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A new geometric morphometrics-based shape and size analysis discriminating anthropogenic and non-anthropogenic bone surface modifications of an experimental data set

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***Abstract* – Reliable discrimination of anthropogenic and non-anthropogenic bone surface modifications (BSM) is crucial to reconstructing the taphonomic history of bone assemblages and past behaviors of hominids and other animals. This discrimination is hindered by equifinality, i.e., BSM with similar morphologies that were produced by different agents. Here we propose a new method to identify the taphonomic agents responsible for BSM and apply it to an experimental data set containing 177 BSM produced by anthropogenic (stone tool-induced cut marks) and non-anthropogenic agents (carnivoran and crocodylian bite marks, and trampling marks). We used 3D topographic models of BSM built from confocal microscopy and applied geometric morphometrics-based shape and size analyses to cross-sectional profiles extracted from the BSM. The new method considers both average profiles and intra-mark variability of profiles. Multivariate analyses of several shape and size variables result in a new synthetic morphospace where anthropogenic and non-anthropogenic BSM show very little overlap.**

I. INTRODUCTION

Identification of the taphonomic agents responsible for bone surface modifications (BSM) is crucial in paleontology and zooarchaeology. Being able to distinguish anthropogenic BSM from non-anthropogenic ones is especially relevant to understanding behaviors of past hominids.

The Dikika case study well encapsulates the debates surrounding identification of anthropogenic BSM. Linear BSM observed on a fragmentary ungulate rib from this Pliocene site in Ethiopia were initially interpreted as the earliest evidence for stone tool-induced cut marks, dating to as early as 3.4 million years ago [1]. Other researchers pointed out the strong similarity of such marks to non-anthropogenic BSM, such as trampling marks made in coarse sediments [2] and bite marks left by crocodylians

[3]. Equifinality, i.e., similar morphologies of BSM produced by different taphonomic agents, is therefore considered as a major factor hindering reliable identification of isolated marks based on their gross morphology.

Classic studies of BSM rely extensively on contextual data from whole bone assemblages and analyses of discrete, qualitative characters of BSM (e.g., [4]). The latter are prone to subjectivity of coding and result in high intra- and inter-observer errors (e.g., [5]). In the context of the Dikika case study, several research groups recently developed quantitative methods whose aim is to more objectively identify taphonomic agents (e.g., [6], [7], [8]). Such studies rely on shape and size analyses using traditional morphometrics or geometric morphometrics applied to 3D models of BSM acquired using various methods (microphotogrammetry, confocal microscopy, surface scanning).

Here we propose a new method that builds on previous studies (geometric morphometrics-based shape and size analyses of cross-section profiles) but differs by a better characterization of intra-mark variability. We apply our new method to an experimental data set comprising diverse anthropogenic and non-anthropogenic linear BSM.

II. MATERIAL

We used an experimental data set comprising 177 linear BSM that document a diverse array of taphonomic agents. Our data set comprises cut marks made with stone tools, bite marks from carnivorous mammals and crocodylians, and trampling marks made in different types of sediments.

We used BSM from butchery experiments conducted using four different categories of stone tools, with various raw materials and tool types, for a total of 55 analyzed cut marks. The first butchery experiment was conducted by JP using simple, unretouched flakes made with basalt (n = 22 marks). The three other butchery experiments were produced within the context of the PCR "Des Traces et des Hommes". A detailed description of those butchery experiments can be found in [9]. Some cut marks were reproduced using simple, unretouched flakes (with convex cross-sections and cutting edges with angles inferior to 45°) made with quartzite (n = 11 marks). Some cut marks were reproduced using denticulates (blanks with micro- to macro-denticulated retouches, showing plano-concave to biplane cross-sections, and cutting edges with angles ranging from 64° to 77°) made with medium-grained quartzite (n = 12 marks). Some cut marks were reproduced with denticulates (blanks with micro- to medium-sized denticulations, with plano-convex to biplane cross-sections, irregular profiles, and cutting edges with angles ranging from 43° to 65°) made with Murs or Bergeracois flint (n = 10 marks).

We used BSM from previous controlled-feeding experiments on extant carnivorous mammals and crocodylians in order to document their bite marks [10], [11], [12], [13]. Our data set comprises a total of 77 linear bite marks produced by five different taxa: (1) alligators (*Alligator mississippiensis*; n = 13 marks); (2) wolves (*Canis lupus*; n = 22 marks); (3) dholes (*Cuon alpinus*; n = 9 marks); (4) lions (*Panthera leo*; n = 11 marks); and (5) tigers (*Panthera tigris*; n = 22 marks).

We used BSM produced in previous trampling experiments by burying bones in two different kinds of sediments and having them trampled by different animals [14], [15]. We analyzed a total of 33 trampling marks coming from two experiments: (1) bones buried in sandy sediments and trampled by large ungulates (n = 22 marks); (2) bones buried in clayey sediments and trampled by *Homo sapiens* (n = 11 marks). We also analyzed BSM produced by burying bones into compost laden with various stone tools (flakes, blades, bladelets, nuclei) made with flint and having them trampled by *Homo sapiens* (n = 12 marks) [16].

III. METHODS

We first molded each BSM using molding products commonly used in dentistry (polyvinylsiloxane elastomers, Coltene President), allowing the capture of microscopic details of the topography. We acquired high-resolution surface topography of the molded BSM using a Sensofar S neox confocal microscope driven by SensoScan 6.6 software (Sensofar, Barcelona). The 20x objective allowed for a lateral resolution of 0.645 μm, a vertical reproducibility of 8 nm, and an optical resolution of 0.31 μm.

We analyzed the obtained surfaces using SensoMap 7.4 software package (Sensofar, Barcelona). We first filled the missing points with the nearest neighbor algorithm using surrounding valid points (only surfaces with more than 90 % of measured points were analyzed). We then automatically deleted outliers resulting from measurement noise. We automatically corrected leveling using the least-squares plane method and inverted the Z axis to obtain the topography of the original BSM.

We extracted two kinds of cross-section profiles along the long axis of linear BSM. First, we extracted one mean profile per BSM corresponding to the average profile automatically compiled by SensoMap based on all single profiles extracted within a rectangular box covering the whole BSM (Figure 1). The number of single profiles used to compile the mean profile is different for each BSM as it depends on the length of the rectangular box and the resolution of the surface. For example, for BSM DS-S1-1, a cut mark made with a denticulate in flint (Figure 1), 4432 single profiles were extracted along a ca. 4.5 mm-long rectangular box, with each single profile comprising 161 points along a constant width of ca. 160 μm. This high number of single profiles ensures that the resulting mean profile is not significantly influenced by local variations or artefacts and is representative of the whole BSM. We then extracted 10 single profiles per BSM, one profile every

10 % of the whole BSM length (from 5 % to 95 %; Figure 1). This approach allows us to consider both shape and size variability of mean profiles and intra-mark variability in shape and size along the mark using the 10 single profiles.

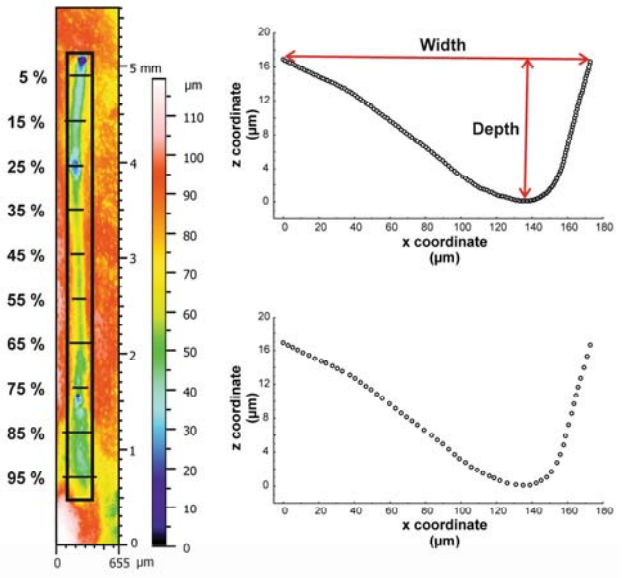

Fig. 1. Left panel shows the topography of a linear BSM in false colors (high points in hot colors, low points in cold colors) and the position of the unique (horizontal black lines) and mean (rectangular black box) cross-section profiles extracted for shape and size analysis. Right panels show a profile extracted from a surface and its quantification using landmarks and semi-landmarks.

The shape of a profile also depends on the direction chosen by the operator when positioning the BSM and extracting the profiles. Depending on this arbitrary choice, a profile or its exact mirrored symmetric version can be extracted. In order to circumvent this issue, we included the extracted profile and its mirrored symmetric version into the shape analysis for each mean profile and each single profile.

All analyses were conducted using the R software (packages Momocs, Morpho, FactoMiner). We quantified shape and size of each profile using two landmarks at each extremity to serve as anchor points and 58 sliding semi-landmarks equally spaced between the two extremities (Figure 1). Two-dimensional coordinates of the landmarks were then superimposed using Generalized Procrustes Analysis (GPA) to remove all differences related to size, position, and orientation. Superimposed coordinates of landmarks and semi-landmarks were then subjected to a Principal Component Analysis (PCA) in order to assess major axes of variation of cross-section profile shape.

We also compared size of profiles using centroid size (CS), a global size variable commonly used in geometric morphometrics and corresponding to the square root of the summed squared distance from each landmark/semi-landmark to the centroid of the configuration (the centroid being the average of all landmarks). Size was also assessed through basic linear measurements of profile width (W) and depth (D) (Figure 1).

The first GPA was done on mean profiles. The corresponding PCA resulted in several shape variables describing different aspects of the mean profile. $PC1_{mean}$ describes the global shape of the mean profile, $PC2_{mean}$ describes the degree of asymmetry of the mean profile (see below), and $PC3_{mean}$ describes the shape of the mean profile bottom. The variables CS_{mean}, W_{mean}, and D_{mean} quantify the size of mean profiles.

Extracted profiles and their mirrored symmetric versions display the exact same PC1 and PC3 values, suggesting that those variables are not affected by the symmetry of the profiles. Along PC2, each pair of symmetric profiles displays the same absolute value but one profile displays a positive value whereas its symmetric version displays a negative value. PC2 absolute values close to 0 indicate profiles that are relatively symmetric whereas higher PC2 absolute values indicate profiles that are relatively asymmetric.

The second GPA was done on single profiles (10 per BSM). For each BSM, we then quantified the dispersion of the 10 unique profiles in terms of shape and size by compiling the inter-quartile range (IQR) for each shape and size variable obtained from the PCA conducted on the superimposed landmark/semi-landmarks coordinates. IQR were preferred to ranges as they are less sensitive to extreme values. The variables IQR_{PC1}, IQR_{PC2}, IQR_{PC3}, IQR_{CS}, IQR_{W}, and IQR_{D} therefore reflect intra-mark variability in the aforementioned shape and size variables.

A final global PCA was then conducted using all shape and size variables of the mean profiles as well as all the IQR from the analysis of intra-mark variability.

IV. RESULTS

Figure 2 shows a bivariate graphic showing PC1 versus PC2 of the final global PCA. This represents a synthetic morphospace of cross-section profiles, taking into account both shape and size of mean profile and intra-mark variability. The PC1 and PC2 axes of the final global PCA represent 33.5 % and 28.0 % of total variance in shape and size of profiles, respectively.

BSM with high PC1 values display profiles with high intra-mark variability in shape and high D/W ratio. BSM with low PC2 values display high intra-mark variability in profile size and high profile size (as indicated by CS, width, and depth). Cut marks are characterized by the highest values on both PC1 and PC2 and are especially variable in PC1. This indicates a strong variability in shape and intra-mark shape variability. On average, cut marks display higher intra-mark variability in profile shape and higher D/W ratio than non-anthropogenic BSM.

Trampling marks display lower and much less variable PC1 values compared to profiles from cut marks but their

PC2 values are similar (albeit slightly less variable). This indicates lower intra-mark variability in both size and shape of profiles from trampling marks compared to cut marks. Trampling marks made on flint stone tools-laden compost are similar to those of trampling marks on PC1 but display lower values on PC2.

Crocodylian and carnivoran bite marks are characterized by lower PC2 values compared to profiles from cut marks and trampling marks and their PC1 values are somewhat intermediate between those of profiles from trampling marks and cut marks. On average, profiles from crocodylian bite marks display higher PC2 values than profiles from carnivoran bite marks. The latter are very variable on PC2. Compared to cut marks, carnivoran and crocodylian bite marks display much lower PC2 values, indicating that they show much higher intra-mark variability in size and are on average deeper and wider than bite marks.

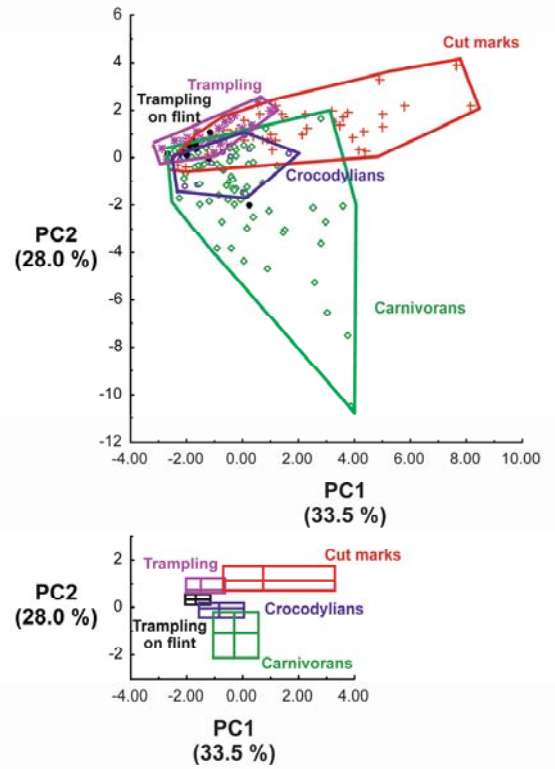

Fig. 2. Bivariate graphic PC1 versus PC2 representing the analyzed BSM into a synthetic morphospace combining shape and size variables of mean profiles as well as intra-mark variability of profiles. Top panel shows raw data with convex hull polygons. Bottom panel shows corresponding median values (lines) and inter-quartiles ranges (boxes).

V. DISCUSSION AND CONCLUSIONS

Overall, when considering medians and interquartile ranges (Figure 2), the synthetic PC1-PC2 shape and size morphospace shows a good discrimination between the profiles extracted from linear BSM made by different anthropogenic and non-anthropogenic taphonomic agents.

Although there is some overlap in the morphospace, cut marks are overall well discriminated from every type of non-anthropogenic BSM represented in our reference data set. This confirms that equifinality is real but possibly smaller than hinted by recent studies (e.g., [3]). The discrimination between cut marks, trampling marks, and crocodylian bite marks provides a promising, quantitative method for identifying similar BSM in the fossil record, including the hotly debated Dikika traces.

The discrimination between anthropogenic and non-anthropogenic BSM is even stronger when considering only cut marks induced by simple, unretouched flakes made with basalt (Figure 3). This comparison would be even more relevant for the Dikika case study as Pliocene-aged deposits have yielded only simple flakes and most archeological sites older than 2 Ma in eastern Africa only produce stone tools made with volcanic rocks such as basalt.

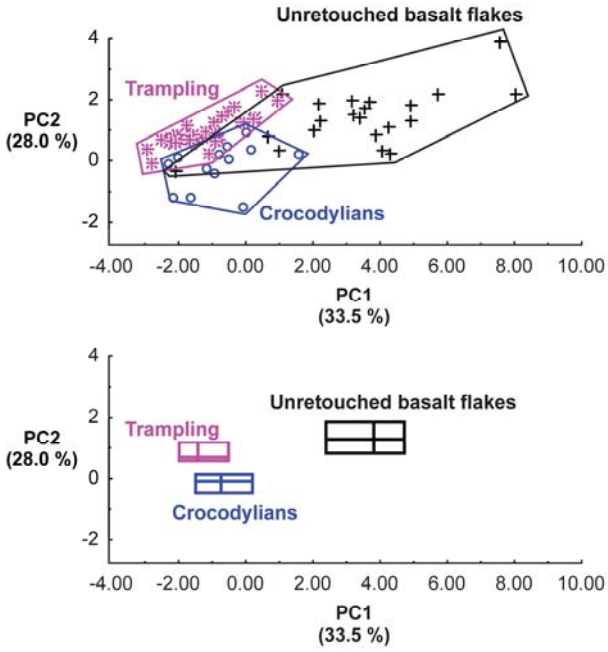

Fig. 3. Bivariate graphic PC1 versus PC2 representing the analyzed BSM into a synthetic morphospace combining shape and size variables of mean profiles as well as intra-mark variability of profiles. Same PCA analysis as Figure 2 but with only the three main possible agents for the Dikika BSM displayed to highlight the stronger differences between anthropogenic and non-anthropogenic BSM when only cut marks produced by unretouched basalt flakes are considered. Top panel shows raw data with convex hull polygons. Bottom panel shows corresponding median values (lines) and inter-quartiles ranges (boxes).

The aforementioned discrimination of different types of anthropogenic and non-anthropogenic BSM by our newly developed method suggests that it is an efficient and promising tool with strong potential for future applications to paleontological and archeological sites (and even forensic contexts), whenever confirmation of anthropogenic origin of BSM is crucial. This approach can be used in combination with "classic" zooarchaeological data (skeletal profiles, mortality profiles, fractures, number and position of BSM) when the latter are available.

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REFERENCES

[1] S.P.McPherron, Z.Alemseged, C.W.Marean, J.G. Wynn, D.Reed, D.Geraads, R.Bobe, H.A.Béarat, "Evidence for stone-tool-assisted consumption of animal tissues before 3.39 million years ago at Dikika, Ethiopia", Nature, vol.466, August 2010, pp. 857-860.

[2] M.Domínguez-Rodrigo, T.R.Pickering, H.T.Bunn, "Configurational approach to identifying th earliest hominin butchers", PNAS, vol.107, No.49, December 2010, pp. 20929-20934.

[3] Y.Sahle, S.El Zaatari, T.D.White, "Hominid butchers and biting crocodiles in the African Plio-Pleistocene", PNAS, vol.114, No.50, December 2017, pp. 13164-13169.

[4] M.Domínguez-Rodrigo, S.de Juana, A.B.Galán, M.Rodríguez, "A new protocol to differentiate trampling marks from butchery cut marks", J. Archaeol. Sci., vol.36, No.12, December 2009, pp. 2643-2654.

[5] M.Domínguez-Rodrigo, P.Saladié, I.Cáceres, R.Huguet, J.Yravedra, A.Rodríguez-Hidalgo, P.Martín, A.Pineda, J.Marín, C.Gené, J.Aramendi, L.Cobo-Sánchez, "Use and abuse of cut mark analyses: the Rorschach effect", J. Archaeol. Sci., vol.86, October 2017, pp. 14-23.

[6] L.A.Courtenay, J.Yravedra, M.A.Maté-González, J.Aramendi, D. González-Aguilera, "3D analysis of cut marks using a new geometric morphometric methodological approach", Archaeol. Anthropol. Sci., vol.11, No.2, February 2019, pp. 651-665.

[7] M.C.Pante, M.V.Muttart, T.L.Keevil, R.J.Blumenschine, J.K.Njau, S.R.Merritt, "A new high-resolution 3-D quantitative method for identifying bone surface modifications with implications for the Early Stone Age archaeological record", J. Hum. Evol., vol.102, January 2017, pp. 1-11.

[8] M.A.Maté-González, J.Aramendi, J.Yravedra, R.Blasco, J.Rosell, D.González-Aguilera, M.Domínguez-Rodrigo, "Assessment of statistical agreement of three techniques for the study of cut marks: 3D digital microscope, laser scanning confocal microscopy and micro-photogrammetry", J. Microsc., vol.267, No.3, May 2017, pp. 356-370.

[9] M.-C.Soulier, S.Costamagno, "Let the cutmarks speak! Experimental butchery to reconstruct carcass processing", J. Archaeol. Sci.: Reports, vol.11, February 2017, pp. 782-802.

[10] S.K.Drumheller, C.A.Brochu, "A diagnosis of *Alligator mississippiensis* bite mark with comparison to existing crocodylian datasets", Ichnos, vol.21, No.2, May 2014, pp. 131-146.

[11] J.A.Parkinson, T.W.Plummer, R.Bose, "A GIS-based approach to documenting large canid damage to bones", Palaeogeogr. Palaeoclim. Palaeoecol.,

vol.409, September 2014, pp. 57-71.

[12] J.A.Parkinson, T.Plummer, A.Hartstone-Rose, “Characterizing felid tooth marking and gross bone damage patterns using GIS image analysis: an experimental feeding study with large felids”, J. Hum. Evol., vol.80, March 2015, pp. 114-134.

[13] J.-C.Castel, “L’influence des canidés sur la formation des ensembles archéologiques. Caractérisation des destructions liées au loup”, Rev. Paléobiol., Genève, vol.23, No.2, Décembre 2004, pp. 675-693.

[14] D.A.Cusimano, “Trampling modification: an actualistic study in taphonomy”, Master’s thesis, California State University East Bay.

[15] L.Rozada, R.Allain, J.-F.Tournepiche, “Trampling experiments on bones in fine and soft sediments”, Quaternaire, vol.29, No.1, 2018, pp. 39-44.

[16] M.Barisic, “Étude de l’effet du piétinement humain sur des ossements de faune mélangés à un amas de taille”, Master’s thesis, Université de Bordeaux.