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A new experimental study on percussion marks and notches and their bearing on the interpretation of hammerstone-broken faunal assemblages

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ABSTRACT

Preliminary experiments on bone breakage have shown the potential utility of quantifying some of its diagnostic features (percussion marks, percussion notches) for taphonomic inferences about human and carnivore involvement in bone breakage in faunal assemblages. The present study increases the range of experiments undertaken to understand the identification of hammerstone percussion (dynamic loading) and its differences from carnivore bone breakage through tooth pressure (static loading). This study contributes to a better understanding of frequencies of percussion marks, uncovers and quantifies those percussion marks that lack key diagnostic features to be identifiable and that could be mistaken with carnivore tooth marks, quantifies notch types, shows different size ranges for notches on bones from small and large fauna than previously reported, quantifies the proportion of notches bearing percussion marks, and introduces new size data for percussion (impact) flakes and percussion marks. Furthermore, all these variables have been applied to a dual experimental set: one experiment using non-modified hammerstones and another based on the use of modified hammerstones. Results vary considerably according to hammerstone type. Some of these taphonomic variables increase the range of equifinality when identifying marks and notches created by different human and non-human agents. This calls for further caution when using isolated variables and features rather than a holistic approach to make taphonomic inferences.

1. Introduction

Recognizing the exploitation of marrow-bearing resources is an important part of the zooarchaeological study of faunal assemblages. The recognition of the diagnostic features created by hammerstone use (Turner, 1983; Blumenschine and Selvaggio, 1988) on bone surfaces enabled the taphonomic differentiation of carnivore-inflicted tooth marks and hammerstone-generated percussion marks (Blumenschine and Selvaggio, 1988, 1991; Pickering and Egeland, 2006). The subsequent quantification of both types of marks on bone assemblages broken by humans and carnivores was used to develop analogues on tooth and percussion mark frequencies resulting from bone breaking by each agent (Blumenschine and Selvaggio, 1991). The application of these estimates to the archaeological record was used to make interpretations of primary or secondary access to carcass resources by Plio-Pleistocene hominids (Blumenschine, 1995; Blumenschine et al., 2007; Capaldo, 1995, 1997).

Two types of percussion marks have been identified: isolated striae fields and pits with associated striations (Blumenschine and Selvaggio, 1988; Pickering and Egeland, 2006; Turner, 1983). The former were initially interpreted as resulting from the absorption of impact by an anvil (Turner, 1983). Later they were shown to also result from direct impacts during hammerstone bone breakage, which is the main cause of pits with associated striations (Blumenschine and Selvaggio, 1988; Pickering and Egeland, 2006). Recently, it has been shown that isolated striae fields could also occur as a result of trampling (Prendergast and Domínguez-Rodrigo, in press), which shows that equifinality is not completely eliminated when analyzing these types of marks. Fortunately, striae fields are a small portion of the percussion marks in a hammerstone-broken bone assemblage (less than 25%). A recent refinement of the study of percussion provided more detailed data on the frequencies of each type of percussion mark, with pits and associated microstriations outnumbering the presence of isolated striae fields (Pickering and Egeland, 2006).

The present study addresses a set of questions. First, is the identification of percussion marks, especially the most abundant type (pits and associated microstriations) as frequent and straightforward as initially argued by Blumenschine and Selvaggio (1988, 1991)? If so, do the diagnostic criteria proposed by these authors apply to all pits resulting from percussion? If not, this could confirm some degree of equifinality in those percussion pits that could potentially not be differentiated from carnivore-inflicted

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tooth pits. If so, taphonomists may “identify” some carnivore activity where there was initially none. Second, most experiments on percussion marks have used non-modified cobbles as hammerstones. Does the use of modified hammerstones (e.g., choppers) make any difference in the resulting morphology and frequency of percussion marks and in their identification?

Bone breaking has also been approached from the study of notches created by dynamic and static loading agents (Capaldo and Blumenschine, 1994). It was suggested that measurements of notch shape could be potentially used to differentiate between both types of loading. It was also suggested that notch type distribution (single notches *versus* double opposing and double overlapping notches) could also be used to discriminate dynamic loading from carnivore-inflicted static loading (Domínguez-Rodrigo et al., 2007). The latter inference is in need of a proper analogue given that the experiments on which it was based were preliminary. Does the proportion of notch types vary according to loading type (dynamic *versus* static) or carcass size (with thicker bones from larger carcasses requiring more impacts and therefore, resulting in higher occurrences of double notches)? Controlling for these two different variables is essential to understand if the loading type is solely responsible for the different notch frequencies.

Furthermore, some of the signatures of percussion, such as percussion mark size and the dimensions of percussion (impact) flakes, have not been previously quantified and published. Pickering and Egeland (2006) carried out the most complete documentation of percussion signatures in any experiment published so far. They tallied the frequencies of mark types, notches and impact flakes per element type according to raw material used (quartzite *versus* sandstone). They also studied the relationship between the number of hammerstone blows and the resulting percussion mark frequency.

This study continues the trend initiated by previous researchers of refining both the identification of hammerstone-inflicted marks and breakage signatures and their frequency on human-broken assemblages, with the goal of strengthening current analogues applied to the archaeological record. Some important differences with previous studies are stressed; among them, the frequency of percussion mark types, the problems in identifying an important number of these marks, and a new expanded range of variability of notch dimensional properties.

The potential use of this type of study to address major evolutionary questions lies in the correct identification of bone breakage processes. Mistaking tooth marks with some of the marks that will be shown here could yield interpretations fatally flawed and provide biased support to hominid scavenging scenarios by over-interpreting the actual number of tooth marks or even the tooth-marking agent. Also, interpretations of hominid and carnivore bone breakage by using some taphonomic criteria, such as notch dimensions, will have to be revised under the new information provided by this study.

2. Method and sample

A total of 66 long bones were used for the present study both from small (five goats) and large (two cow) carcasses (Table 1). They were broken by laying them horizontally on anvils and impacting their surface with a hammerstone at an oblique angle. No specific sections of the shaft surfaces were targeted to make bone breaking easier, since the main goal was not to minimize the number of blows to break open the elements. Selecting specific sections would have implied assuming that hominids would also have selected the same areas. One might argue that our approach could have resulted in different percussion mark frequencies *vis-a-vis* experiments where specific bone areas were targeted (Blumenschine and Selvaggio, 1991). However, the frequencies reported here are similar to and within the range of variation of experiments using the same kind of hammerstones and targeting certain areas during bone breakage (Blumenschine, 1995; Blumenschine and Selvaggio, 1991; Pickering and Egeland, 2006).

Table 1
Number of elements (MNE), specimens (NISP) and frequencies of percussion-marked fragments and impact flakes resulting from experiments using modified and non-modified hammerstones. Numbers in parentheses are for percentages according to NISP.

	Cow	Goat
Non-modified hammerstone		
	4 humeri	8 humeri
	4 femora	8 femora
	4 radii-ulnae	8 radii-ulnae
		8 tibiae
		7 metacarpals
		6 metatarsals
MNE	12	45
NISP	86	541
NISP-PM (%)	28(32.5)	121(22.3)
Impact flakes	11	8
Modified hammerstone		
	4 humeri	1 femur
	4 femora	2 tibiae
	2 radii-ulnae	1 metatarsal
MNE	10	4
NISP	59	50
NISP-PM (%)	41(69)	30(60)
Impact flakes	5	7

Two different sets of experiments were designed, one using a non-modified cobble and one using two modified hammerstones: a chopper and a polyhedron (Fig. 1). Bones were defleshed and disarticulated with the aid of metal knives. Bone breakage was performed without removing periostium. Broken bones were cleaned by boiling them in water and a solution of neutral detergent. Marks were identified with hand lenses (15–20×) under strong light (60 W) and a binocular (up to 80×) microscope. Each specimen was inspected separately by the four researchers to control agreement on identifications. Rarely was there any disagreement in mark identification, and the protocol used was to discard any specimen with marks whose identification was not agreed by at least three authors ($n = 2$).

Percussion marks are traditionally characterized as “pits, grooves or isolated patches of microstriations. Pits and grooves are usually associated with densely packed and shallow patches of microstriations oriented approximately transverse to the long axis of the bone…these patches of microstriations occur within and/or emanate from the depression. Microstriations also occur as isolated patches.” (Blumenschine, 1995, p. 29). The isolated patches of microstriations have been called isolated striae fields (Pickering and Egeland, 2006; Turner, 1983). Percussion marks were identified in our study as one of three types: isolated striae fields, pits with microstriations – as defined by Blumenschine (1995) and Pickering and Egeland (2006) – and pits without associated microstriations. The latter could be identified as pits with identical morphology to the pits created with associated microstriations or as shallower pits resulting from the loss of cortical bone after impact.

Notches were identified according to the following classification (modified from Capaldo and Blumenschine (1994)):

1. Complete notches have two inflection points on the cortical surface and a non-overlapping negative flake scar.
2. Double opposing complete notches are two complete notches that appear on opposite sides of a fragment and result from two opposing loading points.
3. Incomplete notches are missing one of the inflection points.
4. Double overlapping notches have negative flake scars that overlap with an adjacent notch. The shape of both notches has to be visible from both the cortical and the medullary surfaces.

Fig. 1. Both experimental scenarios, involving non-modified (A) and modified hammerstones (B).

5. Inverse notches have double scars, one emanating from the cortical surface and the other from the medullary surface.
6. Micronotches (<1 cm).

Notch, impact flake and percussion mark measurements were taken by using a high-resolution caliper and angles were taken with a goniometer. The frequencies of percussion marks associated to notches were also documented. The association was established by the presence of percussion marks at a distance from the notch edge not exceeding 20 mm in bones from small animals and 30 mm in bones from large animals. The selection of different distances according to carcass size is because those measurements and the depth of the associated notches cover roughly at least one-fourth of the shaft circumference section, which varies depending on animal size. Also, marks associated with notches are the result of using the area surrounding the notch as an impact area. In our experimental sample, no marks associated with notches on goat bones were documented beyond 20 mm and on cow bones beyond 30 mm. Marks existing on the same notch-bearing specimens were either documented within those distances or farther than 50 mm from the notch. No mark was documented within the 20/30–50 mm range. This does not preclude that they could appear in this range in other experiments, but justifies our choice of distances in our study per each carcass size.

Frequencies of each variable were established on the sample of specimens larger than 2 cm. Hammerstone breakage often generates smaller splinters, but since these are more easily affected by post-depositional processes and are not frequently preserved at sites, they were discarded in order to make the experiments more comparable to archaeofaunal assemblages. For all variables we compared results from the experiments performed with modified hammerstones to those performed with non-modified hammerstones. Data from both experimental sets were statistically analyzed with R. All graphs derived from these data were also programmed in R. Differences between experiments were analyzed through *T*-tests. Ranges of variation for samples were shown through 95% confidence intervals (CI) and bootstrapped estimates. To understand how the observed frequencies reflect the underlying population values, which could be affected by sample size, mean values and 95% confidence limits were also generated by bootstrapping percussion mark frequencies and hammerstone notch dimensions 10,000 times. Comparisons among mark type frequencies were also made by using one-way ANOVA procedures.

3. Results

3.1. Percussion-marked specimen frequencies

A total of 32.5% of all the fragments larger than 2 cm resulting from breaking the cow bones with non-modified hammerstones bear at least one percussion mark. The smaller goat bones show a more reduced frequency of percussed specimens (22.3%) (Table 1). Both carcass sizes show mean percentages that are within the range of variation of previous hammerstone-broken experiments (Blumenschine, 1995; Pickering and Egeland, 2006). Given that goat bones include not only the same elements as those used for cows (humeri, radi-ulnae and femora), but also tibiae and metapodials, a comparison using goat humeri, radi-ulnae and femora shows a similar frequency of percussion marks (18.9%), which indicates that element type is not a confounding variable.

The experimental sample created with modified hammerstones shows a significantly higher number of specimens bearing at least one percussion mark: cow bone fragments (69%) and goat bone specimens (60%) show more than twice the percentage of specimens bearing percussion marks than when non-modified hammerstones were used. These higher frequencies can be related to the increased difficulty in breaking bones when using any hammerstone with edges, as can also be documented in the ratio of percussion marks to NISP (Table 2). Cow bones broken with non-modified hammerstones show a ratio of 0.43 and goat bones show a ratio of 0.37. Experiments with modified hammerstones show a much higher frequency of percussion marks per specimen with a ratio of 5 for cow bones and 1.1 for goat bones.

When dividing the sample from each experiment type in percentages of bone fragments bearing percussion marks according to element type (e.g., humerus, femur), in order to observe the internal variability in each sample, the frequencies in the experimental sample obtained using non-modified hammerstones can be compared to those derived from using modified hammerstones. A *T*-test comparing both shows that there is a significant difference in the mean values of percussion-marked bones from cows ($t = -3.5196$, $p = 0.024$) and those from goats ($t = -3.6232$, $p = 0.050$) when using modified or non-modified hammerstones. Given the small size of most of the experimental samples, to increase the reliability of this interpretation, a comparison between bootstrapped samples was necessary. A *T*-test of samples bootstrapped 10,000 times shows that broken bones from cows

Table 2
Frequencies of percussion mark types according to carcass size in each experimental set using non-modified and modified hammerstones. Numbers in parentheses are percentages according to NISP.

	Number of PM	Pits-micro (%)	Striae fields (%)	Pits (%)
Non-modified hammerstone				
Cow	37	15(40.5)	13(35.1)	10(27)
Goat	204	92(45)	51(25)	61(29.9)
Modified hammerstone				
Cow	296	241(82)	37(12.5)	18(6)
Goat	56	39(69.6)	15(26.7)	2(3.5)

($t = -247.48$, $p = 0.000$) and from goats ($t = -246.29$, $p = 0.000$) are significantly different in percussion-marked specimen frequencies.

3.2. *Frequencies of percussion mark types*

Currently available experiments on bone breakage using non-modified hammerstones have shown that percussion pits with associated microstriations are substantially more abundant than isolated striae fields (Pickering and Egeland, 2006). Our results initially support this assertion. In our experiments, we have documented a frequently inconspicuous but notable third type of percussion mark consisting of pits without associated microstriations (Fig. 2), including both deep and shallow pits resulting from the loss of some of the outermost cortical layers and in several cases, deeper pits showing internal crushing (Fig. 2B). This type of percussion mark was also reported by Pickering and Egeland (2006). They observed "pits with and without emanating striae" (p. 466) in their experimental sample. In our experiments using non-modified hammerstones, pits with associated microstriations are still the most abundant type of percussion mark, followed by striae fields and isolated pits (Table 2). The latter could range between 27% and almost 30% of all the marks created. This distribution differs from that documented in the experiments carried out with modified hammerstones. The results in the latter show the overwhelming dominance of pits with associated microstriations (70–82%), followed marginally by isolated striae fields (12–27%) and even more marginally by isolated pits without microstriations (3–6%), depending on carcass size (Table 2). This result is very similar to that reported by Pickering and Egeland for pits with microstriations and striae fields (Pickering and Egeland, 2006).

A one-way ANOVA analysis of the three types of marks in both experiments shows the statistical divergence of both samples (using both types of hammerstones) for cow ($F = 169.334$, $p = 0.000$) and goat ($F = 323.320$, $p = 0.000$) bones. Given their small size, they were bootstrapped 10,000 times and a previous Kolmogorov–Smirnov test and a Levine test were applied, which showed both their normal distribution and homocedasticity. If splitting the sample into percussion mark type for each of the two experiment types according to carcass size, *T*-tests also show the divergences of both types of experiments. Regarding cow bones, the smallest degree of variation between experimental samples is documented in striae fields ($t = 2.49$, $p = 0.040$). Significantly larger differences regarding pits with microstriations ($t = 7.59$, $p = 0.002$) and pits without microstriations ($t = 5.73$, $p = 0.005$) between both experiments using modified and non-modified hammerstones were also observed. Among the goat bones, percentages of pits without microstriations ($t = 3.96$, $p = 0.017$), pits with microstriations ($t = -1.90$, $p = 0.013$) and isolated striae fields ($t = -0.339$, $p = 0.752$) seemed also to differ between experiment types. Hammerstone type, therefore, plays a relevant role in the frequencies of percussion mark types.

Beyond the differences in frequencies of traditional percussion mark diagnostic traces (pits with or without microstriations and isolated striae fields), the experiment using modified hammerstones also produced another diagnostic feature: the particular morphology of pits. About 20% of all the pits created with a chopper or polyhedron were oval pits indistinguishable from those created using non-modified cobbles. However, 12% of the pits were actually score-shaped and 68% were neither ovals nor scores but showed irregular shapes whose outline had some angularity (see Fig. 2C,E,F). This trait, given its prevalence in the percussion marks created by modified hammerstones, could be a potential signature in archaeological assemblages detectable through taphonomic studies.

3.3. *Distribution of notch types*

For non-modified hammerstones, the frequencies of notches vary substantially according to carcass size. About 27% of specimens from the cow bones show at least one notch. This frequency is substantially lower in the goat bone sample (3.5%). In the modified hammerstone sample, cow bone specimens also show a high frequency of notches (25.4%), whereas those from goats show a slightly lower percentage (18%). These frequencies vary from those reported by Pickering and Egeland (2006), which are much

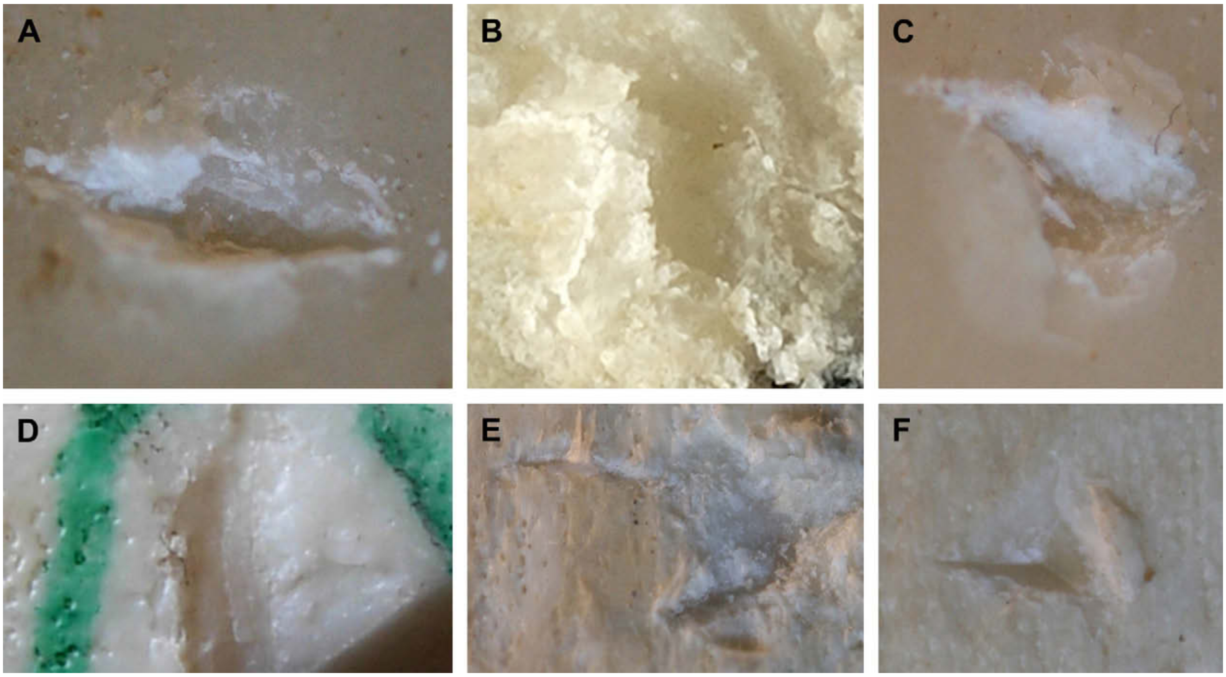

Fig. 2. Some examples of percussion marks, without associated microstriations (A–C), created by non-modified hammerstones (B), and some types of percussion marks created by modified hammerstones (A, C, D–F). In the latter one can see the typical scores with internal microstriations (D) (chop marks), the highly variable geometrically-shaped pits (E), and the irregularly-shaped marks with angular outline (F).

lower, probably because their NISP counts included splinters smaller than 2 cm or because notches on smaller animal bones (deer) are not as frequent as those generated on bones from larger carcasses (cow). In any case, the large variability documented makes notch frequencies an unreliable indicator of hammerstone breakage.

Table 3 shows the distribution of notch types in both experimental assemblages according to carcass type. Single notches (either complete or incomplete) are by far the most abundant of the four main notch types. Double opposing notches are more abundant than double overlapping notches and the latter were not documented on goat bones (Fig. 3). This result contrasts with those derived from bones broken by static loading (e.g., carnivore gnawing) as preliminarily observed by Domínguez-Rodrigo et al. (2007) (Fig. 3). Therefore, the ratio of double opposing/single notches to double overlapping/single notches can be used to differentiate dynamic from static loading on bovid bones.

3.4. Dimensions of complete notches

The mean values and ranges of variation expressed in 95% confidence intervals for each experimental set are shown in Table 4. The ratio of notch breadth-depth to flake scar breadth-depth shows that there is some variation not documented in previous experiments by Capaldo and Blumenschine (1994), probably due to small sample size (Fig. 4). The present study shows more moderate variation. Fig. 4 shows the ranges of variation of 95% CI samples for each experiment type both for the actual sample sizes and for their values transformed through bootstrapping (10,000 times). Sample sizes fit well with the bootstrapped values, which indicates their capability to separate dynamic loading from static loading processes in bone breakage when using complete sets of notches rather than isolated notches.

Capaldo and Blumenschine had a sample of two hammerstone-created notches on bones from large carcasses. This probably accounts for the large range of variation documented in their study and the strong overlap with their carnivore notch sample. In our study, our sample shows a different trend, with hammerstone-made and carnivore-made notch values overlapping far less. Except for a couple of outliers, most of the notches in our hammerstone sample occur outside the ranges of variation documented for carnivore notches. They cluster either in or around the 95% CI ranges for hammerstone-created notches. They are generally larger viewed from the cortical perspective than from the medullary surface. This tendency is the opposite in carnivore-made notches. Therefore, hammerstone notches spread along the *X*-axis, whereas carnivore notches expand on the *Y*-axis (Fig. 4a). The exception to this are those notches created by modified hammerstones, which either show roughly equal values when viewed from either the cortical or medullary surface, or the medullary dimensions are bigger but well outside the ranges documented for carnivores. Hammerstone type, therefore, seems to play an important role in notch morphology, with non-modified hammerstones generating notches that are broader from a cortical view and more easily differentiated from carnivore-made notches.

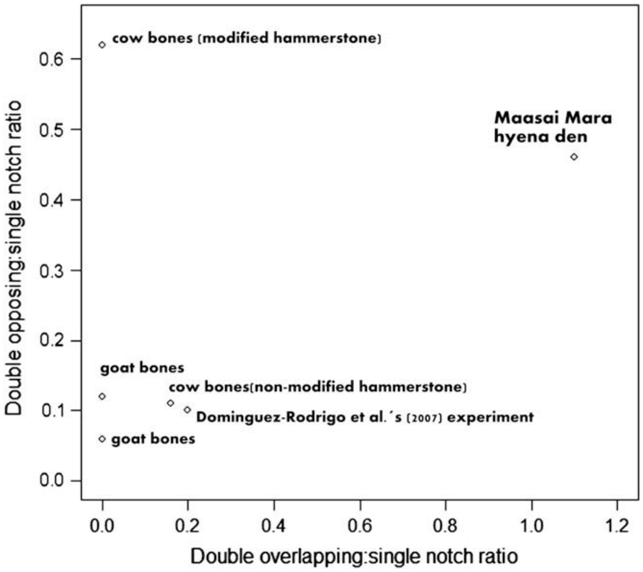

Fig. 3. Proportion of double overlapping and double opposing notches according to the number of single notches. Each ratio type is shown for the hammerstone-broken bone experiments according to carcass size and compared to the carnivore-broken notch sample of Maasai Mara (Domínguez-Rodrigo et al., 2007).

Notch values from small carcasses are surprisingly more ambiguous, in contrast with Capaldo and Blumenschine's previous study where their sample size allowed them to differentiate static from dynamic loading more clearly than in larger carcasses (Fig. 4b). The main reason for our different results may lie in the fact that in our experiments we did not obtain any large notches, whereas Capaldo and Blumenschine did. Only those broad notches are clearly diagnostic of hammerstone loading. Since we only obtained notches with flake scar ratios <15, most of our notches cluster very closely around the carnivore-made sample. Notches generated by modified hammerstones seem to differ more from the static loading sample than those created by non-modified hammerstones. In sum, the bulk of the notches obtained on small carcasses in our experiment can only be differentiated from carnivore-made notches using the same pattern as documented in bones from larger carcasses: that is, by exhibiting broader cortical dimensions than medullary ones.

According to the data from the present study, notches created by hammerstone use on bones from larger animals could be more easily differentiated from those made by carnivores than on bones from smaller carcasses. Probably the stronger impact necessary to break open larger bones and the resulting expansive and reabsorptive distribution of forces by bone tissue during breakage can be partly accountable. When using non-modified hammerstones, about 12% of the notches from the cow bones show a percussion mark associated with the perimeter of the notch. This frequency is much smaller in notches from goat bones (0.5%). Modified hammerstones produced a much larger sample of notches with associated percussion marks. All but one of the notches made on cow bones (92%) had an associated percussion mark within 30 mm of

Table 3
Distribution and frequencies of notch types according to carcass type. Numbers in parentheses are for percentages according to total NISP, excluding micronotches.

	No. of notches[a]	Single complete	Single incomplete	Double opposing	Double overlapping	Inverse notch	Micronotch
Cow	24	7(29.1)	11(45.8)	2(8.3)	3(12.5)	1(4.1)	2
Goat	19	12(63.1)	5(26.3)	1(5.2)	0	1(5.2)	7
Cow	15	4(26.6)	4(26.6)	5(33.3)	0	2(13.3)	5
Goat	9	4(44.4)	4(44.4)	1(11.1)	0	0	3

[a] Excluding micronotches.

Table 4
Mean values, standard deviation and 95% confidence interval of notch dimensions according to carcass size (cow *versus* goat) and experiment type (non-modified *versus* modified hammerstones) from cortical and medullary dimensions (in mm). A carnivore control sample (Maasai Mara hyena den) is also included as a contrast. See Fig. 4 for the graphical representation of these values.

	Cow		Goat	
	Cortical notch	Medullary notch	Cortical notch	Medullary notch
Non-modified hammerstone				
Mean	6.44	4.71	6.90	4.25
s.d.	2.15	1.98	5.42	2.18
No.	10	10	12	12
95% C.I.	(5.11–7.78)	(3.47–5.94)	(3.83–9.96)	(3.01–5.48)
Modified hammerstone				
Mean	2.89	5.46	8.67	9.12
s.d.	2.05	3.79	2.57	3.25
No.	10	10	4	4
95% C.I.	(1.62–4.17)	(3.10–7.81)	(6.15–11.19)	(5.94–12.30)
Bootstrapped samples				
Non-modified hammerstone				
Mean	6.44	4.70	6.95	4.26
95% C.I.	(5.18–7.71)	(3.50–5.91)	(3.93–9.86)	(3.05–5.91)
Modified hammerstone				
Mean	2.89	5.46	8.68	9.13
95% C.I.	(1.74–4.04)	(3.24–7.67)	(6.49–10.85)	(6.36–11.88)
Carnivore sample				
Maasai Mara hyena den				
	Large			Small
	Cortical notch	Medullary notch	Cortical notch	Medullary notch
Mean	5.61	9.9	6	7.82
95% C.I.	(3.99–7.33)	(5.9–13.9)	(4.27–7.73)	(5.14–10.5)

the notch rim. In the goat bone sample, 54% of the notches bore associated percussion marks within 20 mm of the notch rim. Modified hammerstones, therefore, leave a higher frequency of marks on notches as a result of generating an overall higher percentage of percussion marks on bone surfaces.

3.5. Impact flakes

A total of 31 impact flakes (4% of NISP) were obtained in this experimental set (Table 1). This is a negligible percentage given the high fragmentation of the goat bones. However, if considering only bones from larger carcasses, the frequency increases to 11% of NISP (Table 5). Given that no current taphonomic study quantifies percussion-like flakes in carnivore assemblages, no criteria exist that show whether this flake type is more abundant in bone assemblages created by humans or carnivores. However, these percentages are similar to those reported by Pickering and Egeland (2006) on deer bones.

When comparing impact flakes produced by modified and non-modified hammerstones (Fig. 5), a strong overlap can be observed in bones from large carcasses. Modified hammerstones seem to create somewhat longer flakes. Differences become more noticeable when comparing percussion flakes from goat bones, where the trend of longer flakes produced when using modified hammerstones can be more clearly seen. These can be as long as flakes from bones from larger animals, but substantially narrower. Potentially, percussion flakes obtained by the use of modified hammerstones could be differentiated more easily from flakes created by carnivores, given the overall narrower notch shapes of the latter (Capaldo and Blumenschine, 1994) (see above).

3.6. Percussion pit sizes

Given the irregular oval shape of percussion pits, their size was measured by taking the maximum width of any given pit. Percussion pits generated by both types of hammerstones are very similar in size ($t = -0.895$, $p = 0.385$). Therefore, if treated as a single sample, the mean largest dimension of those marks that can be clearly identified as pits is 2.47 mm (S.D. = 1.15). The range includes pits as small as 1 mm and as large as 4.7 mm. Larger pit-like flaked areas result from impacts that generate marks that in our experiment do not have the oval-like shape shared by most pits; rather, they look more like scores. If including these score-like marks, we document a mean value of 5.63 mm and a range of 3.9–10 mm. Most of these score-shaped marks, which in most cases (>95%) are associated with microstriations, are created using modified hammerstones. Therefore, they should not be mistaken with carnivore tooth scores. However, pits without the associated microstriations can potentially be mistaken with carnivore tooth pits. When looking at the size data documented for tooth pits created by carnivores on dense cortical bone surfaces, the mean value of the percussion pits in our experiment is similar to the mean value of medium-sized

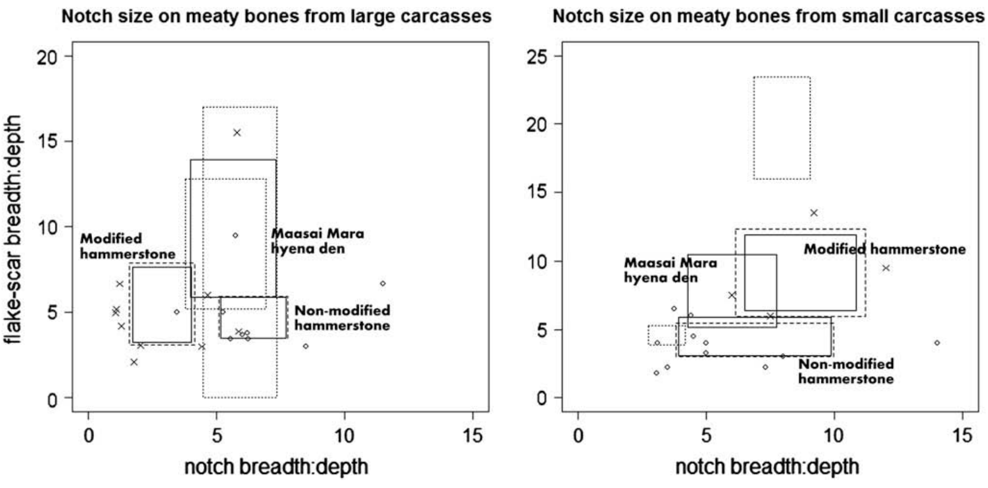

Fig. 4. Dimensional values of notches created through dynamic (hammerstone) and static (carnivore) loading on bones. Rectangles show 95% CI ranges. Dotted rectangles show Capaldo and Blumenschine (1994) experimental values for dynamic (tallest rectangle) and static loading. Dashed rectangles show the values for our hammerstone experimental sample, with enclosed grey-outlined rectangles showing the bootstrapped values. The largest grey rectangle shows the values for notches from size 3 bones broken by hyenas, as documented in Maasai Mara hyena den (Egeland et al., in preparation). Diamonds are notches created by non-modified hammerstones. Crosses are notches created by modified hammerstones.

Table 5
Dimensions of impact flakes from cow and goat bones created by non-modified and modified hammerstones; 95% confidence interval (two-tailed alpha = 0.025) is also included.

	Cow		Goat	
	Length	Width	Length	Width
Non-modified hammerstone				
Mean	33.1	18.7	23.3	7.2
No.	11	11	8	8
95% C.I.	(25.2–41	(14.9–22.4)	(16.6–30)	(4.8–9.6)
Modified hammerstone				
Mean	41	19	39.1	11.5
No.	5	5	7	7
95% C.I.	(29.3–52.6)	(13.4–24.5)	(32–46)	(8.9–14.2)

carnivores (like hyenas) or omnivores like baboons (Domínguez-Rodrigo and Piqueras, 2003). The size range values would overlap with those of all carnivores larger than 5 kg except lions and hyenas, which can create pits longer than 5 mm. This means that many pits without associated microstriations could be confused with tooth pits from a large array of carnivore taxa.

4. Discussion and conclusions

Non-modified hammerstones seem to be more efficient at breaking bones than modified hammerstones if judging from the number of percussion marks left on bone surfaces, which could potentially reflect the number of blows or the ergonomics of each hammerstone type when impacting bone surfaces. There are significant differences in the frequencies of marks created by each hammerstone type for both small and large carcasses.

Notch types created through hammerstone bone breakage are dominated by single notches (complete and incomplete), followed at a distance by double opposing and double overlapping notches. The latter are more represented in bones from large animals, probably because of repeated impact on the same area of thicker cortical bone. However, at least for bovid bones, the frequencies of double opposing and especially double overlapping notches can be used as an indicator of agent of bone breakage. Experiments with thicker bones from other animals, such as equids and even larger fauna, are necessary to ascertain whether this distinction also holds for these other faunal groups.

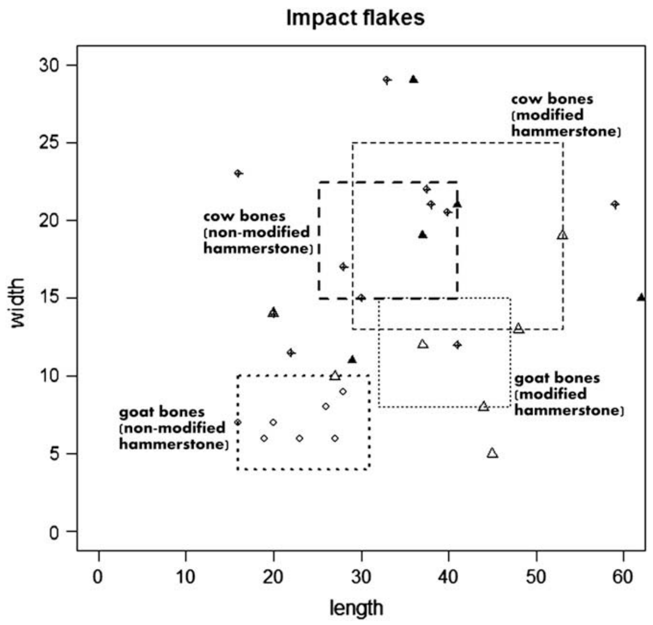

Fig. 5. Dimensional values of impact flakes created through dynamic (hammerstone) loading on bones. Rectangles show 95% CI ranges. Dotted rectangles show the experimental values for small fauna (goat). Dashed rectangles show the values for large fauna (cow). Circles are notches created by non-modified hammerstones. Crosses are notches created by modified hammerstones. Encircled crosses are for single impact flakes created by non-modified hammerstone on cow bones; open diamonds are for impact flakes created by non-modified hammerstone on goat bones; closed triangles are for impact flakes created by modified hammerstone on cow bones; open triangles are for impact flakes created by modified hammerstone on goat bones.

Notch measurements grant support to the caution with which Domínguez-Rodrigo et al. (2007) used the available referential analogues (Capaldo and Blumenschine, 1994), indicating that some large variation and intense overlapping between different agents could be due to small sample sizes. Our study has shown this to be the case for notches on bones from large carcasses. It has also shown that notches created by static and dynamic loading on small animal bones are less clearly separated than earlier. Overall, the current data suggest that hammerstone-created notches show larger dimensions from cortical view than medullary view. This trend is the opposite in notches generated by static carnivore loading. The results in the present study suggest that notch dimensional data should be used in conjunction with other taphonomic indicators (e.g., notch type distribution, tooth mark frequencies, etc.) in order to determine if bones were broken by hominids or carnivores. Only very broad notches seem to be produced more frequently by hammerstones.

These broader notches result in the occurrence of similarly broad impact flakes. Future studies should determine the extent to which “impact” flakes created by carnivores, namely hyenas, overlap in size with those created by hammerstone percussion. Furthermore, it will be necessary to determine what percentage of those notches bear traces of carnivore activity in the form of tooth marks. The present study provides a preliminary analogue for frequencies of percussion marks associated with notches.

Modified and non-modified hammerstones generate different frequencies of percussion mark types. Modified hammerstones result in very abundant numbers of pits/scores with associated striations and very few isolated striae fields. These former marks are also similarly dominant over the latter in assemblages generated by non-modified hammerstones. However, the difference is more relative due to the presence of pits without microstriations. One of the most innovative conclusions of this study is the quantification of those percussion marks that do not show the same diagnostic features as the other percussion marks and that cannot be differentiated from carnivore tooth marks. A little less than one-third of all percussion marks created by non-modified cobble hammerstones have no associated microstriations. This creates a situation of equifinality, since taphonomists can easily mistake these marks for carnivore marks and make interpretations of dual-patterned (hominid-carnivore or carnivore-hominid) models in assemblages where only hominids were responsible for bone modification. The reason for this equifinality lies in the similar oval shape of these percussion marks and tooth marks, their internal features (crushing and flaking) (Fig. 2B), and their size: we have documented in our sample that percussion pits without microstriations range from 1 mm to 4.4 mm. The reasons for hammerstones creating marks without leaving the typical microstriations may lie in a combination of factors, including the polished cortical surface of non-modified cobbles and the protective periostium layer of bones, which frequently prevents the microscopic mineral particles of a cobble from abrading the bone surface. This was previously suggested by Pickering and Egeland (2006, p. 467) when addressing the lack of correlation between hammerstone blows and percussion mark frequency.

We observed a difference in our sample with markedly thicker periosteum on the radii than on the humeri. Periosteum and residual *musculature not only had the potential to cushion bones from receiving percussion marks under direct blows, but they also caused significant slippage of specimens during some impact events.*

This potential equifinality extends beyond the quantification of marks and also affects the identification of specific non-anthropogenic agents using isolated marks. For instance, Njau and Blumenschine (2006) introduced diagnostic criteria for tooth marks created by crocodiles. One of the diagnostic types of tooth marks imprinted by these agents consisted of bisected pits/scores (oval or score-like shaped), sectioned by a striation resulting from the morphology of crocodile teeth. In words of Njau and Blumenschine (2006, p. 149):

Crocodiles produce two classes of marks we have not observed on bones modified by mammalian carnivores. We refer to one of these classes as bisected marks. These include pits and punctures that are bisected by a sharp to more rounded V-shaped depression within the mark. The bisecting depression can extend beyond the circumference of the pit or puncture in one or two directions. The bisections are formed by the bicarinated tooth crown.

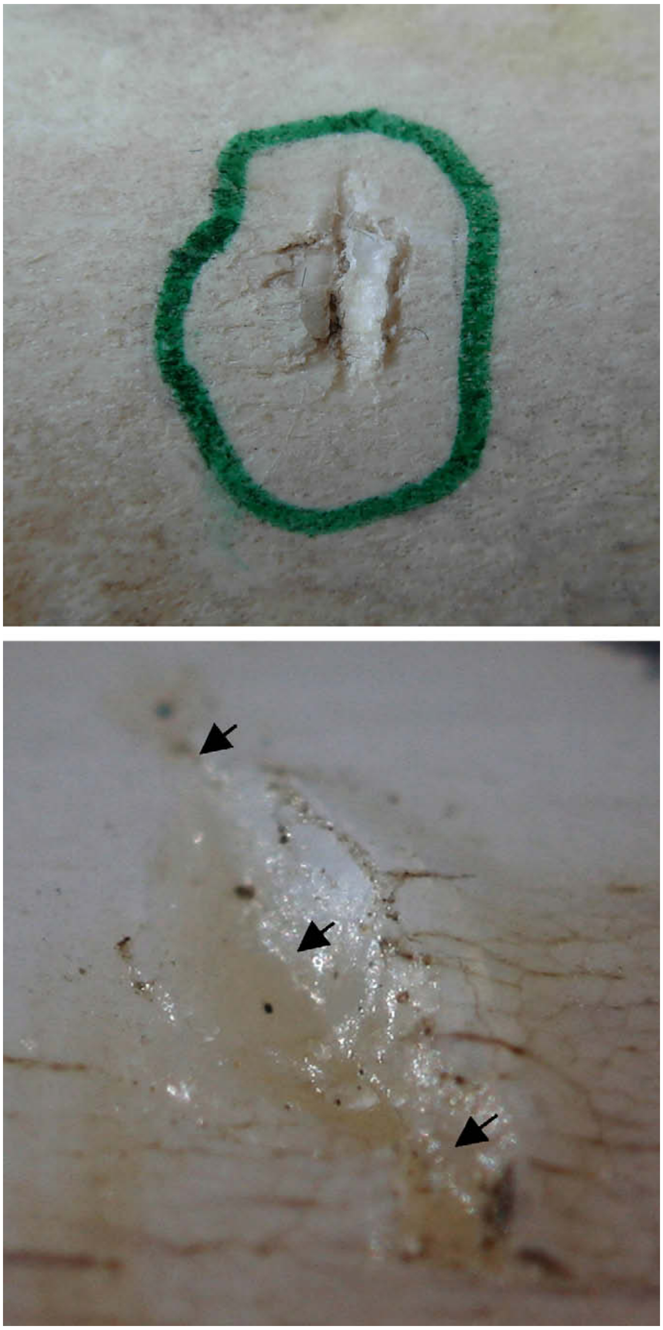

Fig. 6. Percussion marks showing an oval-shaped pit dissected by a striation. Arrows in the lower figure show the trajectory of the striation inside the pit. See Pobiner et al. (in press) for interpretation of similar bisected marks in fossil specimens as crocodile tooth marks.

Bisected pits and scores similar to those documented by Njau and Blumenschine (2006) have been observed in our experimental sample created by modified hammerstones ($n = 4$; 9.7%). The edges of the chopper and the edges and corners of the polyhedron are responsible for the occurrence of scores and pits that show a bisection (see Fig. 6). Therefore, the marginal occurrence (sometimes one or two marks) of crocodile tooth marks reported for some of the Olduvai Bed I sites (Njau, 2006) or some of the recently studied new Koobi Fora sites (Pobiner et al., in press) could also be the result of hominids using some modified hammerstones to break bones, even in those cases when bones broken by non-modified hammerstones make up the bulk of the faunal assemblage. This seems to be the case at FLK Zinj in Olduvai Bed I, where a couple of specimens bearing percussion marks show geometric scoring probably caused by the edge of a lithic implement (Domínguez-Rodrigo and Barba, 2006; Domínguez-Rodrigo et al., 2007), and it is definitely the case at BK (Olduvai Bed II), where several specimens bear percussion scores caused by hammerstones with edges (Domínguez-Rodrigo et al., submitted for publication). A similar interpretation has been suggested for some Oldowan South African lithic implements (Thackeray et al., 2005). This urges caution in the use of isolated criteria to make taphonomic inferences and calls for the comprehensive use of several taphonomic variables and indicators to make interpretations of bone modification by human and non-human agents.

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