A new method for determining the 3D spatial orientation of molar microwear
A New Method for Determining the 3D Spatial Orientation of Molar Microwear

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Summary: Many types of behavioral and dietary information can be extracted from studies of tooth microwear. Some studies have even been successful at determining the overall directionality of microwear in order to establish gross masticatory movement (Williams et al., 2009, PNAS, 106, 11194–11199). However, microwear has never been successfully visualized in situ in 3 dimensions (3D), visualized virtually and quantified. The ability to accomplish this yields information on exact masticatory movement which can then be used to address any number of eco-biological and physiological questions in extant and extinct organisms. In order to create 3D virtual reality (VR) representation of microwear, fossil molars from the Javanese Sangiran 7 (S7) Homo erectus tooth collection and from historic hunter/gatherer meta-populations were imaged, the microwear in 3 dimensions was extracted, this information was then placed back on VR representations of the molars and quantified. The methodology contained herein demonstrates the efficacy and importance of such a technique in determining gross masticatory movement in fossil and recent hominin molars. This methodology could, in theory, be applied to any organism which produces microwear on its dentition. Applications in the fields of dentistry, orthodontics, climatology and dietary and habitat reconstructions can also be envisioned.

Key words: molar microwear, 3D functional morphology, virtual anthropology, Homo erectus, Sangiran

Introduction

Many hominin species are best physically represented and understood by the sum of their dental morphologies. Generally, taxonomic affinities and evolutionary trends in development (ontogeny) and morphology (phylogeny) can be deduced from dental analyses. More specifically, the study of dental remains can yield a wealth of information on many aspects of hominin evolution such as life history, physiology, and ecological adaptation; in short, the organisms paleobiomics. Functionally, teeth present information about masticatory function and therefore dietary preferences, that is, the dietary niche in ecological context.

As the amount and types of information that can be gleaned from 2-dimensional (2D) tooth measurement exhaust themselves, 3-dimensional (3D) microscopic modeling and analysis presents a largely fertile ground for reexamination and reinterpretation of dental characteristics (Bromage et al., 2005). As such, a novel, non-destructive approach has been developed which combines the work of two established technologies (confocal microscopy and 3D modeling) adapted specifically for the purpose of mineralized tissue imaging. Through this method, 3D functional masticatory and therefore occlusal molar microwear is able to be visualized and quantified. This method differs from other microwear investigative techniques (defining “pits” vs. “scratches,” dental topography and microtexture analysis etc.)
(Gordon, ’82, ’84; Teaford and Walker, ’84; Bullington, ’91; Bunn and Ungar, 2009; Calandra et al., 2012) in that it defines a molars masticatory micro- and macrowear functional interactions in 3D as its baseline dataset for further interpretations and analyses while most other methods simply characterize wear signals based on various foods/environments without micro/macro-functional consideration.

Some other pros and cons associated with various techniques are: scanning electron microscopy to count and measure individual micro-features produces somewhat readily attainable high resolution images but which are 2D representations of 3D surfaces and image quality is dependent on instrument working parameters and specimen orientation (Gordon, ’88). They are also subject to high intra- (7%) and interobserver (9%) error rates (Grine et al., 2002); a return to low-magnification microscopy has gained some recent popularity and represents a rapid and inexpensive method used to qualify and quantify microwear features to distinguish at least gross dietary difference. (Souloulias and Semprebon, 2002; Rivals and Semprebon, 2006). However, it is not easy to discern differences between some microwear features such as puncture pits versus dentine lakes and micron-scale features are not resolvable. As in high-powered microscopy, there also still remains the issue of observer error; microwear texture analysis has several advantages over the above in that it defines “Surface parameters for complexity, scale of maximum complexity, anisotropy, heterogeneity, and textural fill volume...” which are “…repeatable, quantitative characterizations of 3-dimen-sional surfaces, free of observer measurement error.” (Ungar et al., 2003; Scott, 2005; Scott et al., 2006). Its disadvantages stem from “…the newness of the technique and challenges imposed by developing such cutting edge technology” (Teaford, 2007).

Methodologically, the new approach described herein produces a 3D facet microwear vector (fmv) signature for each molar which can then be compared for statistical similarity. Microwear (and, as such, the fmv signatures) was defined by the regular, parallel striations found on specific cusp facets known to arise from patterned, directional masticatory movements. This differs significantly from post-mortem or taphonomic microwear which produces striations at irregular angles on multiple, non-masticatory surfaces (Puech et al., ’85; Teaford, ’88). A “match value” is produced to determine the similarity of two molars fmv’s. The “match values” are ranked (high to low) and these rankings can be used to statistically analyze intra- and inter-overall functional masticatory similarity.

Materials

Our 3D method was developed initially for the investigation of 25 molars from the Javanese Sangiran 7 (S7) Homo erectus collection all currently housed at the Senckenberg Research Institute, Frankfurt, Germany. From 1937 to 1941 G.H.R. vonKoenigswald oversaw the collection of the S7 Homo erectus remains from the Sangiran Dome, Java. Each molar was collected as an isolated surface find and their precise locations (as per modern extractive methods) was not recorded although their relative stratigraphic positions were noted. Indeed, Huffman et al. (2005) report that: “von Koenigswald was often careless or unconcerned about exact field circumstances from which fossils came.”

The sample is broken down into two meta-populations based on the Sangiran Dome’s stratigraphic horizons from which they originated. The horizons are separated unconformably by the Grenzbank conglomerate. Grine and Franzen (’94) state that the molars “…most probably came from a section between the middle Pucangan [Sangiran] and the middle Kabuh [Bapang], which would place these specimens between 1.3 and 0.7 million years.” Ten molars, designated Sangiran 7b, are of the younger Bapang Formation. The remaining 15 molars, designated Sangiran 7a, are of the older Sangiran Formation. Kaifu (2006) reviewed vonKoenigswald’s allocation of 13 specimens (molars and pre-molars) to the Bapang Formation and agreed with their placement excepting S7-8. He does not give a reason for this nor suggest an alternate allocation for S7-8 but states that the crown size does not differ significantly from other Sangiran area molars. Kaifu et al. (2005) also state that “some” of the S7 molars resemble remains from the Grenzbank conglomerate based on their state of fossilization though they do not state exactly which teeth they are referring to. All molars are from adults or sub-adults, specific age and sex cannot be determined and only three of the molars (S7-3b, -3c, and -3d) can be associated with one individual.

The physical condition of each molar varies with some being almost completely unworn to others being worn quite flat. The crowns are all complete except for S7-14 whose distal enamel edge is missing. The enamel surfaces range from almost pristine to [likely] acid etched to the degree that microwear is barely discernable (S7-64). It is important to note that from examination of facet microwear, distinct, individual patterns were discernable which indicate that none of the molars (except the above mentioned) were affected by environmental factors to such a degree as to damage or alter the macro- or microanatomy of the occlusal surfaces.

Due to the poor specimen collection techniques mentioned above, the very complex geologic nature of the Sangiran Dome and disagreements over its chronostratigraphy, the S7 molars exact taxonomic and temporal inter- and intra-stratigraphic relationship has been open to interpretation. As such, only very few scientific works have addressed the S7 molars. Since they were discovered over 70 years ago, only five papers have dealt specifically with the sample. Three of the
teeth were described by Grine ('84) then Grine and Franzen ('94) described the collection qualitatively with some very preliminary quantitative data being acquired. This quantitative data has never been applied to any sort of larger statistical analysis. Dean et al. (2001) used specimen S7-37 in an analysis of enamel growth increments while Kaifu (2005) used seven of the molars in a comparative study of crown areas. Finally, Indriati (2004) simply included them in a catalogue of Indonesian fossil hominins. Based on the relative paucity of research conducted and the fact that it may represent the oldest ex-African *H. erectus* population and therefore ancestral to all Asian *H. erectus*, the sample presents itself as ripe for systematic quantitative interpretation and inclusion into and comparison with the larger body of hominin dental remains.

**Methods**

**Microwear Image Acquisition**

*Imaging system and specimen alignment*

A K2S Bio portable confocal microscope (Technical Instrument Co. Sunnyvale, CA; Bromage US Pat. App. No.: 10/960,325, OIL Id. No.: BRO03-01PRO.) was chosen due to its unique imaging capabilities as previously demonstrated for use in examinations of hominin dentition by Bromage and Perez-Ochoa (2003) and Bromage *et al.* (2005, 2007). However, due to technical considerations inherent to this project, some methodological modifications were necessary. The first and most important modification is that the imaging system and stage need to leveled, aligned and squared in exact XYZ planes per a right-handed Cartesian Coordinate System with “+X” toward the viewer, “+Y” to the right and “+Z” straight up (Fig. 1). Although there are different configurations of the coordinate system across various disciplines (mathematics, computer graphics etc.), this configuration was chosen because “Z” is normally used as the distance between the specimen and objective lens in microscopy and for correspondence across the analysis platforms used here.

Leveling etc., were accomplished through the use of a spirit level and two laser levels. The spirit level is placed atop the confocal module which is then adjusted to horizontal (in the XY plane). As there is some play in attachment of the objective lens, the laser levels are placed at right angles (at a distance sufficient enough to allow the beams to trace the vertical length of the objective tube) focusing their beams vertically on the center of the objective tube to ensure that it is vertical (XZ and XY planes). The camera mount does not seat the camera itself in any specific direction and so the camera itself must be squared to the coordinate system. This also can be accomplished using the laser levels at right angles to each other. The camera also must be mounted so that the image is *in situ* and not rotated 180°.

A manual goniometer stage is then affixed to a modified XY stage (Fig. 2). A goniometer is added here so that the exact position of the specimen (here a tooth) in space can be recorded as it is rotated into optimum position for viewing of individual facet microwear. Any method of affixing the goniometer onto the XY stage may be used but modeling clay was available and found to be quite adequate and functional. Clay is firm yet malleable which allows the goniometer to be delicately manipulated while centering and squaring it with the XY stage. This centering and squaring is again accomplished using the level lasers at right angles to each other. This entire apparatus is then squared beneath the objective lens (and with the confocal module itself) using the laser levels.

![Fig. 1. Right-handed cartesian coordinate system (from Wikipedia).](image1)

![Fig. 2. Goniometer atop modified XY stage.](image2)
The specimen tooth must then be oriented in a standardized manner. As Gordon (’88) states, “Variation in specimen orientation can affect the definition of microwear features.” and so the orientation process was developed with this in mind. A small glass platform/stage was customized from microscope slides such that one side lies directly in the XZ plane, another directly in the YZ plane and the base in the XY plane. The YZ side lies only in the −Y axis while the XZ side lies only on the −X axis so that a 90˚ Corner is formed. This corner defines a space occurring from the origin (0,0,0) into (−X, −Y, Z) (Fig. 3). Glass microscope slides were used so that laser light could penetrate and illuminate the tooth in preparation for a future alignment step. Before the tooth can be affixed to the platform it must be measured to determine its morphological center in XY (½ bucco-lingual by ½ mesio-distal dimension). A small dot is placed on the tooth at this point using a non-permanent, fine point marker.

The tooth is then placed on a small piece of clay (to hold and stabilize the tooth) affixed in the corner of the glass platform with its mesial border flush with the XZ side of the platform and its buccal or lingual border (depending on if the tooth is sinistral or dextral) flush with the YZ side. The tooth is then leveled in XY using its cervical margin as the reference. The two level lasers are configured to project beams at the same height in the XY plane from opposite sides of the tooth. This ensures that a solid line is cast around the entire tooth in the XY plane. Tooth position is then adjusted so that the cervical margin lies in the XY plane. If the cervical margin is unclear or damaged, then a “best-fit” margin is determined and used. Each successive tooth can now be squared and leveled in the same manner regardless of its root size or height. The height of the tooth in Z is then taken using calipers. This measurement is defined as the distance of the central occlusal fossa from the center of rotation upon the goniometer and is essential for being able to reposition the digitized tooth in later steps. The tooth is now cleaned using a small, soft bristle paint brush (cotton swab fibres tend to snag in small cracks and fissures in the tooth surface) using an 80/20 water/alcohol or water/acetone solution. Cleaning is done at the end of the alignment process as much handling and manipulation of the tooth is required which introduces not insignificant amounts of skin oils etc., onto the enamel surface.

Finally, the glass stage with aligned tooth is affixed to the goniometer platform (again using clay) so that the morphological XY axis of the tooth is lined up at the center of goniometer platform. This “center” is easily recognized as the illuminating light emanating from the objective lens passes directly through here (assuming all alignment has been done properly) (Fig. 4). The height (or Z) of each tooth is measured from the top of the goniometer specimen base to the morphological axis so the tooth’s center of rotation can be factored back into 3D model alignment. Dennis et al. (2004) employed similar specimen orientation techniques of which Ungar et al. (2002) had previously deemed to be repeatedly precise to within 1%.

Microwear imaging

After the system and specimen have been squared, imaging can commence. Three wear facets per tooth were chosen for imaging of microwear. These facets are representative of buccal and lingual Phase I and Phase II masticatory movements. For maxillary and mandibular molars, facets 3 and 4 correspond to buccal Phase I shearing while facets 5 and 6 correspond to lingual Phase I shearing. Facet 9 is representative of Phase II crushing and grinding movements in both upper and lower molars (Fig. 5) (Hiiemae and Kay, ’73; Kay and Hiiemae, 1974; Maier and Schneck, ’81; Janis, ’90). In the event that a facets microwear was not discernable.
due to diagenetic and/or taphonomic etc., reasons (which occurred more frequently in the *H. erectus* sample but much less in the historic HG sample), another facet representing the same occlusal phase was chosen. For example, if maxillary facet 9 demonstrated no wear, then facet 12 was substituted.

Using the underlying XY stage, the goniometer with affixed tooth is slid beneath the objective lens so that the facet under investigation is directly under the illuminating beam. The goniometer is then manipulated so that the specimen is tilted in such a manner that the facet under investigation is as near horizontal (into the XY plane) as visually possible. Achieving maximum horizontality allows a larger area of the facet to be continuously imaged without having to make major adjustments in focus. Any blurring or distortion caused by out of focus planes is also minimized. The entire facet is initially scanned with a 5X objective to determine whether the facets microwear is present and if it truly represents microwear and not taphonomic and/or diagenetic artifact. Microwear is evident as multiple parallel striae running in a consistent direction (Fig. 6). There can be more than one area per facet with differently angled concentrations of striae. These concentrations can overlap others. Multiple concentrations of striae angled differentially indicate that the facet was used in more than one direction. On any tooth, no more than five of these concentrations were identified and this occurred only on a very small percentage of facets with approximately 2.5 concentration areas per facet being the average. Striae that were singular, very deeply cutting into the facet surface, irregularly wide or moving in an inconsistent direction were deemed to be artifact and not imaged.

If microwear was evident using the 5X objective then an image was acquired. When possible, the entire facet surface was imaged but if striae were concentrated in specific regions, only these were imaged. Several images were normally required to adequately document striae concentrations. These image sequences were saved as jpeg files, numbered consecutively and manually montaged at a later stage. Once an image is captured, the goniometer is read for ± tilt of the XY plane about the X or Y axis. Positive X values are read on the right scale (right side up) and negative on the left (left side up) while positive Y values are read on the front scale (front side up) and negative on the rear (back side up). For example, the configuration shown in Figure 2 above would correspond to the values (−1.5, 0, 0) as the left side of the goniometer is up, there is no XY tilt around Y and Z is zero as no specimen is affixed. In order to reduce the amount of reorientation necessary in

![Fig. 5. Schematic illustration of masticatory movements and the wear facets related to this study. Masticatory movements begin in the lower right diagram with the mandible starting its incursive movement from the inferio-lateral of the maxilla and driving superio-medially. As this occurs, complementary Phase I buccal (4&3) and lingual (5&6) facets shear past each other. Phase I shearing ends as centric occlusion is reached (upper central diagram) with the mating of complimentary facets 9. Crushing occurs between these facets at the transition from Phase I to Phase II movements. Phase II continues with a grinding action between facets 9 in an inferio-medial direction. There is a seamless transition from Phase I to II. This is an idealized and somewhat simplistic representation of what is actually occurring during mastication as it implies simple up/down right/left movement when in actuality the incursive and excursive movements can begin and end through a large range of horizontal and vertical movements depending upon wear stage and diet. Numerical system after Maier and Schneck (’81) and color coding after Kullmer et al. (2009).](image-url)
later steps, rotation around the Z axis was done very rarely and only when a facets striae could not be adequately imaged otherwise. Magnification was also recorded to facilitate reproducibility. If microwear was not readily imageable with the 5X objective then the 10X objective was employed. Rarely was it necessary to employ a higher power objective. This was also undesirable as the field of view becomes increasingly small and, as such, the ability to judge whether the striae being imaged were relevant (i.e., actually identifying true directions of movement across the facet surface as opposed to random artifact) decreases. Gordon (’88) showed that magnification could materially affect the “perceived wear fabric” while Semprebon et al. (2004) showed that low magnification microscopy (as opposed to high magnification electron microscopy which is often used in microwear studies) had low inter- and intra-observer measurement error. Also, the portability of the confocal system engenders certain design restrictions which contribute to image “bounce” or vibration at higher magnifications in many situations. First, the system must be lightweight and so a heavy or vibration resistant base cannot be included. Second, the system must be easily and readily assembled and disassembled which sacrifices some solidity of the systems components. Most modern buildings (as found in developed nations) contain large ventilation systems which introduce a considerable amount of vibration into a building itself which becomes an issue at high magnifications. Several vibration dampening measures are included in the system but none have been completely successful in eliminating all “bounce” or vibration. Many buildings in developing nations do not contain these ventilation systems and so, interestingly, this issue is less of a problem in “remote” locations.

Mating of 2D and 3D Molar Images

Using 3D optical topometric methods established by Kullmer et al. (2002) and employed elsewhere by Ulhaas et al. (2004, 2007), Fiorenza (2009a), Forenza et al. (2010) and Kullmer et al. (2009), the hunter/gatherer and H. erectus molars were scanned to a surface resolution of ~50 μm and digitized to create 3D virtual reality (VR) models. Fiorenza (2009b) contains a detailed discussion of the methods employed in model generation and post-processing. The 2D microwear striae acquired above are then mated to these 3D VR models employing several different image manipulation programs and processes.

Tooth model alignment and facet delimiting

The 3D VR molars are imported into the IMEdit module of PolyWorks® 10.1 (InnovMetric Software Inc.) where they are oriented to exactly match the coordinate position of the original tooth from which microwear was imaged. They first must be leveled in the horizontal (XY plane) by digitally defining a best-fit line around the cervical margin and then translating the cervical line and associated tooth to the XY plane (Fig. 7) (Fiorenza, 2009a). The tooth is then digitally rotated so that the mesial border is flush with the XZ plane (Fig. 8). The morphological axis is marked digitally using the same measurements as above. This point was used to measure the height of the crown above the goniometers axis of rotation (recorded during image acquisition) and so the tooth needs to be translated vertically to match this height.

The facets from which the striae were acquired are then defined by manually inserting a polyline around the facets anatomical border (Fig. 9 showing only one facets delimitation and already rotated into the position in which the microwear was imaged as per below). The original tooth or cast was always at hand to visually confirm this border. A best-fit plane is created which defines the surface bounded by the polyline (Fiorenza 2009a).

Fig. 6. Three different microwear directions on facet 5 of Sangiran 7-3c (5X mag.).

Fig. 7. H. erectus specimen Sangiran 7-20 (S7-20) aligned via its cervical margin to the XY plane.
Mating of 3D facet and microwear striae

First, the entire VR tooth is returned to the coordinate position in which a facets microwear striae were imaged. Using the rotational measurements recorded from the goniometer, an automated rotational feature in IMEdit ensures that the tooth’s (and thus facets) 3D position during microwear striae imaging is exactly reproduced (Fig. 9). The plane representing the facets occlusal surface in 3D space is then saved as a separate bitmap file.

The facet planes bitmap file is then imported into Rhinoceros 4.0 NURBS modeling software (McNeel). For unknown reasons, Rhinoceros flips the facet planes vertically resulting in the need to flip the original microwear images vertically as well (this is not a 180° rotation but a vertical flip!). The microwear images are then imported into Rhinoceros as well and aligned beneath the facet plane. The microwear striae are now visible beneath their 3-dimensionally oriented facet as they originally appeared on the tooth (Fig. 10). The microwear images can be aligned anywhere beneath the facet image as it’s the microwears gross direction that is of importance and not its exact position on the facet.

A line drawing tool is then used to trace one striae from each microwear concentration onto the facet plane (yellow line Fig. 10). Only one striae from each concentration needs to be reproduced as a facets totality of microwear yields no further information here. If multiple microwear striae concentrations were present on a facet, a line from each concentration can be drawn in sequence. The facet planes bitmap image with inserted microwear striae are then saved as a single image. The inserted lines now exactly reproduce that facets microwear striae in 3 dimensions.

The facet and striae bitmap images are then imported back into IMEdit. As long as the VR tooth was not moved from the position it was oriented in to extract the facet surface for export into Rhinoceros, the facet is automatically mated back to its original position on the occlusal surface. The exact 3-dimensional orientation of the microwear striae (Fig. 11 in black) are now fused to and visible upon their appropriate facets of the VR tooth (Fig. 11 in yellow). Working backwards from the goniometer readings for that facet, the tooth is then returned to its original squared position in preparation for repeating the process for each facet.

Creation of Facet Microwear Vector Signature Diagrams

The composite directionality of all facet microwear vectors (fmv’s) cannot be readily interpreted from simply viewing the 3-D tooth with the vectors in place on the facets. They must therefore be subjected to...
several modifications and re-visualized in a form which produces easily compared representations of their directionality in 3-D space. Thus, facet microwear vector signature diagrams were developed to facilitate this.

The initial length of the fmv’s were all variable as they were drawn according to the breadth of the facet surface. Therefore, any facet could have multiple vectors of differing lengths crossing its surface requiring that they need be standardized for length. This was done using an algorithm specifically written for use on this project (described in detail below). The algorithm first mirrored all left teeth to the right in order to increase sample size. It then extracted the fmv 3-D positionality data from the appropriate Polyworks files, standardized the length of each fmv to 1 (an arbitrary unit useful for visualizing the vectors), translated the origin of the fmv’s to the coordinate systems central axis (0,0,0) and exported the fmv’s into a new Polyworks IMEdit file such that each fmv is now represented by an x, y, z coordinate in space. The fmv’s were translated to (0,0,0) in order to meaningfully visualize the fmv’s as movement into/out of maximum intercuspation (see Fig. 5). The fmv’s in this new file were then color coded according to which facet they originated from following Kullmer et al. (2009).

In order to give directional reference to the fmv’s, a red circle with radius 5 was created in the XY plane (Fig. 12). Each circle’s superior direction (0/360˚) corresponds to mesial position in the mouth (capital M in red) and “right” (90˚) corresponds to buccal direction. Here Z is coming straight out of the page at the viewer and represents an occlusal view of the tooth intended to relatively match the position of the tooth as it would naturally sit in the mandible. Placing the fmv’s within a circle delimited the dip direction of each fmv while also yielding a rough idea of the fmv’s dip angle. As such, if the fmv is touching the bounding circle it means that the dip angle is zero or very near that. As the dip angle increases, the end of the fmv moves farther from the bounding circle as it is pointing more inferiorly or superiorly from zero inclination (Kullmer et al., 2009).

All the fmv’s on the right side of the bounding circle (blue and yellow vectors located from 0˚ to 180˚) represent incursive Phase I buccal and/or lingual mandibular movements which necessarily end at centric occlusion (central axis (0,0,0). A small red sphere was placed at this location to highlight the termination of

Fig. 11. The facet with associated microwear striae imported from Rhinoceros back onto S7-20.

Fig. 12. Facet microwear vector (fmv) signature diagram of S7b-43: lm1 (Sangiran).
incursive movements and the beginning of excursive movements. All the fmv’s on the left side of the bounding circle (green and sometimes orange vectors located from 180˚ to 360˚) therefore represent excursive Phase II mandibular movements. The right diagram is simply the left diagram tilted mesially 90˚ into the ZX plane so that now –Y is coming straight out of the page directly at the viewer. A red circle of radius 2.5 was created in the ZX plane to aid in demonstrating dip angle. The arrow at the tip of each fmv is an artifact of the vector creation process and should not be construed as indicative of movement or directionality.

Facet Microwear Vector Analysis Algorithm

In order to quickly and efficiently compare directionality of fmv’s, an algorithm was written in C++ programming language which automates the processes described below. The facet microwear vectors are represented in IMInspect with two-point polylines (straight lines with two end points) which contain data on the fmv’s dip and dip direction (Kullmer et al. 2009). Essentially, the algorithm extracts this data and compares each tooth’s individual fmv’s dip and dip direction to all other teeth with the same row number (1st, 2nd, or 3rd molar) and wear stage (stages 1 through 5) to establish overall similarity of facet microwear direction between each tooth’s homologous facets. Left teeth are reflected to the right in order to increase sampling ability. A weighted number is then assigned to each “match” and these numbers can be statistically compared. Where multiple facets for comparison exist this process would be repeated for each facet comparison. The similarity values for each facet are then added and divided by the total number of facets compared to obtain the overall match average termed the “Match Value.” As the Match Value increases, similarity between teeth decreases.

Weighing function

To accurately characterize fmv similarity between two facets (and therefore between teeth), categories must be established to define what constitutes correspondence of angular separation. When visually comparing the fmv signatures between two teeth, it is possible to identify which teeth appear similar and, as such, dissimilar. The weighting function attempts to mathematically quantify this admittedly subjective appraisal. So, from an extensive visual appraisal of the fmv signatures, it was determined that if a pair of vectors was separated by 10.0˚ or less, they matched very well in dip and dip direction and would be assigned a weight of 1. Angular separation between 10˚ and 20.0˚ receives a weight which falls off linearly as the separation increases. This linear correcting was necessary as differences in the 3-dimensional angular separation of dip and dip direction begin to become more pronounced as the angle approaches 20.0˚. Any vector comparisons with an angular separation larger than 20.0˚ are considered poor matches and receive a low weight.

Statistical Analysis

As this is a completely new method for understanding the complexity of molar microwear/diet interactions, the novel data could have been statistically considered in many ways. At this early stage of inquiry, it was deemed more logical to begin with the simplest forms of analysis in order to gain a basic understanding of the initial data being generated and the most meaningful ways of interpreting that preliminary data. This as opposed to trying to implement any number of more complex statistical methods for interpreting that data when the methodology itself was just beginning to be understood. Therefore, the somewhat basic yet expedient and descriptive analytical method of comparing match values was used as the primary means for interpreting the data.

As stated above, it is believed that this method will eventually yield more robust interpretations of masticatory movement/microwear with regard to diet which will necessitate more complex forms of statistical analysis. The small sample size of the H. erectus specimens precluded more in depth, multivariate analysis of inter- and intra- sample variation. Boot-strapping may provide a “fix” to this issue but increasing the hominin sample size would yield results that are more conducive to multivariate analyses such as ANOVA/MANOVA. Statistical analyses of inter- and intraspecific fmv directional movement (incursive 3D angle vs. excursive 3D angle) as seen in and based upon the fmv diagrams should be possible. Also, several researchers (Gordon, ’82; Kay and Hiiemae, ’74) have used homologous facet microwear from both upper and lower molars (but the same molar in the tooth row) to increase sampling ability as the mandibular tooth produces wear in the same direction on the maxillary as it does upon itself. Using the new method described here, the correct angular transformations respective of the topographic “male/female” mating of occlusal facets could be undertaken thus increasing sample size. This may also lead to the feasibility of using a singular molar to predict the microwear upon a corresponding absent molar.

Results

As this paper is intended as only an introduction to a novel methodology, comparatively quantitative results have been purposely omitted. However, the preliminary quantification of fmv signatures has been used
elsewhere to comparatively interpret dietary preference intra- and inter- the two spatially and temporally defined meta-populations of the Javanese S7 H. erectus (as described above) with respect to several ecodietarily defined historic hunter/gatherer (H/G) meta-populations (n=63) (Tausch, 2012). A more full description of those results is planned in a forthcoming publication. The method described here has demonstrated its usefulness in functionally analyzing a novel 3D molar microwear dataset as it occurs upon its macro-molar (individual cusp facets) substrate. The results show that occlusal movement direction varies as well as the number of microwear directions per wear facet. It also demonstrates that these functional datasets can be successfully defined, visualized, extracted and quantified in their exact in situ 3D orientations in extant and extinct populations. Moreover, it offers a method to define an individual tooth’s masticatory functionality and therefore perhaps overall organismal masticatory strategy via the unique fmw signature of those individual teeth.

**Discussion**

This project presented a unique set of problems and challenges for several reasons. The initial objective of visualizing for analysis both macro- (molar crown facets) and micro- (microwear upon those facets) 3D information simultaneously entailed the use of several somewhat disparate imaging technologies. These technologies each extract different levels/types of information, use different imaging platforms/methods for such and have never been employed together. As such, the merging of confocal microscopy with 3D optical topometric methods to produce virtual reality models inclusive of micro- and macro-data required novel thought about and application of these imaging/analysis platforms.

Foremost of the difficulties was that, although microwear images contain 3D information of dental movements, the images themselves are, by nature, 2D ("flat" pictures) representations of that spatial information. Methodologically the problem then was how can 2D information be converted to or mated with 3D virtual representations of where that 2D information was extracted?

The problem is compounded when the ultimate objective is added to the above. This objective entails reproducing the functional direction of mandibular movement for individual molars. This then, in effect, could be considered a 4-dimensional problem; facet orientation in the X, Y, and Z axes plus microwear directional movement through these axes. Visualizing, extracting and statistically analyzing this novel and quite variable data also then required innovative methods to measure microwear striations in their spatial orientation. The variableness of occlusal movement direction as well as the number of microwear directions per wear facet is probably due to the differing hardness/toughness properties of various food items as well as their particle size and shape. Each of these factors influence major directions of masticatory movements. Further high resolution in vivo reconstructions of masticatory occlusal movements are necessary to determine exactly which of the above food properties most directly produce specific microwear patterns upon individual facets.

Only one similar study is known whereby 2D microwear images were mated to a 3D tooth surface (Williams et al., 2009). However, this study was conducted on hadrosaurid dinosaurs, microwear images were captured with an SEM, visualized using stereographic projection techniques and is not a true virtual reality reconstruction. There are a few other studies of a similar kind but they deal only with wear facet spatial position inclusive of 3-dimensional occlusal movements without the added quantitative microwear signatures (Fiorenza et al., 2010; Fiorenza et al., 2011; Kullmer et al., 2009, 2012). Although this new method requires somewhat specialized equipment and more time and perhaps individual precision in data extraction, the novelty, depth and robustness of information produced as well as the potential widespread application warrants the effort. It might be possible to use alternate visualization methods in order to obtain the 3D VR tooth models necessary. It may also be hypothetically feasible to substitute more traditional light microscopy methods for the confocal technology employed here in order to image individual facet microwear. Each of the above suggestions could potentially broaden this new methodologies accessibility to other researchers.

Future work would include a pan- H. erectus molar sample in order to illuminate broader populational, taxonomic and dietary correlations within and among supra-regional H. erectus specimens. A larger, more heterogenous historic H/G sample would also be included in order to provide a geographically wider dietary comparative population. This method can be further extended to include and compare any and all hominin taxa as well as any organism which produces microwear upon it molars. Also, the data obtained and resultant fmw signature diagrams have the potential to be incorporated into 3D VR reconstructions of masticatory movement in extinct organisms leading to more robust anatomical and physiological investigations especially when viewed in the context of larger environmental conditions or fluctuations.

**Conclusions**

The discussion herein proposes a novel method for visualizing, quantifying, and statistically analyzing molar facet microwear in 3 dimensions. This technique
has been used in the examination of *H. erectus* as well as *Homo sapiens* molars and could be logically extended to use on any teeth that demonstrate microwear. The gross directionality information as visualized through the facet microwear vector signature diagrams can be used in analyses of masticatory movement which may yield ecodietary information. Other functional and clinical applications in dentistry and orthodontics to analyse individual chewing directions and other paramasticatory behavior can be envisioned as well.

References


