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A new high-resolution 3-D quantitative method for identifying bone surface modifications with implications for the Early Stone Age archaeological record

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ABSTRACT

Bone surface modifications have become important indicators of hominin behavior and ecology at prehistoric archaeological sites. However, the method by which we identify and interpret these marks remains largely unchanged despite decades of research, relying on qualitative criteria and lacking standardization between analysts. Recently, zooarchaeologists have begun using new technologies capable of capturing 3-D data from bone surface modifications to advance our knowledge of these informative traces. However, an important step in this research has been overlooked and after years of work, we lack both a universal and replicable protocol and an understanding of the precision of these techniques. Here we propose a new standard for identifying bone surface modifications using high-resolution 3-D data and offer a systematic and replicable approach for researchers to follow. Data were collected with a white-light non-contact confocal profilometer and analyzed with Digital Surf's Mountains® software. Our data show that when methods are standardized, results between researchers are statistically indistinguishable. Multivariate analyses using the measured parameters allow discrimination between stone tool cut marks and mammalian carnivore tooth marks with 97.5% accuracy. Application of this method to fossil specimens resulted in 100% correspondence with identifications made by an experienced analyst using macroscopic observations of qualitative features of bone surface modifications. High-resolution 3-D analyses of bone surface modifications have great potential to improve the reliability and accuracy of taphonomic research, but only if our methods are replicable and precise.

1. Introduction

Over the last 40 years, bone surface modifications have made increasingly important contributions to our understanding of the taphonomic complexity of archaeological site formation (Isaac, 1983). Nowhere has this contribution been more significant than with the Pliocene and early Pleistocene archaeological assemblages, which mark a major adaptive shift in hominin behavior that likely included an increasingly carnivorous diet that is traditionally inferred by interpreting assemblage-scale patterns in specimens bearing both butchery traces and carnivore tooth marks (Binford, 1981; Bunn and Kroll, 1986; Oliver, 1994; Selvaggio, 1994, 1998; Blumenschine, 1995; Capaldo, 1995, 1997; Domínguez-Rodrigo, 1997; Pobiner et al., 2008; Pante et al., 2012; Ferraro et al., 2013; Pante, 2013). However, interpretations based on these feeding traces have been limited by our ability to confidently infer their taphonomic origin on fossil specimens (Njau, 2012; James and Thompson, 2015). Currently, the morphological criteria used to describe these marks and distinguish them from traces left by other taphonomic processes are almost exclusively qualitative. As a result, the reliability of identifications can be evaluated only through blind-testing and the degree of correspondence among

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independent analysts (Blumenschine et al., 1996; Thompson et al., 2015). This has led to high-profile and unresolved disagreements about the origin of marks in the Dikika (Domínguez-Rodrigo et al., 2010, 2011, 2012; McPherron et al., 2011; Thompson et al., 2015) and FLK *Zinjanthropus* assemblages (Domínguez-Rodrigo and Barba, 2006; Blumenschine et al., 2007; Domínguez-Rodrigo et al., 2014; Pante et al., 2015; Parkinson et al., 2015), both of which have been central to defining the carnivorous feeding behavior of our ancestors. These debates are likely to remain unresolved without an objective and quantifiable method for identifying bone surface modifications.

In an attempt to quantify the analysis of bone surface modifications, zooarchaeologists have turned to technology that is capable of collecting high-resolution 3-D data from bone surfaces with hopes of detecting features in the micromorphology of marks not observable with traditional macroscopic techniques. The methods used include photogrammetry (González et al., 2015), 3-D digital microscopy (Bello and Soligo, 2008; Bello et al., 2009; Bello, 2011; Bonney, 2014; Duches et al., 2016) and spinning disk laser light confocal microscopy (Archer and Braun, 2013). These studies have focused on variations in the micromorphology of cut marks resulting from tool type, raw material or butchery techniques and have quantified cut marks with measurements that include breadth, depth, opening angle of the cut mark and radius of the floor of the cut mark. However, the precision of these methods has yet to be demonstrated, while errors of up to 17.2% have been reported for reproducing mean values for individual cut mark parameters (Bello and Soligo, 2008). Methods need to be standardized and precision in both collecting 3-D data and measuring parameters needs to be demonstrated before any of these techniques can be broadly applied to support meaningful inferences about the behavior and ecology of our ancestors.

In this paper we introduce a systematic and replicable method of 3-D data collection from both cut and tooth marks and evaluate the precision of our protocol. The parameters measured are unique in using not only profiles extracted from the collected data, but also the entire 3-D model. We also provide the first completely quantitative method for distinguishing between cut and tooth marks on bone surfaces and demonstrate the effectiveness of this technique by applying it to a small sample of fossil specimens from Middle Bed II, Olduvai Gorge, Tanzania. Ultimately, these methods may unlock new behavioral and ecological information that is captured in the 3-D micromorphology of bone surface modifications allowing for the identification of specific carnivore taxa from tooth marks (Muttart et al., 2016) or the tool types (i.e., flakes or handaxes) that were used during butchery from cut marks (Keevil and Pante, 2016).

2. Methods

The objective of this study is to describe a systematic and replicable method for the collection and analysis of metric data from bone surface modifications. Below we provide a detailed account of our methods so that our procedure can be replicated.

2.1. Profilometer

All 3-D data were collected using a Nanovea ST400 white-light non-contact confocal profilometer equipped with a 3 mm optical pen (objective) that has a resolution of 40 nm on the z-axis. The ST400 can scan areas as large as 150 mm × 150 mm and depths of 20 mm without the need for stitching (joining multiple smaller scans to create a larger composite file). It can also accommodate objects as thick as 200 mm making it uniquely capable of collecting 3-D data from bones that are variable in shape and size. The device used in this study is also equipped with an optional video microscope that can accurately select the desired area for scanning, which minimizes scan time and maximizes precision, defined as our ability to reproduce measurements.

2.2. Profilometer settings

The profilometer collects a series of profiles at set increments along the y-axis. The resolution of scans can be set on both the x- and y-axes in increments of 1 μm. Increasing the resolution or sampling rate of the x-axis improves the detail of the individual profiles, while increasing the resolution of the y-axis will result in the collection of more profiles. Increases in resolution come at a cost of longer scanning times. As such, considerable analysis went into the selection of the 5 μm sampling rates used here on the x-axis and 10 μm on the y-axis. The goal was to scan an average cut or tooth mark in roughly 1 h, while not sacrificing important details captured within the mark profiles. After repeated measurements of the same marks, it was determined that it would be impractical to sample at rates of less than 5 μm in either axis and that by increasing the resolution on the y-axis to 10 μm we were able to cut the time of scans in half, while maximizing the resolution of individual profiles.

The profilometer can also modify the frequency at which data are collected. The ST400 is capable of scanning at two frequencies between 100 and 2000 Hz simultaneously in order to minimize missing data points, “holes”, that occur due to variations in the reflectivity of bone surfaces. Dozens of scans were collected in order to determine the frequencies that are most effective in the collection of 3-D data from dry, greasy and fossilized bones. It was determined that a dual frequency setting of 300 Hz and 1000 Hz was the most effective at minimizing the number of holes in the data. Despite the dual frequency capability of the machine, it was difficult to produce scans that were not missing data points due to variations in the reflectivity of bone surfaces. This was particularly true for bones that were greasy. The problem was effectively addressed by applying a thin layer of face and body bronzer to bone surfaces prior to scanning. The bronzer was provided as part of a kit with a Next-engine 3-D scanner and serves to reduce reflectivity of bone surfaces. Excess bronzer was blown off bone surfaces to minimize any effect on data collection. Pre- and post-scans to test the effect of the bronzer showed the data did not vary beyond what is normal for individual scans of the same mark.

2.3. Modern sample

Data were collected from 51 known cut marks and 29 known tooth marks. The cut marks were produced during experimental defleshing of an adult white-tailed deer radius ($n = 12$) and also by dragging a tool across the midshafts of defleshed cow femurs ($n = 39$). All cut marks were produced with stone tools that included both flakes and bifaces. Tools used to cut the cow femurs were made from a Texas chert, while tools used to butcher the deer limbs were made from basalt. There is evidence to suggest that cut mark morphology and depth can vary with bone portion and animal size (Bello et al., 2009; Merritt, 2012; Braun et al., 2016). We limited our scans to midshafts, but did not control for animal size. Tooth marks were located on the midshafts of a size 3a bovid (see Bunn, 1982 for size classes) radius, ulna and tibia that was partially observed by RJB to have been defleshed and demarrowed by a spotted hyena. However, other consumers cannot be ruled out in the initial defleshing of the carcass. Twelve of the cut marks and 10 of the tooth marks were scanned and analyzed separately by three of us (MCP, TLK, and MVM) to test the precision of our results. There were no specific criteria for selecting the marks used in inter-