

# 3D analysis of cut marks using a new geometric morphometric methodological approach

Lloyd A. Courtenay<sup>1</sup> · Jose Yravedra<sup>1,2</sup> · Miguel Ángel Mate-González<sup>3,4</sup> · Julia Aramendi<sup>1,2</sup> · Diego González-Aguilera<sup>3</sup>

Received: 7 June 2017 / Accepted: 11 October 2017  
© Springer-Verlag GmbH Germany 2017

**Abstract** The arrival of new methodological approaches to study microscopic qualities in cut mark morphology has been a major improvement in our understanding of butchering activities. Micro-morphological differences can be detected in multiple different taphonomic alterations on bone cortical surfaces that can later be used to compare different trace mark types. Through this, we can generate studies that are able to diagnose the specific taphonomic agents and activities that produce said traces that can be found on osteological surfaces. This paper presents experimental data that have been studied using micro-photogrammetry and geometric morphometrics, successfully distinguishing morphological differences in cut marks produced by different lithic tool types as well as different raw materials. The statistical results and methodologies presented here can later be applied to archaeological sites; aiding in our understanding of raw material exploitation, tool production as well as the different butchering activities that are present in faunal assemblages.

**Keywords** Taphonomy · Experimental archaeology · Geometric morphometrics · Cut marks · Raw materials

✉ Lloyd A. Courtenay  
ladc1995@gmail.com

<sup>1</sup> Department of Prehistory, Complutense University, Prof. Aranguren s/n, 28040 Madrid, Spain

<sup>2</sup> IDEA (Institute of Evolution in Africa), Covarrubias 36, 28010 Madrid, Spain

<sup>3</sup> Department of Cartography and Terrain Engineering, Polytechnic School of Avila, University of Salamanca, Hornos Caleros 50, 05003 Avila, Spain

<sup>4</sup> C. A. I. Archaeometry and Archaeological Analysis, Complutense University, Professor Aranguren s/n, 28040 Madrid, Spain

## Introduction

Studying taphonomic traces within the archaeological record can be complex and difficult to the untrained eye; through this, the use of experimentation has become essential to build a series of theoretical frames of reference (Gifford-Gonzalez 1991) that contribute towards a middle range theory (Merton 1967; Binford 1967, 1968, 1981) that can aid in our understanding of ancient hominid populations.

Some of the greatest taphonomic debates have fallen under the common difficulty many analysts face in correctly diagnosing the presence of anthropic intervention in faunal accumulations (Blumenschine et al. 1996). Cut marks are one of the main traces of human exploitation activities that have been identified in the fossil record. A cut mark is a “groove” or “linear mark” (Fernández-Jalvo and Andrews 2016) that penetrates the surface of the bone through the displacement and movement of organic tissue in the process of moving a sharpened edge against bone. While the common understanding of cut mark production is most commonly associated to lithic tools, many other raw materials can produce cut marks such as bamboo (Spennemann 1990; West and Louys 2007; Bonney 2014), shell tools (Choi and Driwantoro 2007; Weston et al. 2015) or metal tools (Greenfield 1999, 2008; Bartosiewicz 2009).

The greatest difficulty many analysts have to face is the distinction of cut marks over trampling (Behrensmeyer et al. 1986; Olsen and Shipman 1988; Thompson 2005; Blasco et al. 2008; Domínguez-Rodrigo et al. 2009). According to classical definitions, a cut mark can be distinguished by its characteristic V shaped cross section, as well as a series of qualitative characteristics that can be associated with the primary groove (Binford 1981; Shipman and Rose 1983; Olsen and Shipman 1988; Yravedra 2006; Domínguez-Rodrigo et al. 2009; Juana et al. 2009; Fernández-Jalvo and Andrews

2016). Trampling marks on the other hand have a much wider and more superficial groove, its cross section presenting a \\_ / shape where the walls and floor of the mark can be distinguished (Domínguez-Rodrigo et al. 2009). This simple diagnosis, however, has become obsolete as presented by multiple experimental studies (Domínguez-Rodrigo et al. 2009; Marín-Monfront et al. 2013; Reynard 2013), showing that the morphology of cut marks are dependent on many other conditioning factors. It has become increasingly clear that new techniques have to be adopted in order to provide a higher accuracy in cut mark diagnosis.

Morphological studies of cut marks have been relatively scarce up until the beginning of the 21st century. With the development of new methodologies to study the shape of cut marks, taphonomers have been able to achieve higher degrees of resolution to study the internal properties of cut marks, the nature of their formation and, as of recently, the morphological differences between certain cut marks (Walker and Long 1977; Blumenschine et al. 1996; Domínguez-Rodrigo et al. 2009; Juana et al. 2009). These morphological differences, in general, are qualitative in nature; however, through a number of different methodological approaches, we can go further than simply measuring the cut mark.

The first morphological studies of cut marks came about in the late '70's with the work of Walker (1978) and Walker and Long (1977). These papers correctly pointed out a number of characteristics that can be observed in the shape of a cut mark produced by different tools and raw materials; the technology employed by these authors, however, were majorly limited. A number of different authors have developed this field of study by establishing a series of basic characteristics that can be observed in cut mark morphology; the size of the grain in certain raw materials produces different widths in cut mark shapes (Dewbury and Russell 2007; Moclán Ramos 2016; Maté-González et al. 2016; Yravedra et al. 2017a, b) as well as defining how different tool types may also affect the width and depth of a cut mark (Greenfield 1999, 2008; Lewis 2008; Domínguez-Rodrigo et al. 2009; Juana et al. 2009; Merritt 2012; Galán and Domínguez-Rodrigo 2013a, b; Moretti et al. 2015). Some authors have gone a step further producing complementary studies analysing the efficiency of these different tool types in butchering activities (Machin et al. 2006; Galán and Domínguez-Rodrigo 2013b; Braun et al. 2016). Rather interesting studies have also been carried out relating to morphological changes produced by the relative sharpness of the stone tools, implying how a tool that has been worn down through use produces wider marks than recently knapped tools (Braun et al. 2016).

While the application of these studies remain fairly limited to experimental studies, research has been carried out applying this reference material to archaeological sites (Bello et al. 2009; Bello 2011; Yravedra et al. 2017a, b) or at least trying to (Val et al. 2017).

The arrival of new methodology to study microscopic qualities in cut mark shapes has been a major improvement in our understanding of hominid activities. With improvements in cut mark studies generated by Silvia Bello (Bello and Soligo 2008; Bello et al. 2009, 2013; Bello 2011) and geometric morphometry later by Maté-González et al. (2015, 2016, 2017a, b), Yravedra et al. (2017a, b) and Arriaza et al. (2017), investigators have been able to produce higher definition studies of microscopic quantitative morphological shapes between taphonomic alterations on bone surfaces. These advances, however, work solely upon two-dimensional cross sections of taphonomic traces, only being able to register a confidence interval between 39 and 70% of the cut mark's total length. While the development of 3D analysis has been carried out, as presented by authors such as Aramendi et al. (2017) in their analysis of pit morphology between carnivores, this approach has yet to be used as a form of processing anthropic taphonomic traces; highlighting the objectives of this paper. 3D analysis is capable of capturing the entire morphological shape of the cut mark, and through our understanding of cut mark morphology, we can imply a number of different elements produced by the effector in a taphonomic trace (Gifford-Gonzalez 1991).

This paper proposes a new methodological approach to studies in cut mark morphology that successfully presents a way of distinguishing between cut marks produced by raw materials of different granular properties and different lithic tool types. Through experimental studies, based upon the concept of uniformitarianism (Hutton 1794; Playfair 1802; Lyell 1830; Whewell 1847), we have been able to provide controlled actualistic observations, creating a theoretical window into the past of our species. This information, registered through microphotogrammetry and geometric morphometrics, allows us to understand a series of concepts including raw material exploitation and the association of lithic tools with faunal accumulations. Integrating this knowledge allows us to understand the cognitive features that hominid populations present in lithic tool productions and ancient economical exploitation of animal carcass present in the zooarchaeological fossil record.

## Methodology

### Experimentation

For the purpose of this study, experimental cut marks were produced using different tools and raw materials. In order to test the accuracy of our new methodological approach, a preliminary study was performed with simple flakes of different raw materials, as well as statistical analyses to assess the best landmark configuration for the study. To understand how raw materials affect the morphology of a cut mark, the first sample selected included the results of previous experimentations (see

Maté-González et al. 2015); cut marks were produced by simple flakes in the following raw materials: flint (from the Iberian Peninsula), quartzite (from the Olduvai Gorge), basalt (from Olduvai) as well as metal (for reference). Twenty-five marks were processed by each of these raw materials, making a total sample size of 100 cut marks in this preliminary study.

The main body of our experimentation consisted of studying the morphological differences produced by different tool types; for this, a total of 150 marks were produced using the quartzite obtained from the Naibor Soit of Olduvai Gorge. So as not to produce discrepancies in our experiment, it was seen that, for the comparison of different tool types, the same raw material was needed in the production of all cut marks. This way the experimental value could remain analogous (Bunge 1981) as we are controlling all possible variables (Popper 1935) that could affect the morphology of the mark while only changing the tool type. This way our observations on tool type variations in cut mark morphology can be restricted only to the changes produced by these specific tools.

According to diverse publications on the geological nature of the raw materials found in the Olduvai Gorge, the raw material used in our experiment is considered a quartzite (Santonja et al. 2014), despite how the texture and granular nature of said raw material was cause enough to create doubts among other authors (Blumenshine et al. 2008; de la Torre and Mora 2013; de la Torre et al. 2013) who consequently identified this material as a Quartz. This type of quartzite is typical from the Naibor Soit (Olduvai Gorge, Tanzania) and presents a large granular texture of 0.5 cm crystals. The identification of the geological characteristics present within this raw material are defined and observed by Maté-González et al. (2017b) through their production of thin sections in cross-polarised light.

The quartzite was processed producing a total of three different tool types, including five simple flakes (Fig. 1), a biface (Fig. 2) and five retouched flakes (Fig. 3), making sure that the cutting edge was sharp enough to produce an incision across the bone's surface. The flakes produced were knapped by one of the authors (JY) following the common type of lithic tool production observed in Olduvai (Leakey 1971; Diez-Martín et al. 2009; Sánchez-Yustos et al. 2017), consisting in large bifacial tools as well as Mode 1 Oldowan simple and retouched flakes (Yravedra et al. 2017a, b). Details on each of the tools used within this experiment can be found in Table 1.

As for the bones selected, the incisions were performed on bones obtained from a local butcher's, all with scraps of meat intact. The bones belonged to small animals, mostly *ovicaprids* and *suidae*, and consisted in a number of different anatomical elements, including scapulae, femora, humeri and ribs. Taking into account that the majority of Pleistocene archaeological sites present adult populations to a higher degree than any other age group, the experiment was carried out on adult individuals. Along these same principles, the cut marks



**Fig. 1** Simple flake; experimentally produced using quartzite from the Olduvai Gorge

were also concentrated on the diaphysis of each element so as to create a sample that could be compared to the majority of cut marks in the zooarchaeological assemblage.

In total, an average of 200 cut marks were produced by a single right-handed individual (MAMG) for each experiment.

### Digitalization and virtual reconstruction

The process of digitalizing the cut marks was carried out with the use of a structured-light 3D scanner, consisting in a



**Fig. 2** Bifacial tool; experimentally produced using quartzite from the Olduvai Gorge



**Fig. 3** Retouched flakes; experimentally produced using quartzite from the Olduvai Gorge. The retouched cutting edge is indicated in each case by a red arrow

camera, a projector and a calibration marker board. The first phase consists in the calibration of the equipment. In order to carry out this process, a DAVID USB CMOS Monochrome camera is positioned and fit with a macro lens alongside an ACER K132 projector, both facing towards the calibration marker board at an angle between 15° and 25°. The projection produced by the projector has to cover the entire calibration marker board; in our case, the size and calibration pattern corresponds to a 15-mm scale. Within the DAVID software the scale is introduced as displayed on the calibration marker board, the camera's exposure is adjusted accordingly while the focus is adjusted of all instruments. The equipment is then calibrated. During this process the camera, as well as the projector, have to remain fixed and stable throughout the entire calibration process, ensuring the quality of the scans.

The second phase consists in substituting the calibration marker board for the bone we intended to scan. The

structured-light SLS-2 DAVID scanner is able to produce a density of up to 1.2 million points, the advantages of this technological approach to scanning our cut marks is the production of much higher resolution 3D images of that could then be processed in Amira 5.0 for landmark placement. The scanner used in this experiment produced a higher quality resolution than the scanner used in Maté-González et al. (2015); thanks to the technological advances in this field. This new scanner was able to achieve similar results to the photogrammetric methods used in Maté-González et al. 2015, 2016, 2017a, b) and Yravedra et al. (2017a, b).

As previously explained, a total 50 cut marks were processed for each tool type and 100 cut marks were processed for the raw material samples; 25 cut marks per raw material type.

### Geometric morphometric analysis

The application of geometric morphometrics (GMM) has also changed morphological analyses over the decades, substituting traditional descriptive methods for statistical ones allowing the study of size and shape variation (Kendall 1989; Goodall and Mardia 1993), and also allowing for the visualisation of resultant covariation in terms of warpings and transformation grids (see review in Rohlf and Marcus 1993; Slice 2005). Shape and size information is contained in the form of landmarks, homologous points that can be located among the elements we intend to study. These landmarks are points of reference that contain information that can be studied and compared in the form of cartesian coordinates (O'Higgins and Johnson 1988; Bookstein 1989; Goodall 1991; Hall 2003; Manríquez et al. 2006; Klingenberg 2008). Our landmark configuration consists of a series of three-dimensional points established on the exterior and interior surface of each cut mark. Type II and III fixed landmarks (Bookstein 1991; Dryden and Mardia 1998) based

**Table 1** Table presenting a descriptive list of the stone tools used in the experiment regarding tool type

Raw material <sup>1</sup>	Tool type	Max. length (mm)	Max. width (mm)	Weight (g)	Cutting edge Angle (°)	Platform
Quartzite	Hand axe	200	115	45	75–80	Plain
Quartzite	Simple flake	60	58	12	62	Plain
Quartzite	Simple flake	74	76	15	58	Plain
Quartzite	Simple flake	90	68	15	57	Plain
Quartzite	Simple flake	92	70	21	54	Plain
Quartzite	Simple flake	86	72	17	56	Plain
Quartzite	Retouched flake	36	60	14	74	Plain
Quartzite	Retouched flake	61	41	13	63	Plain
Quartzite	Retouched flake	33	51	10	82	Plain
Quartzite	Retouched flake	58	40	10	76	Plain
Quartzite	Retouched flake	41	45	18	62	Broken

<sup>1</sup> Raw material has been classified in accordance to Santonja et al. (2014) and the thin sections in cross-polarised light studied by Maté-González et al. (2017b)

on criteria established in accordance to certain qualitative features present in a cut mark were located using the Avizo software (Visualisation Sciences Group, USA). Based on the fact that a cut mark presents a homogenous central groove with no distinction between the floor and the walls of the mark (Domínguez-Rodrigo et al. 2009), only one landmark (see landmark 3 in Table 2 and Fig. 4) was established on the inside of the groove, marking the central most profound point that indicates the trajectory, depth and opening angle of the mark (Bello and Soligo 2008; Bello et al. 2009, 2013; Bello 2011). Since in taphonomic practice cut marks are often confused with trampling marks, other eight landmarks mapping the outer morphological characteristics of the incision were added (Table 2, Fig. 4). In that way, differences related to cross-section shape and homogeneity of the groove trajectory were included in the analysis. A further detailed model including extra variables such as the opening and closing angles of the marks (see landmarks 10–13 in Table 2) was created, trying to generate a better morphological comparison of the width and curvature of the marks (Fig. 4).

The two models were compared statistically to determine which one best represents the morphological shape of a cut mark and provides better statistical results in distinguishing between the various tool types through the morphological shape of the cut marks produced.

Landmarks were only established in cut marks where points one and two were clear, in cases where the bone was fractured or if cut marks superimposed and the beginning and end of the mark could not be found, these cut marks were

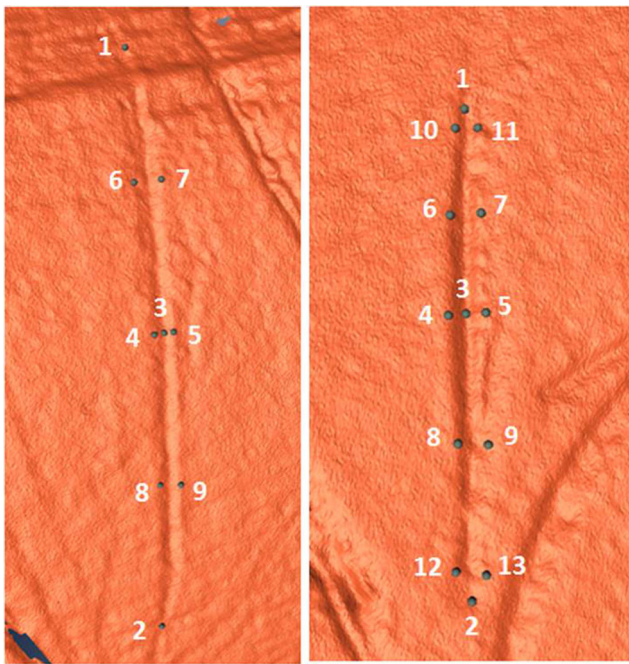
excluded from the analysis. If cut marks were abnormally curved, they were also excluded as later on, statistically, these marks produce a great deal of statistical noise that affect our results. The depth of the marks were dependent on the natural curvature of the bone as, if the mark was abnormally deep then the mark was processed, however, if later this same mark appeared as an anomaly in the statistical results another mark was taken, thereby excluding said anomaly. Extra qualitative features (presence of shoulder effect, for example) that were not captured by our landmark configuration and that are relevant for mark identification were all noted separately.

Geometric morphometric analyses are based on Procrustes superimposition, otherwise known as generalised Procrustes analysis (GPA). The form information contained in the landmark data is normalised through a series of superposition procedures; translating, rotating and scaling the elements under study (Goodall 1991). The GPA reveals all Procrustes residuals separated by Procrustes distances that allow us to determine the variation and covariation between the elements we are comparing (Monteiro et al. 2000). These coordinates are projected onto a flat Euclidian space that can later be analysed through common multivariate statistical analyses (Rohlf 1999; Rohlf and Corti 2000; Slice 2001).

Several principal component analyses (PCA) were performed to assess morphological variance. The use of a PCA allows us to convert each cut mark into a single point which can be easily plotted against a graph. The PCA tests were performed solely in shape space excluding size. Changes in shape were visualised with the aid of transformation grids and

**Table 2** Table presenting the list of landmarks for both models used in this study alongside a description of their location. Landmark types are established according to Bookstein (1991) and Dryden and Mardia (1998)

Model 1		Landmark Type	Model 2	
N°	Location		N°	Location
1	Beginning of the cut mark	II	1	Beginning of the cut mark
2	End of the cut mark	II	2	End of the cut mark
3	Deepest point in the middle of the cut mark	II	3	Deepest point in the middle of the cut mark
4	Left hand shoulder of the middle of the cut mark	II	4	Left hand shoulder of the middle of the cut mark
5	Right hand shoulder of the middle of the cut mark	II	5	Right hand shoulder of the middle of the cut mark
6	Left hand shoulder, halfway between the beginning and the middle of the cut mark	III	6	Left hand shoulder, halfway between the beginning and the middle of the cut mark
7	Right hand shoulder, halfway between the beginning and the middle of the cut mark	III	7	Right hand shoulder, halfway between the beginning and the middle of the cut mark
8	Left hand shoulder, halfway between the middle and the end of the cut mark	III	8	Left hand shoulder, halfway between the middle and the end of the cut mark
9	Right hand shoulder, halfway between the middle and the end of the cut mark	III	9	Right hand shoulder, halfway between the middle and the end of the cut mark
		II	10	Left hand shoulder, at the opening angle of the cut mark
		II	11	Right hand shoulder, at the opening angle of the cut mark
		II	12	Left hand shoulder, at the closing angle of the cut mark
		II	13	Right hand shoulder, at the closing angle of the cut mark



**Fig. 4** Landmark locations as explained in Tables 1 and 2 for both Model 1 (left) and Model 2 (right). Images obtained through Amira 5.0, the computer software used for Landmark placement

warpings computed using thin-plate splines (Bookstein 1989). PCAs were performed in MorphoJ (Klingenberg 2011) and Morphologika 2.5 (O'Higgins and Jones 1998).

From the PC scores, a multiple variance analysis (MANOVA) was carried out in R (Core-Team 2015) to see if, on a statistical level, the cut marks could be distinguished. Finally, canonical variate analyses (CVA) and linear discriminant analyses (LDA) were used to determine the shape features that best distinguish among cut marks produced with different tools and raw materials. CVA and LDA were performed in MorphoJ.

## Results

### Choosing a landmark model

The statistical analysis of the two models created to register cut marks shows that the most descriptive model, Model 2, best represents the morphological changes in cut mark morphology.

The PCA of Model 1 is represented by a total of 20 principal component coefficients (PCs) with the first two PC scores representing 56.0% of the sample. In the PCA scatter plot, the grouping of each sample is rather inconclusive; almost all groups are overlapping completely while biface and retouched flakes are practically indistinguishable (Fig. 5). The MANOVA results (Wilks' Lambda = 0.3664,  $F = 2.999$ ,  $p = 0.005394$ ) pointed out limited differences between

samples while the Pairwise MANOVA (Table 3) results indicate that there is no significant difference between the means of the cut mark groups produced with biface and simple flakes ( $p$  value = 0.1515) whereas biface and retouched flakes were statistically distinguishable ( $p$  value = 0.039488) as well as retouched and simple flakes ( $p$  value = 0.037553). The CVA graphs (Fig. 6), however, show a clear distinction between group types; however, the distances between each group are fairly limited.

Results obtained with Model 2 are more conclusive. Though the PCA scatter plot, with the first two PC scores representing 58.1% of the variance, still shows some slight overlapping between groups (Fig. 5), the Pairwise MANOVA results (Table 3: Wilk's Lambda = 0.3036,  $F = 3.748$ ,  $p = 0.0009826$ ) point out that differences among group means are more prominent and better registered with the second Model; especially as differences between groups are always significant. CVA results are somehow more conclusive for the first model where the distances among groups are statistically significant ( $p < 0.05$ ), whereas Model 2 results indicate that there is no clear Procrustes separation between biface and simple flakes in the Procrustes distances.

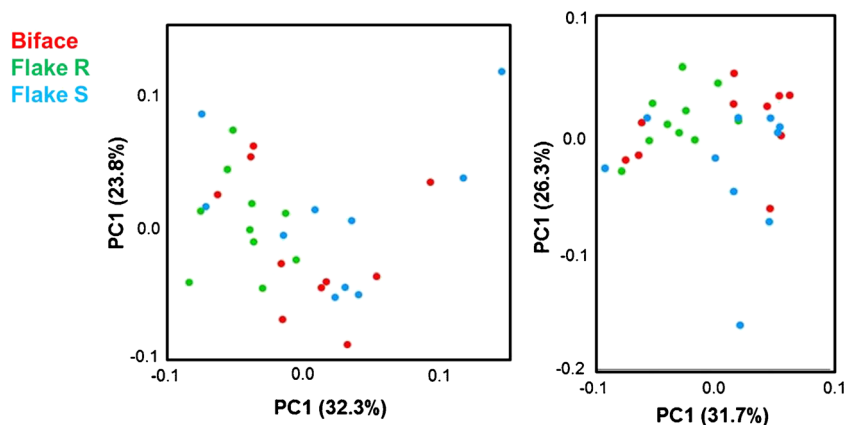
As can be seen in all of the statistical tests, Model 2 has a better chance of distinguishing morphological differences between cut marks produced by the different tool types than Model 1. Thus, Model 2 was used to register the total of the cut mark sample and conduct the following statistical analyses.

### Comparing raw materials

The PCA generated for the 100 cutmarks analysed is divided into 32 principal component coefficients with the first two representing 53.9% of the variance of the sample. The PCA graphs seem rather chaotic with groups formed by different raw materials overlapping in shape space (Fig. 7), the Pairwise MANOVA (Table 4: Wilks' Lambda = 0.3036,  $F = 3.748$ ,  $p = 0.0009826$ ) indicates a significant differences between all groups minus basalt and flint.

The CVA scatter plot, where 86.3% of the sample (CV1 = 51.4%, CV2 = 34.9%) is explained (Fig. 8), shows a more clear representation of the groupings, where different raw material types can be better distinguished. While basalt and flint still overlap being practically indistinguishable, quartzite and the metal blade present clear differences, coinciding with the results produced by Maté-González et al. (2016). Quartzite, metal and the flint/basalt groups are also easily distinguishable. As for the numeric results of these tests, all the Mahalanobis distances from the CVA results are all significant ( $p = <0.0001$ ), but the Procrustes distances cease to be significant in the case of flint and basalt ( $p = 0.7318$ ), supporting the rest of statistical results that the two raw materials have similar morphological components in the cut marks present. It cannot be denied that the CVA graph (Fig. 8)

**Fig. 5** Scatter plots of the PCA results comparing Landmark Models 1 (left) and Model 2 (right)



visually presents the possibility of distinguishing between raw material type; however, when analysing an archaeological site, this larger marginal error presented by Mahalanobis and Procrustes distances still has to be taken into account in order to maintain validity in our interpretations of statistical results.

The cross-validated scores calculated for the LDA also show a great overlap between flint and basalt. The numeric results in a classification/misclassification table (Table 5) presents that, statistically, the system is able to correctly allocate 52 and 56% of each sample to their correct groups (flint and basalt, respectively) in contrast to the rest of raw materials that are able to distinguish over 60% of the sample. The best results in cross-validation analyses are between metal and basalt with a 72 and 68% true allocation of basalt and metal, respectively.

**Comparing different tool types**

The total sample of 50 cut marks per tool type (150 cut marks in total) was subjected to a PCA that is explained by a total of 32 principal component coefficients with the first two PC scores representing 64.5% of the variance of the sample. Looking at the PCA graphs produced in Fig. 9, while at a first glance the groups seem to overlap a fair amount, certain trends can be identified seeing how simple flakes appear much more spread out across the graph. Retouched flakes and bifaces appear clustered and, while they do indeed overlap, the two groups can still be identified at a more detailed look at each graph. Upon comparing the different PCA plots using the first three PC scores, this trend is consistent in all graphs; simple flakes are plotted spread out across the graph while bifacial

tools and retouched flakes are clustered and positioned side by side in the centre of the graph.

The Pairwise MANOVA tests (Wilks’ Lambda = 0.5535,  $F = 9.841$ ,  $p = 3.754e-14$ ) indicate a strong significant difference between each tool type being able to perfectly distinguish between each group, providing exponential  $p$  values in all cases (Table 6).

The CVA results (Fig. 10) provide significant values in both Procrustes and Mahalanobis distances for all three different tool types. The sample is represented by two CV scores (CV1 = 62.0%, CV2 = 38.0%) represented in a scatter plot where (Fig. 10) the three different tool types can be clearly differentiated. While some overlapping occurs in the three groups present, the number of cases that appear in these different groups is minimal, distinguishing almost perfectly all three different tool types. As for the LDA results, the cross-validated classification/misclassification tables (Table 7) present a high percentage of correctly allocated groups, proving that the sample at hand strongly represents the morphological changes between each tool type. Of the three different tool types, the simple flakes are perhaps the group that presents the lowest percentage of correctly distinguishing between the different tool types; however, the percentage is still high enough to argue that the sample data strongly represents the morphological differences produced in cut marks.

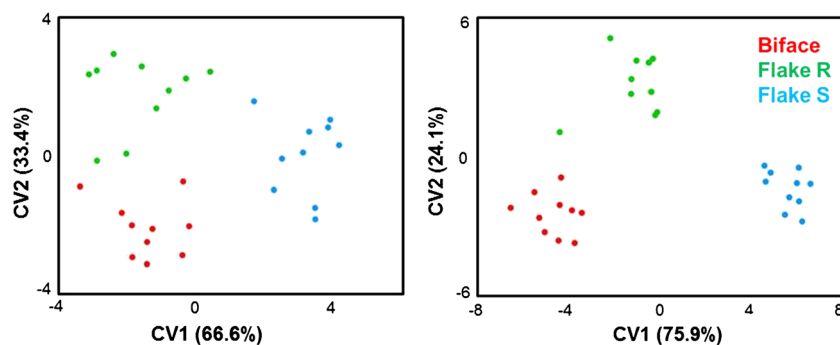
**Qualitative observations**

Upon observing the presence or lack of any sign of shoulder effect in the cut marks, what can be seen is how the different

**Table 3** Pairwise MANOVA  $p$  values for both models 1 and 2

Model 1			Model 2				
	Biface	Flake R	Flake S		Biface	Flake R	Flake S
Biface		0.39488	0.1515	Biface		0.035147	0.043899
Flake R	0.039488		0.037553	Flake R	0.035147		0.01969
Flake S	0.1515	0.037553		FlakeS	0.043899	0.01969	

**Fig. 6** Scatter plots of the CVA results comparing Landmark Models 1 (left) and Model 2 (right)



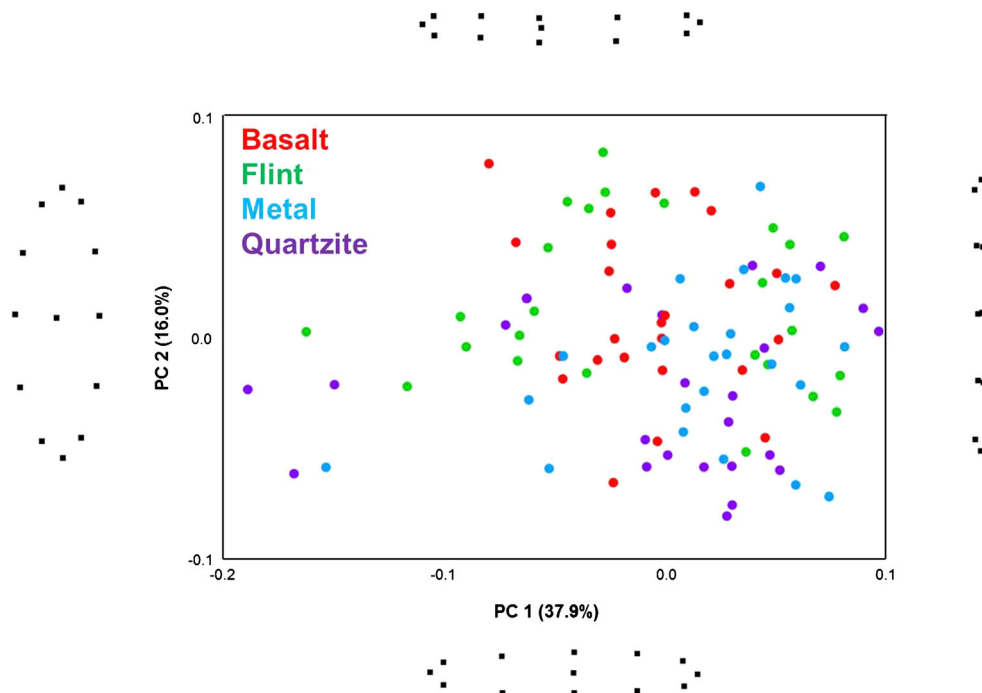
variables are conditioning variables in their appearance. Using a linear modal ANOVA test in R, the different tool types can be seen to be an important conditioning factor ( $p = 1.114e-06$  \*\*\*,  $F = 15.069$ ) in producing any shoulder effect. Raw materials, on the other hand, did not prove to be significant ( $p = 0.5322$ ) with relatively low  $F$  values (0.6364) as well. Using simple percentage statistics, the different raw materials can be seen to condition the presence of shoulder effect, basalt, for example, proving to be the raw material that produces the highest amount of cut marks with shoulder effect (24%,  $n = 6$ ) while quartzite (16%,  $n = 4$ ) and flint (12%,  $n = 3$ ) produce a smaller amount of cut marks related to shoulder effects. Seeing as the ANOVA results reject the significance of these percentages, however, we cannot argue that the presence of shoulder effect is caused by the different raw materials. The different tool types, on the other hand, clearly produce different quantities of this qualitative feature with bifacial tools (62%,  $n = 31$ ) presenting a much higher degree of cut marks with shoulder effect than any other tool type (simple flake = 14%,  $n = 7$ ; retouched flake = 32%,  $n = 16$ ).

## Discussion

This study presents a new methodological approach to the analysis of cut marks, using 3D virtual reconstructions of experimentally produced bone alterations and appropriate statistical studies to compare the morphological factors at hand. While microscopic, statistical and quantitative studies already exist in this field (namely the work of Bello and Soligo 2008; Bello 2011), this paper presents a new series of techniques that allows us to carry out this analysis with a greater degree of accuracy at higher resolutions, supporting the published work of Maté-González et al. (2015, 2016) and Palomeque-González et al. (2017).

The statistical results presented are conclusive in their comparison of different tool types. While the study applied to raw materials has already been carried out by Maté-González et al. (2016, 2017a, b) and Yravedra et al. (2017a, b), the results presented here present a more accurate way of deducing the raw material through cut mark morphology. Seeing as the

**Fig. 7** Scatter plot of the PCA results comparing the morphological shapes of cut marks produced by different raw materials in shape space. Extreme shape changes described by PC scores 1 and 2 are represented on their corresponding axis limit



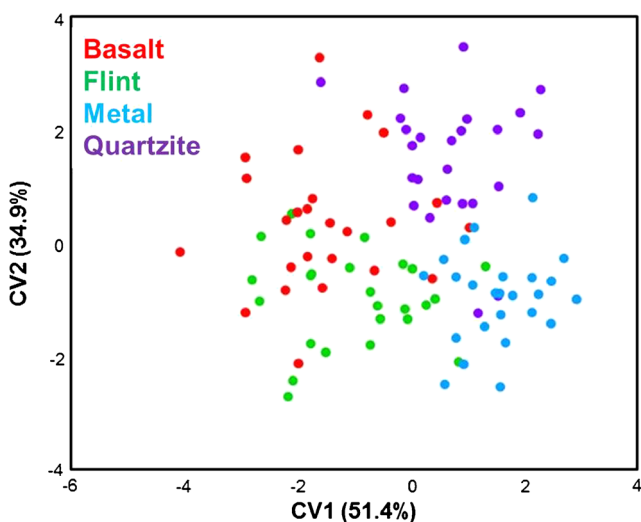


**Table 4** Pairwise MANOVA *p* values comparing the morphological differences of cut marks produced by different raw materials

	Flint	Quartzite	Basalt	Metal
Flint		0.0044147	0.50931	0.0018309
Quartzite	0.0044147		0.0031372	0.0094933
Basalt	0.50931	0.0031372		4.89e-05
Metal	0.0018309	0.0094933	4.89e-05	

similarities between flint and basalt have already been noted, and are still seen in the results presented here, the two raw materials through the techniques established in this paper are easier to distinguish. This proves that alongside two-dimensional studies of cut mark intersections, the three-dimensional techniques established here are a better methodological approach to studying cut mark morphology. This, however, does not imply that two-dimensional studies cut mark profiles should be rejected, on the contrary; the methodology presented by other authors (Maté-González et al. 2015, 2016) are perfectly valid if collaborated with the methodological approach presented here.

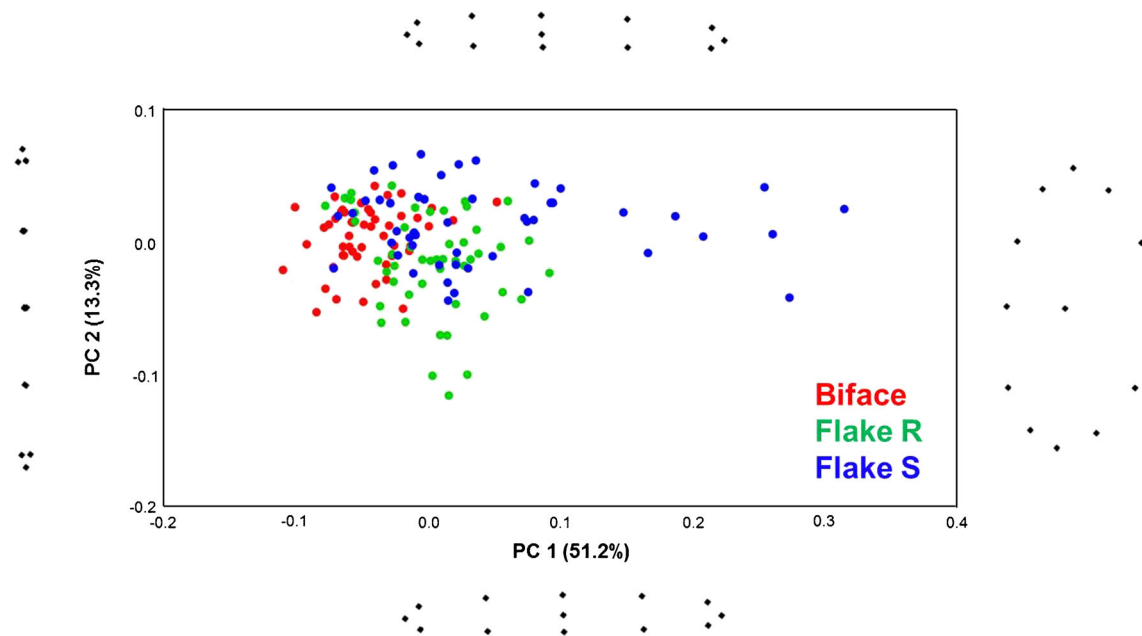
The implications this study provides to the future of taphonomy applied to zooarchaeology are growing in value. If we are able to indicate, through the morphology of cut marks found in faunal assemblages, the associated tool kit that was used in butchering activities, we can begin to understand a series of cognitive and behavioural factors present in ancient hominid populations. Through this, we can decipher economic variables such as raw material exploitation present in sites, as well as the functionality of lithic technologies associated with faunal accumulations. These studies can be collaborated with other investigators, such as traceologists as well as experts in lithic tool production, which can permit a greater understanding and interpretation of different Palaeolithic

**Fig. 8** Scatter plot of the CVA results comparing the morphological shapes of cut marks produced by different raw materials**Table 5** Cross-validation classification/misclassification percentages comparing samples of cut marks produced by flint and basalt

		Allocated to	
		Basalt (%)	Flint (%)
TRUE	Basalt	52	48
	Flint	44	56

technocomplexes. We can also understand to a higher degree the behavioural characteristics and cognitive relations between hominid populations and the fauna present in their immediate surroundings. Outside of the Palaeolithic record, this can also be applied to later prehistoric sites, unravelling the transition periods between stone tool use and the different metal tools present in metallurgical societies. Could it even be possible to study the morphological differences between bronze blades and steel blades? This field of study even creates new windows for analysts in prehistoric art (Güth 2012; Bello et al. 2013; Charlin and Hernández Llosas 2016; Nelson et al. 2017), understanding the functionality of tools such as burins (Moretti et al. 2015), as well as certain patterns present in fluted cave engravings that analysts such as Van Gelder and Cooney have been trying to identify (Van Gelder 2010; Cooney and Van Gelder 2011; Van Gelder 2014, 2015; Van Gelder and Sharpe 2015).

Needless to say, before any application of this methodological approach to actual archaeological sites can be carried out, more experimental samples are required to ensure accuracy in the reference sample. These experimental samples have to take into account all the possible variables that may be affecting cut mark morphology. For example, an interesting variable that has been observed in this paper can be seen as another conditioning variable; bone morphology and densities. Taking into account that a cut mark is defined as an incision in osteological material (Olsen and Shipman 1988; Potter 2005; Fernández-Jalvo and Andrews 2016), the depth of the cut mark is highly dependent on not only the force applied in producing the incision but also the material that is being altered. It can be seen in our experimental data that cut marks found on denser bones, such as the diaphysis of a long bone, are much shallower than cut marks found on bones with cancellous tissue such as an epiphysis or part of the axial skeleton. The differences in bone density throughout the skeleton (Lam et al. 1998, 1999, 2003) is a factor that has already been studied in relation to faunal representations and the taphonomic processes that may affect osteological conservation rates (Batram and Marean 1999; Stiner 2002; Pickering et al. 2003; Faith et al. 2006); however little has been mentioned about cut mark morphology in relation to bone density (apart from Braun et al. 2016 who include experimentation on different sections of bone to observe morphological



**Fig. 9** Scatter plot of the PCA results comparing the morphological shapes of cut marks produced by different tool types in shape space. Extreme shape changes described by PC scores 1 and 2 are represented on their corresponding axis limit

differences). Simply put, if we consider the physical action that produces a cut mark (Potter 2005), a bone made of softer tissue will be easier to cut, producing a much deeper groove.

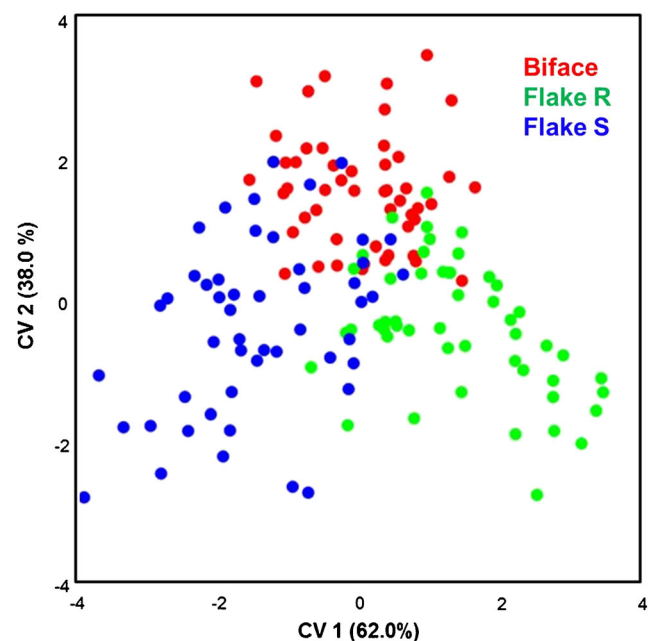
As can be seen, the wider marks presented in the original graphs (Fig. 9) are much deeper (Fig. 11) than the thinner cut marks. While a number of publications have mentioned the depth of metal cut marks being much deeper, it can still be observed how the marks remain thin in nature. The morphological boundaries that are presented in these studies become increasingly complex depending on the depth of the incision which can, in itself, be dependent on the density and natural curvature of the bone. While this factor has not been experimented with in this paper, it is definitely a question worth asking ourselves when planning future studies in this field.

A further factor that has come to light through the work of Braun et al. (2008, 2009, 2016) is the possible sharpness of the tool being used. It is commonly understood that retouching techniques could have been used to sharpen a blunt tool or to generate different tool types (Hiscock 2007; Braun et al. 2016); it can be assumed that as the stone tool loses the sharpness of its cutting edge, the tool may have been retouched to continue using the same flake. This argument receives some

conflict, however, from other studies arguing that the exploitation of flakes in many sites are dependent on the availability of the raw material, time span in which butchering activities were carried out and the possibility that discard of a flake was more likely than the actual sharpening of the flake through retouching techniques (Leakey 1971; Potts 1988; Domínguez-Rodrigo et al. 2002). As stated by Braun in his work, the sharpness of the blade upon use produces repeatedly wider cut marks (Braun et al. 2016) as chipping is produced

**Table 6** Pairwise MANOVA  $p$  values comparing the morphological differences of cut marks produced by different tool types

	Biface	Flake R	Flake S
Biface		1.30e-06	1.07e-08
Flake R	1.30e-06		3.23e-07
Flake S	1.07e-08	3.23e-07	



**Fig. 10** Scatter plot of the CVA results comparing the morphological shapes of cut marks produced by different tool types

**Table 7** Cross-validation classification/misclassification percentages comparing the different samples produced by different tool types

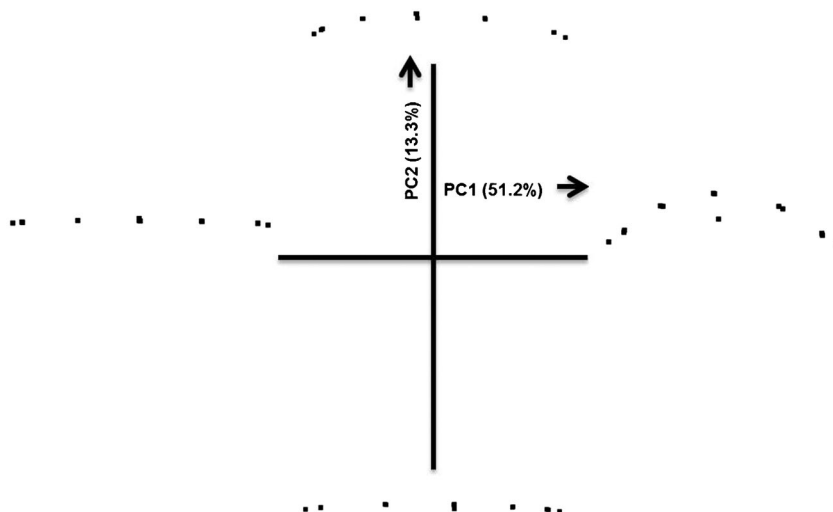
		Allocated to	
		Flake R (%)	Flake S (%)
TRUE	Flake R	76	24
	Flake S	32	68
		Allocated to	
		Biface (%)	Flake S (%)
TRUE	Biface	80	20
	Flake S	36	64
		Allocated to	
		Biface (%)	Flake R (%)
TRUE	Biface	84	16
	Flake R	30	70

and the file of the edge is worn down. This is quite possible a conditioning factor that may have to be taken into account for future studies.

According to our observations and taking the numerous morphological factors into account, a series of simple qualitative observations have been made regarding cut mark morphology:

- Bifacial cut marks are much shallower than simple and retouched flakes. This can be seen through their position in the PCA scores presented in Fig. 10.
- Bifacial cut marks also tend to present a morphological section in the shape of “\\_/” whereas simple cut marks have much steeper walls.
- Bifacial cut marks present a higher probability of producing a shoulder effect associated with the main groove as shown in our ANOVA results.
- The depth of a cut mark is *possibly* dependant on the density and morphological nature of the bone itself.

**Fig. 11** A graph presenting morphological changes in the depth of cut marks ranging across the PCA graph shown in Fig 14. Extreme shape changes in cut marks produced by different tools can be observed at the limits of their corresponding axis



- The raw materials used produce different morphological features that can be considered as dependent on the granular nature of the said raw material.

Having said this, it can be considered, through the research presented within this paper, that three principal variables are conditioning factors in cut mark morphology; the raw material, the tool type and, possibly, the density of the bone at hand. In order to correctly use this information and apply our methodology to archaeological sites, the following methodological steps have to be carried out in order for the statistics to be reliable:

- In order to correctly detect the raw materials used, experimentation has to be carried out directly with the raw materials from the site. This may, in many cases, prove problematic if confronting a site where the hominids have brought the raw materials into the area from a different source, however, the granular components of each raw material can condition greatly the morphological characteristics of the cut mark. This variable becomes especially clear when looking at a number of archaeological sites that have not even had a decent study of the raw materials present. The effect of different granular compositions between stone tools is currently a work in progress, studying how different types of quartzite, with different sizes in their granular components, leave different, or in some cases similar, shaped cut marks.
- A detailed understanding of the lithic technology present in an archaeological site is necessary to compare the different tools that may have been produced. While this characteristic may seem relatively obvious, it is still worth mentioning. Experimentation must be carried out following the knapping qualities presented in the site so as not to generate noise in the statistical results.
- Upon scanning the material prior to the morphological comparisons, photographic evidence of the cut marks

should be provided so that the investigator establishing the landmarks is able to correctly process each cut mark with the greatest degree of accuracy possible.

- Taphonomic variables must also be taken into consideration; seeing as abrasion, erosive agents, polishing and rounding of bone surfaces can also be conditioning factors in the preservation of cut marks and, in as such, their morphology. This concept, however, is still being experimented with, trying to see how erosive taphonomic agents can affect cut mark morphology following experiments carried out by Pineda et al. (2014).
- In addition to this, it may be worthwhile annotating separately any qualitative features observable in each cut mark, following the criteria established by Domínguez-Rodrigo et al. (2009) and extended by Juana et al. (2009). These separate features may aid in the withdrawal of hypotheses as well as the correct diagnosis of any of the cut marks that will be processed through the techniques presented in this paper.

## Conclusions

In conclusion, this paper presents a new three-dimensional geometric morphometric study that permits the identification of raw materials as well as the tool type used during butchering activities. This study provides statistical as well as experimental data to support our methodological approach, also implying a great deal of questions that can be confronted in future studies and developments of this methodology. The experimental results provide a possible starting point that could be used to establish new models that can later be applied to the archaeological record, alongside the photogrammetric reconstructions and analysis of cut mark cross sections (Maté-González 2015, 2016). However, the taphonomical agents that may have produced modification to these cut marks can appear so complex that the investigator(s) intending to carry out our methodological approach are required to construct an adequate statistical and referential sample for future comparisons. As a consequence of this, experimental samples have to be developed and expanded upon in order for the results of this research to be valid.

This article presents a strong starting point for future experimentation; however, needless to say, this methodological approach has its limitations. Many variables that have not been presented in this paper can also be considered for future research questions. It also has to be considered how a combination of all of these variables can lead to complications in the application of this approach to the archaeological record. This can be overcome, however, with an extensive experimental sample that covers all the possible conditioning variables present within an archaeological site. A strong understanding of

the site is thus essential in planning a study such as the one presented within this paper.

As for the methodology, the current technology available in this study could still be improved seeing how the resolution of the laser scanner is still unable to successfully capture inconspicuous marks, superficial marks and some cases of trampling. The constant improvements made to the quality of laser scanners, however, alongside the work of researchers such as Maté-González et al. (2017a) means that the issues presented with resolution may be overcome in the near future.

Analysing ancient hominid diets and hunting strategies is a key component of understanding our evolutionary development as a species. Studying faunal accumulations in this way is another piece of the puzzle that describes the story of how ancient hominid populations faced brutal living conditions and survived while adapting to their surroundings in the long journey that led to the conception of our species. The methodological approach explained here introduces a possible way of deciphering cognitive features such as lithic industry production and associating the stone tool to its daily function. By means of virtual reconstruction and geometric morphometrics, it could be possible to raise key investigatory questions that may help in painting a more detailed picture of the cognitive capacity of the numerous species that came before us. Through developing our methodological approach and expanding our experimental sample—including different variables such as carcass body/size, age at the death of the animal, degree of use-wear—we can begin opening up numerous possibilities this field of research may provide and, more importantly, provide key information necessary to piece together certain factors of our human evolution.

**Acknowledgements** We would like to thank the TIDOP Group from the Department of Cartographic and Land Engineering of the High Polytechnics School of Avila, University of Salamanca, for the use of tools and facilities. We want to recognise the technical support provided by C.A.I. Arqueometry and Archaeological Analysis from Complutense University which has been very useful to carry out the present work. Julia Aramendi would like to thank Fundación La Caixa and the Spanish Education, Culture and Sports Ministry (FPU15/04585) for funding her postgraduate education programmes. We also appreciate the help Andrea Martínez Fernández, Nicolas Alix González and Irene Faza Aladro provided with the photographic documentation of the experimental lithic tools. The corresponding author would also like to thank Abel Moclán for his advice on countless occasions.

## Bibliography

- Aramendi J, Maté-González MA, Yravedra J, Cruz Ortega M, Arriaza MC, González-Aguilera D, Baquedano E, Domínguez-Rodrigo M (2017) Discerning carnivore agency through the three-dimensional study of tooth pits: revisiting crocodile feeding behaviour at FLK-Zinj and FLK NN3 (Olduvai Gorge, Tanzania). *Palaeogeogr Palaeoclimatol Palaeoecol*. <https://doi.org/10.1016/j.palaeo.2017.05.021>

- Arriaza MC, Yravedra J, Domínguez-Rodrigo M, Mate-González MA, García Vargas E, Palomeque-González JF, Aramendi J, González-Aguilera D, Baquedano E (2017) On applications of micro-photogrammetry and geometric morphometrics to studies of tooth mark morphology: the modern Olduvai carnivore site (Tanzania). *Paleo*
- Bartosiewicz L (2009) Skin and bones: taphonomy of a medieval tannery in Hungary. *J Taphon* 7(2):91–107
- Batram L, Marean C (1999) Explaining the “Klasies Pattern”: Kua ethnoarchaeology, the Die Kelders Middle Stone Age Archaeofauna, long bone fragmentation and carnivore ravaging. *J Archaeol Sci* 26:9–29
- Behrensmeyer AK, Gordon K, Yangi GT (1986) Trampling as a cause of bone surface damage and pseudo-cutmarks. *Nature* 319:768–773
- Bello S (2011) New results from the examination of cut-marks using three-dimensional imaging. In: Ashoton NM, Lewis SG, Stringer CB (eds) *The ancient human occupation of Britain*. Elsevier, Amsterdam, pp 249–262
- Bello S, Soligo C (2008) A new method for the quantitative analysis of cutmark micromorphology. *J Archaeol Sci* 35:1542–1552
- Bello S, Parfitt S, Stringer C (2009) Quantitative micromorphological analyses of cut marks produced by ancient and modern handaxes. *J Archaeol Sci* 36:1869–1880
- Bello S, Groote I, Delbarre G (2013) Application of 3-dimensional microscopy and micro-CT scanning to the analysis of Magdalenian portable art on bone antler. *J Archaeol Sci* 40:2464–2476
- Binford L (1967) Smudge pits and hide smoking. The use of analogy in archaeological reasoning. *Am Antiq* 32(1):2–12
- Binford L (1968) Archaeological perspectives, new perspectives in archaeology. Aldine, New York, pp 5–32
- Binford L (1981) *Bones: ancient men and modern myths*. Academic Press Inc, New York
- Blasco R, Rosell J, Fernández Peris J, Cáceres I, María Vergès J (2008) A new element of trampling: an experimental application on the level XII faunal record of Bolomor cave (Valencia, Spain). *J Archaeol Sci* 35:1605–1618
- Blumenschine RJ, Marean WC, Capaldo SD (1996) Blind tests of inter-analyst correspondence and accuracy in the identification of cut marks, percussion marks, and carnivore tooth marks on bone surfaces. *J Archaeol Sci* 23:493–507
- Blumenschine RJ, Masao FT, Tactikos JC, Ebert JI (2008) Effects of distance from stone source on landscape-scale variation in Oldowan artifact assemblages in the paleo-Olduvai Basin, Tanzania. *J Archaeol Sci* 35:76–86
- Bonney H (2014) An investigation of the use of discriminant analysis for the classification of blade edge type from cut marks made by metal and bamboo blades. *American J Phys Anthr* 154:575–584
- Bookstein F (1989) Principal warps: thin-plate spline and the decomposition of deformations. *Transactions on Pattern Analysis and Machine Intelligence* 11(6):567–585
- Bookstein F (1991) *Types of landmarks, morphometric tools for landmark data: geometry and biology*. Cambridge University Press, New York, pp 63–64
- Braun D, Pobiner B, Thompson J (2008) An experimental investigation of cut mark production and stone tool attrition. *J Archaeol Sci* 35:1216–1223
- Braun D, Plummer T, Ferraro J, Ditchfield P, Bishop L (2009) Raw material quality and Oldowan hominin toolstone preferences: evidence from Kanjera South, Kenya. *J Archaeol Sci* 36:1605–1614
- Braun DR, Pante M, Archer W (2016) Cut marks on bone surfaces: influences on variation in the form of traces of ancient behaviour. *Interface Focus* 6. <https://doi.org/10.1098/rsfs.2016.0006>
- Bunge M (1981) Analogy between systems. *Int J Gen Syst* 7:221–223
- Charlin J, Hernández Llosas I (2016) Morfometría Geométrica y Representaciones Rupestres: Explorando las Aplicaciones de los Métodos Basados en Landmarks. *Arqueología* 22(1):103–125
- Choi K, Driwantoro D (2007) Shell tool use by early members of *Homo erectus* in Sangiran central java, Indonesia: cut mark evidence. *J Archaeol Sci* 34:48–58
- Cooney J, Van Gelder L (2011) Child labour in the past: children as economic contributors and consumers. *Annual Society for the Study of Childhood in the Past*, University of Cambridge, Conference
- Core-Team R (2015) A language and environment for statistical computing. R Foundation for statistical computing. <https://www.Rproject.org/>. Accessed the 14<sup>th</sup> of May, 2017
- Dewbury A, Russell N (2007) Relative frequency of butchering cutmarks produced by obsidian and flint: an experimental approach. *J Archaeol Sci* 34:354–357
- Diez-Martín F, Sánchez P, Domínguez-Rodrigo M, Mabulla A, Barba R (2009) Were Olduvai hominins making butchering tools or battering tools? Analysis of a recently excavated lithic assemblage from BK (bed II, Olduvai Gorge, Tanzania). *J Anthr Archaeol* 28:274–289
- Domínguez-Rodrigo M, de la Torre I, Luque L, Alcalá L, Mora R, Serralonga J, Medina V (2002) The ST site complex at Peninj, West Lake Natron, Tanzania: implications for early hominid behavioural models. *J Archaeol Sci* 29(12):639–665
- Domínguez-Rodrigo M, Juana S, Galán AB, Rodríguez M (2009) A new protocol to differentiate trampling marks from butchery cut marks. *J Archaeol Sci* 36:2643–2654
- Dryden IL, Mardia KV (1998) *Statistical shape analysis*. John Wiley & Sons, Chichester
- Faith T, Marean C, Behrensmeyer A (2006) Carnivore competition, bone destruction and bone density. *J Archaeol Sci* 34:2025–2034
- Fernández-Jalvo Y, Andrews P (2016) *Linear marks, atlas of taphonomic identifications*. Springer Science+Business Media Dordrecht, Vertebrate Paleobiology and Paleoanthropology Series, London, pp 35–100
- Galán AB, Domínguez-Rodrigo M (2013a) An experimental study of the anatomical distribution of cut marks created by filleting and disarticulation on long bone ends. *Archaeometry* 55(6):1132–1149
- Galán AB, Domínguez-Rodrigo M (2013b) Testing the efficiency of simple flakes, retouched flakes and small handaxes during butchery. *Archaeometry*. <https://doi.org/10.1111/arcm.12064>
- Gifford-Gonzalez D (1991) Bones are not enough: analogues, knowledge, and interpretive strategies in zooarchaeology. *J Anthr Archaeol* 10:215–254
- Goodall C (1991) Procrustes methods in the statistical analysis of shape. *J R Stat Soc Ser B Methodol* 53(2):285–339
- Goodall C, Mardia K (1993) Multivariate aspects of shape theory. *Ann Stat* 21(2):848–866
- Greenfield HJ (1999) The origins of metallurgy: distinguishing stone from metal cut-marks on bones from archaeological sites. *J Archaeol Sci* 26:797–808
- Greenfield HJ (2008) Metallurgy in the near east, a zooarchaeological perspective on the origins of metallurgy in the near east: analysis of stone and metal cut marks on bone from Israel. In: Selin H (ed) *Encyclopedia of the history of science, technology, and medicine in non-western cultures*. Springer, Netherlands, pp 1639–1647
- Güth A (2012) Using 3D scanning in the investigation of upper Palaeolithic engravings: first results of a pilot study. *J Archaeol Sci* 39(10):3105–3114
- Hall B (2003) Descent with modification: the unity underlying homology and homoplasy as seen through an analysis of development and evolution. *Bio Rev* 78(3):409–433
- Hutton J (1794) Experience considered as the cause of knowledge, or as an operation in which the human intellect is made to proceed, an investigation of the principles of knowledge: and of the progress of reason, from sense to science and philosophy. *Strahan T Cadell Lond* 2(3):105–120
- Hiscock P (2007) Looking the other way: a materialist/technological approach to classifying tools and implements, cores and retouched

- flakes. In: McPherron S, Lindley J (eds) Tools or cores? The identification and study of alternative core technology in lithic assemblages. University of Pennsylvania Museum, Philadelphia, pp 189–222
- Juana S, Galán AB, Domínguez-Rodrigo M (2009) Taphonomic identification of cut marks made with lithic handaxes: an experimental study. *J Archaeol Sci* 37:1841–1850
- Kendall D (1989) A survey of the statistical theory of shape. *Stat Sci* 4(2): 87–120
- Klingenberg C (2008) Novelty and “homology-free” morphometrics: what’s in a name? *Evol Bio* 35:186–190
- Klingenberg C (2011) MorphoJ: an integrated software package for geometric morphometrics. *Mol Ecol Resour* 11:353–357
- Lam Y, Chen X, Marean C, Frey C (1998) Bone density and long bone representation in archaeological faunas: comparing results from CT and photon densitometry. *J Archaeol Sci* 25:559–570
- Lam Y, Xingbin C, Pearson O (1999) Intertaxonomic variability in patterns of bone density and the differential representation of bovid, cervid and equid elements in the archaeological record. *Society American Archaeol* 64(2):343–362
- Lam Y, Pearson O, Marean C, Chen X (2003) Bone density studies in zooarchaeology. *J Archaeol Sci* 30:1701–1708
- Leakey M (1971) Olduvai Gorge, volume 3: excavations in beds I and II, 1960–1963. Cambridge University Press, Cambridge
- Lewis J (2008) Identifying sword marks on bone: criteria for distinguishing between cut marks made by different classes of bladed weapons. *J Archaeol Sci* 35:2001–2008
- Lyell C (1830) Principles of geology: being an attempt to explain the former changes of the Earth’s surface, by reference to causes now in operation. Penguin Classics, Wiltshire
- Machin AJ, Hosfield RT, Mithen SJ (2006) Why are some handaxes symmetrical? Testing the influence of handaxe morphology on butchery effectiveness. *J Archaeol Sci*. <https://doi.org/10.1016/j.jas.2006.09.008>
- Manríquez G, González-Bergás F, Carlos Salinas J, Espouey O (2006) Deformación Intencional del Cráneo en Poblaciones Arqueológicas de Arica, Chile: Análisis Preliminar de Morfometría Geométrica Con Uso de Radiografías Craneofaciales. *Revista de Antropología Chilena* 38(1):13–34
- Marín-Monfront M, Pesquero M, Fernández-Jalvo Y (2013) Compressive marks from gravel substrate on vertebrate remains: a preliminary experimental study. *Quat Int*. <https://doi.org/10.1016/j.quaint.2013.10.028>
- Maté-González MA, Yravedra J, González-Aguilera D, Palomeque-González JF, Domínguez-Rodrigo M (2015) Microphotogrammetric characterization of cut marks on bones. *J Archaeol Sci* 62:128–142
- Maté-González MA, Palomeque-González J, Yravedra J, González-Aguilera D, Domínguez-Rodrigo M (2016) Microphotogrammetric and morphometric differentiation of cut marks on bones using metal knives, quartzite and flint flakes. *Archaeol Anthro Sci*. <https://doi.org/10.1007/s12520-016-0401-5>
- Maté-González MA, Aramendi J, Yravedra J, Blasco R, González-Aguilera D (2017a) Assessment of statistical agreement of three techniques for the study of cut marks: 3D digital microscope, laser scanning confocal microscopy and micro photogrammetry. *J Microscopy* 00(0):1–15
- Maté-González MÁ, Yravedra J, Martín-Perea D, Palomeque-González J, San-Juan-Blazquez M, Estaca-Gómez V, Uribealarea D, Álvarez-Alonso D, Gonzalez-Aguilera D (2017b) Flint and quartzite: distinguishing raw material through bone cut marks. *Archaeometry*. <https://doi.org/10.1111/arc.12327>
- Merrit S (2012) Factors affecting early stone age cut mark cross-sectional size: implications from actualistic butchery trails. *J Archaeol Sci* 39: 2984–2994
- Merton RK (1967) On theoretical sociology: five essays, old and new. The Free Press, New York
- Moclán Ramos A (2016) Marcas de Corte, Análisis Zooarqueológico y Tafonómico del Nivel F del Abrigo de Navalmaillo (Pinilla del Valle, Madrid). Master’s Thesis, Universitat Rovira i Virgili, pp 103–109
- Monteiro LR, Bordin B, Furtado dos Reism S (2000) Shape distances, shape spaces and the comparison of morphometric methods. *TREE* 15(6):217–220
- Moretti E, Arrighi S, Boschin F, Crezzini J, Aureli D, Ronchitelli A (2015) Using 3D microscopy to analyze experimental cut marks on animal bones produced with different stone tools. *Ethnobiol Lett* 6(2):267–275
- Nelson E, Hall J, Randolph-Quinney P, Sinclair A (2017) Beyond size: the potential of a geometric morphometric analysis of shape and form for the assessment of sex in hand stencils in rock art. *J Archaeol Sci* 78:202–213
- O’Higgins P, Johnson D (1988) The quantitative description and comparison of biological forms. *Critical reviews in anatomical. Sciences* 1: 149–170
- O’Higgins P, Jones N (1998) Facial growth in *Cercocebus torquatus*: an application of three dimensional geometric morphometric techniques to the study of morphological variation. *J Anat* 193:251–272
- Olsen SL, Shipman P (1988) Surface modification on bone: trampling versus butchery. *J Archaeol Sci* 15:535–553
- Palomeque-González J, Maté-González MA, Yravedra J, San Juan-Blazquez M, García-Vargas E, Martín-Perea D, Estaca-Gómez V, González-Aguilera D, Domínguez-Rodrigo M (2017) Pandora: a new morphometric and statistical software for Analysing and distinguishing cut marks on bones. *Int J Archaeol Sci* 13:60–66
- Pickering TR, Marean CW, Domínguez-Rodrigo M (2003) Importance of limb bone shaft fragments in zooarchaeology: a response to “on in situ attrition and vertebrate body part profiles” (2002), by M. C. Stiner. *J Archaeol Sci* 30:1469–1482
- Pineda A, Saldíe P, María Vergès J, Huguet R, Cáceres I, Vallvedú J (2014) Trampling versus cut marks on chemically altered surfaces: an experimental approach and archaeological application at the Barranc de la Boella site (la Canonja, Tarragona, Spain). *J Archaeol Sci* 50:84–93
- Playfair J (1802) Figure of the Earth, illustrations of the Huttonian theory of the Earth. William Creech, Edinburgh, pp 488–509
- Popper K (1935 [Translated into English in 1959]) Theory and experiment, logic of scientific discovery. Routledge Classics, London, pp 88–94
- Potter SL (2005) The physics of cutmarks. *J Taphon* 3(2):91–106
- Potts R (1988) Early Hominid activities at Olduvai Gorge: foundations of human behaviour. Aldine de Gruyter, New York
- Reynard JP (2013) Trampling in coastal sites: an experimental study on the effects of shell on bone in coastal sediment. *Quat Int*. <https://doi.org/10.1016/j.quaint.2013.11.007>
- Rohlf FJ (1999) Shape statistics: Procrustes superimpositions and tangent spaces. *J Classif* 16:197–223
- Rohlf FJ, Corti M (2000) Use of two-block partial least-squares to study covariation in shape. *Syst Bio* 49(4):740–753
- Rohlf FJ, Marcus LF (1993) A revolution in morphometrics. *Tree* 8(4): 129–132
- Sánchez-Yustos P, Díez-Martín F, Domínguez-Rodrigo M, Duque J, Fraile C, Baquedano E, Mabulla A (2017) Diversity and significance of core preparation in the developed Oldowan technology: reconstructing the flaking processes at SHK and BK (middle-upper bed II, Olduvai Gorge, Tanzania). *Boreas*. <https://doi.org/10.1111/bor.12237>
- Santonja M, Panera J, Rubio-Jara S, Pérez-González A, Uribealarea D, Domínguez-Rodrigo M, Mabulla AZP, Bunn HT, Baquedano E (2014) Technological strategies and the economy of raw materials

- in the TK (Thiongo Korongo) lower occupation, bed II, Olduvai Gorge, Tanzania. *Quat Int* 322-323:181–208
- Shipman P, Rose J (1983) Evidence of butchery and hominid activities at Torralba and Ambrona; an evaluation using microscopic techniques. *J Archaeol Sci* 10:465–474
- Slice D (2001) Landmark coordinates aligned by Procrustes analysis do not lie in Kendall's shape space. *Syst Bio* 50(1):141–149
- Slice D (2005) *Modern morphometrics in physical anthropology*. Plenum Publishers, New York
- Spennemann DHR (1990) Don't forget the bamboo. On recognising and interpreting butchery marks in tropical faunal assemblages, some comments asking for caution, problem solving in taphonomy. *Archaeological and palaeontological studies from Europe, Africa and Oceania* 2:80–101
- Stiner M (2002) On in situ attrition and vertebrate body part profiles. *J Archaeol Sci* 29:979–991
- Thompson JC (2005) The impact of post-depositional processes on bone surface modification frequencies: a corrective strategy and its application to the Loiyangalani site, Serengeti plain, Tanzania. *J Taphon* 3(2):67–90
- de la Torre I, Mora R (2013) The transition to the Acheulean in East Africa: an assessment of paradigms and evidence from Olduvai Gorge (Tanzania). *J Archaeol Method Theory*. <https://doi.org/10.1007/s10816-013-9176-5>
- de la Torre I, Benito-Calvo A, Arroyo A, Zupancich A, Proffitt A (2013) Experimental protocols for the study of battered stone anvils from Olduvai Gorge (Tanzania). *J Archaeol Sci* 40:313–332
- Val A, Costamagno S, Discamps E, Chong S, Claud E, Deschamps M, Mourre V, Soulier MC, Thiébaud C (2017) Testing the influence of stone tool type on microscopic morphology of cut-marks: experimental approach and application to the archaeological record with a case study from the middle Palaeolithic site of Noisetier cave (Fréchet-Aure, Hautes-Pyrénées, France). *J Archaeol Sci: Reports* 11:17–28
- Van Gelder L (2010) 10 years in Rouffignac: a collective report on findings from a decade of finger flutings research, IFRAO congress, September 2010 – Symposium: Pleistocene Art in Europe (Pre-Acts)
- Van Gelder L (2014) Paleolithic finger flutings and the question of writing. *Time and Mind* 7(2):141–153
- Van Gelder L (2015) Counting the children: the role of children in the production of finger flutings in four upper Palaeolithic caves. *Oxf J Archaeol* 34(2):117–138
- Van Gelder L, Sharpe K (2015) Evidence for cave marking by Palaeolithic children. *Antiq* 80(310):937–947
- Walker P, Long J (1977) An experimental study of the morphological characteristics of tool marks. *Soc American Archaeol* 42(4):605–616
- Walker P (1978) Butchering and stone tool function. *Soc Am Archaeol* 43(4):710–715
- West J, Louys J (2007) Differentiating bamboo from stone tool cut marks in the zooarchaeological record, with a discussion on the use of bamboo knives. *J Archaeol Sci* 34:512–518
- Weston E, Szabó K, Stern N (2015) Pleistocene shell tools from Lake Mungo Lunette, Australia: identification and interpretation drawing on experimental archaeology. *Quat Int*. <https://doi.org/10.1016/j.quaint.2015.11.047> (Consulted the 10th of April, 2017)
- Whewell W (1847) *Of the fundamental antithesis of philosophy, the philosophy of the inductive sciences founded upon their history, vol 2*. John W Parker, London, pp 16–50
- Yravedra J (2006) *Las Marcas de Corte, Tafonomía Aplicada a la Zooarqueología*. UNED, Madrid, pp 188–195
- Yravedra J, Maté-González MA, Palomeque-González JF, Aramendi J, Estaca Gómez V, San Juan Blazquez M, García Vargas E, Organista E, González-Aguilera D, Carmen Arriaza M, Cobo-Sánchez L, Gidna A, Uriberlarrrea del Val D, Baquedano E, Mabulla A, Domíngue-Rodrigo M (2017a) A new approach to raw material use in the exploitation of animal carcasses at BK (upper bed II, Olduvai Gorge, Tanzania): a micro-photogrammetric and geometric morphometric analysis of fossil cut marks. *Boreas*. <https://doi.org/10.1111/bor.12224>
- Yravedra J, Díez-Martín F, Egeland C, Maté-González MA, Palomeque-González JF, Carmen Arriaza M, Aramendi J, García Vargas E, Estaca-Gómez V, Sánchez P, Fraile C, Duque J, Francisco Rodríguez S, González-Aguilera D, Mabulla A, Baquedano E, Domíngue-Rodrigo M (2017b) FLK west (lower bed II, Olduvai-gorge, Tanzania): a new early Acheulean site with evidence for human exploitation of Fauna. *Boreas*. <https://doi.org/10.1111/bor.12243>