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Application of geometric morphometrics to the analysis of cut mark morphology on different bones of differently sized animals. Does size really matter?

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ABSTRACT

Recent techniques applied to taphonomy have made advances in our understanding of bone surface modifications. For many years, differences in bone density according to element and variations in animal size have been considered conditioning factors for many taphonomic processes. While several studies highlight how animal size and density affect fracture patterns and bone preservation rates, variations in cut mark morphology are yet to be confronted against these variables. Here, we assess the effect of these variables and their potential effect on cut mark morphology by comparing a considerable amount of cut marks on different anatomical elements of both suids and bovids. Experimentally produced cut mark samples were then digitally reconstructed using a David Laser scanner that allowed the statistical analysis of each cut mark's shape and form. Geometric morphometric analysis using 2D and 3D landmark models were unable to find substantial differences in cut mark morphologies caused by either element type of carcass size.

1. Introduction

Cut mark analysis has become a key subject in archaeological taphonomic studies, since cut marks are one of the main anthropogenic traces identified in faunal accumulations since the beginning of zooarchaeological and taphonomic analyses (Boucher de Perthes, 1849; Lartet, 1860; Lartet and Christy, 1865–1875; Martín, 1907; Weigelt, 1927). Half a century after the discovery of cut marks and their relevance for the study of early archaeological sites, taphonomists have embraced these microscopic traces and placed a special emphasis on their study. Neotaphonomic research into cut marks and other bone surface modifications (BSMs) has enabled deciphering different features of butchery activities (e.g., Binford, 1981; Shipman and Rose, 1983; Shipman et al., 1984; Domínguez-Rodrigo and Yravedra, 2008; Pickering and Hensley-Marschand, 2008; Egeland et al., 2014), or discriminating between different agents and the order of their intervention in the accumulation based on cut mark distribution and frequencies (Domínguez-Rodrigo, 1997, 2015; Lupo and O'Connell, 2002). Cut mark frequencies have also been studied exposing systematic meat exploitation patterns (Abe et al., 2002; Domínguez-Rodrigo and Yravedra, 2009; López-Cisneros et al., 2018). Such studies have been fundamental in understanding the hunting activities of ancient hominin populations (Domínguez-Rodrigo and Piqueras, 2003; Domínguez-Rodrigo and Barba, 2006, 2007; Blumenschine et al., 2007; Domínguez-Rodrigo et al., 2007). Nevertheless, while the hunting debate has been a major subject in taphonomic research throughout decades, BSM analysis has expanded beyond it and has a much wider application in modern day studies of archaeological sites.

Certain studies have considered the differences between cut marks produced by different raw materials, such as flint, basalt, quartz, quartzite and metal (Walker and Long, 1977; Shipman and Rose, 1983; Olsen and Shipman, 1988; Greenfield, 1999; Bello et al., 2009, Bello, 2011; Courtenay et al., 2017; Yravedra et al., 2017a,b; Moclán et al., 2018), while also paying particular attention to the type of tool used (Bello et al., 2009; Domínguez-Rodrigo et al., 2009; Juana et al., 2010; Moretti et al., 2015; Courtenay et al., 2017; Yravedra et al., 2017a).

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Alternative raw materials like bamboo and shell have also been investigated as tools used in butchery activities (West and Louys, 2007; Bonney, 2014; Weston et al., 2015).

Recently, morphological analysis of cut marks has expanded our way of analysing BSMs. Since the initial reflections of Walker and Long (1977), few studies have come to assess cut mark morphology, however very recent technologies have provided new insights into BSMs morphological characteristics. The pioneering work of Bello (Bello and Soligo, 2008; Bello et al., 2009; Bello, 2011), inspired the application of geometric morphometric (GMM) techniques in cut mark analysis (Maté-González et al., 2015, 2016, 2017a; Yravedra et al., 2017a; b, 2019). The applications have even been expanded to other BSMs such as carnivore tooth marks (Arriaza et al., 2017, 2018; Aramendi et al., 2017; Yravedra et al., 2017c). Developments in 3D technology, through the comparative use of microphotogrammetry (Maté-González et al., 2015, 2016, 2019), 3D digital microscopy (Maté-González et al., 2017a, b, c; Courtenay et al., 2018b), confocal microscopy (Maté-González et al., 2017b, c; Pante et al., 2017; Gümrükçu and Pante, 2018; Orlikoff et al., 2017), and structured light laser scanning have been a powerful tool in this particular field of cut mark investigation (Courtenay et al., 2017, 2018a; Maté-González et al., 2017c, 2019).

Additionally, a great number of conditioning variables in cut mark morphology are still to be explored, including biostratinomic and diagenetic taphonomic processes that may produce equifinality (Pineda et al., 2014, Under Review; Gümrükçu and Pante, 2018), sharpness of the tool cutting edge (Braun et al., 2008), and the effects of bone density and cortical hardness on the incision shape.

Differences in bone density have been studied in great detail (Kreutzer, 1992; Lam et al., 1998, 1999, 2003), especially regarding quantitative zooarchaeological studies of skeletal part representation (Marean and Frey, 1997; Stiner, 2002; Pickering et al., 2003; Faith et al., 2007). These particular variables have inspired research regarding bone fracturing and fragmentation, identifying variables that can be used to discern different carnivore (Capaldo and Blumenschine, 1994; Blumenschine, 1995; Marean et al., 2004), and hominin agencies (Pickering et al., 2005; Pickering and Egeland, 2006; Galán et al., 2009; Juana and Domínguez-Rodrigo, 2011; Blasco et al., 2014; Moclán and Domínguez-Rodrigo, 2018). Breakage patterns have also been investigated in relation to prey size and bone density (Juana and Domínguez-Rodrigo, 2011), but only very recent studies have considered the effects of carcass size and density on cut mark features (Moclán et al., 2018), as well as their morphology (Merritt, 2012, 2016; Braun et al., 2016; Pante et al., 2017). Thus more evidence is needed to evaluate the importance of such a variables.

In this paper we use GMM methods to statistically analyse the variability in cut mark morphology, studying both the location of cut marks on different anatomical elements as well as the influence of carcass size. Through the use of tests regarding effect size, this study demonstrates how bone density and cortical hardness are not a significant conditioning factor in cut mark morphology.

2. Methods and samples

For the purpose of this study a total of 473 cut marks were produced and analysed. Such a large sample size was produced considering the statistical power required to truly evaluate cut mark variability (Chartier and Allarie, 2007; Faul et al., 2007; Reinhart, 2015; Courtenay et al., 2018a). Cut marks were produced on different anatomical parts of two different taxa using a metal knife; one prime adult bovid and one prime adult suid were selected for the study (Fig. 1). All cut marks were performed while bones were still fresh and had meat intact. Cut marks were produced on long bone diaphyses (n = 118, bovid = 58, suid = 60), epiphyses (n = 120, bovid = 60, suid = 60), ribs (n = 118, bovid = 58, suid = 60) and scapulae (n = 117, bovid = 57, suid = 60).

During the process, the cutting edge was controlled so that no blunting occurred. All marks were performed by a single right handed individual and with a single motion along the length of the bone, maintaining the same cutting angle as well as consistency in force. Bones were then cleaned with boiling water and a small solution of natural detergent before being digitalized and studied.

Fig. 1. Example of bones used in the experiments, including appendicular and axial elements of both suid and bovids.

3. Digitalization of marks and collection of landmark data

Cut marks were digitalized with a DAVID structured-light scanner SLS-2, located at TIDOP, University of Salamanca (Spain). This laser consists of a DAVID USB CMOS Monochrome camera, an ACER K132 projector, and a calibration marker board (Fig. 2). Calibration of this equipment was carried out as explained in Courtenay et al. (2017) and Maté-González et al. (2017b). The process of scanning each bone cortical surface and producing a 3D model lasts less than 1 min. The SLS-2 can produce up to a density of 1.2 million points. Final 3D models correspond to meshes coming from a triangulation algorithm based on Delaunay strategy. This data is then imported into Avizo (Visualisation Sciences Group, USA) software for visualisation of the model or can be treated with the Glopal Mapper software.

After obtaining the virtual models, cut marks were analysed in two different ways. First, cut mark cross-section profiles were obtained at mid-length (always between 30 and 70% of the mark's total length) using the Global Mapper software. These profiles were then imported into tpsDig2 (v.2.1.7) were seven 2D measurements were taken following Bello and Soligo's (2008) description. Using this same software, the 2D 7-landmark model proposed by Maté-González et al. (2015) was used to assess differences in morphology. Along with the 2D analysis of cut mark profiles, cut mark 3D models were studied in their entirety using the 3D 13-landmark configuration proposed by Courtenay et al. (2017). Landmarking was performed in Avizo (Visualisation Sciences Group, USA), only when their location was unambiguous.

Landmark data was then formatted and imported into the free software R for further statistical analysis (www.rproject.org, Core-Team, 2014). Considering the format of the landmark files

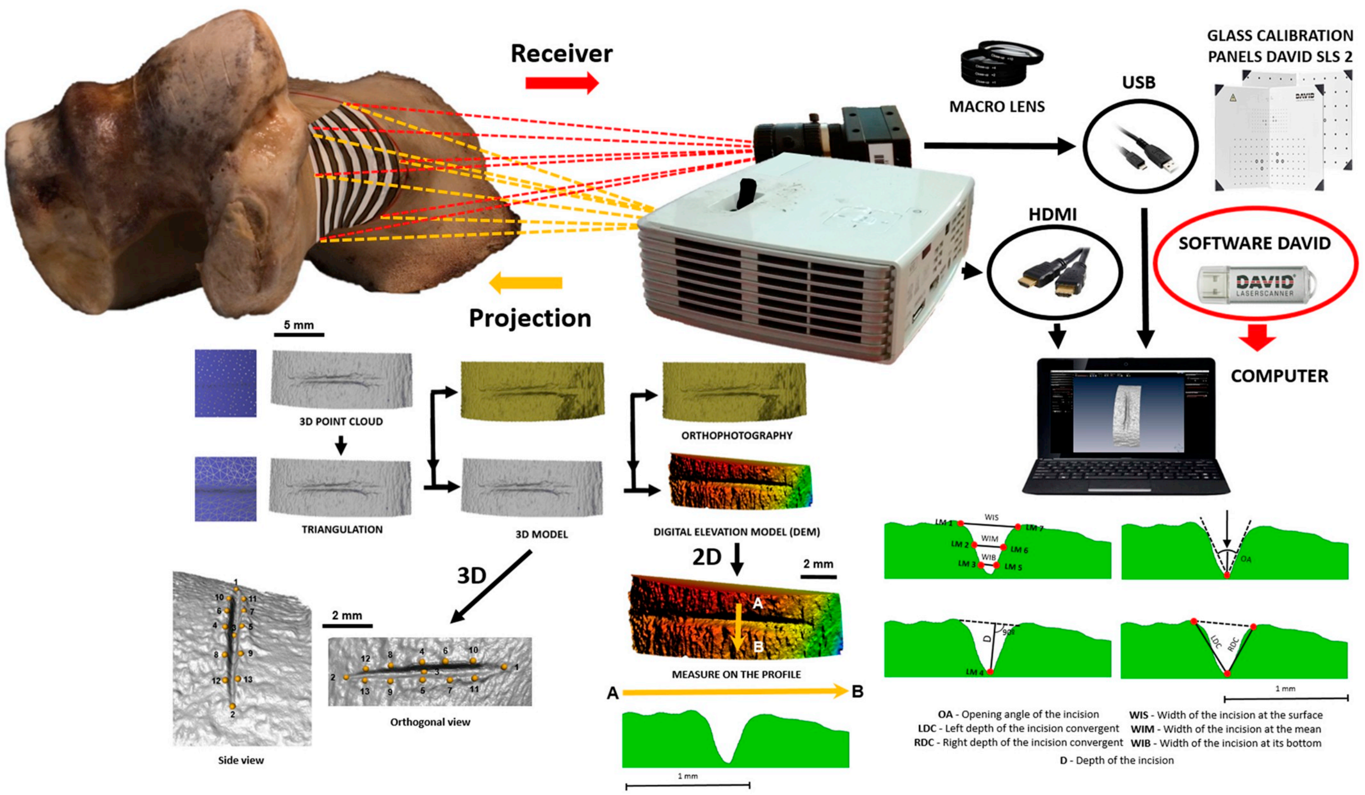

Fig. 2. The Davis SLS-2 Structured Light 3D Scanner: The equipment and protocol used for digital reconstruction of experimental cut marks.

(.landmarkAscii for 3D files and .tps for 2D files), as well as the final Morphologica file (.txt), a file processor was created to speed up the formatting process. This system required the simple inputting of the number of landmarks per file and their location on the computer while the Windows Executable .exe application produced an output file that could be instantaneously imported into the R environment without further need for modification.

4. Statistics

Statistical analyses were carried out in the free software R (www.rproject.org, Core-Team, 2014).

Comparisons of cut mark profiles were first performed measuring differences in thickness, depth and opening angles, following the methodological approach proposed by Bello and Soligo (2008). Biometric data was later imported into R, where the 7 variables were first subjected to Principal Components Analysis (PCA) to assess differences in variation among data while defining the weight of variables in the samples. For that purpose, the FactoMineR library (Lê et al., 2008) was used. Considering previous observations (Maté-González et al., 2017b; Courtenay et al., 2018a) on the weight of the variables suggested by Bello and Soligo (2008), tests were performed both including and excluding the opening angle of the incision (OA). Measurements were then tested for normality according to the Shapiro-Wilk normality test before being subjected to a jack-knifed Linear Discriminant Analysis (LDA) with the use of a confusion matrix to discrimination between samples. For this, the MASS R package (Venables and Ripley, 2002) was used.

Assessment of the magnitude of differences and significance of overlapping in samples was assessed according to Cohen's d, using the "two one-sided" equivalence test (TOST) from the TOSTER library (Cohen, 1988; Lakens, 2017). This means that differences between samples were independently documented for higher and lower orders of effect magnitude. This statistical procedure originates from pharmacological studies, frequently used to assess similarities between the efficiency of old and new pharmaceutical products (Hauk and Anderson, 1984). Through TOST equivalence testing, upper and lower equivalence bounds are calculated based on the effect size of interest (Schurimann, 1987), producing a *p* value that indicates the presence or lack thereof considerable differences between samples. If $p > 0.05$, conclusions can be drawn to argue an important difference between variables. The use of TOST equivalence testing provides a means of ensuring that "meaningful effects" are absent (Dienes, 2016), concluding with more precise hypotheses the nature of conditioning variables in scientific experimentation (Gigerenzer, 1998; Anderson and Maxwell, 2016; Lakens, 2017).

Next, GMM analysis of cut mark profiles using the 2D 7-landmark model and 3D cut mark virtual models was carried out separately using the geomorph package (Adams et al., 2017). Firstly, an orthogonal tangent projection and full Procrustes fit was used to normalise data in preparation for complex statistical analysis (Dryden and Mardia, 1998). This technique, commonly referred to as Generalized Procrustes Analysis (GPA) is used to standardize the form information through the use of superimposition procedures including translation, rotation and scaling. Morphological differences are thus exposed through patterns of variation and covariation that can be assessed statistically (Rohlf, 1999; Slice, 2001). PCA in shape space and form space on the Procrustes superimposed landmarks were then carried out. Changes in both shape and form were further visualized with the aid of transformation grids (Bookstein, 1989). PC scores were then extracted and used for further statistical analysis by jack-knifed LDA testing. Finally, degrees of equivalence were assessed using the TOST equivalence test according to Cohen's d.

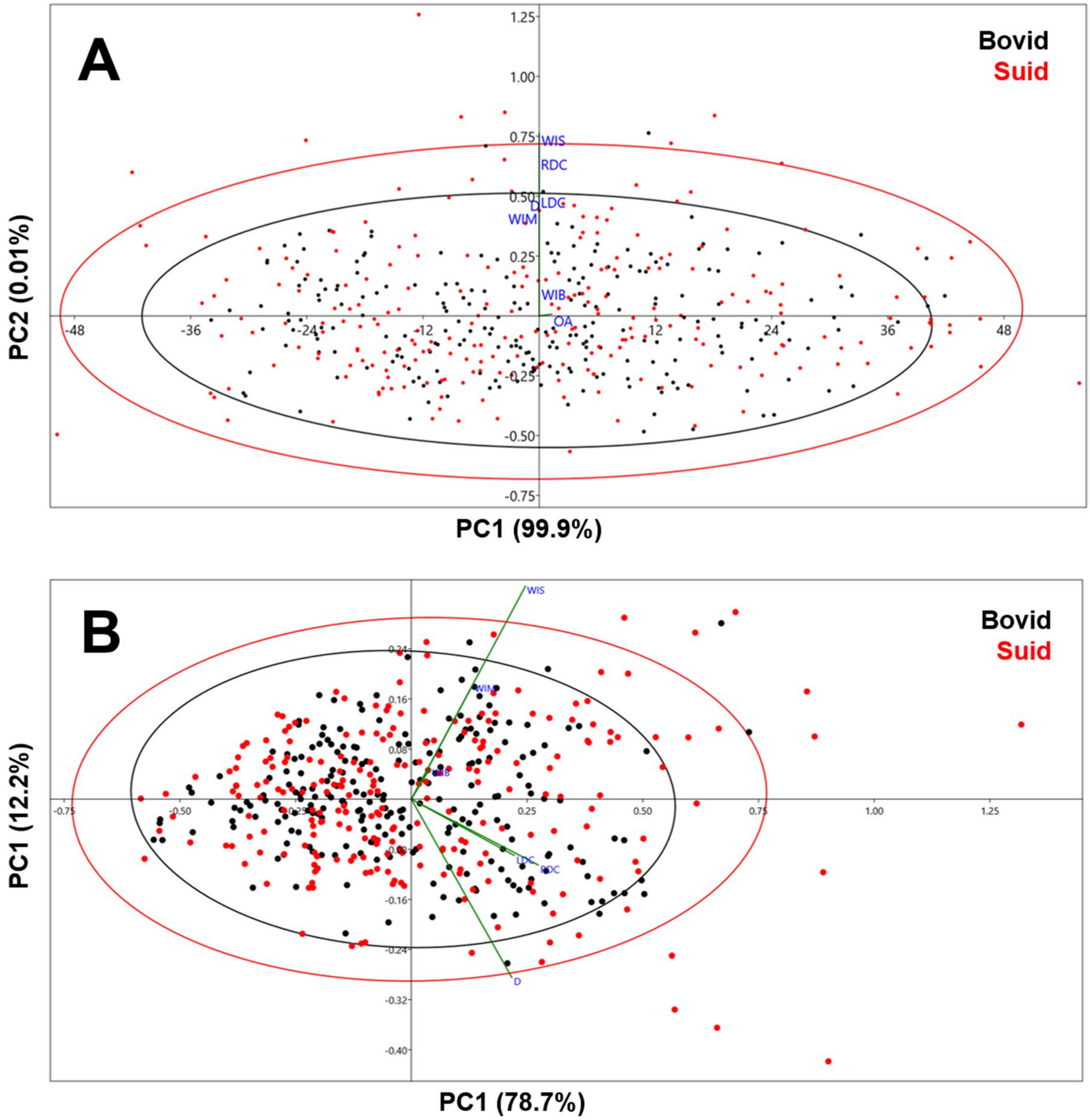

Fig. 3. PCA plots presenting variance in cut mark dimensions found on bones of different taxa (A) including and (B) excluding the variable OA.

5. Results

5.1. 2D analysis

Biometric PCA including (Fig. 3a) as well as excluding (Fig. 3b) the variable Opening Angle (OA) result in scattering plots where cut marks on both bovid and suid bones completely overlap. This can also be extended to comparisons of different anatomical elements (Fig. 4), yet to a lesser degree. Both taxa and skeletal elements are represented by as few as 7 and 6 PC scores, when including and excluding OA respectively. Results when considering the effect size according to Cohen's d (Table 1) underline a significant overlapping degree and thus conclude that morphological differences are insignificant. LDA results (Table S1) are unable to correctly classify more than 46–54% of cut marks in all cases (see Table 2).

2D GMM data are expressed by PCA graphs with highly overlapping samples in both shape space (Fig. 5), represented by 10 PC scores, and form space (Fig. 6), across 13 PC scores. Variability is minimal and is due to the stochastic process of tool-bone contact angle and depth. Both studies display a practically identical distribution of samples when comparing taxa; however, in form space, slight differences indicate a trend in grouping long bones and flat bones (Fig. 4). Nevertheless, the overlapping of samples in all cases can be considered significant. Exploring variations in morphology across PC scores present an equal mixture of deep as well as superficial marks across PC1 in both cut marks on suids and on bovids, with no real difference regarding the anatomical element. Changes in form indicate a slight increase in cut mark depth according to anatomical element across PC2. Nevertheless, the percentage of variation represented by PC2, alongside the significant overlapping of samples, suggest that such difference is minimal and as expected as a result of different strength applied to mark creation due to bone hardness.

Results when considering effect size suggest a lack of effect in the majority of tests (Tables 3 and 4). According to our results, GMM studies of cut mark cross sections are more susceptible to change when including form, while shape is only affected when comparing cut marks found on some anatomical elements of bovids. In the case of LDA results (Table S2), classification/misclassification tables reveal a 42–46% confusion rate in shape, whereas form implicates a slightly higher percentile of correctly classified marks (47–64%) when considering differences in taxa.

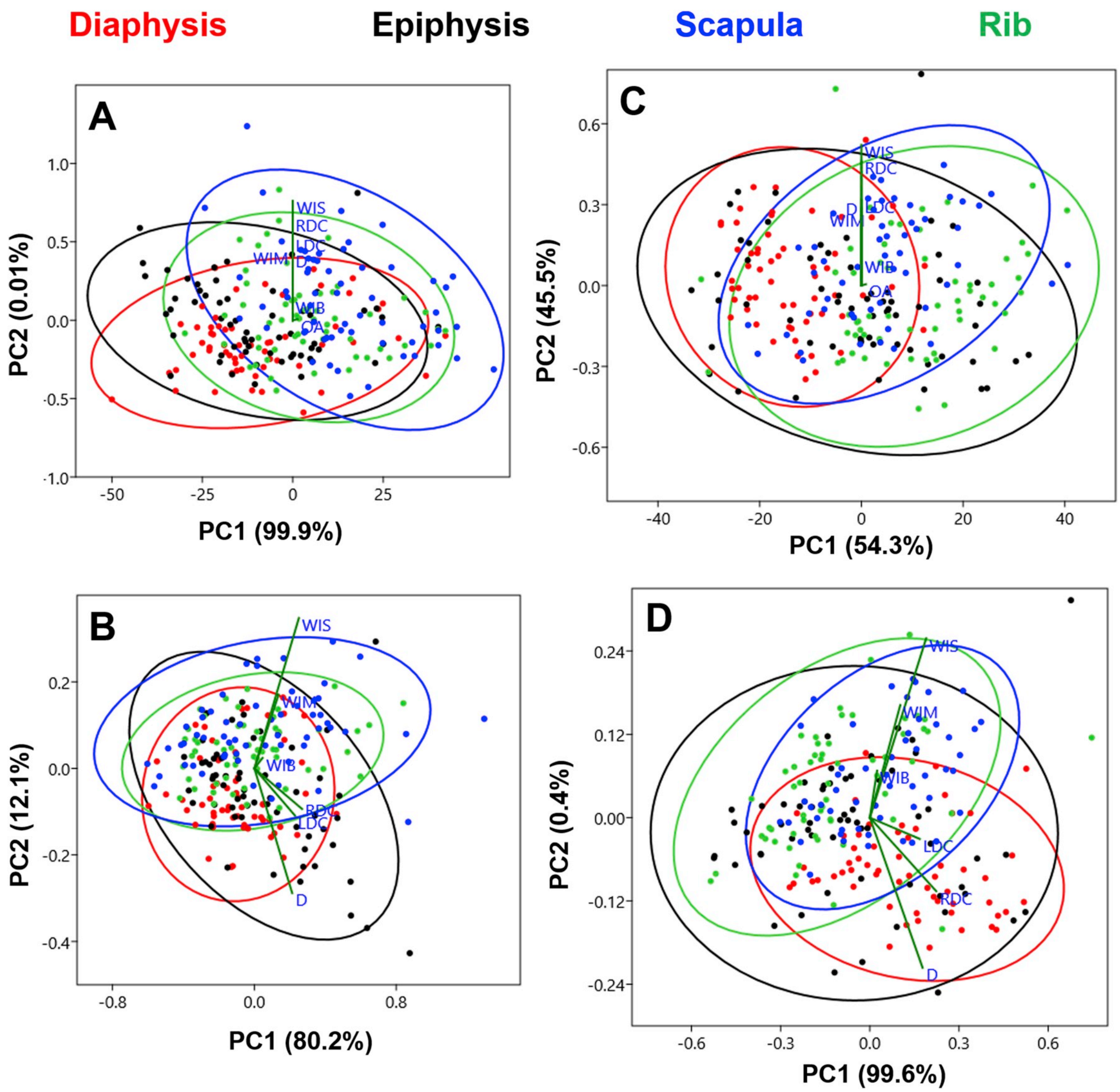

Fig. 4. PCA plots presenting variance in cut mark dimensions found on different skeletal elements. (A) Suid bones including and (B) excluding OA. (C) Bovid bones including and (D) excluding OA.

Table 1
Effect size p-values for 2D biometric measurement comparing differences between cut marks found on different elements of bovid bones and suid bones, including as well as excluding the Opening Angle (OA).

	Including OA	Excluding OA
Diaphysis	0.008	0.051
Epiphysis	0.020	0.032
Rib	0.021	0.019
Scapula	0.011	0.011

5.2. 3D analysis

3D GMM data in shape space generate PCA graphs (Fig. 7) that present a complete lack in variation according to anatomical element, yet begin to display a higher degree of sample variability when comparing taxa, Marks on suids display a higher range of shape, but this embodies the morphological range of marks created on bovid bones, thus showing an overall similar pattern. A total of 32 PC scores represent the entirety of this sample with PC1 and PC2 displaying a cumulative representation of 59.67%. Transformation grids across PC scores indicate little variation in the case of PC2, with PC1 indicating the presence of some slightly wider cut marks among suid bones. Effect size p-values show no significant differences in most cases (Tables 5 and 6). LDA results (Table S2) correctly classify 78% of cut marks found on suid and bovid bones, with a much lower classification rate (46%) when considering anatomical element.

Table 2
Effect size p-values for 2D biometric measurement of cut mark profiles on different bones (diaphyses, epiphyses, ribs and scapulae), including as well as excluding the Opening Angle (OA).

		Including OA	Excluding OA
Dia - Epi	Bovid	0.149	0.041
	Suid	0.028	0.014
Dia - Rib	Bovid	0.006	0.003
	Suid	0.004	0.005
Dia - Scap	Bovid	0.051	0.155
	Suid	0.051	0.019
Epi - Rib	Bovid	0.034	0.011
	Suid	0.018	0.018
Epi - Scap	Bovid	0.005	0.011
	Suid	0.021	0.022
Rib - Scap	Bovid	0.005	0.065
	Suid	0.002	0.030

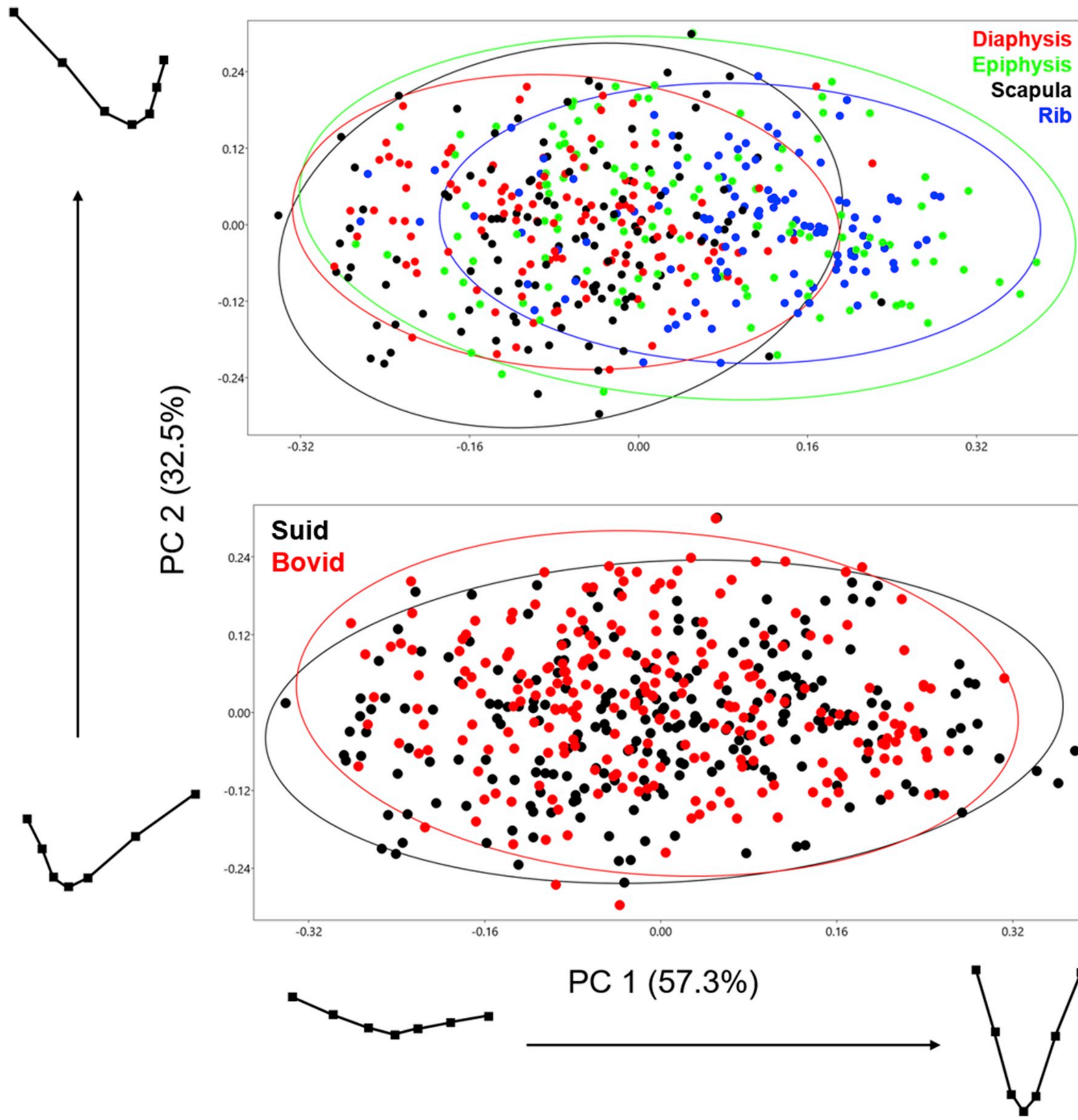

Fig. 5. PCA plots presenting variance in cut mark cross-section shape using the 7-landmark model. Variance in shape is presented for the extremities of both PC scores along their respected axes.

Analysis in form space are expressed by almost identical PCA graphs (Fig. 8) represented by a total of 37 PC scores. Differences in transformation grids are minor, with cut marks on suid bones separating slightly from those on bovids due to a slightly wider morphology. Cohen's d highlights the lack of differences between groups (Table 6). LDA results correctly classify 78% of cut marks found on bovid and suid bones, while only 40% of marks found on different anatomical elements are correctly associated (Table S2).

6. Discussion and conclusion

Recent studies in BSM have approached multiple different perspectives. Since the first studies in cut marks more than a century ago (Boucher de Perthes, 1849; Lartet, 1860; Lartet and Christy, 1865–1875; Martín, 1907; Weigelt, 1927), BSM evaluation has come a long way with the aid of 3D reconstructions and high resolution metric methods (Bello and Soligo, 2008; Bello et al., 2009; Maté-González et al., 2015, 2016, 2017a, 2019; Courtenay et al., 2017, 2018a). Recent observations revolve around the potential importance of animal size and the type of bone in cut mark morphology. Several authors have discussed bone density as a conditioning factor for the study of cut marks produced using different tools (Bello et al., 2009; Pobiner and Braun, 2005; Merritt, 2012; Braun et al., 2016; Pante et al., 2017).

The present study describes the use of statistical tests of equivalence to confirm the significance of statistical equifinality between cut marks found on different bones, considering variations in cortical hardness and density. This equifinality is especially evident when using GMM approaches. Here, we have shown that little statistical distinction is present among biometric data. Additionally, 3D analyses are not significantly different according to most of the tests conducted throughout the study.

Multiple authors have already discussed the effects of carcass size on cut mark frequencies (Pobiner and Braun, 2005), geometry (Merritt, 2016), dimensions (Merritt, 2012), and morphology (Merritt, 2012; Pante et al., 2017), while further critical responses have also pointed out anatomical element and tool attrition as additional conditioning factors (Braun et al., 2008, 2016). As far as morphology is concerned, the results obtained here argue strongly against considering the anatomical element and carcass size as important variables of statistical significance. Instead we think that the physical attributes of the cutting

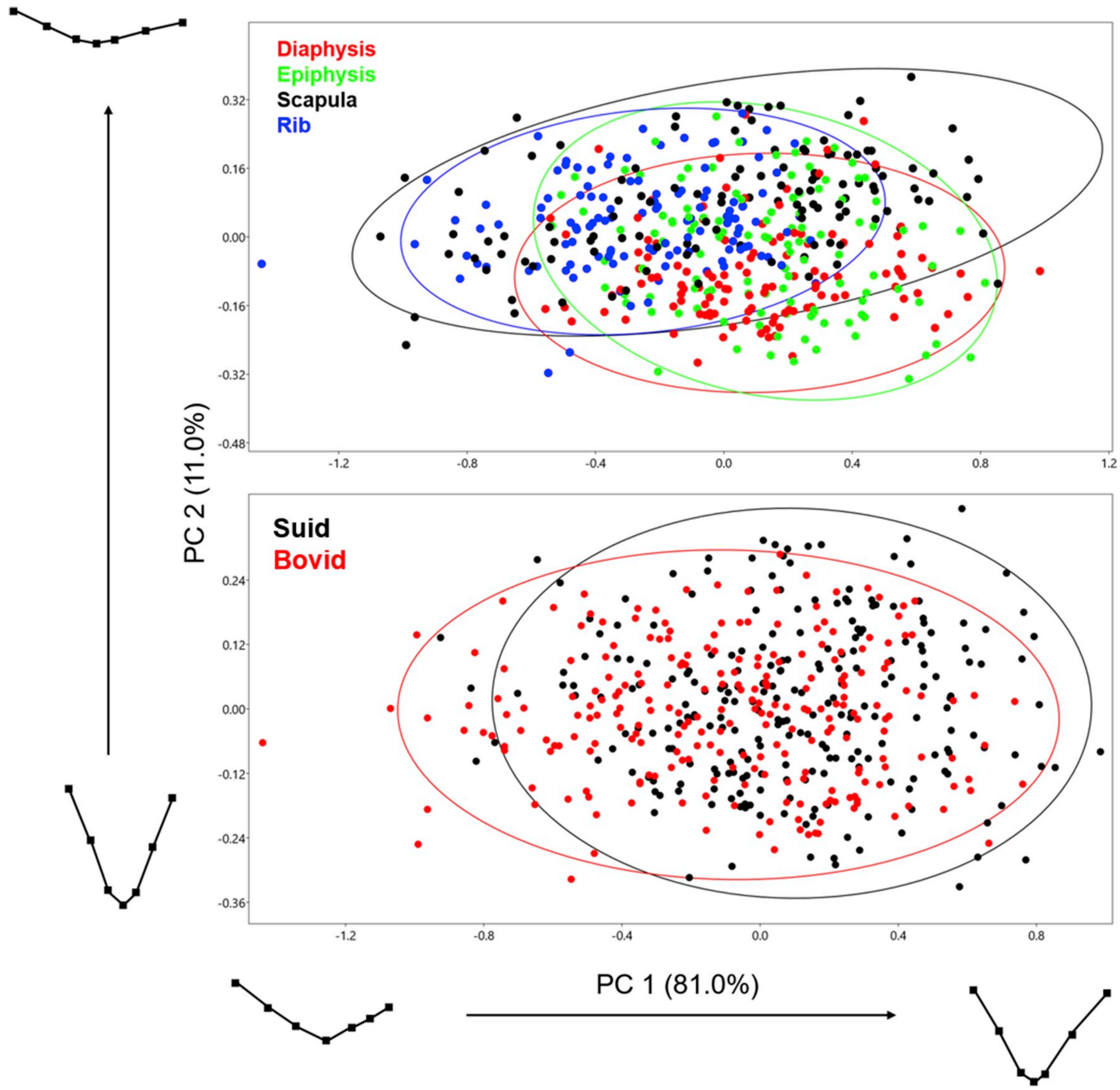

Fig. 6. PCA plots presenting variance in cut mark cross-section form using the 7-landmark model. Variance in form is presented for the extremities of both PC scores along their respected axes.

Table 3
Effect size p-values for 2D geometric morphometric models, comparing differences between cut marks found on different elements of bovid bones and suid bones.

	2D Shape	2D Form
Diaphysis	0.008	0.056
Epiphysis	0.007	0.004
Rib	0.001	0.017
Scapula	0.010	0.234

implement are more important and should be taken into consideration in experimental studies. Recently cut mark analysis has focused on the tool itself, with variables such as raw material (Bello et al., 2009; Maté-González et al., 2015, 2016, 2017a; Courtenay et al., 2017, Pending Publication; Yravedra et al., 2017a, b, 2019; Moclán et al., 2018), tool type (Moretti et al., 2015; Courtenay et al., 2017), cutting angle (Otárolla-Castillo et al., 2017; Courtenay et al., 2018a), and attrition (Braun et al., 2008), being strongly emphasised in the study of anthropic BSMs.

From another perspective, Wallduck and Bello (2018) have confronted the stage of carcass decay as a conditioning factor, producing quantifiable data to show how different levels of force exerted in butchering practices are likely to cause alterations in morphology. A key question here, however, lies more in cortical hardness. Considering the physical properties of cut mark production (Potter, 2005), a key component is the structural integrity of bone over the time of decay

Table 4
Effect size p-values for 2D geometric morphometric models, comparing differences between cut marks found on different bones (diaphyses, epiphyses, ribs and scapulae).

		2D Shape	2D Form
Dia - Epi	Bovid	0.057	0.003
	Suid	< 0.001	0.034
Dia - Rib	Bovid	0.278	0.032
	Suid	0.008	0.106
Dia - Scap	Bovid	0.135	0.008
	Suid	0.046	0.107
Epi - Rib	Bovid	0.013	0.224
	Suid	0.005	0.085
Epi - Scap	Bovid	< 0.001	0.145
	Suid	0.036	0.003
Rib - Scap	Bovid	< 0.001	0.005
	Suid	< 0.001	0.406

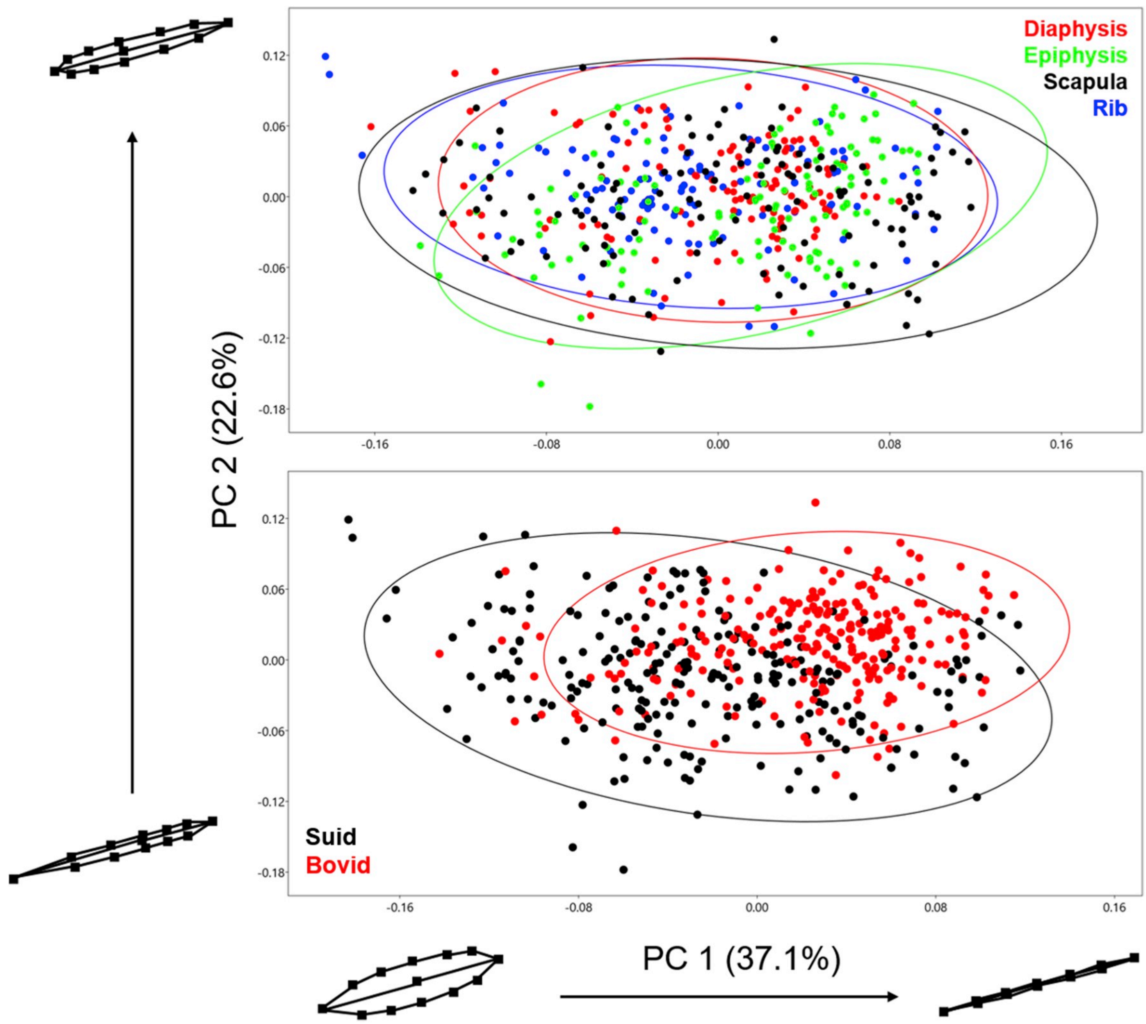

Fig. 7. PCA plots presenting variance in entire cut mark shape using the 13-landmark model. Variance in shape is presented for the extremities of both PC scores along their respected axes.

Table 5
Effect size p-values for 3D geometric morphometric models, comparing differences between cut marks found on different elements of bovid bones and suid bones.

	3D Shape	3D Form
Diaphysis	0.010	0.069
Epiphysis	0.006	0.050
Rib	0.001	0.005
Scapula	< 0.001	< 0.001

Table 6
Effect size p-values for 3D geometric morphometric models, comparing differences between cut marks found on different bones (diaphyses, epiphyses, ribs and scapulae).

		3D Shape	3D Form
Dia - Epi	Bovid	< 0.001	< 0.001
	Suid	0.002	< 0.001
Dia - Rib	Bovid	0.018	< 0.001
	Suid	0.011	0.002
Dia - Scap	Bovid	< 0.001	< 0.001
	Suid	0.001	0.007
Epi - Rib	Bovid	0.005	0.002
	Suid	0.023	< 0.001
Epi - Scap	Bovid	0.003	0.002
	Suid	0.005	0.003
Rib - Scap	Bovid	< 0.001	< 0.001
	Suid	0.003	0.004

(Walden et al., 2017; Öhman et al., 2012). The loss in organic material and the process of progressive dehydration, cause differences in cortical hardness (Walden et al., 2017), likely generating the results described in Wallduck and Bello (2018). Under this premise, also cortical hardness in areas of muscle insertion, as well as trabecular bone, a supposed to present significant differences (Öhman et al., 2012). From a physical perspective, these variables alone *could* produce significant changes in cut mark morphology (Potter, 2005), but the results presented in this paper highlight insignificant statistical differences in 3D morphology, whereas studies of 2D cross sections through either GMM methods or the biometric measurements employed by Wallduck and Bello (2018) are more susceptible to variability. Nevertheless, variation is minute and restricted to a limited number of cases.

A fundamental problem in recent experimentation lies in statistical power and scientific analogy. Recent debates have called out insignificant sample sizes (Otárolla-Castillo et al., 2017; Courtenay et al., 2018a), while levels of subjectivity in taphonomic research have also been highlighted (Domínguez-Rodrigo et al., 2017). As a response to this, statistical research has begun to revise previous studies and sites with particular scrutiny (Domínguez-Rodrigo et al., 2017; Egeland et al., 2018; Domínguez-Rodrigo and Baquedano, 2018), finding new means of efficiently processing data with exceptional statistical power,

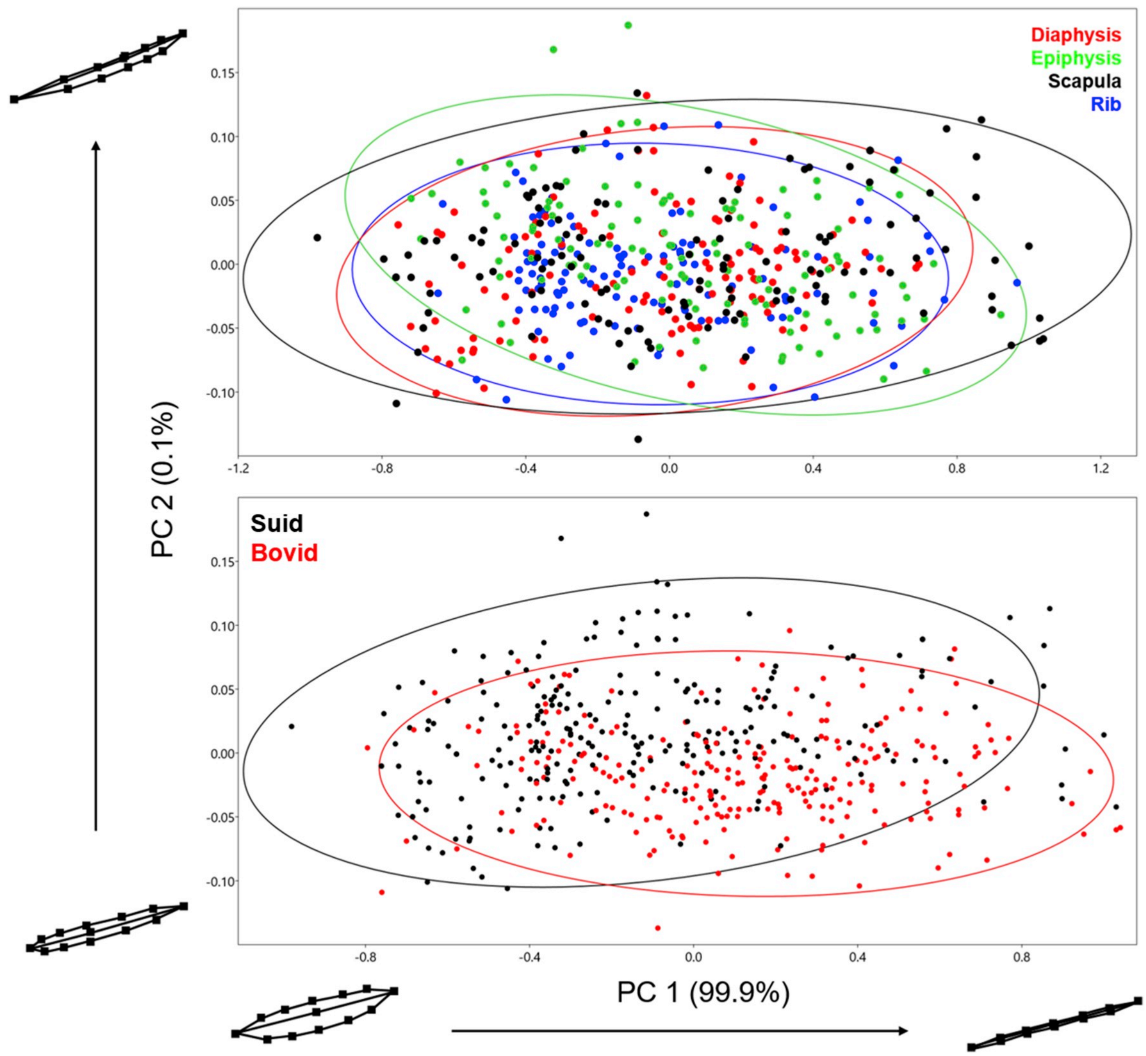

Fig. 8. PCA plots presenting variance in entire cut mark form using the 13-landmark model. Variance in form is presented for the extremities of both PC scores along their respected axes.

e.g. the application of Machine Learning algorithms to taphonomic research (Domínguez-Rodrigo, 2018). From a similar perspective, certain experimental conditions can cause difficulties in the study of some archaeological sites where many taphonomic variables are not being considered (Val et al., 2017). Experimental analogy is therefore especially important in many taphonomic debates over key sites (Egeland et al., 2018), including the problematic case of Dikika (McPherron et al., 2010; Thompson et al., 2015; Domínguez-Rodrigo et al., 2011; Domínguez-Rodrigo and Alcalá, 2016), or the "2.8 Ma cut marks" from India (Malassé et al., 2016a, b).

Nevertheless, a great deal of variables still require greater attention, e.g. stone tool attrition, which could be studied from a GMM perspective. In response to comments made regarding carcass size and anatomical element (Pobiner and Braun, 2005; Merritt, 2012, 2016; Braun et al., 2016; Pante et al., 2017), our results prove that this is not a real conditioning factor. However, studies regarding neonate, infantile and senior individuals have revealed significant differences in cortical structure (Öhman et al., 2012). This may be a more interesting variable to consider rather than the actual size of the animal at hand. Likewise, considering the results presented here, tool type and raw material are more likely to condition mark morphology than cortical structure, as it has been previously stated by Maté-González et al., (2017a) In this paper the granular composition of certain raw materials seems to be causing morphological differences in cut marks; even differences in grain among the same type of raw material (e.g. quartzite) appears to be a conditioning morphological factor (Courtenay et al., Pending Publication).

According to our results, animal size is not as important concerning cut mark morphology as some authors may claim. The significance of these results however provides a positive outcome for future experimental designs.

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Appendix A. Supplementary data

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