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RESEARCH

Identification of chemically altered cut marks: an experimental approach from Geometrics Morphometrics

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Abstract

Cut marks are striae accidentally produced by the contact made between the edge of a cutting tool and bone surfaces by anthropogenic activity, presenting evidence of hominin carcass processing and behaviour, butchery activities or diet. Post-depositional processes can cause the alteration (chemical or mechanical) of bones surfaces, changing their composition and causing the modification of bone surfaces. Previous research has addressed the problem of chemical alteration from a qualitative perspective, resulting in the loss of all diagnostic characteristics of the cut marks affected by these processes. Geometrics Morphometrics has led to great progress in the study of cut marks from a quantitative perspective and can be useful for the study of altered cut marks. In this study, an experiment was carried out in which 36 cut marks were reproduced and chemically altered. These marks were scanned and digitized before and after each phase of alteration. They were analyzed metrically as well as using Geometric Morphometrics, in order to study the evolution of modifications to cut mark morphology during the experiment. Results show clear morphological differences between the different phases of alteration with altered cut marks presenting a general tendency towards a decrease in both the width and depth over time. Research of this type opens up a new path for the study of the chemical alteration of cut marks, as well as other striae, through the application of Geometric Morphometrics.

Keywords Bone surface modifications · Chemical abrasion · Experimental archaeology · Geometrics Morphometrics · Taphonomy

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Introduction

Cut marks are striae identified on the surface of bones, produced accidentally as a result of various butchery activities, when the edge of a tool comes into contact with the cortical of the bone (Binford 1981; Potts and Shipman 1981; Shipman 1981; Shipman and Rose 1983a). Their correct characterization and identification is of great importance as they are a direct evidence of anthropic processing of animal carcasses, providing a wealth of information regarding hominin behavior, diet, or the sequence of access to the carcasses by these and other accumulating and modifying agents (e.g. Binford 1981; Bunn 1981; Blumenschine 1986; 1988; Blumenschine and Selvaggio 1988; Capaldo 1997; 1998; Nilssen 2000).

Cut marks are mainly characterized by having a V-shaped cross-section with variable depth, a mostly straight trajectory, with the presence of internal micro-striations and the absence of overlapping striation (Binford 1981; Shipman 1981; Domínguez-Rodrigo et al. 2009), among other features. Cut marks can be easily differentiated from other surface striations that are not intentional or directly related to consumption, such as trampling striae (Olsen and Shipman 1988), which are striae produced by the contact between the bone surface and the sedimentary particles (Behrensmeyer 1978; 1986; Andrews and Cook 1985; Olsen and Shipman 1988; Fernández-Jalvo and Andrews 2016). Trampling striae are superficial and irregular, tend to have a random location in the bone and to be shorter than cut marks, although the microscopic features are highly variable (Andrews and Cook 1985; Olsen and Shipman 1988).

In the archaeological record, the correct identification of cut marks and differentiation with other striae is not always possible, specially in contexts in which these marks have been altered as a consequence of biostratinomic and diagenetic processes, leading to equifinality problems. Many papers have focused on the characterization of cut marks and differentiation with other striations, such as trampling striae, from a qualitative point of view (Binford 1981; Potts and Shipman 1981; Shipman 1981; Shipman and Rose 1983a, b; Olsen and Shipman 1988; Domínguez-Rodrigo et al. 2009, 2010a, b, 2017; Gaudzinski-Windheuser et al., 2010; Pineda et al. 2014; 2019; Sahle et al. 2017). However, this methodology of analysis, observation and identification of striae on bones is burdened by the subjectivity of the analysis itself and of the observers (Domínguez-Rodrigo et al. 2010b, 2017, 2019; Harris et al. 2017; Sahle et al. 2017), which gradually led to the development of quantitative methods of cut mark analysis to mitigate these biases (Bello and Soligo 2008; Bello et al. 2009, 2013; Maté-González et al. 2015, 2019a, 2023; Harris et al. 2017; Pante et al. 2017; Courtenay et al. 2018, 2019a, c, 2020a; Gümrückçü and Pante 2018; Otárola-Castillo et al. 2018; Pizarro-Monzo and Domínguez-Rodrigo 2020; Pizarro-Monzo et al. 2022; Pineda et al. 2023).

The application of quantitative techniques has been an improvement in addressing and trying to solve taphonomic problems of equifinality. Bello and Soligo (2008) proposed a first innovating methodology that allowed the 3D reconstruction of the morphology of cut marks, through the quantification of metric parameters extracted from their profile and micro-topography. This model inspired the analysis conducted by Maté-González and colleagues (2015), who developed these measurements to also include the use of Geometrics Morphometrics (GMM) for the study of cut marks, analyzing profiles lying between 30% and 70% of the total length of the mark (Maté-González et al. 2015). This study originally proposed the use of recording the position and relationship between seven landmarks manually placed along the profile, a method that has since been refined and corrected using sliding semi-landmarks in an attempt to reduce inter and intra-analyst subjectivity and error (Valtierra et al. 2020). Later developments by Courtenay and colleagues (2019a) proposed the basis of a 3D technique extracting morphological information from the mark as a whole, as opposed to focusing solely on a 2D profile derived from 3D information. Based on these advances, both the seven and the 13-landmark models provide an empirical and quantitative means of analyzing cut mark morphological variability, leveraging the use of multivariate statistics and the tools provided by GMM (Courtenay et al. 2019a).

Experimental works have been the base pillar from which this proxy has developed. The differentiation of the raw materials or type of tools that would have produced the cut marks (Yravedra et al. 2017, 2019; Maté-González et al. 2018; Moclán et al. 2018; Courtenay et al. 2019b), or the differentiation between these marks and other surface striations of non-anthropic origin, such as trampling (Courtenay et al. 2019c, 2020a) have been the main topics addressed from a quantitative point of view.

From this perspective, it can be seen that GMM provides a powerful tool set that makes it possible to move beyond descriptive methodology and apply quantitative analysis to the study of variations in the size and shape of striae (Courtenay et al. 2019a). This has made it possible to observe statistical differences between different striae or the evolution of the marks after various mechanical alteration processes (Gümrükçü and Pante 2018; Valtierra et al. 2020; Pineda et al. 2023). Deep learning (DL) methods have been shown as useful tools to address this topic (Pizarro-Monzo and Domínguez-Rodrigo 2020).

The aforementioned alteration of cut marks and other surface modifications occurs due to the physical changes in the bone tissue by direct action of a modifying agent without changing its composition. It may happen for various reasons, such as the physical action of flowing water, trampling, as a result of weathering when remains are exposed on the surface, or trephic processes both during and after the excavation. Mechanical alterations have been addressed by several authors from different perspectives (Gaudzinski-Windheuser et al., 2010; Gümrükçü and Pante 2018; Pineda et al. 2019; 2023; Pizarro-Monzo and Domínguez-Rodrigo 2020; Valtierra et al. 2020), with the aim of achieving a clear differentiation between altered and unaltered marks. From a qualitative standpoint, differentiation between marks is sometimes attainable if they retain at least one of their diagnostic features after alteration. However, from a quantitative perspective, it is possible to observe a trend towards altered cut marks presenting a greater width and a reduced depth compared to non-altered incisions (Gümrükçü and Pante 2018; Pineda et al. 2023).

On the other hand, chemical alteration leads to a variation in the chemical composition of the bone, an aspect that can be caused by various agents such as fungi, bacteria and the alkalinity of the sediment or the leaching of soluble elements present in the sediment (Marchiafava et al. 1974; Piepenbrink 1989; Fernández-Jalvo 1992; Fernández-Jalvo et al. 2002; Pineda et al. 2014; Pizarro-Monzo et al. 2022). These changes can lead to the alteration of anthropogenic striae. This aspect has been studied qualitatively and descriptively by Pineda et al. (2014) and quantitatively by Pizarro-Monzo and colleagues (2022). Pineda et al. (2014) presented a descriptive evaluation of the evolution of cut and trampling marks by means of the descriptive methodology proposed by Domínguez-Rodrigo et al. (2009), with an experiment considering two alteration phases of 10 s each. The study recorded the loss of diagnostic characteristics of both types of striae after chemical alteration, thus preventing their identification and correct differentiation. Recently, Pizarro-Monzo et al. (2022) attempted to distinguish between unaltered and altered cut marks (in both acid and alkaline contexts) employing DL. Cut-marked specimens were buried in containers, covered with both types of sediments, and periodically monitored. According to their results, the ability to differentiate between altered and unaltered cut marks was high and clear, not as much when differentiating the two types of alteration and the different phases of each alteration type.

In the present work, cut marks were reproduced using a metal knife, with the aim to analyze the evolution of chemically altered cut marks by applying a quantitative analysis based on Geometric Morphometrics, following an experimental model similar to that carried out by Pineda et al. (2014). It could be argued that the intentional creation of cut marks could limit the applicability of the results since they do not faithfully replicate butchery cut marks found in archaeological assemblages. However, it is necessary to conduct an experiment in which the variability derived from the use of lithic raw materials was suppressed in order to achieve a better control over the evolution of the morphology of each cut mark. The aim is to observe the existence of statistically important differences between altered and non-altered marks and to open a new path of research that can solve the problems present in archaeological contexts affected by chemical alteration.

Materials and methods

Three partially defleshed inmature bovine (*Bos taurus*) femora were used for the experiment, although they retained small patches of flesh and periosteum. A circular saw with an abrasive disc was used to separate the epiphyses and fragment the shafts into four fragments of approximately eight centimeters. A mechanical saw was used to avoid any type of alteration in the bone cortical surfaces that could be confused with other process, as well as to fragment the diaphysis with the maximum precision possible. 12 fragments were obtained, of which nine were selected for their suitability for the reproduction of the cut marks, while the remaining three fragments were discarded (Fig. 1, A, B).

Four cut marks were made on each fragment, using a thin-edged metal knife, cutting from left to right and perpendicular to the longitudinal section of the bone (Fig. 1, C). The use of a metal knife made it possible to reproduce more uniform cut marks, controlling different variables that would bring greater variability to the experiment, as what typically happens with raw materials such as those of lithic origin due to edge attrition after use. This was performed by a single right-handed individual with similar force. In total, 36 cut marks were obtained (Table 1).

Fragments were then subjected to chemical alteration (Fig. 1, D). For this, they were immersed in a solution of distilled water and 5% hydrochloric acid (950 ml. of distilled water and 50 ml. of hydrochloric acid) emulating the experiment of Pineda et al. (2014). The choice of the acid was made as it is a corrosive element that allows the cut marks to survive when it is in low solution and the exposure is low, so the study of the evolution of the cut marks is possible, and it mimics the effect of the natural chemical alteration as it causes the loss of the diagnostic features (e.g. internal micro-striations, shoulder effect and other features described by Domínguez-Rodrigo et al. (2009). Each fragment was immersed for five seconds and then neutralized in water to stop the action of the acid. This process was repeated in two cumulative alteration phases. The 3D models of the cut marks were obtained before chemical alteration (Phase 0) and after each of the alteration processes: Phase

Fig. 1 Experimental process. **A**) Bos taurus femurs; **B**) Fracturing of the shafts; **C**) Production of cut marks; **D**) Chemical alteration

1, after five seconds of alteration and Phase 2, after 10 s of alteration. The bones were frozen at the different stages of the process to avoid the degradation of the organic part (raw meat and periosteum) during the course of the experiment.

Digitization of marks and obtaining 3D models

The digitization process of the cut marks was carried out using the 3D scanner "DAVID SLS-3 Structured-Light Surface". This consists of a camera and a projector that can be connected to a protable computer, facilitating the handling of such equipment and proving very efficient for fast scanning in remote locations. For this study the equipment used consisted of a HP 3D Camera Pro + OMRON 3Z4S-LE ML-1214 12 mm f1.4 and an ACER K132 led projector, connected to a computer that includes the HP 3D Scan Pro 5.2.0 software. All equipment is located in the Archaeometry and Archaeological Analysis Unit of the Research Assistance Center (C.A.I) of Earth Sciences and Archaeology of the Complutense University of Madrid (UCM). Calibration of the camera and the projector was performed using a 15 mm calibration marker board. Once calibrated, neither the camera nor the projector can be moved. The scanning process per mark takes an average of 30 s, allowing to obtain the 3D model of each mark in "*.obj*" format. These mesh are then exported and subsequently processed with the free software CloudCompare (Girardeau-Montaut 2016).

During the digitization of the unaltered marks (Phase 0), two marks were discarded because their long length made their complete digitization impossible, and a total of 34 marks were digitized. After the first phase of alteration, the disappearance of one cut mark was documented, so the number of digitized marks went down to 33. After the second phase of alteration, no more marks disappeared, so the entirety of the sample could be analysed (Table 1). Nevertheless, one of the Phase 2 cut marks (CM27) presented problems in the placement of landmarks, so it was discarded at this point. At all times, more than 30 marks were analyzed in each phase.

Marks were analysed using the 3D 13-landmark model described by Courtenay et al. (2019a; Table 2), studying the complete morphology of the cut mark. Landmarks provide information about the size and shape of the cut mark in the form of Cartesian coordinates, allowing for subsequent comparison. The model consists of both type II and III landmarks (LM) (*sensu* Bookstein 1991; Wärmländer et al. 2019). For this model, LM_1 and LM_2 mark the beginning and the end of the trace, while LM_3 captures the deepest

Table 1 Bones, fragments and cut marks. Digitization phase. x: Preserved and digitized mark; -: Missing or non-digitizable mark; *: Discarded due to impossibility of placing landmarks. CM2 and CM26 were discarded because their length made it impossible to completely digitize them

			PHASE 0	PHASE 1	PHASE 2
FEMUR 1	*1*	*CM1*	x	x	x
		CM2	-	-	-
		CM3	x	x	x
		CM4	x	x	x
	2	*CM5*	x	x	x
		CM6	x	x	x
		CM7	x	x	x
		CM8	x	-	-
	3	*CM9*	x	x	x
		CM10	x	x	x
		CM11	x	x	x
		CM12	x	x	x
FEMUR 2	*1*	*CM13*	x	x	x
		CM14	x	x	x
		CM15	x	x	x
		CM16	x	x	x
	2	*CM17*	x	x	x
		CM18	x	x	x
		CM19	x	x	x
		CM20	x	x	x
	3	*CM21*	x	x	x
		CM22	x	x	x
		CM23	x	x	x
		CM24	x	x	x
FEMUR 3	*1*	*CM25*	x	x	x
		CM26	-	-	-
		CM27	x	x	x*
		CM28	x	x	x
	2	*CM29*	x	x	x
		CM30	x	x	x
		CM31	x	x	x
		CM32	x	x	x
	3	*CM33*	x	x	x
		CM34	x	x	x
		CM35	x	x	x
		CM36	x	x	x

point at 50% of the cut mark's length. LM_4 and LM_5 then capture the left and right shoulders at 50% of the mark's length. The relationship between LM_3, LM_4 and LM_5 thus obtain the incision angle. The rest of the landmarks provide information about the trajectory of the cut, except for LM_{10} to LM_{13}, which provide information about the opening and closing angle of the beginning of each incision (Fig. 2).

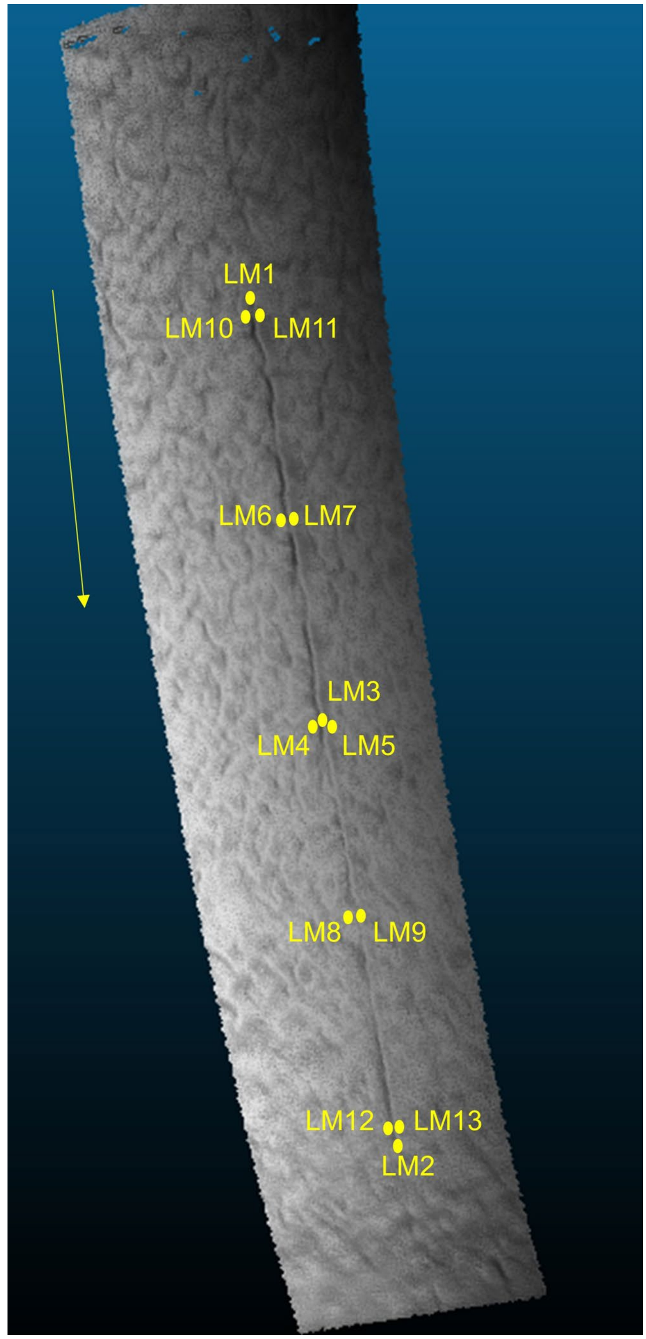

Fig. 2 Location of the 13 landmarks of the 3D model described by Courtenay et al. (2019a). The arrow shows the direction of the slice. Ex: F1_3_CM10 (Phase 0)

So as to leverage the relationship between LM_3 to LM_5 and thus complement other variables typically used for cut

Table 2 Shapiro-WIlks test for the different measures and phases of alteration. **Bold implies notable statistical differences**

	WIS		LDC		RDC		D		OA	
	Sh	*p*	Sh	*p*	Sh	*p*	Sh	*p*	Sh	*p*
PHASE 0	0.977	0.701	0.973	0.565	0.957	0.199	0.947	0.105	**0.709**	**6.684e-07**
PHASE 1	**0.866**	**8.1e-04**	0.918	0.016	**0.798**	**3.05e-05**	0.942	0.079	**0.594**	**2.304e-08**
PHASE 2	**0.885**	**0.002**	0.973	0.607	**0.840**	**2.5e-04**	0.959	0.254	**0.723**	**1.936e-06**

mark analysis (Bello and Soligo 2008; Maté-González et al. 2015), the Euclidean distance $d(p_1, p_2)$ between different landmark coordinates was then calculated, where p_i represents a landmark in 3D space. From this perspective we can use the following formula (Eqs. 1–3);

$$s_1 = d(LM_4, LM_5) = WIS \tag{1}$$

$$s_2 = d(LM_4, LM_3) = LDC \tag{2}$$

$$s_3 = d(LM_3, LM_5) = RDC \tag{3}$$

To calculate the Width of the Incision at Surface (WIS), as well as the length of the mark's walls labelled the Right and Left Depth Convergence (LDC and RDC). Based on these measurements, the Depth (D) of the incision can be derived in conjunction with heron's formula (Eqs. 4–5);

$$\rho = \frac{s_1 + s_2 + s_3}{2} \tag{4}$$

$$D = \frac{\sqrt[2]{\rho(\rho - s_2)(\rho - s_3)(\rho - s_1)}}{s_1} \tag{5}$$

$$\theta = \arccos\left(\frac{s_2^2 + s_3^2 + s_1^2}{2s_2s_3}\right) \tag{6}$$

Finally we can also calculate the Opening Angle (OA) in radians of the incision (Eq. 6);

Conversion of θ to degrees is simply performed through $\theta(180/\pi)$.

Considering the observations of Courtenay et al. (2021), the trigonometric properties of OA are unsuitable for multivariate statistical analyses when combined with linear (Euclidean) measurements (see supplementary file S1 of Courtenay et al. 2021). Because of this, for multivariate statistical purposes, the variable OA requires an additional transformation and projection into a linear feature space. This metric (OA_{lin}) can be calculated by $\cos(\theta)+\sin(\theta)$.

Considering the extremely high correlation between the variable WIS and other measurements of width proposed by Maté-González et al. (2015) along the depth of each incision (see file S1 of Courtenay et al. 2021; and similar observations by Boschin et al. 2021), it can be considered that, statistically, such a high correlation implies that a single measurement (WIS) would provide the same information as the three measurements together. From this perspective, the inclusion of three variables that describe the same patterns of variation can be considered redundant. For this reason, the present study has only included one measurement of width for the study of cut mark profiles (Fig. 3).

Metric analysis

Univariate and multivariate statistics were applied to the measurements obtained from the cut marks and landmarks. First, the Shapiro-Wilks test was used to assess the normality ($p > 0.003$) or non-normality ($p \leq 0.003$) of each variable. For circular data and their normality, the "*Robust Reflective Symmetry*" test (Pewsey 2002) was applied.

Depending on the homogeneity of samples, univariate tests were then performed on each variable separately to assess whether differences were present between samples. For this purpose, either Analysis of Variance (ANOVA) or Kruskal-Wallis tests were performed, for Gaussian and non-Gaussian distributions respectively. Distributions were also analyzed by applying descriptive statistics, using either traditional or robust metrics according to sample homogeneity (Höhle and Höhle 2009; Rodríguez-Martín et al. 2019; Courtenay et al. 2020b, 2021). Descriptive statistics included the calculation of extreme values (maximum and minimum), together with measures of central tendency and deviation. For samples that fit a Gaussian distribution, the mean and standard deviation were calculated. If samples were found to be heterogenous, then the median and normalized Median Absolute Deviation (MAD) were calculated instead.

From a multivariate perspective, a Principal Component Analysis (PCA) was used to visualize data distribution,

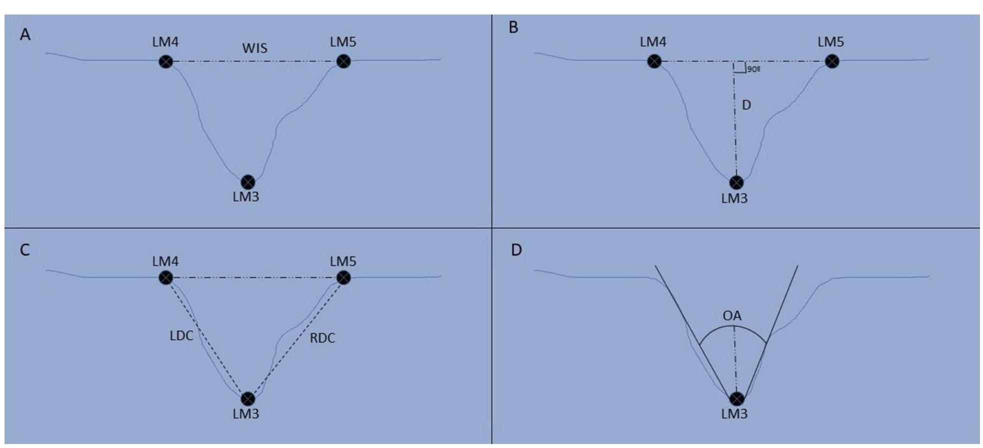

Fig. 3 Measurements extracted using LM3, LM4 and LM5 landmarks. **A**) Measurements of incision width at surface (WIS); **B**) Incision depth (**D**); **C**) Left (LDC) and right (RDC) depth of convergent incision; **D**) Opening angle (OA). Prepared from Courtenay et al. (2019c)

followed by a Multivariate analysis of Variance (MANOVA). For MANOVA, either the Hotelling-Lawley or Wilk's Lambda test statistic were used for homogeneous and heterogenous distributions respectively (Courtenay et al. 2020a).

Geometric morphometrics

For GMM, landmarks were analysed by first standardizing coordinate values to remove the effects orientation, position and size have on data. This was performed by means of a full Generalised Procrustes Fit (Rohlf 1999; Slice 2001). After this, a PCA was applied to observe variations in shape, calculating Thin-Plate Splines in order to appreciate morphological differences along each PCScore (Bookstein 1989, 1991). PCAs were then carefully inspected to assess which PC scores captured information directly related with possible alterations as a product of chemical activity, as opposed to morphological variance attributable to the natural variability of cut marks. Once the PC scores of relevance had been identified, they were either analysed multivariately or univariately, depending on the number of PC scores identified to be of importance. Procrustes Distance tests were then applied to observe statistical notable differences of the data.

Hypothesis testing

Following the recommendations of Benjamin and Berger (2019) and Colquhoun (2019), $p<0.05$ was not used as a threshold to determine whether a hypothesis test is significant or not. In addition, we have avoided the use of the terms "statistically significant" (*sensu* Benjamin and Berger 2019). Instead, the third standard deviation from the mean ($p\leq 0.003$) was used for the purpose of hypothesis testing, considering it to have a remarkably lower probability of producing Type I statistical errors (Courtenay et al. 2021a).

Results

The results presented for both metric analysis and Geometric Morphometrics have been carried out on an experimental sample of 99 cut marks: 34 corresponding to Phase 0, 33 to Phase 1 and 32 to Phase 2. Metric data are available in Supplementary File 1 and Landmarks coordinates are available in Supplemetary File 2. Figure 4 shows the state of two cut marks before and after the experimental process.

Metric analysis

Shapiro Wilks results revealed a mixture of both homogeneous and heterogenous distributions among the measurements included in this study (Table 2). WIS and RDC presented a normal or Gaussian distribution in Phase 0 ($p>0.003$), although after the different phases of alteration they showed a non-Gaussian distribution ($p<0.003$). LDC and D, on the other hand, followed a normal distribution during the different phases of experimentation. Linear OA presented an opposite trend to D and LDC, following a non-Gaussian distribution ($p<0.003$) in the different phases of alteration.

Table 3 gathers and summarizes the basic descriptive statistics (maximum, minimum, central value and deviation) of the different measurements in the different phases of the experiment.

Application of the Kruskal-Wallis test showed the existence of notable differences in the measures of RDC ($t=14.249$; $p=0.001$), although not in the case of WIS ($t=10.046$; $p=0.006$) and OA ($t=7.075$; $p=0.029$). The application of the ANOVA test showed the absence of significant differences between measures LDC ($t=2.124$; $p=0.125$) and D ($t=1.935$; $p=0.150$) (Table 4).

The application of the MANOVA tests were unable to detect differences between the different experimental phases (Table 5). The MANOVA value resulting from the comparison between Phase 0 and Phase 1 is far from important differences ($p=0.581$). The value is closer to notable differences, although lacking it, when comparing Phase 1 and Phase 2 ($p=0.016$) and Phase 0 and Phase 2 ($p=0.008$).

The data extracted from the metric analysis were plotted in a Principal Component Analysis (PCA) (Fig. 5). PC1 explains 58.4% of the variance and PC2 represents the 34% of the total (92.4%). Linear OA and Depth, which can be observed in the positive extreme of PC1, decrease once the alteration starts. The same is notable with the other metric data, located in the positive extreme of PC2. The altered marks follow a tendency towards the negative extremes of both axis, showing a clear trend of metrically shallower and narrower cut marks.

Geometric morphometrics

The Procrustes Distance test did not detect notable differences between Phase 0 and Phase 1 ($p=0.073$), between Phase 1 and Phase 2 ($p=0.052$) nor between Phase 0 and Phase 2 ($p=0.039$) (Table 6).

PCA results (Fig. 6), represented by a total of 39 PC Scores, in contrast with metric variables, do present a general tendency for altered marks to occupy a more reduced portion of feature space towards the negative portions of PC2. The first two dimensions of this PCA explain 84.56% of the variance, while the first 16 PC scores are needed to have a cumulative portion of 99%. Even though a slight difference can be noted in cut mark depth in PC1 (76.49%) (shallower marks on the negative axis and deeper marks on

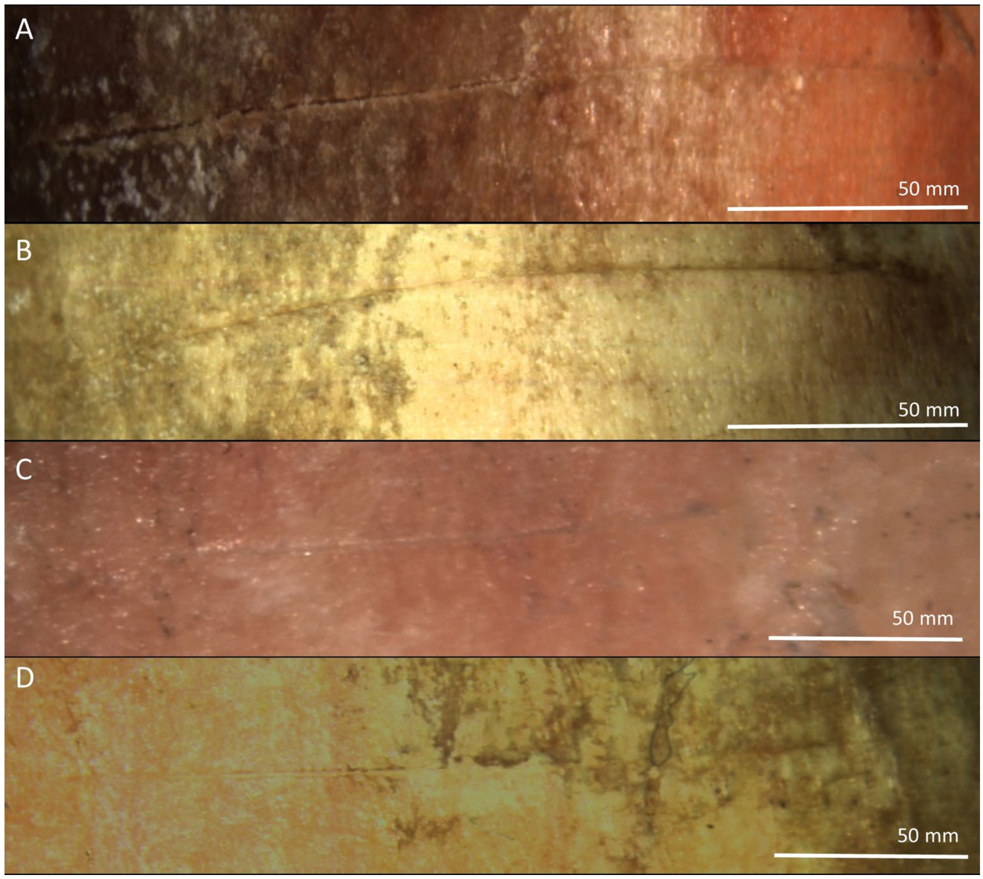

Fig. 4 Two cut marks before alteration and after the experimental process. **A**) F2_1_CM_15 before alteration; **B**) F2_1_CM_15 after the experimentation had ended; **C**) F3_1_CM_25 before alteration; **D**) F3_1_CM_25 after the experimentation had ended. Photographs taken with 3D scanner "DAVID SLS-3 Structured-Light Surface"

Table 3 Descriptive statistics for each measure and each phase. **Bold implies notable statistical differences**. Mean and standard deviation were calculated for Gaussian distributed data, while median and MAD (Median Absolute Deviation) were calculated for non-Gaussian distributed data

		PHASE 0	PHASE 1	PHASE 2
WIS	*Max.*	0.681	**0.891**	**0.559**
	Central.	0.382	**0.340**	**0.275**
	Dev.	0.130	**0.087**	**0.050**
	Min	0.112	**0.159**	**0.172**
LDC	*Max.*	0.361	0.332	0.274
	Central.	0.199	0.180	0.167
	Dev.	0.068	0.072	0.050
	Min	0.054	0.060	0.082
RDC	*Max.*	0.392	**0.568**	**0.317**
	Central.	0.206	**0.182**	**0.138**
	Dev.	0.077	**0.070**	**0.041**
	Min	0.063	**0.083**	**0.089**
D	*Max.*	0.159	0.115	0.107
	Central.	0.058	0.044	0.051
	Dev.	0.032	0.026	0.024
	Min	0.007	0.007	0.014
OA	*Max.*	**175.302**	**173.013**	**164.570**
	Central.	**146.252**	**154.316**	**134.6**
	Dev.	**17.812**	**14.839**	**25.583**
	Min	**10.168**	**13.545**	**12.280**

Table 4 Kruskal-Wallis test and ANOVA. **Bold implies notable statistical differences**

	KRUSKAL-WALLIS	ANOVA	*p*
WIS	10.046	-	0.006
LDC	-	2.124	0.125
RDC	**14.249**	**-**	**0.001**
D	-	1.935	0.150
OA	10.582	-	0.005

Table 5 MANOVA test used to observe differences between phases of alteration from the metric perspective. **Bold implies notable statistical differences**

	PHASE 0	PHASE 1	PHASE 2
PHASE 0	-	0.581	0.008
PHASE 1	0.581	-	0.016
PHASE 2	0.008	0.016	-

the positive one), the main influencing factor in PC1 is the curvature of the cut mark. This PC Score shows a curved trend at the positive end and straight at the negative end. This curvature is not a variable to be taken into account in our experiment, as this variable is conditioned by the microtopography and general curvature of the bone, not by the influence of chemical agents. PC2 (8.07%), on the other hand, does represent changes in the width and depth of the

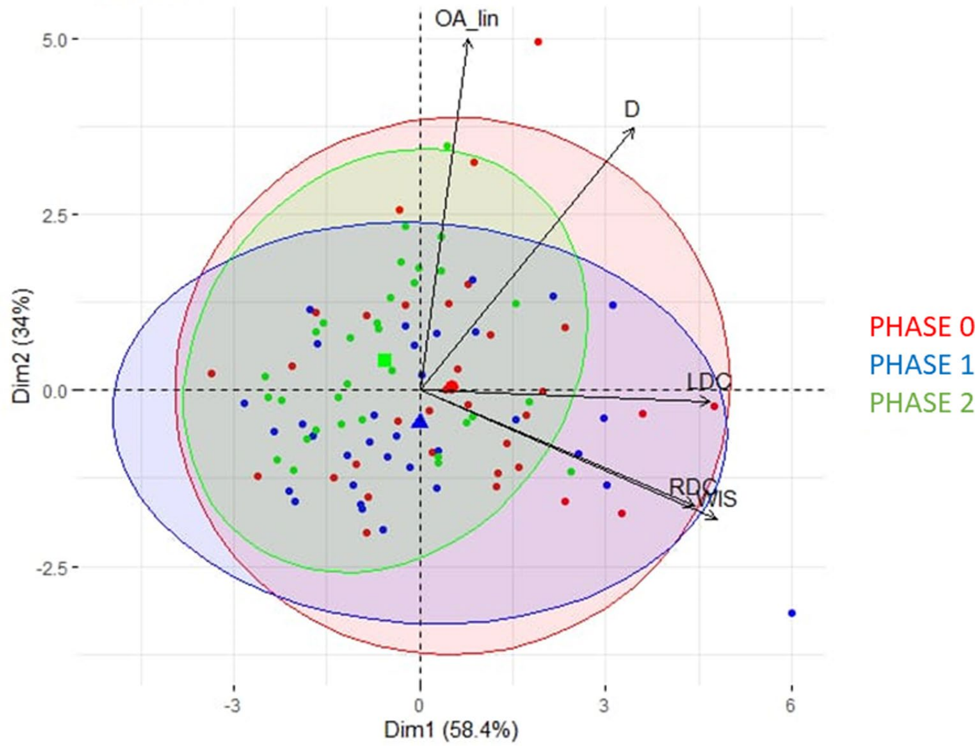

Fig. 5 PCA on the distribution of the different phases using metric analysis

Table 6 Procrustes Distance applied to compare differences between alteration phases. **Bold implies notable statistical differences**

	PHASE 0	PHASE 1	PHASE 2
PHASE 0	-	0.073	0.039
PHASE 1	0.073	-	0.052
PHASE 2	0.039	0.052	-

mark, with thin marks at the negative end and wider marks at the positive end. Unaltered marks tend to be distributed on the positive axis of PC2, where wider and deeper marks are located. The altered marks are mostly distributed on the negative axis of PC2 (Fig. 7), described by shallower and narrower morphological traits. A clear differentiation can be seen between the striae altered for a prolonged period and those that have not suffered any alteration, although there is overlap between two phases. It is interesting to note, however, that the general distribution of marks reduces considerably as the different degrees of alteration increase.

As for other PC Scores, PC3 and PC4 are described by the natural variability of mark morphology, seen in curved trajectories, but without changes that are due to chemical alterations (see Supplementary Fig. 1). After PC4, the amount of represented information decreases considerably (<2%).

Considering these observations, and therefore concentrating our analysis on the PC Scores directly representing relevant patterns of morphological tendencies related with chemical alterations, PC2 can be considered to have a highly heterogenous distribution ($w = 0.88$, $p = 2.96e\text{-}07$). Kruskal-Wallis tests therefore observe the presence of notable

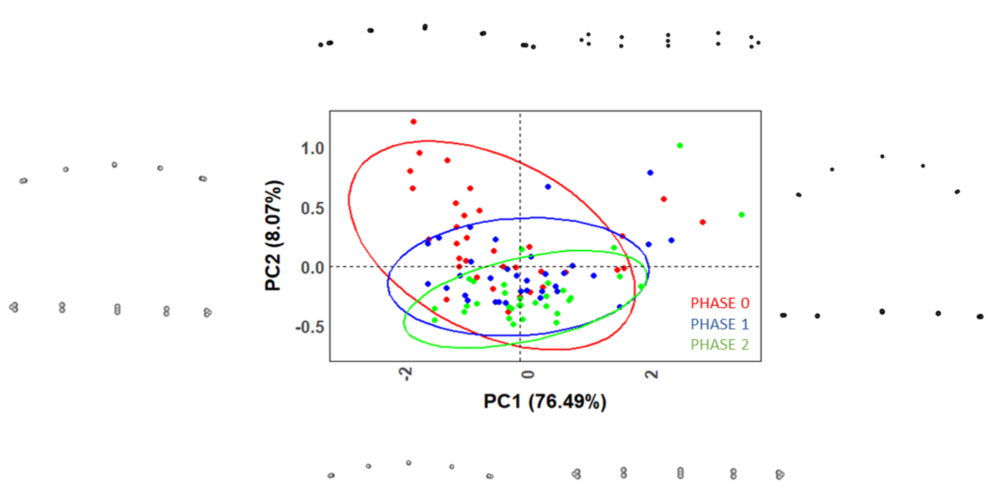

Fig. 6 PCA on the distribution of the different Phases using Geometric Morphometrics. For PC1, lateral view (top) and zenith view (bottom) are shown. For PC2, lateral view (left) and zenith view (right) are shown

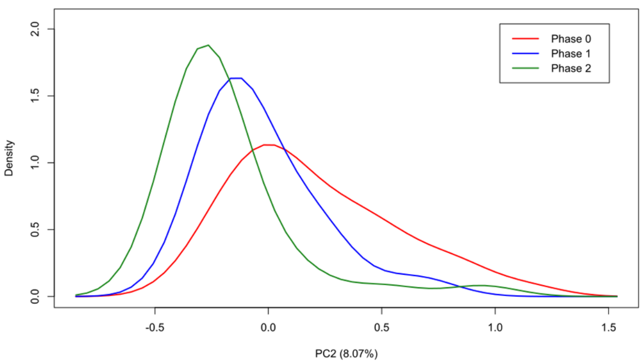

Fig. 7 PC2 feature space

statistical differences between the different phases of alteration ($\chi^2 = 31.2$, $p = 1.69e\text{-}07$). Nevertheless, it is important to note that this dimension only represents a total of 8.07% of the observed morphological variance, and thus describes a very small amount of change due to chemical alterations.

Discussion

In the present study, 36 cut marks were produced on three cow shafts and subjected to chemical alteration in a 5% solution of hydrochloric acid for a total of 10 s in two phases of five seconds each. All cut marks, before and after chemical alteration, were digitized and studied by means of metric and Geometric Morphometrics analysis. The results of the Geometric Morphometrics analysis showed statistically notable differences between the different phases of alteration, with a separate distribution of the cut marks in the PCA due to changes in width and, to a lesser extent, depth. From this perspective, it can be seen how chemical alterations modify the morphology of cut marks, leading towards the apparition of shallower and narrower cut marks.

Chemical alteration involves corrosion of bone tissue and changes in morphology due to variations in bone composition. A first descriptive experimental approach to this problem was developed by Pineda et al. (2014), who analyzed by means of a binocular microscope the evolution of 71 chemically altered cut marks in two phases of 10 s each, relying on the criteria previously established by Domínguez-Rodrigo et al. (2009). The experiment conducted by Pizarro-Monzo et al. (2022), analyzed the evolution of 100 cut marks altered by both alkaline and acidic sediments over 14 weeks under controlled conditions using DL. The researchers observed and photographed the evolution of each mark every two weeks using a binocular microscope. The differentiation between altered and unaltered cut marks was clear and accurate; it was also possible but less precise to classify cut marks altered in acid and alkaline contexts. Finally, Pizarro-Monzo and colleagues (2022) showed that differentiation when analyzing the different phases of alteration was moderately high in the evolution of cut marks subjected to acidity but remarkably low in the alkaline context.

Both qualitative and quantitative studies succeeded in differentiating between chemically altered and unaltered cut marks, but in both cases there were limitations in distinguishing between phases of chemical alteration (Pineda et al. 2014; Pizarro-Monzo et al. 2022). However, the DL approach succeeded in classifying chemically altered cut marks in up to 50% of the cases (Pizarro-Monzo et al. 2022), which is an improvement compared to qualitative studies.

Similarly to DL methods, GMM allow to carry out a quantitative approach to study the morphology and shapes of different striae and alterations, thus going beyond measurements and qualitative observations of morphological differences (Courtenay et al. 2019a). This is why an experiment based on the premises described in Pineda et al. (2014) was conducted to observe the impact of chemical alteration from a deeply quantitative perspective.

Gümrükçü and Pante (2018) and Pineda et al. (2019; 2023) distinguish clearly and with great precision the altered marks from those not mechanically altered. From a qualitative perspective, the marks maintain at least one diagnostic characteristic that allows their differentiation from other striae (Gümrükçü and Pante 2018; Pineda et al. 2019). Quantitatively, they observe a tendency towards a greater width and smaller depth, and achieve a complete differentiation with respect to the unaltered marks (Gümrükçü and Pante 2018; Pineda et al. 2023).

This paper represents the first attempt to characterize the evolution of chemically altered cut marks from GMM. As described by Pineda et al. (2014) and Pizarro-Monzo et al. (2022), altered and non-altered cut marks could be easily differentiated, possibly as a result of the loss of diagnostic characteristics.

Differences between phases of alteration were visible when applying DL as well as when analyzing the Geometric Morphometrics' PCA. Geometric Morphometrics make it possible to observe important differences related to morphological changes around chemically altered cut marks. PC1 showed a little change around depth, but it was not the main explanatory factor of that dimension. PC2 was linked with the alteration process, showing changes around width and depth, although it explains only 8.07% of the variability. Even though the variance explained is so little, this makes it possible to go further than the PCA of the metric analysis in this work, showing morphological differences and being supported by the metric data. Geometric Morphometrics also evoke important differences between phases of alteration.

It is important to highlight the main difference between mechanical and chemical alteration, the former

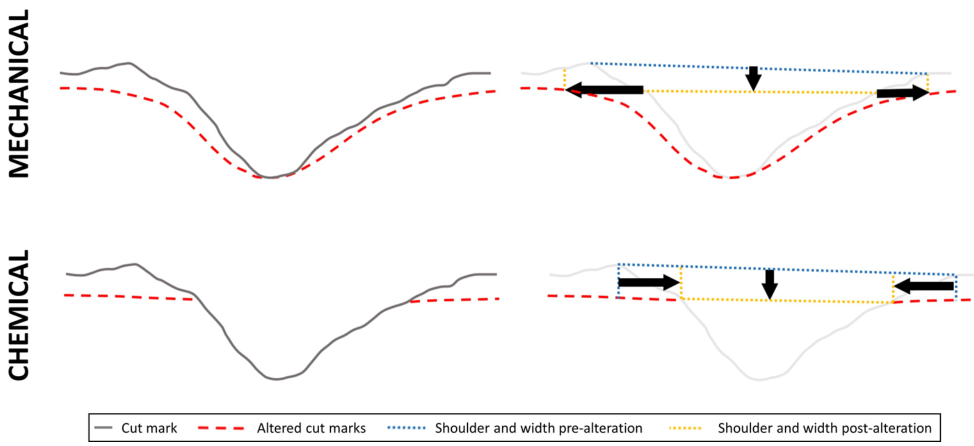

Fig. 8 Bone surface and cut mark alteration by fluvial and chemical processes

characterized by a trend towards an increased width of the incision (Gümrükçü and Pante 2018; Pineda et al. 2023) and the latter characterized by shallower and narrower marks, as demonstrated in this study. A plausible explanation would be that fluvial alteration of the bone leads to rounding of both the cortical bone and the cut mark, thus widening the incision, as the shoulders of the cut mark separate. On the other hand, chemical alteration alters the cortical bone, causing the shoulders of the cut mark to decrease in height and being closer, resulting in shallower and narrower cut marks (Fig. 8).

A comparative perspective using Geometrics Morphometrics to compare trampling marks and chemically altered cut marks would be an interesting future research avenue, as it is known that trampling marks metrically differ from cut marks, from a quantitative perspective (Courtenay et al. 2020c), as trampling marks are much more superficial than cut marks (Domínguez-Rodrígo et al. 2009; Courtenay et al. 2019a, 2020a, c; Pizarro-Monzo and Domínguez-Rodrigo 2020). Although the differentiation between trampling striae and altered cut marks is beyond the main objective of this work, it is important to note that the results obtained in this study offer a chance for further research on trampling morphology and evolution.

The purpose of this study was to observe and control the evolutionary process of chemically altered cut marks. At this point it is important to take into account Levins' (1968) proposals for the realization of scientific models. These models must contain realism, precision and generality to be valid; however, these are mutually exclusive concepts, so each experiment must sacrifice one of the three concepts (Levins 1968: 7). Experimental works, when performed for the realization of direct analogies with the archaeological record and following what was explained by Capaldo (1998), sacrifice generality for the impossibility of simulating all possible scenarios of archaeological context formation (see Téllez et al. 2022: 119). However, the aim of this work is not to make direct analogies with the archaeological record, but rather to gain in-depth knowledge about the evolution of experimental cut marks after being chemically altered. In this sense, realism has been sacrificed in this experiment with the aim of reducing the number of variables to control. The use of a metal knife for the recreation of cutting marks limits the comparison of morphometric analysis data with cutting marks from the archaeological record, but has reduced the variable of morphological change that involves the use of a lithic tool (Courtenay et al. 2019a), obtaining more homogeneous and clearer marks that have allowed to extract generalities of the results. Once the process of alteration and evolution is under control, it will be possible to carry out experiments that represent conditions of greater realism, allowing the direct comparison of possible cut marks from archaeological sites with studied and digitized chemically altered cut marks.

Altered cutting marks are a limitation that is present in many taphonomic investigations. This problem must continue to be addressed from a modern quantitative methodology that allows to understand and control the process of transformation of altered cut marks and specifically under contexts of chemical alteration, with regard to what the results of this work open a new way to develop.

Conclusions

This experimental work contributes to the study of chemically altered cut marks, using Geometric Morphometrics (GMM). The marks were altered in two phases with a 5% hydrochloric acid solution, and were studied before and after each phase metrically and applying Geometric Morphometrics. Comparison of the results of the different phases shows a clear tendency for the marks to decrease in width and depth throughout the experimental process, as opposed to mechanical alteration of bones, which results in wider cut marks. Chemical abrasion entails the loss of diagnostic features, so that chemically altered bones represent a limitation in taphonomic studies due to the possible mistake in the interpretation of the origin of the striae. This work advances in this way in order to be able to work with chemically altered marks in the future, and frames the need to develop experiments, both qualitative and quantitative, that allow studies on the subject to be carried out objectively. Despite the limitations of conducting an experiment in which the realism has been sacrificed, this work has served to evaluate the morphological evolution of cut marks under chemical alteration. Future similar experiments under realistic conditions may complement these results with an approach for proper application to the archaeological record.

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Author contributions D.R.F. experimental development, scanning analysis, data curation, formal analysis, writing the original draft and writing the reviews and editing. L.A.C. software development, data curation, methodological development, validation and revision of the original draft. D.H.R scanning analysis and revision of the original draft.J.Y. conceptualization and revision of the original draft. A.P. conceptualization, experimental development, data curation, writing the original draft and writing the reviews.

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Declarations

Competing interests The authors declare no competing interests.

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