR#1, #2, and #3. Left side, plan view; right side, profile view.

Fig. 2. The rubber-lined hexagonal rock tumbler used for the tumbling experiment. It rotates at 40 rpm and has a 15 lb. capacity (approximately 5 L in volume). It was sealed shut with a rubber-lined lid during the experiments.

F, Omo (Ethiopia; Merrick, 1976; Merrick and Merrick, 1976); 2) butchery by hominins using *unmodified* rocks; this has never been documented in the archaeological record, but can be posited due to observed instances of rock use by chimpanzees and other primates for processing plant foods (Mercader et al., 2002, 2007; Panger et al. 2002); 3) butchery by hominins using *modified* rocks; however, modified stone tools only appear in the archaeological record after 2.6 mya, as mentioned above; 4) butchery by hominins using handaxes; however, handaxes only appear in the archaeological record after 1.6 mya (Roche and Kibunjia, 1994; Asfaw et al. 1992). No evidence for carnivore damage has been reported for the Dikika bones, therefore this possibility is not included in the list. Furthermore, scenarios (3) and (4) are less likely, given that they involve stone tools which do not appear until 1–2 million years later. Logically, therefore, the most likely causes of the Dikika marks are scenarios (1) and (2).

In light of this, the question we asked in this study is "What is the difference in the morphology of marks on bones made by HURs used during butchery, versus those made by HURs during natural processes?" In other words, can we identify any properties of marks made by the same *effector*, HURs, that might reflect a different *actor* (humans versus natural forces)? We therefore designed a study that would hold the effector constant, while varying the actor. We used the same set of HURs in two experiments, one involving defleshing activities by a human, the other involving simulated natural processes. While the most commonly investigated natural process to date has been trampling, in our experiment we simulated tumbling in a fluvial environment, which is the most likely scenario in which bones might come into contact with large, naturally sharp rocks[1] (see Rabinovich, 2012 and Monnier, 2007 for previous experiments simulating tumbling).

2. Methods

We procured ten frozen domestic turkey (*Meleagris gallopavo*) hind limbs from a butcher, thawed them to room temperature, and divided them into two sets of five limbs each: set B (butchery) and set T (tumbling; see Table 1). We also procured a number of naturally sharp rocks from a field in south-central Minnesota to be

[1] The sediments at Dikika have been described as a "relatively low-energy depositional environment" with few particles larger than 8 mm in diameter (McPherron et al., 2010). At present, therefore, no evidence suggests that the bones at Dikika might have been tumbled with rocks in a high-energy environment. This is a distinct possibility, however, for many other early archaeological sites throughout Africa and the rest of the Old World.

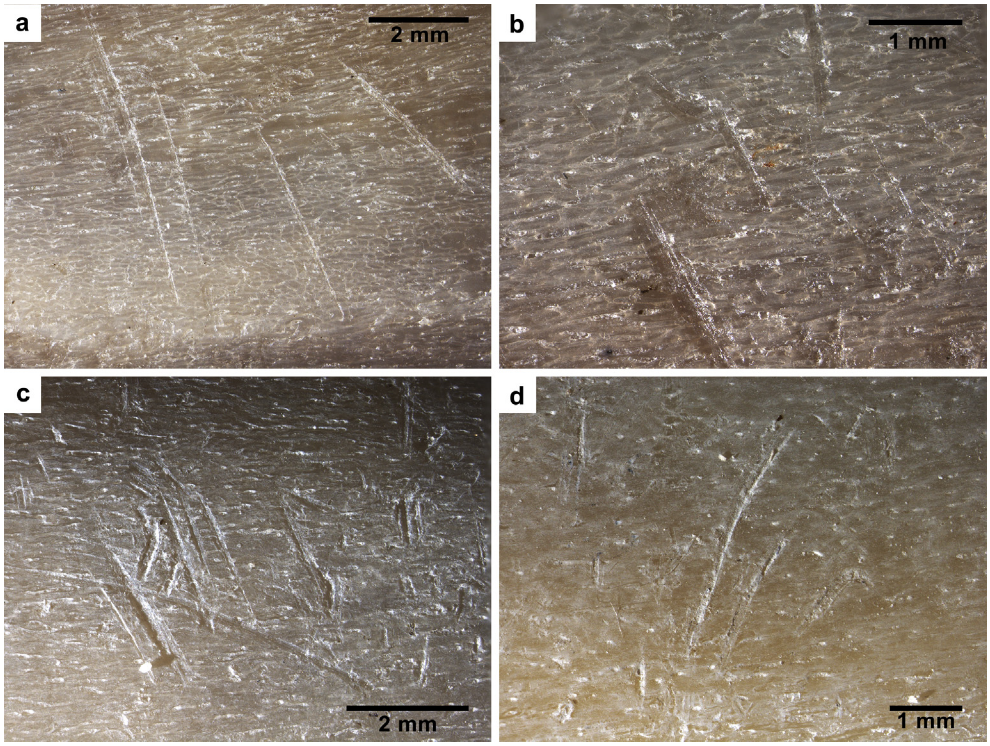

Fig. 3. Examples of marks created by tumbling with humanly unmodified rocks (HURs).

used as our HURs (see Fig. 1 and Table 2). The five "B" limbs were butchered by EB, who used a combination of HURs #1, 2, and 3 to remove muscle and tendons from the bones. Using an overhand motion, she hacked, pounded, and scraped the bones to remove as much meat as possible. After butchery, a small hole was drilled at one end of the bones to allow the marrow to drain; then the bones were cleaned by gently boiling in water for 5 h in a crockpot. The five "T" limbs used in the tumbling experiment were first gently boiled in water for 8 h to remove the meat. After being allowed to air-dry for one day, the bones were placed, one at a time, in a large,

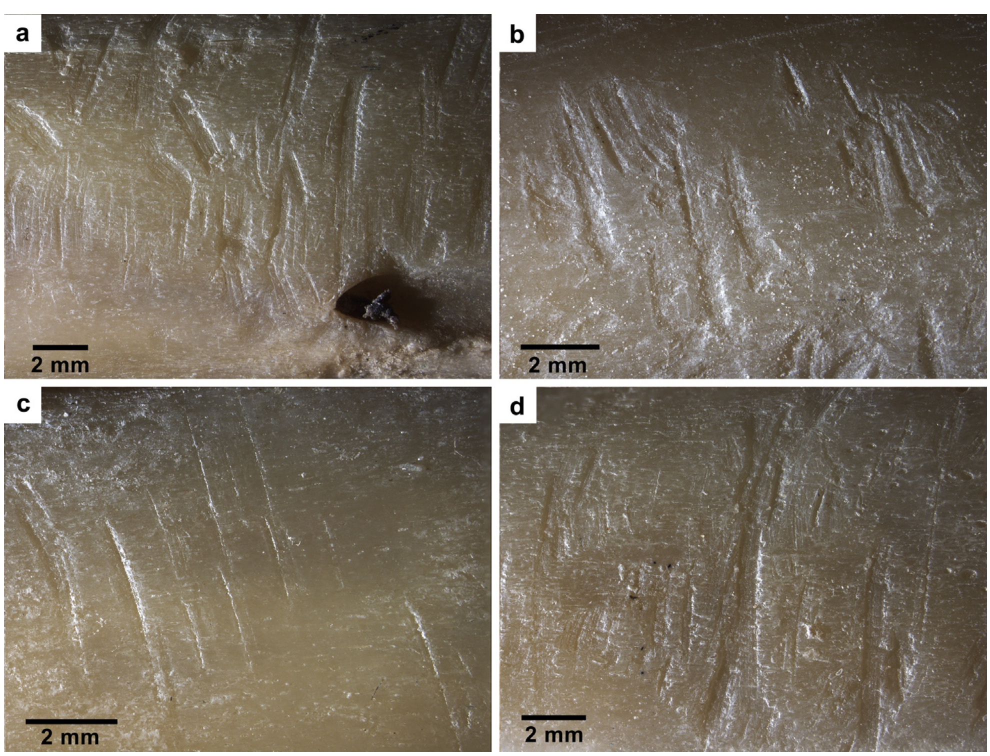

Fig. 4. Examples of marks created by butchery with humanly unmodified rocks (HURs).

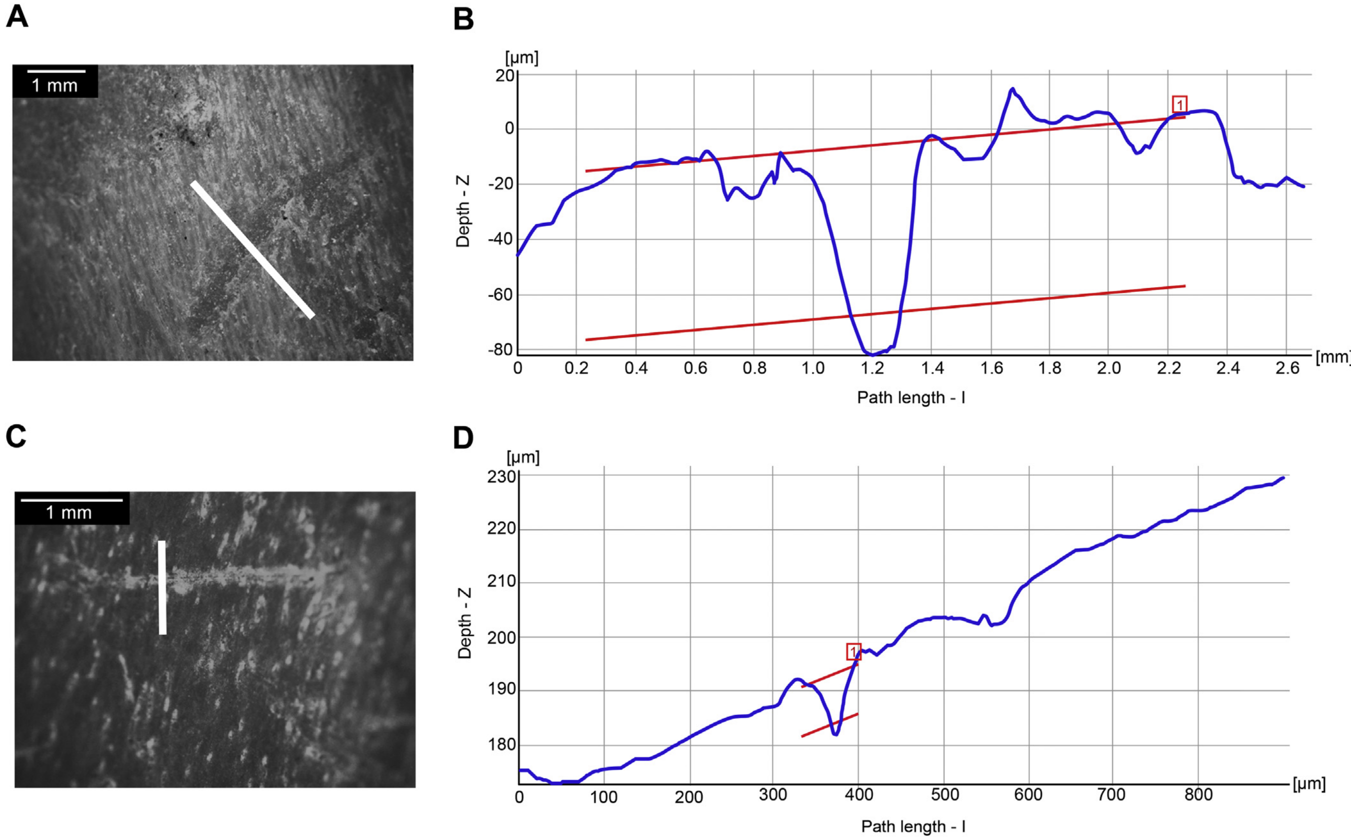

Fig. 5. **A**, 3D model of butchery mark B1M11 seen from plan view; **B**, the profile of the mark at the location indicated by the white line; the two red lines across the profile represent the results of the algorithm used to apply ISO 5436, which fits one line across the top of the groove, and another across the bottom, using the method of least squares. Groove depth is automatically calculated as the difference between the two red lines. **C**, 3D model of tumbling mark T1M13 seen from plan view; **D**, the profile of the mark at the location indicated by the white line; the two red lines across the profile represent the results of the algorithm used to apply ISO 5436, which fits one line across the top of the groove, and another across the bottom, using the method of least squares. Groove depth is automatically calculated as the difference between the two red lines. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

rubber-lined rock tumbler along with the HURs, for five minutes each (see Fig. 2). After tumbling, the bones were removed from the tumbler and stored in a sealed bag in the refrigerator. The HURs were inspected and replaced in the tumbler with the next bone.

In analyzing the resulting marks (see examples in Figs. 3 and 4), we chose the twenty most conspicuous marks per bone, recorded their location on a sketch map of each bone, and then studied them at magnifications of 10–40× using a binocular microscope. We categorized each mark according to the morphological criteria outlined in Domínguez-Rodrigo et al. (2009), using a data entry program (*Entrer-Trois*, at http://www.oldstoneage.com/software/entrer.shtml) configured for this study (data summaries are presented in Table 3). We also measured the lengths and depths of each mark digitally. We did this by gathering stereo image pairs of each mark using a Leica IC3D digital camera mounted on a Leica MZ16 stereomicroscope, which enabled us to generate a 3-D model of each mark using the software Leica Stereoexplorer 2.1 (see Fig. 5). These 3-D models were used to measure mark depths, using the international measurement standard for profile depths A1 of ISO 5436 (ISO, 2000). According to this algorithm, two lines are fitted by the method of least squares, one across the top of the profile, and another across the bottom of it (see the red lines in Fig. 5B and D). The benefit of using this international measurement standard, despite the algorithm's slight but consistent underestimation of maximal mark depth, was the increase in precision, speed, and repeatability of the measurements when compared to measuring profile depths by hand. We measured three separate profile depths across each mark, which we subsequently averaged in order to calculate a mean depth for each profile (see Appendix 1). In

Table 1
Experimental parameters.

	Butchery experiment	Tumbling experiment
Species	*Meleagris gallopavo*	*Meleagris gallopavo*
Elements	5 femurs	5 femurs
Effector	HUR#1, HUR#2, HUR#3	HUR#1, HUR#2, HUR#3
Actor	Undergraduate student (EB)	Rock tumbler
Action(s)	Hacking to remove muscle and tendon, this took ~20 min per limb.	Tumbling for 5 min.
Cleaning method	Gentle simmering in water for 5 h after butchery.	Gentle simmering in water for 8 h before tumbling.

Table 2
Properties of the Humanly Unmodified Rocks (edge angles were measured at several locations along each edge using a goniometer, and were averaged).

	Raw material	Weight (g.)	Average angle, edge#1	Average angle, edge#2	Average angle, edge#3	Average angle, edge#4
HUR#1	Schist	490	85	57	63	97
HUR#2	Schist	463	58	89	71	60
HUR#3	Metavolcanic rock	127	90	57	43	50

Table 3
Experimental parameters and observed frequencies for morphological cut-mark descriptors: this study, Domínguez-Rodrigo et al., 2009, Table 5, and Domínguez-Rodrigo et al., 2012, Table 3.

	This study	This study	Domínguez-Rodrigo et al., 2009	Domínguez-Rodrigo et al., 2009	Domínguez-Rodrigo et al., 2009	Domínguez-Rodrigo et al., 2012
Effector: Actor:	HURs Tumbler	HURs Human, butchering	Sand Human, trampling	Unretouched flakes Human, butchering	Retouched flakes Human, butchering	HURs Human, butchering
Mark Trajectory						
Straight	79/99 (79.8%)	81/95 (85.3%)	75/251 (29.8%)	230/246 (93.5%)	102/105 (97.1%)	91%
Curvy	12/99 (12.1%)	7/95 (7.4%)	42/251 (16.7%)	16/246 (6.5%)	0/105 (0%)	7.9%
Sinuous	8/99 (8.1%)	7/95 (7.4%)	134/251 (53.4%)	0/246 (0%)	3/105 (2.9%)	1.1%
Barb						
Absent	98/99 (99.0%)	92/95 (96.8%)	245/251 (97.6%)	221/246 (89.8%)	99/105 (94.3%)	No data (n.d.)
Present	1/99 (1.0%)	3/95 (3.2%)	6/251 2.4%	25/246 (10.2%)	6/105 (5.7%)	n.d.
Mark orientation						
Parallel	3/99 (3.0%)	11/95 (11.6%)	25/251 (9.9%)	1/246 (0.4%)	0/105 (0%)	n.d.
Perpendicular	44/99 (44.4%)	58/95 (61.1%)	20/251 (8%)	96/246 (39%)	3/105 (2.9%)	n.d.
Oblique	52/99 (52.5%)	26/95 (27.4%)	206/251 (82.1%)	149/246 (60.6%)	102/105 (97.1%)	n.d.
Mark shape						
V	16/99 (16.2%)	15/95 (15.8%)	10/251 (4%)	238/246 (96.7%)	6/105 (5.7%)	31%
Wide	83/99 (83.8%)	80/95 (84.2%)	241/251 (96%)	8/246 (3.3%)	99/105 (94.3%)	69%
Mark symmetry						
Symmetrical	52/99 (52.5%)	49/95 (51.6%)	226/251 (90%)	212/246 (86.2%)	42/105 (40%)	n.d.
Asymmetrical	47/99 (47.5%)	46/95 (48.4%)	25/251 (9.9%)	34/246 (13.8%)	63/105 (60%)	n.d.
Shoulder effect						
Present	1/99 (1.0%)	17/95 (17.9%)	15/251 (5.9%)	81/246 (32.9%)	78/105 (74.3%)	47%
Absent	98/99 (99.0%)	78/95 (82.1%)	236/251 (94.1%)	165/246 (67.1%)	27/105 (25.7%)	53%
Flaking on shoulder						
Present	1/99 (1.0%)	5/95 (5.3%)	7/251 (2.7%)	36/246 (14.6%)	54/105 (51.4%)	37%
Absent	98/99 (99.0%)	90/95 (94.7%)	244/251 (97.3%)	210/246 (85.4%)	51/105 (48.6%)	63%
Overlapping striae						
Present	8/99 (8.1%)	23/95 (24.2%)	203/251 (80.3%)	12/246 (12.9%)	0/105 (0%)	n.d.
Absent	91/99 (91.9%)	72/95 (75.8%)	48/251 (19.7%)	234/246 (95.1%)	105/105 (100%)	n.d.
Internal microstriations						
Present	86/99 (86.9%)	76/95 (80%)	188/251 (75%)	190/246 (77.2%)	105/105 (100%)	n.d.
Absent	13/99 (13.1%)	19/95 (20%)	63/251 (25%)	56/246 (22.8%)	0/105 (0%)	n.d.
Microstriation trajectory						
Continuous	39/86 (45.3%)	31/76 (40.8%)	169/251 (67.3%)	190/190 (100%)	105/105 (100%)	n.d.
Discontinuous	47/86 (54.7%)	45/76 (59.2%)	82[a]/251 (32.7%)	0/190 (0%)	0/105 (0%)	n.d.
Shape of microstriation trajectory						
Straight	85/86 (98.8%)	69/76 (90.8%)	140/169 (82.8%)	190/190 (100%)	105/105 (100%)	n.d.
Irregular	1/86 (1.2%)	7/76 (9.2%)	29/169 (17.2%)	0/190 (0%)	0/105 (0%)	n.d.
Location of microstriations						
Walls	11/86 (12.8%)	17/76 (22.4%)	7/251 (2.8%)	180/246 (73.2%)	3/105 (2.9%)	n.d.
Bottom	66/86 (76.7%)	50/76 (65.8%)	219/251 (87.2%)	0/246 (0%)	93/105 (88.6%)	n.d.
Both	9/86 (10.5%)	9/76 (11.8%)	25/219 (10%0	10/246 (4.1%)	9/105 (8.6%)	n.d.
Microabrasion						
Present	7/99 (7.1%)	15/95 (15.8%)	250/251 (99.6%)	240/246 (97.6%)	105/105 (100%)	n.d.
Absent	92/99 (92.9%)	80/95 (84.2%)	1/251 (0.4%)	6/246 (2.4%)	0/105 (0%)	n.d.

[a] This value, copied from Domínguez-Rodrigo et al., 2009, Table 5, is a mistake in the original publication, since only 188 marks with microstriations are present in the sample.

addition, we measured each mark length using the line measurement function in Stereoexplorer.

3. Results

3.1. Categorical variables

As discussed above, experimental work has identified variables which are argued to help distinguish cut marks from trampling marks, such as mark cross-sectional shape; mark orientation; trajectory and location of internal microstriations; and presence of a shoulder effect. Our first task, therefore, was to compare the morphologies of the two sets of marks we generated using the criteria defined in Domínguez-Rodrigo et al. (2009). After the data were collected, we imported them into the software IBM Statistics SPSS 20.0 and cross-tabulated the variable states with mark actor (these data are presented in Table 3, which also includes the data from Domínguez-Rodrigo et al., 2009, 2012). We ran a chi-square test on each variable in order to test for an association between it and actor (human v tumbler). These tests did not yield significant results except in the cases reported below. The following section describes our results for each criterion; interpretations of the results are presented in Table 4.

3.1.1. Mark trajectory

According to Domínguez-Rodrigo et al. (2012), the trajectory of a mark (straight, curved, or sinuous) is one of the four criteria found by Domínguez-Rodrigo et al. (2009) that enable the differentiation of trampling and cut marks in over 90% of cases, along with mark cross-sectional shape, incidence of shoulder effects, and incidence of flaking on the mark shoulder. Domínguez-Rodrigo et al. (2009) found that most (70%) of trampling marks are sinuous or curved, whereas 10% or less of marks made with unretouched flakes, retouched flakes, or HURs are sinuous or curved (see also Domínguez-Rodrigo et al., 2012). In other words, they found a strong association between mark trajectory and mark effector/actor. In our experiment, however, we did not find an association between mark trajectory and mark actor (chi-square test, $N = 194$,

Table 4
Comparison of results between this study and previous studies, and the resulting relevance of each criterion.

	Results, Dominguez-Rodrigo et al., 2009, 2012	Results, this study	Relevance of the criterion for distinguishing between butchery and tumbling when the effector is HURs
Mark trajectory	Butchery marks are usually straight; trampling marks are often sinuous or curvy.	Both tumbling and butchery marks are usually straight.	Not relevant.
Presence of a barb	Rare in all cases.	Rare in all cases.	Not relevant.
Mark orientation	Orientation of marks made by unretouched tools differs from retouched tool & trampling marks.	Orientation of marks differs between tumbling & butchery.	Possibly relevant; great variability in the results of multiple studies requires further research.
Mark shape	Unretouched tools create V-shaped marks; retouched tools & trampling create _/ marks.	Both tumbling & butchery create mostly _/ marks.	Not relevant.
Mark symmetry	Trampling & butchery with unretouched tools produces symmetrical marks; butchery with retouched tools produces asymmetrical marks.	Mark symmetry does not differ between tumbling & butchery.	Not relevant; this criterion does not correlate with actor or lithological effector.
Shoulder effect	Very rare in trampling; common in butchery with retouched tools.	Very rare in tumbling; more common in butchery.	Relevant; shoulder effects are more common in butchery marks.
Flaking on the shoulder	Rare in trampling; more common in butchery, especially with unretouched tools & HURs.	Very rare in both tumbling and butchery.	Not relevant.
Overlapping striae	Common on trampling marks; rare on butchery marks.	Rare on tumbling marks; more common on butchery marks.	Relevant; this criterion may reflect some butchery practices.
Microstriation trajectory	Microstriation trajectories in trampling marks are often discontinuous; they are always continuous in butchery marks.	Microstriation trajectory continuity does not differ between tumbling and butchery.	Not relevant.
Shape of microstriation trajectory	Microstriation trajectories are always straight in butchery marks, and in 83% of trampling marks.	Microstriation trajectories in both samples are mostly straight.	Not relevant.
Location of microstriations	Microstriations are often located on the walls of marks produced by unretouched tools; along the bottoms of marks produced by retouched tools and trampling	There is no association between microstriation location and actor.	Not relevant.
Microabrasion	It is ubiquitous on trampling and butchery marks.	It is rare on both tumbling and butchery marks.	Not relevant; this criterion may reflect experimental design.

$X^2 = 1.326$, df $= 2$, $p = .515$). The marks produced by butchery are dominated by straight marks (85%), but so are the marks produced by the tumbler (80%). Our results, in combination with those of Domínguez-Rodrigo et al. (2009), therefore suggest that sinuous or curved marks may be a unique property of trampling; other natural causes, such as tumbling, can produce straight marks in the same frequencies as those produced during butchery.

3.1.2. Presence of a barb

Domínguez-Rodrigo et al. (2009) defined this criterion as "a shallower end of the mark slightly curved to the side in the form of an open hook" and expected to see its occurrence in some butchery marks. According to their results, barbs were present in 2% of trampling marks, 10% of marks made with retouched flakes and 6% of marks made with unretouched flakes (Domínguez-Rodrigo et al., 2009). Our results agree, with barbs present in only 1% of tumbled and 3% of butchered marks. Barbs are therefore exceedingly rare in the scenarios modeled in both our experiment and that of Domínguez-Rodrigo et al., 2009.

3.1.3. Mark orientation

Domínguez-Rodrigo et al. (2009) categorized mark orientation relative to the axis of the bone as parallel, perpendicular, or oblique. They tested Olsen and Shipman's (1988) conclusion that trampling produces marks that are oriented randomly. According to their results, 82% of trampling marks were oblique, as were 97% of marks made with retouched flakes, and 61% of marks made with unretouched flakes (Domínguez-Rodrigo et al., 2009). They concluded that trampling marks are *not* more randomly oriented, therefore, than butchery marks, *contra* Olsen and Shipman 1988.

In our experiment, only 27% of the orientations of butchery marks are oblique, and 53% of the orientations of tumbler-produced marks. The frequency of oblique mark orientations in our experiment is therefore much lower than that seen in Domínguez-Rodrigo et al. (2009). Furthermore, if randomness of orientation is defined as a more even distribution of mark orientations, our butchery marks (27% oblique, 61% perpendicular, 12% parallel) are more randomly oriented across the three categories than our tumbling marks (53% oblique, 44% perpendicular, 3% parallel) (a chi-square test shows a strong association between mark orientation and mark actor, $N = 194$, $X^2 = 15.084$, df $= 2$, $p = .001$). This difference in mark orientation across marks made by butchery versus those made by the tumbler shows that mark orientation, therefore, reflects actor rather than effector; furthermore, there is probably a good deal of variability from one actor to the next. For instance, mark orientation probably reflects the orientations of the bone and the tool during butchery, as well as the action of the hand wielding the tool. Currently, there are no consistent results across various studies that would indicate that particular mark orientations are more likely to be associated with a particular actor. However, Stiner et al. noted a greater randomness in mark orientations in the Lower Paleolithic assemblage at Qesem Cave than in Middle and Upper Paleolithic assemblages at Ucagizli Caves I and II, and interpreted it as reflecting a greater number of individuals involved in butchery (Stiner et al. 2009).

3.1.4. Mark shape

Mark cross-sectional shape is one of the classic criteria used to describe cut mark morphologies, and is defined by Domínguez-Rodrigo et al. (2009) as either narrow V-shaped or wide V-shaped (_/), in other words, an open mark that is substantially wider than it is deep. Along with mark trajectory, shoulder effect, and flaking on the shoulder, Domínguez-Rodrigo et al. (2012) consider this criterion to be one of the four that enable differentiation of trampling and cut marks in >90% of cases. Their 2009 results showed that 97% of marks made with unretouched flakes are V-shaped, whereas only 4% of trampling marks are V-shaped. This criterion therefore seems to be a powerful one for distinguishing cut marks (made with unretouched flakes) from trample marks. However, cut marks made with retouched flakes are overwhelmingly _/-shaped (94%), and in that respect resemble trample marks. Therefore, mark cross-sectional shape cannot be used to distinguish cut marks made with retouched flakes from trample marks, as Domínguez-Rodrigo et al. (2009) acknowledge. According to Domínguez-Rodrigo et al. (2012), the frequency of V-shaped marks made with HURs is intermediate between that of unretouched and retouched flakes, with 31% of marks made with HURs being V-shaped.

In our results, V-shaped marks are relatively rare, occurring in only 16% of marks made by both actors (tumbling and butchery). The fact that in our experiment, frequencies of V-shaped marks are low, and virtually identical across the two categories, provides strong support for the observation by Domínguez-Rodrigo et al. (2012) that frequencies of V-shapes reflect lithological effector (unretouched flakes, retouched flakes, handaxes, and HURs), since lithological effector was held constant in our study.

3.1.5. *Mark symmetry*

The symmetry of the mark cross-section was one of the criteria employed by Domínguez-Rodrigo et al. (2009). Their results showed that trampled marks and marks made with unretouched flakes are dominated by symmetrical cross-sections (86–90%), although marks made by retouched flakes are slightly dominated by asymmetrical cross-sections (60%). Our results show no differences in symmetry between tumbling marks and butchery marks; both are evenly divided between the symmetrical and asymmetrical categories.

3.1.6. *Shoulder effect*

The presence of a shoulder effect is one of the four criteria considered by Domínguez-Rodrigo et al. (2012) to enable the differentiation of trampling from cut marks in >90% of cases. In addition, they stated that when attempting to distinguish trampling marks from those made by retouched tools, marks that are straight and have a shoulder are much more likely to be cut marks than trampling marks (Domínguez-Rodrigo, 2010). In other words, Domínguez-Rodrigo et al. (2009) showed that a shoulder effect is rare in trampled marks (6%), occurs in approximately 33% of marks made with unretouched flakes, and in 74% of marks made with retouched flakes. On marks made with HURs, it occurs approximately half of the time (Domínguez-Rodrigo et al., 2012).

Our results show a strong association between shoulder effect presence and mark actor, using a chi-square test (all expected cell frequencies were greater than five; $N = 194$, $X^2 = 16.419$, $\mathrm{df} = 1$, $p = 0.000$). Like Domínguez-Rodrigo et al. (2009), we found a greater occurrence of shoulder effects on marks made by a human during butchery (18%), than on marks made by the same effectors in the tumbler (1%). This important result suggests that further research into the causes of shoulder effects is needed; for instance, do mark shoulders reflect the force with which a mark was inflicted? A note of caution, however, is also warranted: while the presence of a shoulder effect may provide evidence for butchery, it is important to remember that 82% of the marks made by butchery, in our experiment, do *not* have a shoulder. Therefore, the *absence* of a shoulder effect cannot be used as evidence *against* butchery with HURs.

3.1.7. *Flaking on the shoulder*

Flaking on a mark's shoulder is considered to be one of the four criteria that enable trampling and cut marks to be differentiated in >90% of cases (Domínguez-Rodrigo et al., 2012). Domínguez-Rodrigo et al., 2009 noted that flaking on the shoulder occurs in only 3% of trampling marks, 15% of marks made with unretouched flakes, and 51% of marks made with retouched flakes. Furthermore, they noted that it occurs in 37% of butchery marks made with HURs (Domínguez-Rodrigo et al., 2012). They have good evidence, in other words, suggesting that flaking on the shoulder is more frequent in butchery marks than trampling marks. Our results show a virtual absence of flaking on the shoulder, regardless of actor. For instance, marks with flaking on the shoulder occur in only 5% of butchered bones. We are at a loss to explain why this is so much lower than the 37% frequency observed by Domínguez-Rodrigo et al., 2012 for the bones butchered with HURs; might it have something to do with the freshness of the bone, such that drier bones might flake more?

3.1.8. *Overlapping striae*

Domínguez-Rodrigo et al. (2009) showed that “striae overlapping or running across the main mark with an oblique angle” are present on 80% of trampled marks, versus only 13% and 0% of marks made with unretouched and retouched flakes, respectively. Accordingly, the presence of overlapping striae was cited by Domínguez-Rodrigo et al. (2010) as a good indicator of trampling. Our results show a strong association between mark actor and presence/absence of overlapping striae (chi-square test, $N = 194$, $X^2 = 9.394$, $\mathrm{df} = 1$, $p = 0.002$). The results, however, are in the opposite direction as those from Domínguez-Rodrigo et al. (2009): in our experiment, overlapping striae are present on only 8% of marks created during tumbling, versus 24% of marks created during butchery. This result is surprising, since it would seem that during tumbling, the random banging of bone and stones would result in many more overlapping striae than during butchery. Tumbling created very few overlapping striae, however. On the other hand, almost one out of every four butchery marks evidences overlapping striae; this could be due to the fact that the human actor in our study (EB) sometimes used a “scraping” motion to remove meat from the bones, and may have gone over previous marks. This anecdote introduces an important cautionary note, reminding us that butchery experiments likely differ from prehistoric butchery behaviors in unknown ways.

3.1.9. *Internal microstriations*

Criteria #11–14 of Domínguez-Rodrigo et al. (2009) have to do with the presence of microstriations inside marks, their trajectories, shape, and location. Domínguez-Rodrigo et al. (2009) posit that these aspects of microstriations might distinguish trampling marks from cut marks. They state in another publication that cut marks made with simple flakes are characterized by continuous, straight trajectories whereas trample marks have discontinuous, irregular striations (Domínguez-Rodrigo et al., 2010).

Domínguez-Rodrigo et al.'s experimental results showed internal microstriations present in 75% of trampled marks, 77% of marks made with unretouched flakes, and 100% of marks made with retouched flakes (Domínguez-Rodrigo et al. 2009). In our experiment, internal microstriations are present in 87% of tumbled mark and 80% of butchered marks. Our results therefore broadly agree with Domínguez-Rodrigo et al.'s in showing that microstriations are frequent in all types of marks.

3.1.10. *Microstriation trajectory*

Domínguez-Rodrigo et al. (2010) stated that the microstriations inside trample marks tend to be discontinuous. According to their data, however, 67% of microstriations inside trample marks are in fact *continuous* (Domínguez-Rodrigo et al. 2009). While this is less than the frequency (100%) of continuous microstriations they observed inside cut marks made by unretouched and retouched flakes, a majority of their trampling marks can nevertheless be said to exhibit continuous microstriations.

Our results, however, show a slight dominance of discontinuous microstriations in marks made by both actors: 55% in tumbling marks, and 59% in butchery marks. In other words, in our experiment, the frequency of discontinuous microstriations is much higher than what was identified by Domínguez-Rodrigo et al. (2009). The frequencies observed in our experiment are also virtually identical across the two actors, suggesting that the continuity of microstriation trajectory reflects effector type rather than actor; the irregularity of the edges of HURs might be responsible for discontinuous microstriations. Unfortunately, Domínguez-Rodrigo et al. (2012) do not report this statistic for marks made by HURs in their butchery experiment.

3.1.11. Shape of microstriation trajectory

Domínguez-Rodrigo et al. (2010) stated that the microstriations inside trample marks tend to be irregular, although, according to their 2009 data, only 17% of microstriation trajectories of trampled marks are irregular. This is nevertheless higher than the occurrence of irregular microstriation trajectories in marks made by unretouched and retouched flakes in their experiments (0% in both cases, Domínguez-Rodrigo et al. 2009), as well as higher than the occurrence of irregular microstriations in our tumbler and butchery marks (1.2% and 9.2%, respectively; this difference is not statistically significant, according to a chi-squared test). Elucidating the factors related to microstriation trajectory shape will require more research into the formation of microstriations, which is probably strongly affected by lithological effector.

3.1.12. Location of microstriations

Finally, Domínguez-Rodrigo et al. (2009) posited that the *location* of microstriations inside a mark (on the walls of the mark, the bottom of the mark, or both) could differ between trampling marks and cut marks. In effect, their trampling marks are dominated by microstriations along the bottoms of marks (87%), whereas marks made with an unretouched flake are dominated by microstriations along the *walls* of the mark (73%). Marks made by retouched tools, however, are, like the trampling marks, dominated by microstriations along the bottoms of the marks (89%). This indicates that unretouched tools produce microstriations in a different location than retouched tools and trampling. Our results show that both tumbling and butchery marks made by HURs are dominated by microstriations on the bottoms of the marks (77% and 67%, respectively; chi-square test is not significant). The results of both of these experiments suggest that certain characteristics more common to the edges of unretouched flakes must be responsible for producing microstriations along the walls of marks.

3.1.13. Microabrasion

Extremely shallow striae (microabrasion) were posited by Domínguez-Rodrigo et al. (2009) to result from trampling. However, while their results confirmed that microabrasion occurs in 99.6% of trampled marks, they also documented its occurrence in 98% of marks made by unretouched flakes, and 100% of marks made by retouched flakes (Domínguez-Rodrigo et al. 2009). Microabrasion, therefore, is ubiquitous in all of these experiments. Surprisingly, our results are the opposite: microabrasion is present in only 7% of marks made by tumbling, and 16% of marks made by butchery (chi-square test not significant, in other words, there is no statistically significant difference between the frequencies observed in tumbling v butchery). Taken at face value, the results from both experiments (ours and Domínguez-Rodrigo et al.'s) suggest that there is no relationship between microabrasion and lithological effector, or microabrasion and actor. Further research into the causes of microabrasion is therefore imperative, since it is so often cited as a feature of trampling (e.g., Olsen and Shipman, 1988).

3.2. Summary of the results using categorical variables

The question we asked in this study is “What is the difference in the morphology of marks on bones made by HURs used during butchery, versus those made by HURs during natural processes?” We applied the criteria defined in Domínguez-Rodrigo et al. (2009) to describe the marks, and found that only three of these criteria show statistically significant patterning between butchery versus tumbling marks: mark orientation, the presence of a shoulder effect, and the presence of overlapping striae. The patterning of mark orientation, which differs across all categories of butchery, trampling and tumbling (in our study and Domínguez-Rodrigo et al. 2009, 2012), is complex and is likely the result of many factors, including butchery practices. Therefore, further controlled studies of this criterion are imperative. Additionally, our study confirms that shoulder effects are more common in butchery marks than in tumbling marks; the former may reflect the greater application of force, including perhaps percussive force, in butchery than in trampling/tumbling activities. With further exploration of its causes, the presence of a shoulder effect may become an important indicator of butchery. Finally, the near-absence of overlapping striae in any sample other than trampling marks and approximately 1/4 of our butchery marks may indicate that this feature reflects trampling and some butchery practices (e.g., scraping).

Why do the other criteria not help us differentiate between marks caused by the two actors?

There are two possible explanations: 1) the morphologies of marks on bone surfaces are in large part controlled by the lithological effector used to produce the marks, and the actor (human versus tumbler, in our case) has very little effect on mark morphology; or, 2) the mark morphologies differ, but these differences are not captured by most of the criteria used in this study. The first explanation would be in keeping with the results of Domínguez-Rodrigo et al.'s (2012) experiment using HURs to butcher bones, which showed that HUR cut mark morphologies overlap extensively with stone tool cut mark morphologies as well as those of trampling marks.

> “Collectively, our results show the great variability in shape and other properties of cut marks created by butchery utilizing HURs. Cut marks inflicted by HURs overlap extensively in their morphologies with those linear marks created by simple (unretouched), retouched and handaxe tools used for butchery *and* with linear trampling marks. These results counsel extreme caution in diagnosing linear marks on fossil bone surfaces of unknown origin as cut marks created by hominin butchery with HURs.”
>
> Dominguez-Rodrigo et al. 2012:213.

It is also possible, however, that the second explanation is true: morphological differences exist, but are not captured by the descriptive criteria. Let's take a closer look at the rest of the criteria, those that did not differentiate between actors in our experiment. First of all, it is clear that some criteria vary too widely and unpredictably to be useful in any taphonomic study. Criteria that belong to this category (noted as “not relevant” in Table 4, column 4) include mark symmetry, continuity and shape of the microstriation trajectories, microabrasion (which varies in opposite directions in our study and that of Domínguez-Rodrigo et al., 2009's), and the presence of a barb. Second, there is a category of criteria which, while not relevant for distinguishing between actors in our experiment, are clearly associated with a lithological effector (e.g., unretouched tools), or a combination of effector and actor (e.g., trampling). For instance, V-shaped marks are strongly associated with unretouched flake tools, as are microstriations on the walls of marks. Sinuous or curved marks are associated with trampling. Finally, flaking on the shoulder may reflect some butchery practices. All of these criteria may be relevant to the goal of discriminating mark actors and effectors, and deserve future research through well-controlled experiments.

However, there is another set of variables which, although frequently mentioned, are rarely quantified: these are the variables related to the *size* of the cut-marks. Olsen and Shipman (1988) emphasized the "fine" and "shallow" nature of the marks they produced by trampling, as well as the fact that they tended to be shorter (less than 3 mm long) than cut marks. Dominguez-Rodrigo et al. (2009) asserted that cut marks are deeper than trampling marks "according to the experience of the senior author" (Domínguez-Rodrigo et al., 2009:2653). The marks generated in our experiment support these observations, as can be seen in Figs. 3 and 4, which show important differences in scale between the two sets of marks.

3.3. Metric variables

Despite the recognition that the size of marks is an important criterion for distinguishing between mark actors and effectors, there have been very few attempts at quantifying this attribute. Measuring mark depth, in particular, is difficult and requires specialized microscopes and software capable of modeling the surface of the bone in three dimensions (see Bello and Soligo, 2008). Our study is the first to provide comparative data on the sizes of marks made by HURs during butchery versus simulated natural forces. Using the stereomicroscope and associated software described in the methods section above, we constructed 3D surface models of each of the cut marks in the analysis, which enabled us to calculate mark depths based upon profile analysis. We also measured individual mark lengths. The raw data are presented in Appendix 1, with the descriptive statistics presented in Table 5. Median depth of butchered marks (33.23 μm) was twice that of tumbled marks (15.17 μm). A Mann–Whitney U test was run to determine whether mean depths of tumbled marks are significantly different from the mean depths of butchered marks. Depth scores for tumbled marks (mean rank = 75.41) and butchered marks (121.78) *are* statistically significantly different ($U = 7{,}009$, $z = 5.735$, $p < 0.0005$). Our data also showed that butchered marks (median, 3.47 mm) are longer than tumbled marks (median, 2.33 mm). A Mann–Whitney U test was run to determine whether these differences are statistically significant. Test results confirm that median length of tumbled marks is statistically significantly different from median length of butchered marks ($U = 6721.5$, $z = 5.005$, $p < 0.0005$). The lengths and depths of the butchery marks in our study, in other words, are much greater than those of the tumbling marks.

Returning to our two possible interpretations for the results of our categorical variables, we are now in a position to conclude that the morphologies of marks created by the two different actors in our study (tumbling versus butchering) using the same effectors (humanly unmodified rocks), *do* differ in some important respects. These differences are the depth and length measurements of the marks. By showing that marks created by the human actor in our study are more than twice as deep and 50% longer than the marks created by the same effectors in the tumbler, we show that mark size is heavily dependent upon force, which was likely much greater during the butchery experiments than in the tumbler. The size of marks, therefore, matters to our interpretation of its cause. This knowledge will help us in the future assess the likelihood that marks on bone surfaces were produced by natural forces, as opposed to by humans during butchery.

Table 5
Descriptive statistics for mark lengths and depths.

		N	Median	Mean	Standard dev.
Mark length	Butchered	95	3.47 (mm)	3.83 (mm)	1.80 (mm)
	Tumbled	100	2.33 (mm)	2.61 (mm)	1.38 (mm)
Mark depth	Butchered	95	33.23 (μm)	40.55 (μm)	27.80 (μm)
(mean of 3 measurements)	Tumbled	100	15.17 (μm)	19.51 (μm)	13.11 (μm)

4. Conclusions

This study was designed to provide a new data set relevant to the suggestion that the earliest tools used by hominins to acquire meat may have been unmodified, naturally sharp rocks (Panger et al., 2002; McPherron et al., 2010). Previous studies have had trouble distinguishing marks on bones made by humanly unmodified rocks (HURs) use for butchery, from marks made by retouched and unretouched stone tools, or trampling processes (Domínguez-Rodrigo et al., 2012). In our tightly controlled experiment, the lithological effector (HURs) is held constant while the action (butchering v tumbling) is varied. Our results confirm earlier studies suggesting that many existing categorical attributes do *not* effectively distinguish between marks made by HURs versus those made by other tools or trampling. However, by modeling bone surfaces in 3D, we are able to *measure* marks, demonstrating in the process that marks made by a human actor are much deeper and longer than those made by natural forces.

The contribution of our study, we hope, will be new data showing a clear association between mark size and actor, and a new methodology for quantifying size variables. We hope that our results will stimulate further research on the relationship between lithological effector, actor, force, and size of marks. Development of this line of research could enable us to evaluate future claims for early cut marks, by predicting the probability that a certain actor is responsible for the marks on the basis of an understanding of how much force is required to generate a certain mark size, and the likelihood that natural forces (such as trampling by animals of the proper size to generate such a force, or tumbling of sufficient velocity) could explain the marks in question (see Potter, 2005 for an important approach to measuring force during butchery with stone tools). Undoubtedly, additional cases of very early cut marks on bones will come to light, as we continue seeking to document the earliest uses of unmodified stones to acquire meat by Pliocene hominins.

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Appendix 1. Mark profile depths (measured three times per mark); mean profile depth and standard deviation; and mark lengths.

Bone#	Mark#	Profile 1 depth (μm)	Profile 2 depth (μm)	Profile 3 depth (μm)	Mean, profile depths (μm)	Standard deviation, profile depths (μm)	Length (mm)
T1	M1	45.97	45.78	50.08	47.28	2.43	0.434
T1	M2	15.79	12.13	14.94	14.29	1.92	4.02
T1	M3	14.86	6.987	4.83	8.89	5.28	3.777
T1	M4	16.91	20.83	14.42	17.39	3.23	3.192
T1	M5	6.25	11.8	13.15	10.40	3.66	0.7756
T1	M6	24.27	8.18	7.69	13.38	9.43	1.995
T1	M7	5.48	8.4	9.54	7.81	2.09	3.56
T1	M8	9.611	12.66	15.16	12.48	2.78	3.64
T1	M9	7.57	5.08	17.48	10.04	6.56	1.38
T1	M10	2.87	14.21	6.17	7.75	5.83	1.51
T1	M11	8.01	10.99	6.63	8.54	2.23	3.46
T1	M12	6.5	12.11	15.74	11.45	4.66	0.848
T1	M13	2.68	6.13	9.72	6.18	3.52	2.2
T1	M14	21.89	29.38	28.1	26.46	4.01	0.929
T1	M15	7.81	6.31	7.7	7.27	0.84	2.62
T1	M16	7.15	4.48	3.43	5.02	1.92	2.04
T1	M17	30.91	4.43	29.88	21.74	15.00	2.54
T1	M18	27.51	24.44	7.32	19.76	10.88	2.49
T1	M19	4.7	4.07	4.52	4.43	0.32	1.1579
T1	M20	23.65	16.33	8.12	16.03	7.77	4.62
T2	M1	53.35	65.11	43.44	53.97	10.85	1.69
T2	M2	15.51	28.79	27.27	23.86	7.27	1.99
T2	M3	16.14	12.63	14.76	14.51	1.77	2.36
T2	M4	12.17	13.61	20.55	15.44	4.48	1.65
T2	M5	9.96	15.88	8.97	11.60	3.74	1.72
T2	M6	25.7	27.02	19.88	24.20	3.80	1.41
T2	M7	15.33	10.34	9.19	11.62	3.26	1.99
T2	M8	15.8	12.04	24.38	17.41	6.32	3.57
T2	M9	6.78	69.33	22.94	33.02	32.47	4.07
T2	M10	20.58	24.12	49.23	31.31	15.62	3.07
T2	M11	11.36	9.41	18.02	12.93	4.51	3.58
T2	M12	20.41	31.52	25.67	25.87	5.56	2.85
T2	M13	18.18	39.15	53.56	36.96	17.79	3.98
T2	M14	39.66	17.73	34.21	30.53	11.42	3.27
T2	M15	23.61	44.32	29.29	32.41	10.70	3.95
T2	M16	9.91	14.12	15.77	13.27	3.02	2.29
T2	M17	4.63	13.39	14.29	10.77	5.34	2.28
T2	M18	38.83	29.59	13.37	27.26	12.89	2.53
T2	M19	17.34	17.56	13.77	16.22	2.13	2.06
T2	M20	12.36	20.47	27.38	20.07	7.52	1.19
T3	M1	33.42	20.96	33.06	29.15	7.09	2.96
T3	M2	30.42	16.11	20.56	22.36	7.32	3.08
T3	M3	36.81	32.74	24.26	31.27	6.40	1.99
T3	M4	6.79	8.9	11.11	8.93	2.16	2.29
T3	M5	23.16	109.6	54.7	62.49	43.74	3.48
T3	M6	39	39.44	25.76	34.73	7.77	2.75
T3	M7	12.17	11.19	15.79	13.05	2.42	2
T3	M8	17.58	35.6	42.44	31.87	12.84	3.9
T3	M9	44.01	37.04	41.66	40.90	3.55	1.64
T3	M10	2.36	16.81	10.96	10.04	7.27	1.23
T3	M11	11	30.84	8.01	16.62	12.41	1.14
T3	M12	20.33	38.61	12.63	23.86	13.34	3.32
T3	M13	40.15	19.79	37.32	32.42	11.03	2.72
T3	M14	25.23	2.59	14.92	14.25	11.34	7.41
T3	M15	6.82	15.89	22.81	15.17	8.02	4.92
T3	M16	24.91	21.83	22.27	23.00	1.67	1.72
T3	M17	35.23	33.9	31.8	33.64	1.73	2.07
T3	M18	65.09	69.66	20.42	51.72	27.21	2.12
T3	M19	27.17	36.41	28.96	30.85	4.90	1.59
T3	M20	6.1	6.1	5.21	5.80	0.51	0.82
T4	M1	14.7	7.27	8.29	10.09	4.03	3.41
T4	M2	9.25	8.98	27.25	15.16	10.47	0.69
T4	M3	16.41	23	20.17	19.86	3.31	2.43
T4	M4	13.39	12.69	9.87	11.98	1.86	3.36
T4	M5	2.56	6.87	5.02	4.82	2.16	4.78

(continued)

Bone#	Mark#	Profile 1 depth (μm)	Profile 2 depth (μm)	Profile 3 depth (μm)	Mean, profile depths (μm)	Standard deviation, profile depths (μm)	Length (mm)
T4	M6	12.74	5.73	2.77	7.08	5.12	3.21
T4	M7	4.11	67.1	7.96	26.39	35.31	1.96
T4	M8	13.52	15.97	9.6	13.03	3.21	1.24
T4	M9	10.5	14.62	5.52	10.21	4.56	2.54
T4	M10	5	2.74	3.26	3.67	1.18	1.49
T4	M11	5.45	5.56	9.41	6.81	2.26	2.26
T4	M12	4.14	8.18	12.43	8.25	4.15	2.28
T4	M13	1.21	0.3816	2.25	1.28	0.94	2.01
T4	M14	5.77	5.64	7.87	6.43	1.25	3.97
T4	M15	10.77	7.86	6	8.21	2.40	3.57
T4	M16	16.22	16.6	14.02	15.61	1.39	1.45
T4	M17	2.56	6.16	8.35	5.69	2.92	0.83
T4	M18	7.27	13.08	4.28	8.21	4.47	1.36
T4	M19	4.54	11.6	20.68	12.27	8.09	1.89
T4	M20	7.18	4.5	5.31	5.66	1.37	1.22
T5	M1	11.27	18.15	3.1	10.84	7.53	0.89
T5	M2	54.12	85.08	27.13	55.44	29.00	0.78
T5	M3	9.61	14.14	2.7	8.82	5.76	1.85
T5	M4	34.55	28.83	32.16	31.85	2.87	2.68
T5	M5	6.14	17.14	19.31	14.20	7.06	5.23
T5	M6	4.3	7.8	5.49	5.86	1.78	3.03
T5	M7	55.97	27.5	70.6	51.36	21.92	1.81
T5	M8	23.09	28.21	26.37	25.89	2.59	3.73
T5	M9	12.04	14.47	21.61	16.04	4.97	6.94
T5	M10	30.63	24.69	28.15	27.82	2.98	1.7
T5	M11	9.46	19.92	2.88	10.75	8.59	1.7
T5	M12	49.12	34.22	22.83	35.39	13.18	1.32
T5	M13	11.88	11.2	14.73	12.60	1.87	7.3
T5	M14	19	21.86	10.73	17.20	5.78	2.46
T5	M15	14.2	25.52	54.84	31.52	20.97	4.27
T5	M16	47.59	42.61	16.52	35.57	16.69	2.38
T5	M17	33.37	9.93	11.24	18.18	13.17	5.65
T5	M18	49.5	46.82	38.22	44.85	5.89	3.19
T5	M19	12.29	7.77	8.91	9.66	2.35	2.92
T5	M20	11.67	18.41	12.69	14.26	3.63	3.73
B1	M1	52.51	36.52	41.81	43.61	8.15	5.24
B1	M2	92.44	23.6	49.34	55.13	34.78	5.45
B1	M3	70.21	63.61	84.41	72.74	10.63	7.17
B1	M4	58.38	66.07	75.96	66.80	8.81	4.11
B1	M5	35.68	29.35	27.57	30.87	4.26	7.56
B1	M6	46.72	48.6	46.81	47.38	1.06	4.61
B1	M7	81.51	88.85	30.34	66.90	31.87	3.24
B1	M8	58.82	58.46	52.09	56.46	3.79	1.48
B1	M9	34.39	38.53	44.47	39.13	5.07	2.04
B1	M10	51.12	54.21	50.36	51.90	2.04	1.86
B1	M11	49.11	59.1	50.16	52.79	5.49	3.91
B1	M12	32.13	43.76	63.09	46.33	15.64	2.8
B1	M13	60.37	143.5	94.53	99.47	41.78	3.23
B1	M14	24.81	49.03	49.69	41.18	14.18	3.2
B1	M15	88.95	103.4	71.64	88.00	15.90	3.69
B1	M16	95.48	138.1	126.2	119.93	21.99	6.66
B1	M17	93.66	67.51	31.68	64.28	31.12	7.79
B1	M18	30.79	21.31	28.64	26.91	4.97	3.47
B1	M19	27.94	21.28	20.12	23.11	4.22	6.73
B1	M20	131.9	167.8	119.5	139.73	25.08	3.16
B2	M1	4.79	16.92	19.22	13.64	7.75	2.7
B2	M2	36.08	20.77	12.92	23.26	11.78	2.79
B2	M3	54.46	20.58	7.9	27.65	24.07	3.86
B2	M4	37.68	12.17	15.87	21.91	13.78	4.05
B2	M5	24.35	15.1	30.69	23.38	7.84	3.23
B2	M6	25.99	32.04	52.37	36.80	13.82	1.36
B2	M7	49.32	60.42	40.48	50.07	9.99	2.32
B2	M8	55.65	60.01	39.14	51.60	11.01	2.74
B2	M9	44.8	74.08	60.02	59.63	14.64	2.17
B2	M10	65.56	48.07	37.56	50.40	14.14	2.76
B2	M11	8.37	27.02	42.59	25.99	17.13	4.85
B2	M12	5.24	25.89	22.25	17.79	11.02	4.59
B2	M13	35.11	39.91	37.16	37.39	2.41	3.22
B2	M14	67.77	62.75	67.24	65.92	2.76	3.74
B2	M15	58.75	46.52	56.4	53.89	6.49	4.63

(continued on next page)

(*continued*)

Bone#	Mark#	Profile 1 depth (μm)	Profile 2 depth (μm)	Profile 3 depth (μm)	Mean, profile depths (μm)	Standard deviation, profile depths (μm)	Length (mm)
B2	M16	78.86	65.67	59.3	67.94	9.98	4
B2	M17	57.83	50.54	37.92	48.76	10.07	5.32
B2	M18	26.43	25.16	20.9	24.16	2.90	5.63
B2	M19	18.41	19.57	11.11	16.36	4.59	5.38
B2	M20	35.94	30.8	25.99	30.91	4.98	1.39
B3	M1	47.33	71.23	17.69	45.42	26.82	9.14
B3	M2	81.19	98.36	73.07	84.21	12.91	5.22
B3	M3	25.33	14.53	12.13	17.33	7.03	3
B3	M4	26.39	33.01	14.78	24.73	9.23	2.43
B3	M5	62.59	97.77	47.17	69.18	25.94	1.97
B3	M6	4.85	16.69	28.78	16.77	11.97	4.95
B3	M7	51.54	52.12	66.96	56.87	8.74	1.39
B3	M8	58.4	68.61	51.86	59.62	8.44	1.52
B3	M9	13.36	50.35	27.22	30.31	18.69	1.77
B3	M10	32.75	29.04	31.37	31.05	1.88	1.97
B3	M11	25.55	17.79	36.61	26.65	9.46	7.35
B3	M12	25.71	18.88	10.43	18.34	7.65	5.24
B3	M13	31.65	39.09	20.23	30.32	9.50	2.29
B3	M14	133.9	71.7	65.06	90.22	37.97	4.15
B3	M15	47.95	20.49	34.07	34.17	13.73	3.42
B3	M16	26.5	44.44	28.74	33.23	9.78	5.67
B3	M17	83.05	64.43	21.16	56.21	31.75	2.97
B3	M18	93.92	76.87	65.06	78.62	14.51	5.88
B3	M19	60.42	70.08	32.55	54.35	19.49	6.87
B3	M20	65	77.82	72.96	71.93	6.47	3.58
B4	M1	9.53	3.61	3.11	5.42	3.57	3.17
B4	M2	2.51	3.08	7.23	4.27	2.58	5.07
B4	M3	6.06	55.6	82.86	48.17	38.93	7.81
B4	M4	21.35	47.39	26.65	31.80	13.76	6.51
B4	M5	30.43	27.45	35.45	31.11	4.04	5.49
B4	M6	60.34	48.05	47.01	51.80	7.41	2.11
B4	M7	68.99	75.68	66.45	70.37	4.77	2.95
B4	M8	93.44	107.3	78.6	93.11	14.35	3.96
B4	M9	3.52	18.1	28.18	16.60	12.40	2.84
B4	M10	6.96	10.38	13.06	10.13	3.06	2.3
B4	M11	17.02	20.17	12.04	16.41	4.10	4.21
B4	M12	3.25	6.12	15.04	8.14	6.15	2.72
B4	M13	68.11	65	51.37	61.49	8.90	3.46
B4	M14	80.14	73.84	94.65	82.88	10.67	3.47
B4	M15	29.82	47.18	16.23	31.08	15.51	3.69
B4	M16	8.92	10.29	13.89	11.03	2.57	3.67
B4	M17	44.65	74.53	60.48	59.89	14.95	4.79
B4	M18	35.46	87.06	108.8	77.11	37.67	6.42
B4	M19	22.37	63.68	54.28	46.78	21.65	2.63
B4	M20	24.99	34.34	24.33	27.89	5.60	4.56
B5	M1	20.16	10.17	29.2	19.84	9.52	2.18
B5	M2	9.32	7.26	7.7	8.09	1.08	3.83
B5	M3	4.89	14.17	5.85	8.30	5.10	6.11
B5	M4	2.75	2.77	5.53	3.68	1.60	4.06
B5	M5	6.45	8.45	16.84	10.58	5.51	2.76
B5	M6	12.6	15.63	4.43	10.89	5.79	2.84
B5	M7	25.62	22.15	16.74	21.50	4.48	2.57
B5	M8	19.22	7.41	12.3	12.98	5.93	1.97
B5	M9	25.52	28.4	15.33	23.08	6.87	5.08
B5	M10	22.14	10.88	15.27	16.10	5.68	5.91
B5	M11	1.15	1.937	2.44	1.84	0.65	0.72
B5	M12	15.06	4.91	1.06	7.01	7.23	1.04
B5	M13	1.92	1.7	1.15	1.59	0.40	0.91
B5	M14	3.51	6.77	3.85	4.71	1.79	1.47
B5	M15	6.04	1.92	1.58	3.18	2.48	1.45

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