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ORIGINAL PAPER

Micro-photogrammetric and morphometric differentiation of cut marks on bones using metal knives, quartzite, and flint flakes

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Abstract In a previous article, we presented an innovative method to analyze cut marks produced with metal tools on animal bones from a metrical and tridimensional perspective (Maté-González et al. 2015). Such analysis developed a low-cost alternative technique to traditional microscopic methods for the tridimensional reconstruction of marks, using their measurements and sections. This article presents the results of an experimental study to test this photogrammetric and morphometric method for differentiating cut marks generated with metal, flint, and quartzite flakes. The results indicate statistically significant differences among cut marks produced by these three types of raw material. These results encourage the application of this method to archeological assemblages in order to establish a link between carcass processing and lithic reduction sequences on different raw materials and also to define the kind of tools used during butchery.

Keywords Taphonomy · Cut marks · Micro-photogrammetry · Computer vision · Image-based modeling · Raw material

Introduction

Cut marks on bones are the direct evidence of human access to carcass resources. They were first documented in the nineteenth century and the beginning of the twentieth century in some French Paleolithic sites (Lartet 1860; Lartet and Christy 1875; Martin 1909). Since then, cut marks have been recognized in a number of sites of diverse chronology. Gona and Bouri are the locations which yielded the oldest undisputed cut-marked bones, dated to 2.5–2.6 Ma (De Heinzelin et al. 1999; Semaw et al. 2003; Domínguez-Rodrigo et al. 2005), which testified that human beings had processed meat resources at rather early times. Although recently, some claims have been made for earlier butchery traces from two fossils from Dikika (Ethiopia), dated at 3.4 Ma (McPherron et al. 2010; Thompson et al. 2015), this evidence is still controversial and some suggest those traces may have a non-anthropogenic origin (Domínguez-Rodrigo et al. 2010; Domínguez-Rodrigo and Alcalá 2016).

Butchery evidence in the form of cut-marked bone becomes abundant after 2 Ma. Even though it is not possible to define the kind of meat consumption documented in Gona and Bouri, at other locations such as Olduvai, Swartkrans, Koobi Fora, Peninj, Atapuerca, and Ain Hanech, with dates older than a million and a half years, the anatomical distribution of cut marks and their frequencies were key to support that humans had primary access to fleshed carcasses (Domínguez-Rodrigo et al. 2002, 2007, 2009a, 2014a; Pickering et al. 2004; Pobiner et al. 2009; Saladié et al. 2011; Sahnouni et al. 2012). The identification of cut marks was also used to suggest cannibalistic practices on

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different hominines along human evolution (White 1992; Fernández-Jalvo et al. 1996, 1999; Defleur et al. 1999; Bello et al. 2015), increasing the interest and attention of the study of cut marks from fauna to humans. Cut marks are present in the different archeological faunal assemblages regardless of the chronology and species, from large proboscideans (Yravedra et al. 2010, 2012) to micro-mammals, reptiles, and birds (Blasco 2008; Stringer et al. 2008; Blasco and Fernández-Peris 2009, 2012; Finlayson et al. 2012).

Some researchers, aware of the importance of cut marks, have thoroughly considered their microscopic attributes in an attempt to improve their identification, definition, and characterization (e.g., Binford 1981; Bunn 1982; Shipman 1981; Fisher 1995; Domínguez-Rodrigo et al. 2009a, b). Other scholars have performed experimental analyses to describe the differences in cut mark morphology according to the kind of tool or raw material used, i.e., metal or stone (Olsen 1988; Greenfield 1999, 2004, 2006a, b; Bello and Soligo 2008; Yravedra et al. 2009), shell (Choi and Driwantoro 2007), or bamboo (Spennerman 1990; West and Louys 2007). Lithic tool types including simple or retouched flakes and handaxes have also been experimentally used to determine a link between tool type and cut mark type (Walker 1978; Shipman and Rose 1983; Bello et al. 2009; Domínguez-Rodrigo et al. 2009b; De Juana et al. 2010; Galán and Domínguez-Rodrigo 2013). Regarding other alterations, some authors have suggested other features to differentiate cut and tooth marks (Martin 1907; Walker and Long 1977; Shipman 1981, 1988; Binford 1981; Bunn 1982; Fisher 1995; Bromage and Boyde 1984; Andrews and Cook 1985; Cruz Uribe and Klein 1994; Blumenschine et al. 1996; and more). The differentiation of certain alterations such as trampling marks remains problematic as evidenced by the debate concerning the identification of cut marks on deposits of more than 3 Ma (see McPherron et al. 2010 and Thompson et al. 2015 versus Domínguez-Rodrigo et al. 2010 and Domínguez-Rodrigo and Alcalá (2016), as well as the extensive literature on this topic: Andrews and Cook 1985; Behrensmeyer et al. 1986; Olsen and Shipman 1988; Dumbar et al. 1989; Fiorillo 1989; Nicholson 1992; Andrews 1995; Fisher 1995; Blasco et al. 2008; Domínguez-Rodrigo et al. 2009a, b, 2010, 2012; De Juana et al. 2010; Yravedra et al. 2014).

Building on this latter research background, this article presents a new analysis which enables the differentiation between cut marks produced with metal, flint, or quartzite tools. Micro-photogrammetric methodology was used here to reconstruct cut marks from both a metrical and a tridimensional—3D—high-resolution perspective.

This article is the continuation of a previous work (Maté-González et al. 2015), where this new tridimensional method for the analysis of cut marks was presented. In that work, cut marks generated with a metal knife were analyzed to examine shape variability along their sections, and the results showed that if avoiding the ends, cut mark sections were morphologically conservative along most of their trajectory. The present work aims to continue that research applying the technique to cut marks produced with other raw materials such as flint or quartzite, to verify if the micro-photogrammetric and morphometric method is valid to identify tools based on their raw material, determined by the different shape resulting from the degree of thinness in which each material type can produce unmodified cutting tools (i.e., flakes).

Materials and methods

This method incorporates the treatment of high-resolution images with micro-photogrammetry and computer vision for the tridimensional reconstruction of cut-marked sections. Following the methodology discussed in our previous work (Maté-González et al. 2015), micro-photogrammetry was used to generate precise metrical models of cut marks when using images taken with oblique photography (Fig. 1). It was demonstrated that more stable and precise sensors captured better quality images, producing more significant results. Like in the previous work, a Canon EOS 700D reflex camera (Table 1) was used, with 60-mm macro-lenses, which obtained high-resolution and high-quality images.

As our interest was to test the validity of this technique and its applicability to archeological contexts, an experiment with cut marks produced with flint and quartzite tools was developed and subsequently compared with the cut marks generated with a metal knife described in Maté-González et al. (2015).

The experiments followed the same protocol as in the previous work. Hence, cut marks were produced when butchering long bones of young sheep by an expert butcher using simple flint and fine-grained quartzite flakes. The cut marks produced with the knife were the ones described in Maté-González et al. (2015).

Marks were subsequently photographed using a tripod to stabilize the camera as stated in Maté-González et al. (2015). In order to homogenize and optimize lighting conditions, the samples were individually placed on a photographic platform adjusting the light to have the bone permanently well exposed to light. Both exposition time and lighting were kept constant during image capture. To produce referenced 3D models, a millimetrical graphic scale was set next to the cut mark. Photographs were then taken following the specified protocol (Fig. 1). Finally, the images were treated with photogrammetric reconstruction software such as Photogrammetry Workbench (PW) (Fig. 2) (González-Aguilera et al. 2013) or other reconstruction software like Agisoft PhotoScan. Once the 3D models with scales were produced, the Global Mapper software was applied to define mark profiles and measure

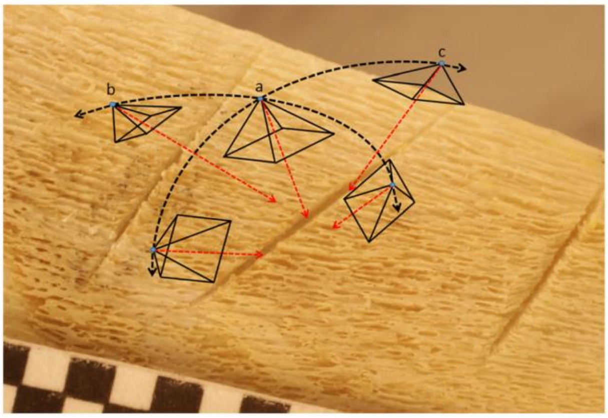


Fig. 1 Protocol for image capture to model a cut mark on a bone by the micro-photogrammetric method, with convergent photographic shots. **a** Master and dependent images in central position, **b** vertical slave images, and **c** horizontal slave images

them (Figs. 3 and 4). Finally, the independent analysis of each cut mark was proposed according to the tool used (Fig. 5) via geometric morphometric analysis. For data collection, a total of 6–10 photos are taken for each mark. The number of photos varies depending on the geometry of the bone and the shape of the mark. The three-dimensional reconstruction of each mark takes 30–45 min depending on the final number of photos taken.

Our goal with the reconstructions is to maximize both, accuracy and completeness. If the separation among images (baseline) increases, the accuracy will improve as the intersection of the perspective rays is more favorable, but the completeness of the object decreases due to the dense cloud algorithms. By contrast, if the separation among images (baseline) decreases, a better completeness of the object will be obtained, but the accuracy will be poorer because of a worse intersection of the perspective rays.

In order to contextualize the accuracy analysis of Photogrammetry and Geoinformatics (PG) methods versus microscopy given that geometric data are dependent from two different sources (scaling and photogrammetric reconstruction—PHO), the variance of the PG could be estimated as follows:

$$\sigma_{\mathrm{PG}} = \pm\sqrt{\left(\sigma_{\mathrm{scaling}}\cdot GSD\right)^2 + \left(e_{\mathrm{PHO}}\cdot \mathrm{GSD}\right)^2}$$

where $\sigma_{\mathrm{scaling}}$ is the scaling precision established as one third of the pixel (Luhmann et al. 2013), e_{PHO} is the reprojection error of the photogrammetric bundle block adjustment expressed in pixels, and GSD is the ground sample distance expressed in meters per pixel. In this way, it is possible to obtain a comprehensive and complete comparison, at geometric and statistical levels.

Table 1 Technical specifications of the photographic sensor with macro-lens

Canon EOS 700D	
Type	CMOS
Sensor size	22.3 × 14.9 mm^2
Pixel size	4.3 μm
Image size	5184 × 3456 pixels
Total pixels	18.0 MP
Focal length	60 mm
Focused distance to object	100–120 mm

Cut marks were measured at mid-length (about 50 % of the mark length) as suggested in Maté González et al. (2015). According to such description, the confidence range to measure the marks hardly varies if they were between 30 and 70 % of the mark length (Fig. 3).

A series of measurements including WIS, WIM, WIB, OA, D, LDC, and RDC (sensu Bello et al. 2013) were made on the mark section (Fig. 4 and Table 2) and were taken as quantitative variables. The measurements for each mark section were later compared using a multivariate analysis of principal components (PCA) of the R freeware (www.r-project.org), which estimated similarities and differences of marks on a bidimensional Euclidean space. Plotting of the PCA results with confidence ellipses was made with the ggplot2 R library.

The geometric morphometric analysis was performed as well as a generalized procrustes analysis (GPA) as a complement to the multivariate metric analysis (Fig. 4). In this case, a morphometric analysis approach was applied, based on seven identical landmarks per section—as shown in Fig. 4 (LM 1–7)—which were considered from each mark using the tpsUtil (v. 1.60.) and tpsDig2 (v.2.1.7) programs, following Maté-González et al. (2015). The location of the seven landmarks respond to the measures considered for the statistical analysis, as seen in Fig. 4. Thus, landmark 1 (LM1) was found at the beginning of the left line in the mark section. LM2 appeared in the middle of this line. LM3 was placed approximately at 10 % of the end of the mark. LM4 was at the very end, and LM5, LM6, and LM7 were in opposed positions to LM3, LM2, and LM1 (Fig. 4). The resulting tps file was imported to R and analyzed via the "geomorph" library (Sherratt 2014).

Lastly, the estimation of the existence or not of differences among the several groups of marks defined by raw materials was performed through a discriminate lineal analysis. The lda

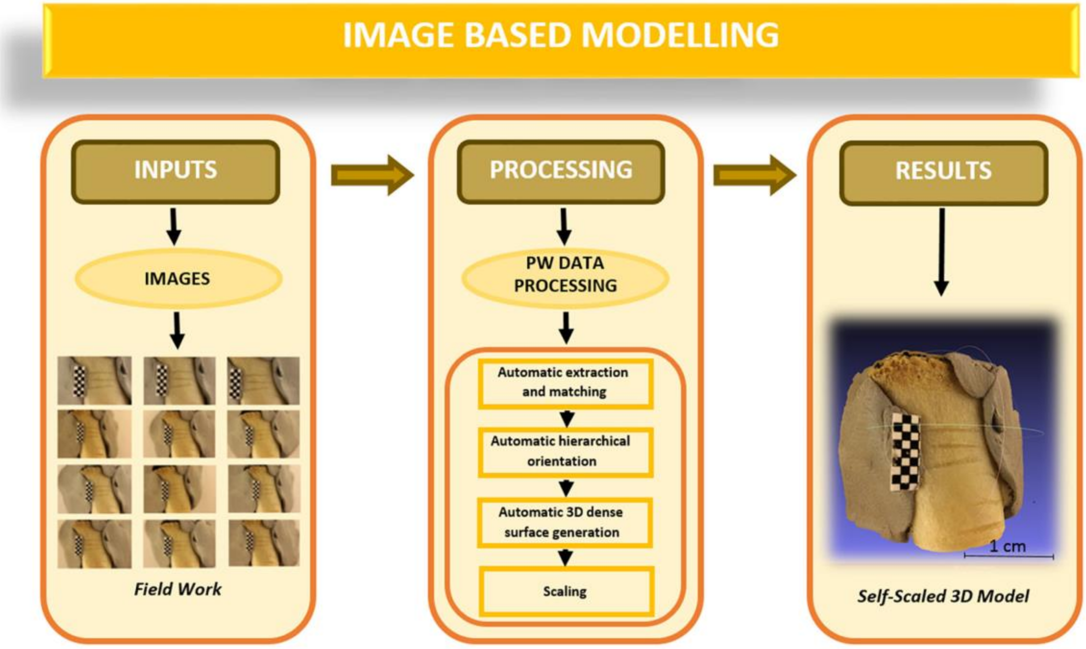


Fig. 2 Workflow of the image-based modeling technique

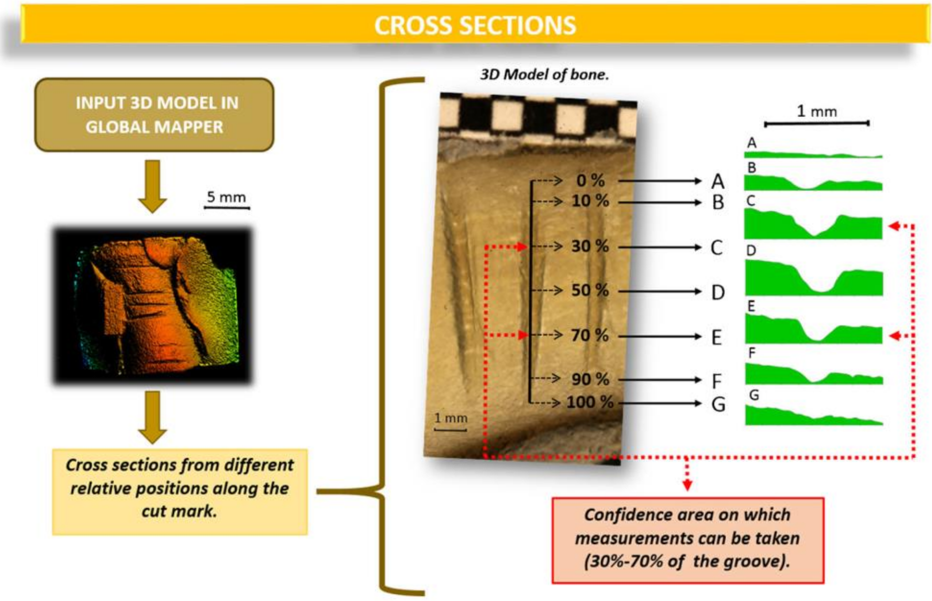
function included in the MASS (XX2) pack in the R statistical program was used.

Experimental results

The micro-photogrammetric analysis enabled the differentiation between cut marks produced with flint and quartzite flakes and metal knives, due to divergent mark section shapes caused by differences in the edge morphology of the flakes of both stone raw materials and the metal knife.

From a qualitative perspective, Fig. 5 shows that metal-produced cut marks were deeper and narrower than the ones generated both with flint and quartzite flakes. Additionally, cut marks made with flint were narrower and deeper than the ones with quartzite (Fig. 5). These results were similar to the ones observed previously (Walker and Long 1977; Walker 1978). Marks produced with metal tools described rectilinear and highly uniform traces which usually did not present the

Fig. 3 Representation of the *A*–*G* sections of the cut mark regarding its length



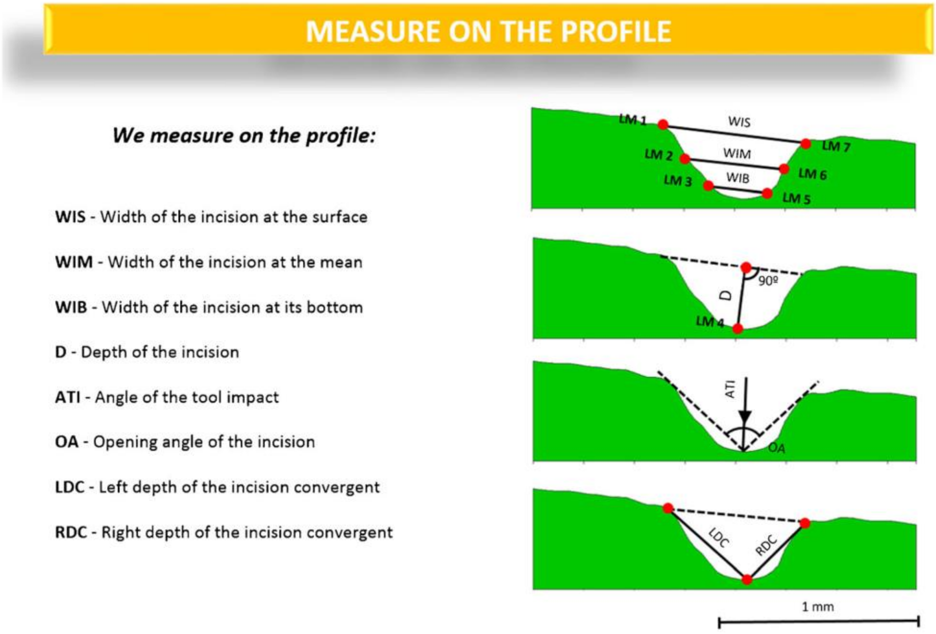


Fig. 4 Location of measurements sensu Bello et al. (2013). Landmarks (*LM1–7*) used for the morphometric model are also represented

micro-striations typical of lithic tools. Marks made with flint flakes had a V section, like the ones made with metal, but this was more open, with a wider upper section (Fig. 5). Quartzite flakes produced V-shaped sections as well, but they were even wider and shallower than those made with flint flakes (Fig. 5).

The 95 % confidence ellipses of the PCA of the measurements (Table 2) specified in Fig. 4 presented a clear difference between quartzite and metal-produced marks (Fig. 6). Flint marks were plotted in the middle of both patterns. Even though some areas overlapped, in a large number of cases it was possible to relate each mark to a specific tool (see below the percentage of correct classification). The three types of marks were quite different when metal and flint (Fig. 6), quartzite and flint (Fig. 6), and metal and quartzite (Fig. 6) were compared pairwise; in the latter, differences were even more significant.

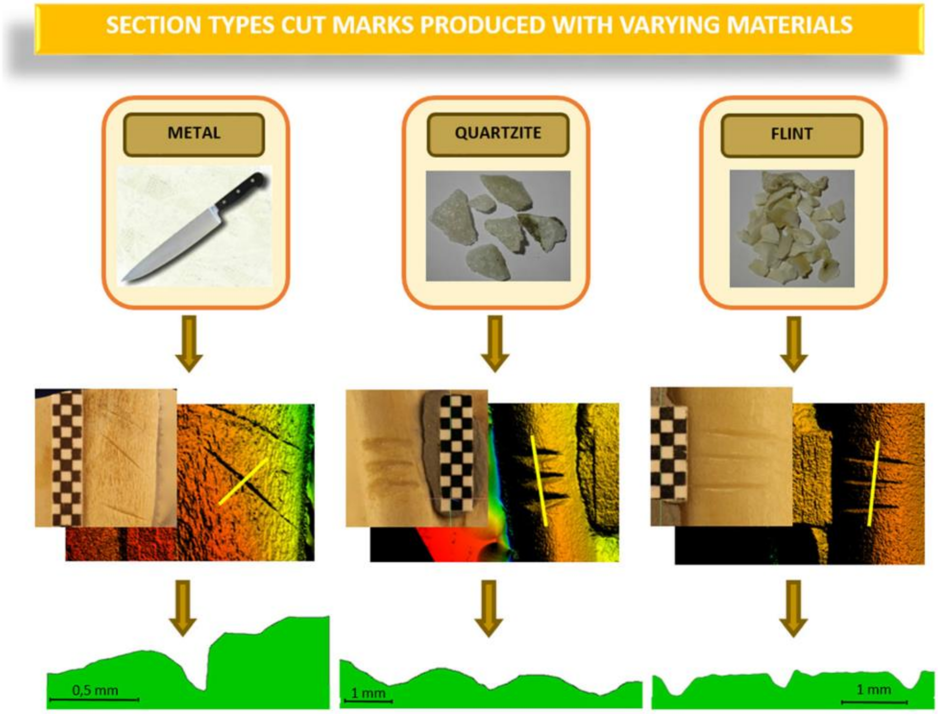


Fig. 5 Cut marks generated with a metal knife, and a quartzite and flint flake. Detail for the V sections in the three types of marks

Table 2 Measurements used to characterize cut mark sections, as described in Fig. 2

WIS	Width of the incision at the surface
WIM	Width of the incision at the mean
WIB	Width of the incision at its bottom
OA	Opening angle of the incision
D	Depth of the incision
LDC	Left depth of the incision convergent
RDC	Right depth of the incision convergent
ATI	Angle of the tool impact

By using the morphometric GPA and the geomorph pack (Palomeque-González et al. 2016) with the seven landmarks (Fig. 4), the silhouettes of all the cut marks produced by the different raw materials were reconstructed (Fig. 7): marks produced with metal (Fig. 7a), flint (Fig. 7b), and quartzite (Fig. 7c). These morphometric reconstructions clearly showed that metal marks were narrower and deeper than flint marks, and the latter were in turn deeper and narrower than quartzite marks, which were consequently the wider and the shallower marks in the sample with respect to width.

Finally, the results from GPA were analyzed by PCA including all raw materials (Fig. 8). All the points representing marks produced with quartzite flakes (green) clustered together; flint (black) and metal (red) were similarly clearly clustered in independent groups. The deformation network depicted the same tendencies noted in previous tests. There was a definite order according to the raw material used.

These analyses evidenced that cut marks produced with flint, quartzite, and metal tools were morphologically different. However, some overlapping was noted in some cases (Figs. 6), particularly between flint and metal (Fig. 6) and flint and quartzite (Fig. 6). In order to estimate the relevance of this overlapping, a discriminate lineal analysis of the cut marks values was performed. A confusion matrix for each individual group was developed, concluding that there was no confusion between the marks made with quartzite and metal (Table 3), an observation which confirmed the situation observed in Fig. 8. This analysis aimed to define the percentage of total marks that was well classified in each group and their misclassification frequency. The study also underlines that morphometric analyses (Figs 7 and 8) provide a better differentiation in the use of different raw materials when comparing cut marks than biometrics (Fig. 6).

According to the confusion matrix, 81.5 % of flint-produced marks, 53 % of metal ones, and 61.6 % of quartzite were accurately classified. Summing up, the rate of correct classification in this experimental assemblage was about 70 %, which proved that in most cases it was possible to distinguish among the different raw materials used to cut the bones.

Discussion

Microscopic categorization of cut marks made with simple flakes, retouched flakes, and even handaxes yielded a high rate of correct classification (and, hence, identification) even when compared with non-anthropogenic marks (e.g., trampling marks) using a multivariate combination of microscopic feature variables (Domínguez-Rodrigo et al. 2009b; De Juana et al. 2010). Recent replication of some of these studies only achieved partial success in replicating differences between cut

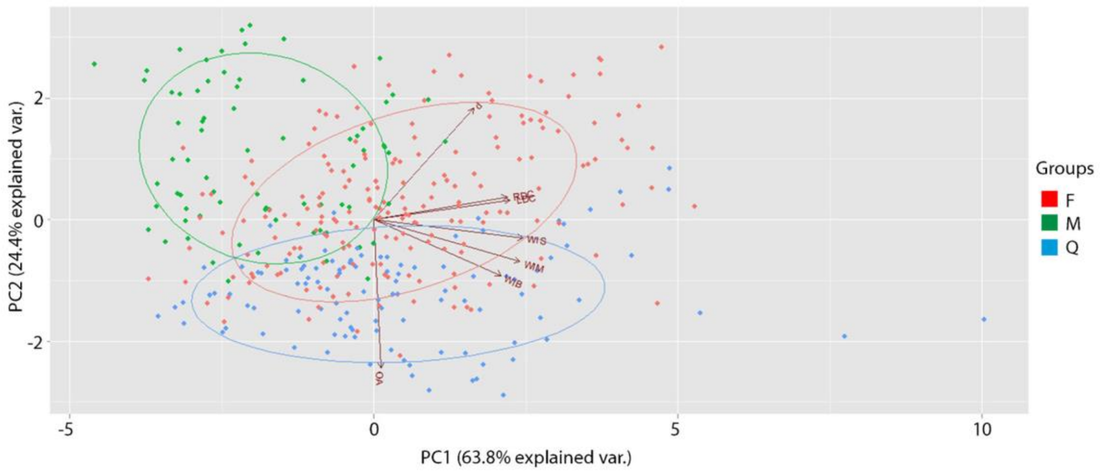


Fig. 6 Principal component analysis (PCA) of cut marks produced with metal (*M*), flint (*F*), and quartzite (*Q*) tools

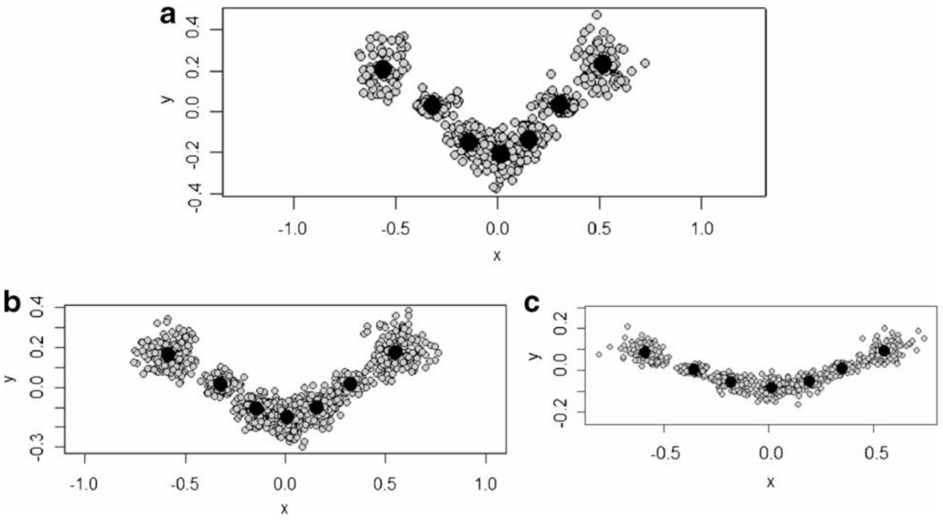


Fig. 7 Silhouettes of cut marks produced with a metal knife (**a**), a flint flake (**b**), and a quartzite flake (**c**). The *black points* are the centroids associated to each landmark

and trampling marks (Monnier and Bischoff 2014). This is mostly due to a methodological artifact: purported trampling was experimentally reproduced in a tumbler containing rocks and a bone (Monnier and Bischoff 2014). This was not done with sediment as trampling is commonly understood and experimentally reproduced (i.e., effectors = sand or gravel; actor = organism applying strength on bone surface via the effectors). The Monnier and Bischoff (2014) experiment produced bone abrasion by prolonged bone-rock friction rather than by the much more intense punctual pressure that trampling agents (e.g., mammal individual stepping on a bone) produce during discrete bone modification episodes. Thus, what Monnier and Bischoff (2014) have shown is that natural processes mimicking continuous friction of a bone with a rock (probably through encasing both elements in the same sedimentary context), which is different from trampling, may result in some (but not all) the microscopic features that discriminate trampling marks from cut marks. This should not come as a surprise. Behrensmeyer et al. (1986) already noticed that continuous friction of a bone with marks against a sedimentary matrix even for periods of time as brief as 3 min resulted in the loss of resolution, with specifically diagnostic characteristics, such as internal groove micro-striations, being lost during the abrasion caused by this continuous sedimentary friction process.

Some authors have built upon two-dimensional diagnosis of cut marks by incorporating features that are only observable in a three-dimensional setting (Bello and Soligo 2008; Bello et al. 2009; Bello 2011; Bonney 2014). The combination of the new three-dimensional diagnosis with the two-dimensional referential frameworks strengthens our ability to differentiate and identify marks when analyzing archeofaunal assemblages. However, in some respects, this recent three-dimensional approach to the study of bone surface

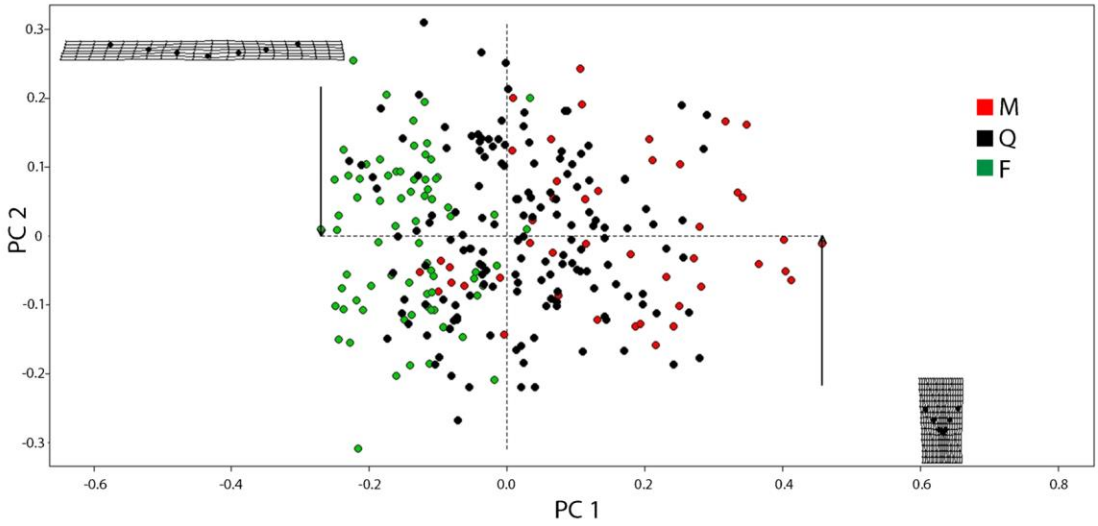


Fig. 8 PCA of the GPA, where quartzite-related marks are in *green*, flint ones in *black*, and metal in *red*

Table 3 Confusion matrix for each individual group showing the number of correctly classified marks (diagonal) and those that were incorrectly classified

	F	M	Q
F	154	12	23
M	35	40	0
Q	41	0	66

F flint, *M* metal, *Q* quartzite

modifications still requires methodological definition and experimental contrasting. For instance, it would be interesting to compare methods for their resolution. Likewise, it would be important to compare cut marks and any other non-anthropogenic mark, such as trampling mark or teeth mark, in 3D to document if the resulting diagnosis is as heuristic as when using a bidimen sional approach. This would shed some light to the debate cut versus trampling marks 3 Ma ago (McPherron et al. 2010; Thompson et al. 2015 versus Domínguez-Rodrigo et al. 2010; Domínguez-Rodrigo and Alcalá 2016.). Unfortunately, we have not achieved the optimal resolution to replicate trampling sections in 3D and thus we have not been able to perform an analysis with a high degree of resolution. In the case of inconspicuous marks or trampling, SEM provides a higher degree of resolution, and thus three-dimensional reconstructions with SEM are suitable to questionable marks. Nevertheless, our methodology has proven to be operative in response to specific questions applied to certain types of marks, such as the identification of the raw material used in the processing of carcasses. Even when comparing cut marks—regardless of the raw material used—with tooth marks such as scores—produced by different carnivores—the technique is operative. Thus, in Figs. 9 and 10, it is possible to distinguish both types of marks.

The analytical method presented here complements other powerful three-dimensional microscopic approaches to the study of cut marks (e.g., Bello and Soligo 2008; Bello et al. 2009; Bello 2011**)**. The three-dimensional approach holds a type of information that has enabled addressing questions like those in the present study that were impossible to answer using a two-dimensional approach. Differentiating among same (flakes) or similar (flake versus knife) tools made on different raw material types was impossible until a proper understanding of a 3D micro-topography of bone surfaces and marks was available. Even though this method presents some limitations, it must be taken into account that it is a new methodology that can be improved. This opens a new window to new questions that will ultimately link the lithic record of any given assemblage (and the differential reduction sequences represented in it via different types of raw materials) and the butchery process.

Conclusions

The study of cut marks holds potential information for our understanding of human behavior in past human societies. Experiments to identify butchery behavior should be particularly emphasized. Among them, the

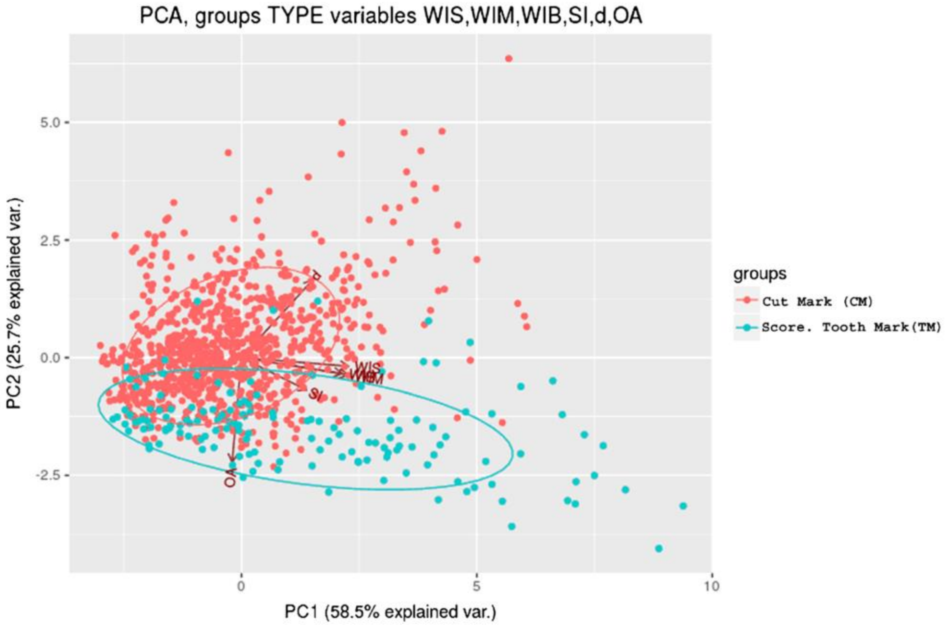


Fig. 9 Principal component analysis (PCA) of cut marks produced with several raw material and scores generated for several carnivores

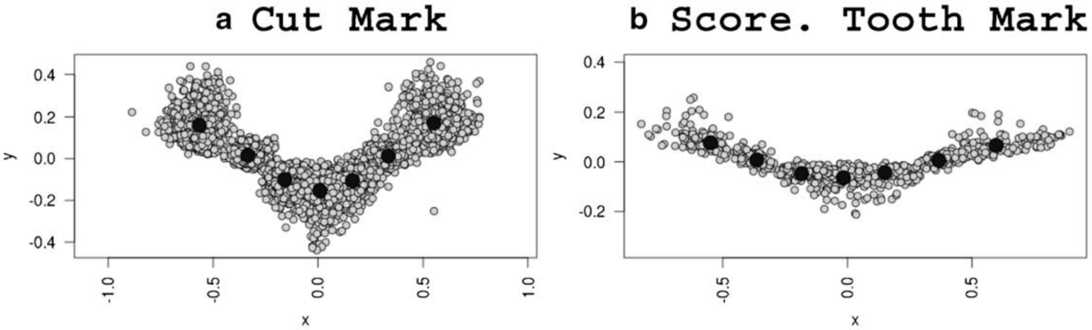


Fig. 10 Silhouettes of cut marks produced with several raw material (**a**) and silhouettes of scores produced for several carnivores (**b**). The *black points* are the centroids associated to each landmark

analysis leading to the discrimination of the raw materials and/or tools used for butchering in archeological sites is of great interest (Greenfield 1999, 2004, 2006a, b; Choi and Driwantoro 2007; Bello et al. 2009). The difference of the present work and previous studies lies in the methodology used for mark identification. Most methods used for cut mark morphology analysis are restricted to optic microscopy, hand lenses and SEM (Shipman 1981; Olsen 1988; Greenfield 1999, 2004, 2006a,b; Smith and Brickley 2004; Lewis 2008), binocular microscope for high-resolution pictures (Domínguez-Rodrigo et al. 2009a, b; De Juana et al. 2010; Marín-Monfort et al. 2014), digital imaging techniques (Gilbert and Richards 2000), 3D reconstruction (Bartelink et al. 2001; During and Nilsson 1991; Kaiser and Katterwe 2001), 3D digital microscope (Boschin and Crezzini 2012; Crezzini et al. 2014), and a recent technique based on the use of Alicona 3D Infinite Focus Imaging microscope (Bello and Soligo 2008; Bello et al. 2009; Bello 2011; Bonney 2014). The technique proposed here incorporates a low-cost methodology based on the treatment of high-resolution images with micro-photogrammetry and computer vision for tridimensional reconstruction of cut marks on bones (Maté González et al. 2015.

The models developed through the micro-photogrammetric method are based on oblique photography and use a reflex camera with a macro-lens, generating high-quality 3D models of cut marks on bone (average GSD (mm) = ± 0.0078; average scaling error (mm) = ± 0.0157; average precision (mm) = ± 0.0238). This method fulfills the requirements of quick capture, automatic processing of images, and high precision. It has been applied to a group of cut marks produced with different raw materials—quartzite and flint flakes, and metal knife—with positive results which provided several evidence guidelines to discriminate cut marks according to the raw material used. Thus, morphological differences among the three raw materials considered were detected (Fig. 5), as well as statistical (Figs. 6) and morphometric deviations (Fig. 7), particularly when morphometry was combined with standardizing methods (Fig. 8). The results coincide with Walker and Long (1977), Walker (1978), Greenfield (1999, 2006b), or Boschin and Crezzini (2012) observations of the contrast between cut marks produced with metal and lithic tools; however, in this analysis a larger sample was used.

All the cut marks observed presented a V section, but metal ones were narrower and deeper, morphometrically different from quartzite marks (Figs. 5, 6, 8, and 10c). Flint marks, in turn, were deeper and narrower than quartzite marks, but not as evident as the ones produced with a metal knife. In morphometric terms, they were in an intermediate position between the quartzite and the metal marks, but different enough to be discriminated from the marks produced with those raw materials (Figs. 5, 6, 7, 8, and 10a). On the other hand, if certain adjustments were made to the measurement procedure, by discriminating among the most diagnostic variable, an improvement in the identification of each kind of mark as well as in the resolution of the method could be possible.

These results proved the usefulness of this methodology when applied to cut marks produced with different raw materials. They showed a high resolution, and although some overlapping was observed between marks, differences among the three kinds of marks were clear, with a more notorious discrimination between quartzite and metal.

This method offers similar benefits to more traditional methods while having some advantages. Firstly, it is a low-cost technique; it does not need sophisticated technical equipments such as microscopes. Secondly, its application does not require much processing time, making it possible to analyze larger samples in a shorter time, including even the complete faunal assemblage, and the technique can be reproduced.

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