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Pandora: A new morphometric and statistical software for analysing and distinguishing cut marks on bones



Juan Francisco Palomeque-González^a, Miguel Ángel Maté-González^{b,c}, José Yravedra^{a,d,*},
María San Juan-Blazquez^a, Elena García Vargas^a, David Manuel Martín-Perea^d, Verónica Estaca-Gómez^a,
Diego González-Aguilera^b, Manuel Domínguez-Rodrigo^{a,d}

^a Department of Prehistory, Complutense University, Prof. Aranguren s/n, 28040 Madrid, Spain

^b Department of Cartographic and Land Engineering, Polytechnic School of Avila, University of Salamanca, Hornos Caleros 50, 05003 Avila, Spain

^c C.A.I. Arqueometry and Archaeological Analysis, Complutense University, Profesor Aranguren s/n, 28040 Madrid, Spain

^d IDEA (Institute of Evolution in Africa), Museo de los Orígenes, Plaza de San Andrés 2, 28005 Madrid, Spain

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ABSTRACT

Cut mark studies have experienced a useful development in the last few years. These studies have allowed us to obtain important information about human prehistory spanning from the origin of meat consumption for chronologies around 2.5 Ma, the detection of human hunting behavior during the lower Pleistocene, or even to determine the uses of diverse raw materials on carcasses. Amongst the different analyses applied to the study of cut marks, there has been an increasing interest in using morphometry in order to differentiate and characterize the raw materials with which the effectors were made. These techniques have proven to be extremely useful. Nevertheless, this 3D methodology demands the use of expensive equipment and does not allow using an extensive sample, making it a complex and problematic technique. Maté-González et al. (2015) considered an alternative technique, by combining different disciplines involving geometric morphometrics, photogrammetry and multivariate statistics (multidisciplinary methodology). Here, we try to continue with this work presenting *Pandora*, a new open software capable of analysing a useful amount of variables from a statistical and morphometric view, accelerating and simplifying the process.

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1. Introduction

Cut marks on bones can provide useful information concerning human behavior. Cut marks have been reported even in sites dated 2.6 Ma, suggesting an early Pleistocene meat consumption by hominins (De Heinzelin et al., 1999; Semaw et al., 2003; Domínguez-Rodrigo et al., 2005). Cut mark frequency and distribution on bones have been used to recognize predatory behaviors for sites dated 1.5 Ma (Domínguez-Rodrigo et al., 2002, 2007, 2009a, 2014; Pickering et al., 2004; Pobiner et al., 2009; Sahnouni et al., 2012). In other chronologies and contexts, cut marks have permitted the identification and use of metal tools in carcass processing from the Chalcolithic to the Bronze Age, showing a functional use of this kind of tools (Greenfield, 1999).

Since the late XIXth century and beginning of the XXth century, cut marks have been observed, documented and studied (Lartet, 1860;

Lartet and Christy, 1875; Martin, 1909). Since then, this type of studies have had a large tradition (Walker, 1978; Shipman and Rose, 1983; Olsen, 1988; Spennerman, 1990; Greenfield, 1999, 2004, 2006a, 2006b; Bello and Soligo, 2008; Bello et al., 2009; Domínguez-Rodrigo et al., 2009b; De Juana et al., 2010; Galán and Domínguez-Rodrigo, 2013; Maté-González et al., 2016), and, nowadays, thanks to the development of new technologies, new study types involving the use of complex technology are flourishing, improving the recognition of these marks. This field has progressed greatly, starting with the development of microscopic analysis with SEM used by Shipman (1981), Shipman and Rose (1983), Olsen (1988), and Greenfield (1999, 2004), followed by high resolution binocular microscope pictures used by Domínguez-Rodrigo et al. (2009b) for cut mark morphological characterization through two-dimensional images and, finally, the implementation of three-dimensional reconstruction systems from 3D digital microscopy (Boschin and Crezzini, 2012; Crezzini et al., 2014), such as the 3D Alicona Infinite Focus Imaging microscope (Bello and Soligo, 2008; Bello et al., 2009; Bello, 2011), or even the use of micro-photogrammetric and morphometric reconstruction of cut marks (Maté-González et al., 2015, 2016).

* Corresponding author at: Department of Prehistory, Complutense University, Prof. Aranguren s/n, 28040 Madrid, Spain.
E-mail address: jyavedra@ghis.ucm.es (J. Yravedra).

Although these methods have allowed cut mark characterization, these have some limitations. On one hand some of these techniques are not easily accessible to everybody due to their elevated cost of the expensive equipment (use of SEM or 3D digital microscopes, for instance). On the other hand, using binocular microscopy to obtain high-resolution pictures implies the generation of a 2D image, which does not allow a three dimensional mark characterization. Nevertheless, Maté-González et al. (2015) have introduced the option of carrying out micro-photogrammetric and morphometric reconstructions, developing 3D mark reconstructions using accessible equipment. This new technique allows working with large mark samples (Maté-González et al., 2016) and improves the traditional systems used to analyse these type of marks.

With this paper, we present instructions on the use of the free *Pandora* software. This open access software offers the user a wide variety of tools, such as the application of several statistical and morphometric tests helping to classify and characterize cut marks appearing in archaeological sites. This program allows a great flexibility, automatization and computerization of the data collection process, and can present the data through a large variety of graphs depending on the tests applied.

To demonstrate the technique's results, an experimental case will be carried out throughout this paper as an example of its application to a practical case: the differentiation of cut marks based on the tool's raw material (flint, basalt or quartzite).

2. Methods

2.1. Description and use of the *Pandora* package

Pandora has been designed to guide the user, step by step, during the data collection and analytical process, simplifying the work required for cut mark microscopic examination. This program has allowed the systematization of all measurements used to classify cut marks, based on the methodology and terminology exposed in Bello et al. (2013) and Maté-González et al. (2015).

Pandora has a series of interactive menus from which the user can make a selection amongst a list of options and configurations, to determine the morphometric and statistical analysis which will be carried out. The main objective of this tool is to obtain a normalized database, allowing different research groups to exchange information and to be able to coordinate studies, synthesizing nomenclature and similar procedures.

Researchers will be able to save their work files in an external file with the extension `*.marks`. By doing this, the *Pandora* software would read and process the data and incorporate it into an extensive database, including all other prior data. Because of this, the comparison of cut mark dimensions, characteristics and shapes could be made easier. The successive incorporation of data generated by different experiments and research teams will allow carrying out morphological and statistical tests with a higher resolution and a lower margin of error, since a wider sample will be studied and the data included in it has been collected and analysed following the same methodology during the entire process.

After the three dimensional mark model reflecting the cut mark section has been obtained using photogrammetric methodologies such as those described in Maté-González et al. (2015) or other microscopic techniques like the ones presented in Bello and Soligo (2008), Bello et al. (2009) or Boschini and Crezzini (2012), the images processed should be saved in `*.JPG` format.

Once all the files are located in the same directory, *Pandora* will automatically introduce them to the software database. Automatically, *Pandora* will ask for the specific variables (e.g. "Site", "Raw material", etc.) of each file in the same directory. After this, *Pandora* will once more ask for the specific variables of each of the directory sections, and will ask for image upload. Once the image is open, the program

will request to locate scale points with a click to set the image to scale. After that, we should indicate the seven semi-landmarks (LM) used for cut mark analysis as described by Maté-González et al. (2015). Finally, after placing the last LM, *Pandora* will automatically measure all lengths and existent relationships between them and then save them in a database.

When all images in a given folder have been treated and analysed, *Pandora* will give the user two options:

- 1) To analyse another directory and introduce new data from another set
- 2) To analyse the introduced images using statistical or morphometric tests

The tests currently included in *Pandora* are ANOVA (Analysis of Variance), MANOVA (Multiple analysis of variance), PCA (Principal Component analysis) and LDA (Linear discriminant analysis) for the statistical tests, and GPA (General Procrustes Analysis), morphometric data PCA and morphometric data LDA referring to the morphometric tests available.

Thus, as soon as the data has been introduced, using several tests, the analysis of a set of cut marks can be done instantaneously. In this case study, we compare the results of various cut marks produced by different raw materials such as flint, quartzite and basalt.

Installing *Pandora* is free, as it is deposited in a repository Github, allowing a quick update whenever necessary and the latest modifications and corrections can always be available and installed (<https://www.github.com>). *Pandora* uses basic functions of R (Core, 2015), as well as functions of the MASS package (Venables and Ripley, 2002), CircStats (Agostinelli, 2012), and Geomorph (Adams and Otarola-Castillo, 2013).

The use of the *Pandora* package allows a more systematic and automatic data input and manipulation for cut mark analysis, avoiding any errors derived from the manual data input. Before *Pandora* was developed, cut mark analysis implied a series of steps which substantially slowed down the process, as well as implying the use of various different programs such as Autocad, Excel and R for scaling, morphometrical and statistical analysis. Here, all this can be carried out with one single program.

2.2. Methods described in the cut mark analysis

Following the methods developed and proposed by Bello et al. (2013), a series of measurements have been taken, as well as a the three-dimensional model of the cut marks studied. These measurements mentioned above have been used as numerical variables for the analysis of the studied cut marks (Fig. 1).

As it was observed in Maté-González et al. (2015), marks have a variable longitude and the morphology of the mark section changes according to the point chosen to make the three-dimensional model. In this case, we made several statistical analyses to prove which section of the cut mark was diagnostic for cut mark morphology, proving that any point taken in the cut mark between 30% to 70% of the groove section trajectory is equally diagnostic (see Fig. 2).

Measurements, including WIS, WIM, WIB, OA, D, LDC, RDC, were made on the cut mark section (Fig. 1). 7 Landmarks were chosen (LM1x, LM1y, LM2x, LM2y, LM3x, LM3y, LM4x, LM4y, LM5x, LM5y, LM6x, LM6y, LM7x, LM7y), referring to Cartesian coordinates (x and y) of each of the Landmarks (Maté-González et al., 2015, 2016). Next to the qualitative measurements general data such as "site", "n_site", "n", and "Material" has to be added. The definition of all variables is listed below:

1. "site": Original site from where the bones are coming, or the experiment code.
2. "n_site": Name of the bone in the data base of the own project.
3. "n": Mark number.

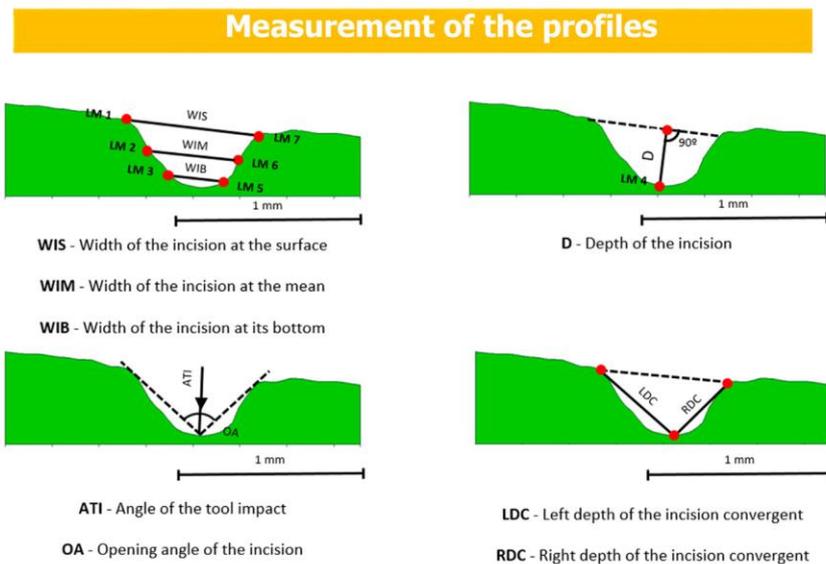


Fig. 1. Location of measurements sensu Bello et al. (2013). Landmarks (LM1–7) used for the morphometric model are also represented.

4. "Material": Edge material producing the mark during the experiment.
5. "Section": Area where has been taken the mark section for the tri-dimensional model.
6. "taxon_bone": Bone taxa.
7. "Anatomical_part": Skull, mandible, tibia, femur, radius, scapula, pelvis, etc.
8. "WIS": Upper section mark width.
9. "WIM": Middle section mark width.
10. "WIB": Lower section mark width.
11. "LDC": Distance between the mark's base and the upper left point.
12. "RDC": Distance between the mark's base and the upper right point.
13. "SI": Symmetry index (difference between LDC and RDC absolute values).

14. "D": Cut mark depth.
15. "OA": Cut mark angle.
16. "ID": Mark identification code.

All these variables are stored in the database when running the program, in order to be analysed at a later time. The package also allows to export information to an external file to save and share it, and it allows making statistical and morphological tests such as:

Pairwise ANOVA: Variance analysis of each variable separating the marks by raw material and comparing paired groups.

MANOVA: Similar to ANOVA test but uses more than one variable at the same time to make the comparison. This test can be applied with all variables at the same time or only with those which result statistically more significant in ANOVA tests.

PCA: Analysis using the total sample, separating the results by raw material. Whether or not different variable combinations maximize existing differences between different cut mark groups can be studied.

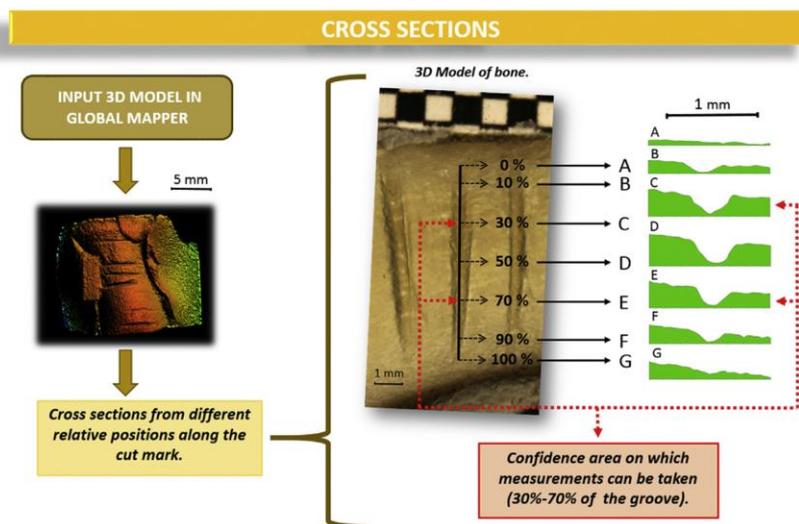


Fig. 2. Representation of the a–g sections of the cut mark regarding its length.

It allows to know if the variables maximize the difference between the different mark groups based on different variable combinations. Results can be shown graphically.

LDA: Lineal discriminant analysis grouping data, showing the degree of similarity between groups and miss classification rates.

GPA: This is the main analysis used for the geometric morphometry. The general procrustes analysis allows nullifying the scale effects as well as image rotation, so it can compare directly the mark shape. This analysis creates the idealized cut mark of each group by calculating the centroids and representing them graphically. Furthermore, since the data is normalized, it is left ready for any future statistical analysis of the overall group.

PCA and “distortion matrix” of the morphometric results: After GPA analysis, a PCA test for the data can be used, which is already prepared in the package “Geomorph” (Adams and Otárola-Castillo, 2013), which produces a graph representing the similarities between different cut marks.

LDA on LM: Similar to PCA analysis, it can make a LDA analysis upon data results to study group classification using morphological variables.

3. Pandora practical application to cut mark study

3.1. Materials and methods

After describing *Pandora*, we proceed to present in this chapter its practical applications in a referential framework comparing cut marks produced with different raw materials such as flint, quartzite and basalt.

A total of 198 flint marks, 10 quartzite marks and 85 basalt marks have been analysed, which means a total of 390 marks for the three raw materials. What we would like to achieve with this exercise is to discriminate the cut marks produced by those three materials and see if they can be distinguished using statistical and morphological tests carried out by *Pandora*.

Mark modelling has been made following the methods presented in Maté-González et al. (2015, 2016). This method incorporates the treatment of high-resolution images with micro-photogrammetry and computer vision for the three-dimensional reconstruction of cut mark sections. Following the methodology discussed in 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. 3). It was demonstrated that more stable and precise sensors captured better quality images, producing more significant results. Like in previous work, a Canon EOS 700D reflex camera (Table 1) was used, with 60 mm macro lenses, which obtained high resolution and

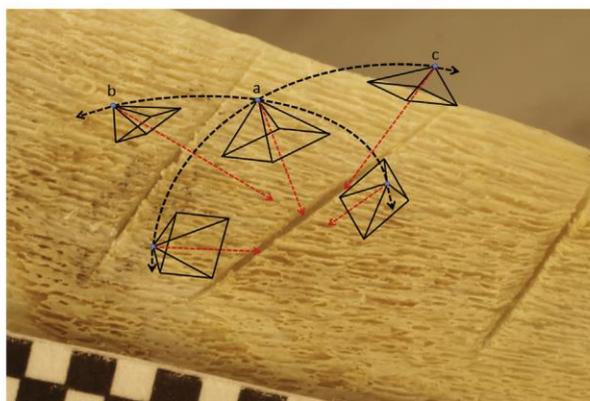


Fig. 3. Protocol for image capture to model a cut mark on a bone by the micro-photogrammetric method, with convergent photographic shots. (a) Master and dependent images in central position, (b) vertical slave images, and (c) horizontal slave images.

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

high quality images. The cut mark experimentations were carried out by butchering long bones of young ovicaprids by an expert butcher using simple flint, basalt and fine-grained quartzite flakes.

Marks were subsequently photographed using a tripod to stabilize the camera as described in Maté-González et al. (2015, 2016). 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. 3). Finally, the images were treated with photogrammetric reconstruction software such as GRAPHOS (inteGRATED PHOTogrammetric Suite) (Fig. 4) (González-Aguilera et al., 2016a, 2016b) or another reconstruction software such as Agisoft PhotoScan, PIX4D or PW (González-Aguilera et al., 2013). Once the 3D models with scales were produced, the Global Mapper software was applied to define mark profiles and measure them (Figs. 1 and 2). Finally, the independent analysis of each cut mark was proposed according to the tool used via geometric morphometric analysis. 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. 1).

After the modelling of the cut mark sections, every file is saved with the format “.marks”, one for each raw material. Right after we proceed to introduce the data and process them by using several statistical tests as described in Section 3. Pairwise ANOVA test for each variable, Pairwise MANOVA test for all variables, and only for statistical significant variables from ANOVA tests, PCA, LDA, GPA, PCA with the statistical results and LDA with the morphometric results.

3.2. Experimental analysis

When carrying out an ANOVA test for each variable measured, carried out for pairs of different raw materials, it is seen that each variable presents a difference in their variance which is statistically significant (5%), for at least two of the raw materials, which means every variable is valid to differentiate between two pieces of different raw materials. That is why, for the next steps those tests will be used.

When MANOVA tests are applied, the following results for *p* values are obtained:

$$“F Q” = 7.06482071842748e-28$$

$$“B Q” = 6.16912152827254e-21$$

$$“B F” = 0.000048241902222198.$$

These results present values for *p* lower than 0.05, meaning statistically significant differences between all the groups studied when this test is applied. Between the raw materials, basalt (B) and flint (F) are the more similar amongst them, with a *p* value larger than any other combination, but still statistically significant.

When the plot analysis of the PCA is applied (Fig. 5), it can be observed that it is difficult to differentiate between flint and basalt. With a 86.6% of the variance explained in the two observable axis, creating confidence ellipses to 95%, showing that the marks made with quartzite

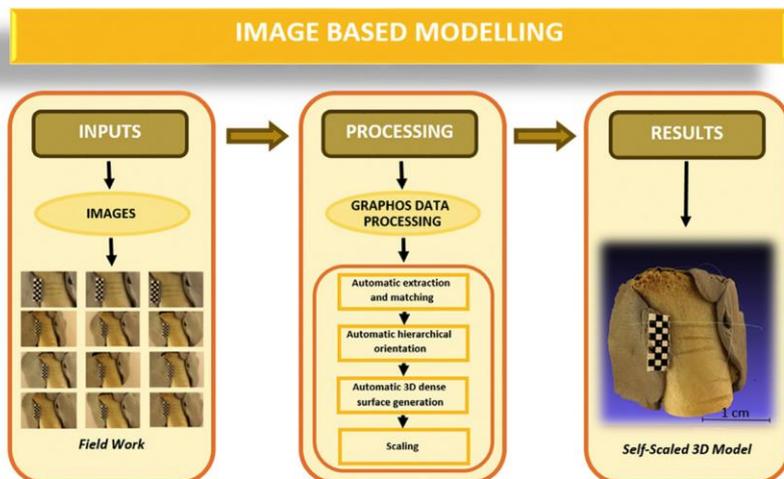


Fig. 4. Image-based modelling technique workflow.

(Q) are clearly separated from the rest. Still, it can be seen that there is an enormous confusion between the marks made with Basalt and Flint, leaving the most part of them overlap with Basalt marks. Employing a LDA we can appreciate it more clearly.

B	F	Q
0.000000	0.994709	0.000000

We can clearly observe that most of the marks made with flint are not distinguishable from other marks.

On the other hand, the morphometric analysis seems more diagnostic than statistical one. The GPA used to normalize and scale coordinates of every Landmark allows us to obtain the centroids of each one (Fig. 6). The data processed, centered and scaled by the GPA is later on analysed with an LDA, which is more decisive to separate cut marks depending on their raw material. As seen on the confusion matrix, we can appreciate differences between the four groups, showing a huge difference between flint and quartzite and between quartzite and basalt. On the other hand, small differences are observed between basalt and flint.

The LDA confusion matrix about morphometric data is:

F	Q	B
0.7460317	0.7102804	0.3882353

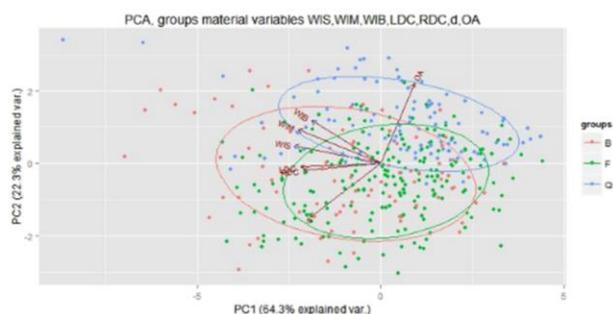


Fig. 5. Flint, basalt y quartzite cut marks PCA.

As flint marks show an enormous variability, if we remove them and remake the LDA just with the basalt and quartzite marks, the resultant confusion matrix is:

Q	B
0.8971963	0.7294118

3.3. Conclusions of the experiment

This experiment allows us to showcase how the Pandora software is a useful tool for the analysis of cut marks since after the inclusion of the data it is immediately possible to use an important number of tests automatically. In addition, it is possible to integrate and compare with such analysis different marks produced by as many raw materials as needed. Being capable of analysing different marks from different perspectives, either morphometrically or statistically, the program can simultaneously analyse ample samples improving our limitations from initial cut mark studies, which would only cover a reduced amount of the total sample (Olsen, 1988; Greenfield, 1999, 2004, 2006a, 2006b). On the other hand, being able to make a link between different cut marks could be a necessary step to build a future tapho-library which could help to identify the raw material used for butchering which caused any studied cut mark in any site.

Referring to the analysis carried out for the variables measured comparing the marks produced with basalt, flint and quartzite, it can be observed that every one of them is proven to be significantly different when separated in groups. This is also true when carrying out a MANOVA test with all the variables. In every case there is a statistical significant difference between the different groups, with a *p* value lower than 0.05, the lowest difference being between basalt and flint. The dimensional PCA is the analysis with the lowest resolution between those materials, which are actually overlapping. Nevertheless, geometric morphometry appears to present the best results. After the LDA, a higher resolution is obtained, being able to distinguish between different cut marks in relation to the raw material being used.

Real-life applications of the techniques carried out in this study can be seen in many recent archaeological cut mark studies. Taphonomical analyses carried out at archaeological sites such as BK and FLK-W in Bed II at Olduvai Gorge (Tanzania) are a great example of how the use of the Pandora package has enabled the differentiation and characterization of cut marks at both sites. Thanks to this software, cut marks have

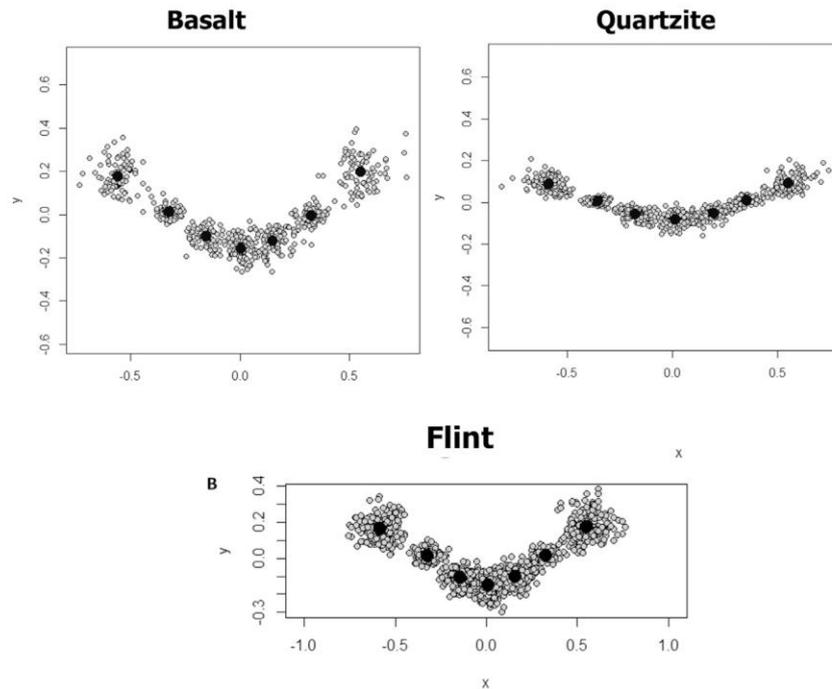


Fig. 6. GPA with each LM centroid.

been inferred to be made with quartzite, not basalt, although both of these raw materials are found at the site (Yravedra et al., 2017a). At FLK-W, faunal remains have been found associated with lithic industry including hand axes (Diez-Marín et al., 2015). By virtue of the use of the *Pandora* software, studies have shown defleshing of the mammal remains was not carried out with said hand axes, but with quartzite chips (Yravedra et al., 2017b).

4. Final considerations

The objective of this paper is to present *Pandora* as a morphometric and statistical analysis tool, which can help to characterize and discriminate cut marks in relation to the raw material used. Even though this study has only been exposed to an experimental analysis comparing marks produced by basalts, flint and quartzite with satisfactory results, the potential of this software is noticeable.

The use of the *Pandora* package implies several advantages: on one hand it is an autonomous system in which the program guides the user during all the process of data acquisition and input; on the other hand, all introduced information is saved globally, allowing the construction of databases which could be used and compared by different research groups. This means studies of cut marks produced with diverse raw materials by different researchers could be contrasted and then be further used to more exhaustively study the archaeological record. Being an autonomous program, it is only necessary to introduce the shape and the Landmarks into the system. Measurements are then calculated by the program automatically, avoiding manual mistakes and saving time. With *Pandora*, when we introduce mark shapes and place Landmarks, all data is kept registered.

Finally, *Pandora's* intuitive interface and detailed guide have been designed to provide easy use and management, meaning anyone with basic computing skills can use the software. The analytical method presented for *Pandora* complements other powerful three-dimensional microscopic approaches to the study of cut marks. Concerning its application, although our research has been focused on cut mark studies, it

could in fact be used to define other marks such as carnivore scores, trampling or even traces made by human beings when producing mobile and parietal art.

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Appendix A. Supplementary data

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