Journal of Archaeological Science 110 (2019) 105012

Contents lists available at ScienceDirect

Journal of Archaeological Science

journal homepage: www.elsevier.com/locate/jas

Why should traceology learn from dental microwear, and vice-versa?

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ARTICLE INFO

Keywords:
Archeology
Artifacts
Confocal microscopy
Dental microwear texture analysis
Paleontology
Quantitative surface texture analysis
Teeth

ABSTRACT

Dental and artifact microwear analyses have a lot in common regarding the questions they address, their developmental history and their issues. However, few paleontologists and archeologists are aware of this, and even those who are, do not take into account most of the methodological insights from the other field.

In this focus article, we briefly review the main developmental steps of both methods, highlight how similar their histories are and how combining methodological developments can improve both research fields. In both cases, the traditional analyses have been strongly criticized mainly because of their subjectivity and their lack of repeatability and reproducibility. Quantitative surface texture analyses have been proposed in response, resulting in dental microwear texture analysis (DMTA) and quantitative artifact microwear analysis (QAMA). DMTA is however a more mature method than QAMA and is well supported within the paleontological community.

In this paper, focused on the methodological framework of both fields, we address this topic by arguing that traceologists could borrow a lot from DMTA; this would allow QAMA to become an established method much more quickly. Dental microwear analysts can also learn from traceology, especially regarding sample preparation, experimentation and residue analysis.

We hope that this focus article will stimulate more awareness, exchange and collaboration between paleontologists and archeologists, and especially between dental and artifact microwear analysts. Paleontology, archeology and the field of surface analysis as a whole would all benefit from such cooperation.

1. Introduction

Dental microwear analysis refers to the study of microscopic marks present on tooth surfaces that result from the wear of food particles and external abrasives (Green and Croft, 2018). It belongs to paleontology, but it also has applications in biology, dentistry and archeology (Merceron et al., 2014; Hara et al., 2016; El Zaatari et al., 2016). It is commonly applied to infer diets of fossil vertebrates (Ungar and Evans, 2016) and to reconstruct paleo-environments (Ungar et al., 2012). *Traceology* is the study of all physical traces on an artifact's surface, which include use-wear, traces of production, non-utilitarian wear (e.g. transport) and post-depositional alterations (Marreiros et al., 2015; Thomas et al., 2011). Surface modifications can be analyzed at different scales; we will focus here on the microscopic scale, and refer to it as *artifact microwear analysis*. Traceology, in this sense, is a sub-discipline of archeology and is included in functional analyses (Marreiros et al., in prep.). It aims at identifying the function of artifacts in terms of action and worked material, i.e. use, to infer past human behavior.

Both dental and artifact microwear analyses try to address similar questions: what have the objects (teeth/artifacts) been used for (food items/worked material) and how (chewing mechanics/tool kinematics)? While the objects analyzed are different, both fields document the wear produced on the sample's surfaces. Both cases therefore represent tribo-systems, i.e. systems of two contacting objects in relative motion to one another (Brown et al., 2018).

The two methods are decades old and have experienced several rounds of developments, mainly driven by the lack of repeatability and reproducibility of early attempts (see below). More recently, methods to quantify surface textures have been developed to counteract these issues. While archeologists are aware that paleontologists apply similar methods (Evans and Macdonald, 2011; Ibáñez et al., 2019; Martisius et al., 2018; Stemp et al., 2015), the reverse is on the whole not true. Generally, the methodological overlap between archeology and paleontology is rarely recognized or exploited and, accordingly, few

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https://doi.org/10.1016/j.jas.2019.105012
Received 17 May 2019; Received in revised form 21 August 2019; Accepted 22 August 2019
Available online 31 August 2019

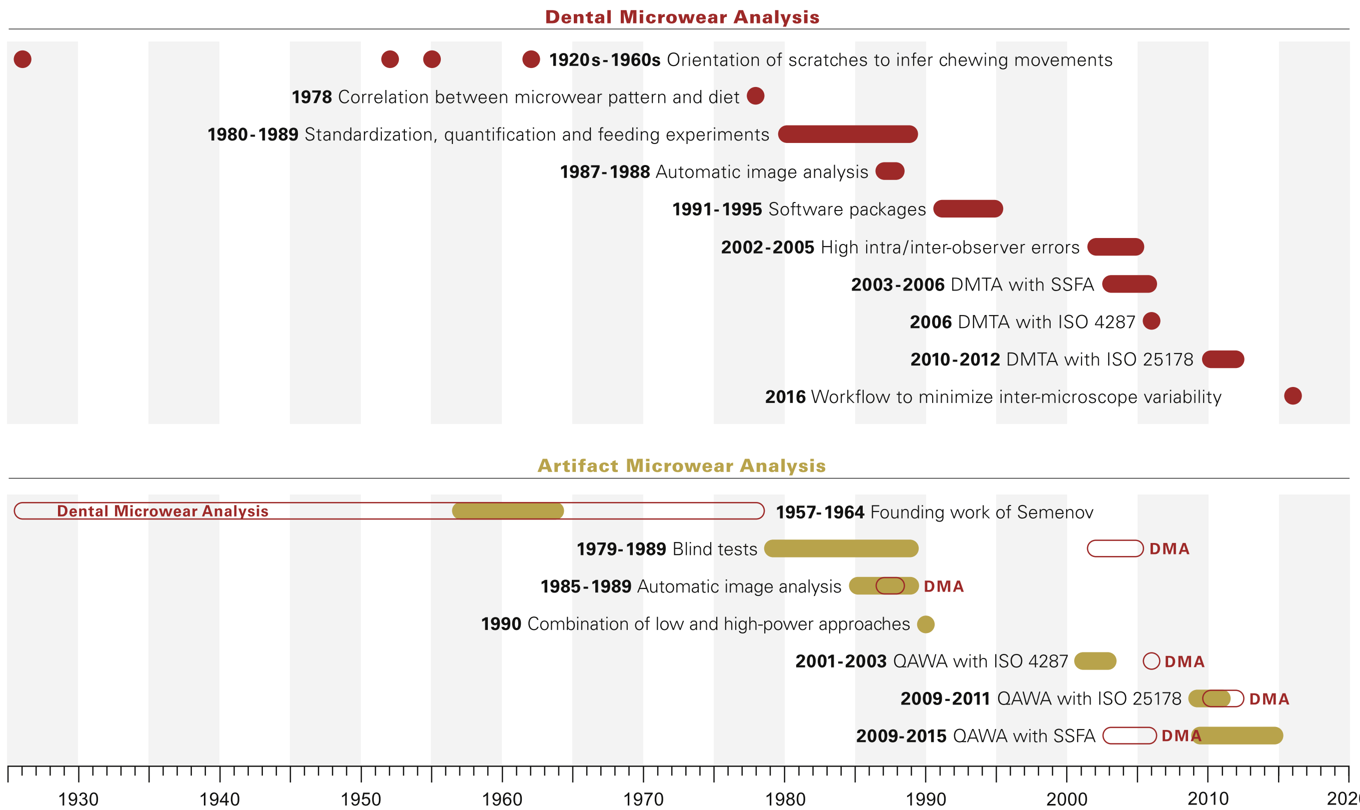

Fig. 1. Main developmental steps of dental **(top)** and artifact **(bottom)** microwear analyses leading to quantitative surface texture analyses (DMTA and QAMA, respectively). Developmental steps of DMA similar to steps on AMA are superimposed in red on the AMA chart at the bottom. All dates correspond to the introduction of a new methodology. In most cases, these new steps were implemented in following studies. See text for details and references. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

insights are transferred. As an illustration, Ungar and Evans (2016, p. 3–4) write that "The papers in this volume demonstrate the value of partnerships between paleontologists *or* archeologists *on the one hand*, and surface metrologists *on the other* …" (our italics).

In this focus article, we will first briefly review the methodological developments of dental and artifact microwear analyses that led to quantitative surface texture analyses (QSTA). We will then detail some aspects that can and should be transferred between the fields. We hope that this article will help both fields move forward so that QSTA can be performed with the same approach and quality standards.

2. Dental microwear analysis

Dental Microwear Analysis (DMA) is the topic of several recent reviews (Calandra and Merceron, 2016; DeSantis, 2016; Green and Croft, 2018; Ungar, 2015). Here we summarize the main steps of its developments leading to QSTA (Fig. 1).

From the 1920s to the 1960s, paleontologists and dentists realized that the orientation of scratches mirrors the direction of chewing movements (Butler, 1952; Dahlberg and Kinzey, 1962; Mills, 1955; Simpson, 1926). DMA became more prevalent in the 1970s with the influential works of Walker et al. (1978) and Rensberger (1978), who showed that the proportions of pits and scratches correlate with diet. These two studies were performed with SEM and, as a result, most subsequent research used this equipment.

The need for standardization of location (tooth, facet) and equipment (SEM settings) soon became evident (Gordon, 1982, 1984; Teaford and Walker, 1984). Intra-specific variation (sex, age, season, geography) was also investigated, emphasizing the need for larger and more controlled samples (Gordon, 1983, 1984; Teaford and Robinson, 1989). DMA became relatively quickly semi-quantitative (Gordon, 1988; Teaford, 1988), and software packages were developed to aid the analysis (Ungar, 1995; Ungar et al., 1991).

However, it has been repeatedly demonstrated that DMA suffers from high intra- and inter-observer errors (DeSantis et al., 2013; Galbany et al., 2005; Grine et al., 2002; Mihlbachler et al., 2012).

In response to these issues, Ungar, Scott, Brown and colleagues proposed to use confocal microscopy to acquire 3D representations of the tooth's surface at high magnifications and to automatically quantify surface textures with Scale-Sensitive Fractal Analysis (SSFA; Scott et al., 2005, 2006; Ungar et al., 2003). Building upon this methodology, other groups of researchers started to apply the standardized 2D ISO 4287 (1997; Kaiser and Brinkmann, 2006) and 3D ISO 25178 (2012; Calandra et al., 2012; Purnell et al., 2012; Schulz et al., 2010) parameters to measure surface textures. Many studies have applied the quantitative analysis now termed *Dental Microwear Texture Analysis* (DMTA) to almost all groups of mammals (Calandra and Merceron, 2016), to fishes (Purnell et al., 2012) and to reptiles (Bestwick et al., 2019; Winkler et al., 2019b). Numerous parameters have been applied to quantify surface textures. The four SSFA parameters are the most used, but 30 ISO 25178 parameters have been regularly applied. Flatness (ISO 12781), motif, furrow, direction and isotropy analyses have also been explored (Schulz et al., 2013a; Winkler et al., 2019a). Interferometry (Estebaranz et al., 2007; Merceron et al., 2014; Souron et al., 2015) and focus variation microscopy (Gill et al., 2014; Purnell et al., 2012, 2017; Zhang et al., 2017) have been tested, but confocal microscopy quickly became the equipment of choice for DMTA (Schulz et al., 2013a).

DMTA has become a well-established method. Several research groups now possess the necessary equipment to acquire 3D surface data. Nevertheless, each piece of equipment and each setting will acquire the surface in a different way (Calandra et al., 2019a). A processing workflow has been proposed to minimize inter-microscope variability (Arman et al., 2016).

Some researchers follow the blind and repeated methodology of Mihlbachler et al. (2012) to limit intra- and inter-observer errors in DMA, but it is not universally adopted (Rivals et al., 2018; Semprebon et al., 2016).

3. Artifact microwear analysis

Some recent reviews have been published on Artifact Microwear Analysis (AMA; Adams, 2014; Dubreuil and Savage, 2014; Marreiros et al., 2015; Stemp et al., 2016). Its developments leading to QSTA are summarized below (Fig. 1). For brevity, this summary focuses on chipped stone tools.

Although the discipline dates back to the 19th century (Olausson, 1980), the seminal work by Semenov (1957, 1964) is usually recognized as having defined the current practice in AMA (Evans et al., 2014a; Stemp et al., 2016). Some researchers emphasized the need for quantification already in the 1970s (Keeley, 1974; Schiffer, 1979). However, besides some attempts with limited results in the 1980s based on digital imaging (Grace, 1989; Grace et al., 1985), interferometry (Dumont, 1982) and tactile profilometry (Beyries et al., 1988), AMA remains largely qualitative. After a long debate over which scale of observation is best suited, a consensus emerged that the high and low-power approaches should be combined (Gräslund et al., 1990; Marreiros et al., 2015; Odell, 2001).

Blind studies performed from the 1970s have demonstrated that this qualitative approach performs poorly for inferring the worked material (Evans, 2014 and references therein). These shortcomings were mostly ignored (Bicho et al., 2015; Collins, 2007; Shea, 2011). Nevertheless, several groups of researchers have developed methods to quantify microscopic traces based on surface roughness, which we call here *Quantitative Artifact Microwear Analysis* (QAMA). QAMA has mainly been applied to chipped stone tools (Evans and Donahue, 2008; Ibáñez et al., 2019), but bone tools (d'Errico and Backwell, 2009; Lesnik, 2011; Martisius et al., 2018; Watson and Gleason, 2016), ground stones (Macdonald et al., 2019; Rosso et al., 2017) and non-functional artifacts (d'Errico and Backwell, 2016; Henshilwood et al., 2018) have also been analyzed applying the same methodology. Surface data have been acquired with a wide range of equipment: tactile (Beyries et al., 1988) and laser (Stemp, 2014; Stemp and Stemp, 2001, 2003) profilometry, atomic force microscopy (Faulks et al., 2011; Kimball et al., 1995, 2017), interferometry (d'Errico and Backwell, 2009; Dumont, 1982), focus variation microscopy (Macdonald, 2014; Stemp et al., 2019), and laser (Evans and Donahue, 2008; Macdonald et al., 2018; Stemp et al., 2013; Stemp and Chung, 2011; Watson and Gleason, 2016) and microdisplay (Calandra et al., 2019b; d'Errico and Backwell, 2016; Ibáñez et al., 2019; Martisius et al., 2018; Sahle et al., 2017) scanning confocal microscopy. The first quantitative analyses measured 2D ISO 4287 parameters (Beyries et al., 1988; Evans and Donahue, 2008; Stemp and Stemp, 2001, 2003). Later, 3D ISO 25178 parameters, the same used in DMTA, were applied (d'Errico and Backwell, 2009; Evans and Macdonald, 2011), but most studies focused on a small subset rather than integrating the properties measured by all parameters. To our knowledge, only Stemp measured fractal parameters on lithics (Key et al., 2015; Stemp et al., 2009, 2018; Stemp and Chung, 2011), and Watson and Gleason (2016) and Lesnik (2011) on bone tools, while this method is widely applied in DMTA. Other norms and analyses have not been explored.

The lack of repeatability/reproducibility is still prevalent in the widely applied qualitative approach (Evans et al., 2014a and references therein). Yet, QAMA remains nascent: many different pieces of equipment are used, almost no effort is made to standardize acquisition and analysis settings (Calandra et al., 2019a), most analyses include only a few parameters, and no study has yet applied it to infer the function of archeological artifacts (except d'Errico and Backwell, 2009 on bone tools). Most importantly, papers on QAMA must still justify why QSTA makes sense (Evans et al., 2014a; Ibáñez et al., 2019; Stemp et al., 2016).

4. What use-wear can learn from dental microwear, and vice-versa

The parallels between DMA and AMA should now have become evident. Both have followed the same methodological developments. However, DMTA is a much better established and accepted method in paleontology than QAMA is in archeology. Indeed, DMTA has been applied in many studies (see section 2) and few paleontologists would not recommend DMTA over DMA. In this section we emphasize the main aspects that each community should borrow from the other.

It should be noted that quantification here refers only to the calculation of surface texture attributes. Such quantification requires the surface topography to first be digitalized into scaled reconstructions of surface profile (2D) or areal (3D). In other words, QSTA has two parts: (1) acquisition of surface data and (2) quantification of surface attributes. While quantification requires acquisition, 3D models can also be assessed visually (d'Errico and Backwell, 2016; Wei et al., 2016).

Based on the success of DMTA, traceologists should recognize that QSTA has great potential. Indeed, this type of analysis can be applied to any surface data (Brown et al., 2018). Of course, which parameters are the most relevant depend on the wear processes. Therefore, traceologists should not be skeptical about QSTA, but rather work to adapt it to the constraints of archeological artifacts (e.g. different raw materials).

Many parameters are available to quantify surface texture. Volume, isotropy and direction parameters in particular might prove relevant to QAMA. All of them are available in MountainsMap Imaging Topography (Digital Surf, Besançon, France), in the modules “advanced topography”, “particle analysis” and “scale-sensitive analysis”.

Protocols to minimize inter-microscope variations have been proposed (Arman et al., 2016; Kubo et al., 2017). There is literature on the (biological) meaning of the ISO/SSFA parameters (see reviews cited before). Finally, the approach of Mihlbachler et al. (2012) could easily be adapted to AMA in order to reduce intra- and inter-observer biases.

To our knowledge, Martisius et al. (2018) is the only study to include specialists from both fields. The study applied an established workflow in DMTA. It also selected some potentially interesting parameters from all classes of ISO 25178 parameters, which eased the subsequent statistical analysis. This collaboration most likely allowed meaningful results to be produced much faster.

The accuracy of molding/casting materials has been investigated by researchers from both fields (Goodall et al., 2015; Macdonald et al., 2018; Mihlbachler et al., 2019). The insights of each study should be transferred to the other field.

Traceology, and archeology in general, have a long tradition of experimenting (Bradfield, 2016; Eren et al., 2016; Lin et al., 2018). Specifically, the effects of e.g. use-duration (Evans et al., 2014b; Martisius et al., 2018), load (Key et al., 2015; Stemp et al., 2015), sample preparation (Macdonald and Evans, 2014) and numerical aperture (Calandra et al., 2019a) on the quantification of artifact microwear have been experimentally tested. On the other hand, dental microwear has only recently resumed with controlled feeding experiments and experimentally induced wear (Hoffman et al., 2015; Karme et al., 2016; Merceron et al., 2016; Ramdarshan et al., 2016; Schulz et al., 2013b; Winkler et al., 2019a).

Residue analysis, is another method to infer the function of a tool (Fullagar, 2014; Haslam et al., 2009). Phytoliths have been found embedded onto primate teeth (Ciochon et al., 1990; Fox et al., 1994) and residues trapped in dental calculus have also been used to infer past human diets (Henry et al., 2011; Weyrich et al., 2017). The extraction and identification of phytoliths could be manageable in extinct vertebrates. Traces of blood, bones, amino acids, proteins, etc. might be preserved and identifiable in fossils too (Bordes et al., 2017; Borgia et al., 2017; Monnier et al., 2018).

5. Future directions

DMTA is a well-established method, more mature than QAMA. Nevertheless, there is scope for refinement and improvement of both methods, especially referring to choice of relevant parameters, comparison of microscopes and understanding of microwear formation.

As for most of our colleagues (Evans et al., 2014a; Kimball et al., 2017; Stemp et al., 2016; Stevens et al., 2010), we do not argue that QAMA should replace AMA; we rather recommend to combine both methods. QAMA could, for example, allow inferring the worked material more precisely once AMA has been performed (Ibáñez et al., 2019; Martisius et al., 2018). Ideally, residue analysis should also be applied in combination (Marreiros et al., 2015; Stemp et al., 2016), although thoughts should be given to sample preparation protocols so that residues are not washed off prior to analysis (Rots et al., 2016).

Post-depositional processes have the potential to blur any functional signal. This topic has been barely addressed in DMTA (Böhm et al., 2019; Calandra and Merceron, 2016; El Zaatari, 2010); QAMA has until now mainly focused on experimental tools, so these processes have rarely been taken into account (Caux et al., 2018; Galland et al., 2019; Vietti, 2016; Werner, 2018). This topic remains of major importance for future studies in both fields.

Each field has a lot to learn but some things can and should be learned from other fields rather than re-invented. Paleontologists and archeologists are used to burrowing from other disciplines (geology, geography, ethnography, tribology, biology, pathology, forensics …). They have worked closely with surface metrologists and we hope that they will continue doing so. When working together, synergistic effects will allow both fields to grow faster, and a quantitative analysis of surface wear common to both teeth and artifacts will have a broader resonance in paleontology, archeology and beyond.

Funding

This research has been supported within the Römisch-Germanisches Zentralmuseum – Leibniz Research Institute for Archeology by German Federal and Rhineland Palatinate funding (Sondertatbestand “Spurenlabor”) and is publication no. 3 of the TraCEr laboratory. The funding source had no involvement in study design; in the collection, analysis and interpretation of data; in the writing of the report; nor in the decision to submit the article for publication.

Conflicts of interest

The authors declare that they have no conflict of interest.

Acknowledgments

We thank Nicole Viehöver for her help with Figure 1.

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