Technical Note: Occlusal Fingerprint Analysis: Quantification of Tooth Wear Pattern

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ABSTRACT Information about food ingestion and mastication behavior during the lifespan of an individual is encoded in the dental occlusal wear pattern. To decode this information, we describe a new method called occlusal fingerprint analysis (OFA). Structural parameters of wear facets on the occlusal surface of teeth are quantified from digitized casts for the interpretation of occlusal aspects. The OFA provides an individual three-dimensional dental occlusal compass that indicates the major pathways of interaction between antagonists, revealing information about development, spatial position, and enlargement of wear facets. Humans develop a very similar overall pattern of crown contacts, although specific characteristics of wear facets reflect an individual's occlusal relationships and masticatory behavior. We hypothesize that the wear pattern is a unique character and therefore valuable for individual identification. Furthermore we suggest that OFA, when further developed, may be useful for identification of behavioral, biological, and chemical factors affecting crown morphology. Am J Phys Anthropol 000:000–000, 2009.

The positional relationships of cusps provide access for the location of the primary contact areas during occlusion of upper and lower teeth (Fig. 1). The fissure pattern and cusp positions describe the major occlusal pathways for incursion and excursion movements of the antagonists. These major directions of possible movements, starting from the maximum intercuspation of the molars (centric position), are described as the occlusal compass (Kordaß and Velden, 1996; Douglass and DeVreugd, 1997; Schulz, 2003, 2008; Schulz and Winzen, 2004) (Fig. 1). Consequently, it is possible to attribute contact wear facet pairs, occurring on the occlusal surface of upper and lower teeth, to specific movements starting from the maximum intercuspation. A characteristic wear facet pattern occurs on cheek teeth in all modern great apes, *Homo sapiens* and ancestral hominoids (Maier and Schneck, 1981). Maier and Schneck (1981) described a maximum of 13 corresponding facet pairs in upper and lower molars possessing a dryopithecine cusp pattern (Fig. 1). The facets vary in number, size, and shape depending on the wear stage, absolute cusp number and morphology. The facet number increases from the beginning of the occlusal contacts until an advanced wear stage is reached, when facets start to fuse, because of the reduction in crown relief height. In heavily worn teeth there are no facets identifiable, because only a flat enamel rim, usually enclosing a large dentine basin, remains on the occlusal surface.

Following the facet labeling system of Maier and Schneck (1981) wear facet pairs 1, 4, 5, and 8 describe lateroretrusive movements of the lower jaw. Facets 2, 3, 6, and 7 are dominated by lateroprotrusion. Higher facet numbers correspond with the mediotrusion as the leading direction of the lower jaw. In facets 9, 10, and 12, the immediate side shift is of greater importance, and facets 11 and 13 seem to be in contact during medioprotrusion (Ulhaas et al., 2007; Schulz, 2008).

The contact areas and the pattern of jaw movement are in close correlation, at least during the short phase of occlusion in the chewing cycle. It is obvious that, besides horizontal motion, upward (surtrusion) and downward (detrusion) lower jaw movements are of great importance for food breakdown. The mandibular surtrusion and detrusion, not recognized in the two-dimensional occlusal compass (Fig. 1), act during mastication in combination with a horizontal translation.

Lateroprotrusion describes lower jaw pathways between laterotrusion and protrusion, forming a distolingual pathway with the upper cusp tips in the lower tooth crown and a mesiobuccal direction with the lower cusp tips in the upper teeth (Fig. 1). Medioprotrusion samples the movements between mediotrusion and protrusion towards mesiopalatinal in the upper jaw and consequently distobuccal in the lower jaw cheek teeth.

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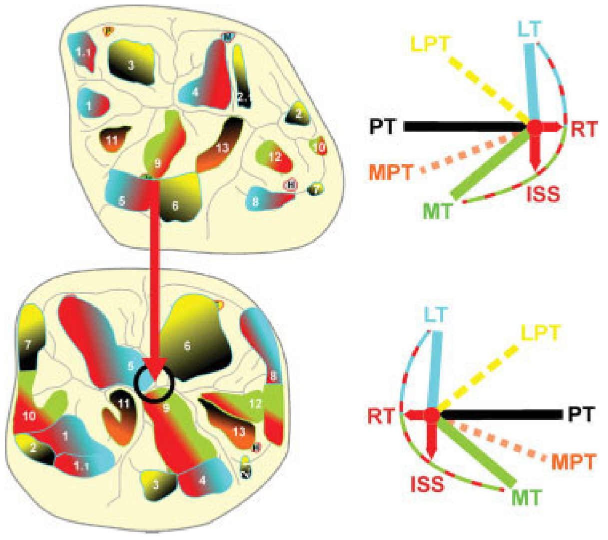

Fig. 1. Schematic illustration of complementary wear facets on upper and lower left first molars in an Angle class I occlusion; numerical system (1–13) after Maier and Schneck (1981). Arrow indicates occlusal relation in maximum intercuspation of protocone apex of the upper molars and central fovea of the lowers. The circle on the lower molar marks the position of the tip of the protocone during maximum intercuspation. Facet pairs 1, 4, 5, and 8 are in contact during lateroretrusion movements (blue/red). Facet pairs 2, 3, 6, and 7 correspond to lateroprotrusion (yellow/black), and facet pairs 9, 10, and 12 are in contact during mediotrusion and immediate side shift (green/red). Facet pairs 11 and 13 correspond to medioprotrusion (orange/black). Facets 7 and 10 in the lower first molar correspond with the second upper premolar, and facets 2, 7, and 10 in the upper first molar are in contact with the second lower molar. To the right, dental occlusal compass (after Schulz, 2003) shows major directions of horizontal occlusal movements for upper molars (above) and lower molars (below), laterotrusion (LT), retrusion (RT), lateroprotrusion (LPT), protrusion (PT), medioprotrusion (MPT), mediotrusion (MT), and immediate side shift (ISS); e.g., the occlusal compass illustrates the directed distally protrusive pathway of protocone cusp in the lower molar and mesially in the upper molar.

Although the pathways of the main movements are fan-shaped, protrusion is the only functional direction which has fixed coordinates, since both condyles of the lower jaw move parallel downward and forward (Ulhaas et al., 2007). Protrusion follows the median-sagittal plane in the lower jaw molar basins distally and in the upper jaw molar basins mesially.

There are two minor threshold areas on the occlusal compass, retrusion, and immediate side shift. The retrusion space marks a field for lower jaw backward moves in which both condyles back up into the articular area of the temporal bone. The immediate side shift indicates a transverse field where the condyle is shifted medially.

The wear pattern emerges on the contact areas because of the interaction of the antagonists during mastication. Teeth do not regenerate their primary morphology after the completion of the enamel formation, and alteration of the enamel surfaces can be observed only in terms of morphological reshaping of occlusal surfaces caused by use.

This phenomenon results in an individual wear facet pattern consisting initially of complementary pairs of facets on the occlusal surface of the antagonists (e.g., Crompton, 1971; Butler, 1973; Kay, 1977; Maier and Schneck, 1981; Ulhaas et al., 2007). Various dynamic influences lead to a gradual change of occlusal surface topology. In the course of ontogeny, this can result in a considerable loss of tooth substance on tooth crowns. The resulting relief is described here as secondary morphology.

Analyses of historical material compared to recent populations (e.g., Smith, 1984, Kaifu et al., 2003) showed that the physical properties of food particles represent a crucial factor for the mode of relief change. Presumably the composition, texture, and toughness of food, the distribution of pressure, as well as the individual direction of chewing have a considerable influence on the wear pattern. This relation has been observed on test subjects showing differences in masticatory movement, depending on the food texture provided (Nakajima et al., 2001).

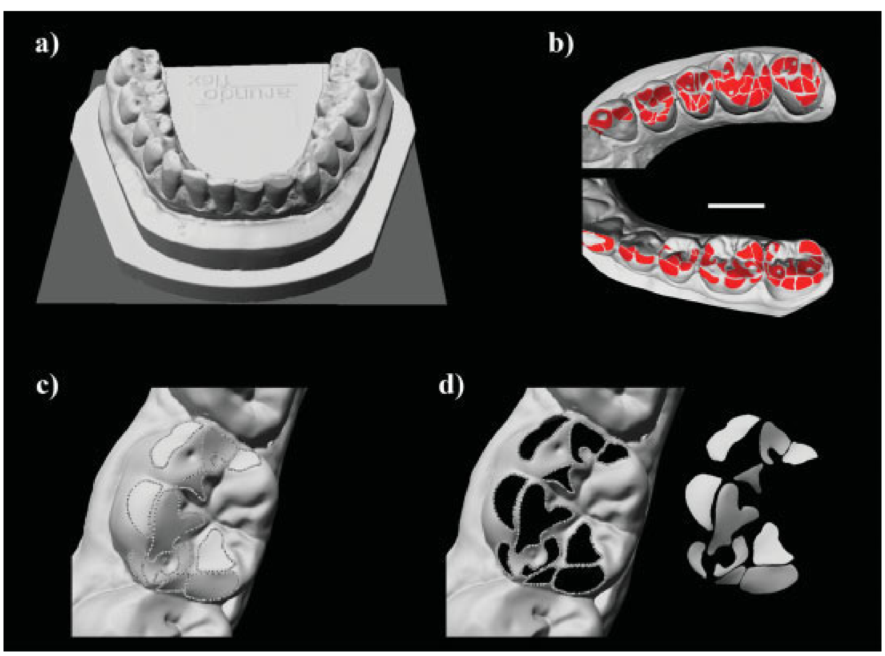

Fig. 2. (**a**) An example of computerized surface model (resolution 60 μm) of a lower dental arch acquired from 3D scanning system (optoSCAN-HE, Breuckmann GmbH); (**b**) upper and lower left cheek tooth row with digitally marked wear facets in red; (**c**) close-up of lower left first molar in occlusal view with polyline selection of wear facet margins. (**d**) segmentation of wear facet surfaces of the lower left first molar for Occlusal Fingerprint Analysis (OFA).

For the comparison and functional interpretation of tooth wear facet patterns and occlusal jaw movements we describe a new method of digital three-dimensional (3D) wear pattern analysis (Kullmer et al., 2002; Ulhaas et al., 2004, 2007) called occlusal fingerprint analysis (OFA). In contrast to traditional qualitative approaches in tooth wear assessment (e.g., Smith, 1984, Kaifu et al., 2003), the quantification of the wear facet pattern has the potential to improve the functional and comparative interpretations of dental wear. The quantitative results should ultimately enable us to characterize tooth wear depending on such factors as specific tooth morphology, occlusal relationships, food spectra, ontogenetic stages, and environment. Furthermore, we hypothesize that clear differences in the 3D occlusal compass of teeth can reveal individual differences in chewing and mastication behavior mirroring the consequences of behavioral, biological, and chemical factors (Lussi, 2006).

MATERIALS AND METHODS

As an example for the description of the OFA method, we have chosen the dentition of a lifetime vegetarian, showing a well-developed wear pattern resulting from a masticatory behavior probably due to the daily diet. The individual is a 48-year-old female, and her daily diet consists of mainly raw and cooked vegetables as well as raw salads with seeds, apples, and citrus fruits 7 days a week. The subject does not consume alcohol or soda. Four to five times a week, fruit juice is taken. The teeth have never been used as tools and there is no indication of tooth grinding such as bruxism. No dental ailment was reported. The individual does not live or work in a dusty environment.

Surface data of teeth and tooth rows were acquired from dental casts applying 3D scanning systems such as optoSCAN-HE (Breuckmann GmbH). To generate complete computerized models of tooth crowns from high resolution casts, one has to make sure that the applied acquisition technique provides surface information in a reasonable resolution (minimum 60 μm) for wear pattern analysis on human teeth (Fig. 2).

Before measuring, it is important to orientate the digital models. In our example the dental arches were perfectly pre-oriented through mounting the casts on split-cast dental plates (arundo flex, Baumann Dental GmbH) after orientation was taken with a face bow registration system (CP-KaVo Protar System, KaVo Dental GmbH) and a silicone bite, following current routines in modern dentistry. The face bow registration is based on the Camper Plane (CP), representing the *xy*-reference plane for the scanning system, the transversal plane from the face bow is parallel to the *xz*-plane, and the *yz*-plane of the coordinate system is given by the sagittal plane. The casts were mounted with dental plaster into a KaVo Protar 9 articulator onto the split-cast plates using the original registration silicone bite and the individually adjusted face bow system. This information allows us to use the split-cast plates attached to the dental arches as a reference orientation for the scanning system. Accordingly, mesiodistal orientation is reflected through the *y*-axis of the split-cast plates.

The digital models are edited in the PolyWorks 10.1 (InnovMetric Inc.) modular software package as described elsewhere (Ulhaas et al., 2004, 2007). For inspection of triangulated crown surfaces, we use IMEdit and IMInspect modules (PolyWorks 10.1, InnovMetric Inc.). These allow the creation and calculation of points, lines, planes, areas, volumes, and perimeters on triangulated surface models. Photographs of occlusal, buccal, and lingual aspects and physical casts of the specimen support the qualitative examination of areas of abrasion and wear facets.

For interactive facet mapping on each tooth crown (Fig. 2), we used the polyline tool in IMEdit (Ulhaas et al., 2004, 2007). Each wear facet was manually marked by placing polyline nodes onto the models surface. Then the facet areas were segmented, and the data were saved separately for further inspection (Fig. 2c). After the isolation of the wear pattern (Fig. 2d), we generated best-fit planes for each wear facet in the IMInspect module (Fig. 3a,b). Afterward, the normal vectors of each facet plane were visualized (Fig. 3c). Then we projected the normal vectors onto the reference plane and afterwards onto the facet planes (Fig. 3d). Now the origin of each vector was translated into an arbitrary point, and the vector lengths were standardized (e.g., 10 mm). Finally, each facet vector was color-coded depending on the dip direction (defined below), and a circle with the radius of the standard vector length was drawn in the reference plane with the vector's origin as midpoint (Fig. 3e,f). Hence, we can measure dip direction and dip angles from facet vector orientation. The spatial position of a wear facet is defined by two angles, the "dip direction" measured counter-clockwise for left and clockwise for right lower molars from the mesial point (Fig. 3g,h), and the "dip" considered as the inclination to the reference plane (CP) (Fig. 3h). The color for directions was defined through the occlusal compass color code (Schulz, 2003, 2008) in Figure 1. The 3D vector graph presents the individual 3D-occlusal compass of a tooth wear pattern showing the major directions of contacts between upper and lower dentition.

RESULTS

The wear pattern map of the example dentition shows a complex pattern of corresponding occlusal facets (Fig. 2b). For applying the OFA method, we chose as an example the lower left first molar crown (Fig. 2c). The occlusal fingerprint of the molar shows well developed facets in an incomplete facet pattern (Fig. 3e, f), lacking lateroretrusive facets 1, 1.1, and 5. The flat wear area enclosing a small dentine basin on the protoconid cusp tip is considered here as tip crushing area differing from typical wear facets by lacking a clear dip direction and marginal edges. Therefore, it is not identified as wear facet 1 (Fig. 1). From thirteen expected molar facets, as imaged in Figure 1, only eleven well-defined occlusal facets are identifiable on the crown. Predominantly, the facet dip angles are relatively steep and show values in a narrow range from 36.5° to 21.5° (Table 1). The dip directions vary reflecting the major directions of the occlusal compass. There are only two lateroretrusive facets (4 and 8) detectable. Untypically, a relatively small facet 4 is situated on the distobuccal slope of the hypoconulid, while a large facet 8 (Table 1) is developed on the distal slope of the entoconid. All four lateroprotrusive facets (2, 3, 6, 7) are well developed, and they show little variation in their dip direction (17.4°–49.6°). The buccal facets 2 and 3 are elongated and are the only wear facets on the buccal flanges of the lower first molar. Lateroretrusion facets dip direction range from 116.5° to 149.6°. Lateroprotrusion and lateroretrusion directions are considerably

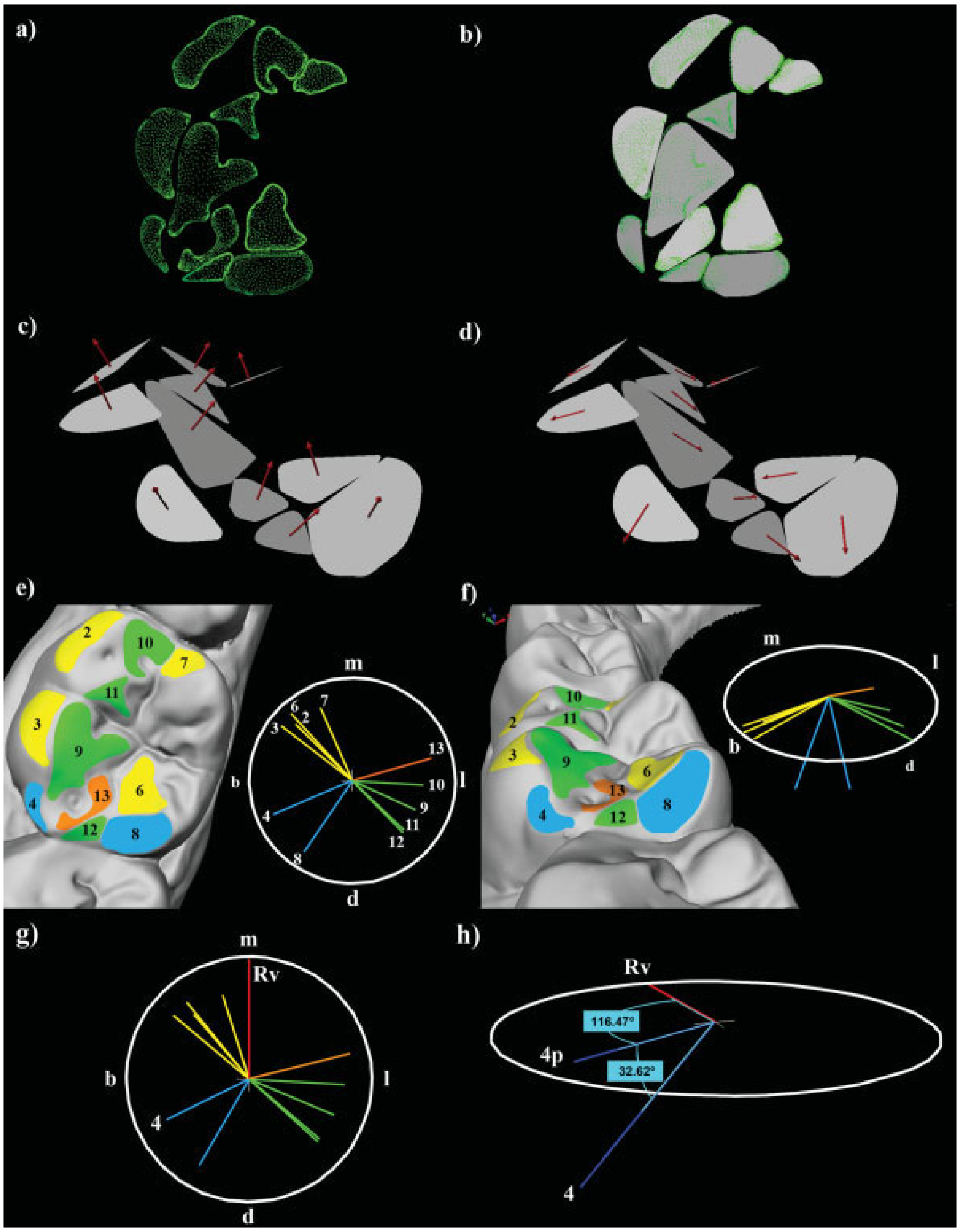

Fig. 3. (**a**) Isolated point clouds of 3D vertices (green) from wear facet surface model in the lower left molar; (**b**) Wear facet best-fit planes representing average dip direction and dip of each facet calculated in IMEdit module (Polyworks Software, InnovMetric Inc.); (**c**) visualization of normal vectors of each facet best-fit plane as red arrow; (**d**) vectors of dip direction for each facet (red arrows) after projection onto best-fit planes. (**e**) Color-coded and labeled facets of lower left molar corresponding to the 3D occlusal compass of facet vectors in occlusal view; (**f**) perspective distal view on color-coded and labeled wear facets with corresponding 3D occlusal compass; (**g**) 3D occlusal compass in occlusal view. Reference vector Rv (red arrow) points mesially, defining 0° for dip direction measuring (e.g., counter-clockwise in lower left teeth); (**h**) each wear facet, e.g., facet 4, is defined through two angles, dip direction 116.5° (between 0° and 360°) and dip angle 32.6° (between 0° and 90°). The complete facet pattern of a tooth is recorded in its individual 3D occlusal compass.

separated by a gap of 67°, while the mediotrusion facets (9–13) sample a dip direction in a range from 228.2 to 284.5°. Facets 10 (267.1°) and 13 (284.5°) are developed as mediotrusive and medioprotrusive areas, whereas well developed facets, 9 (228.2°), 11 (230°) and 12 (247.5°) exhibit a clear medioretrusive component. Facet 9 shows the largest area (Table 1) covering the complete lingual slope of the hypoconid.

Differences in occlusal relationship and in wear stages lead to an individual pattern of contact facets as it is visible in our example dentition. The specific occlusal compass of facets shows a clear retrusive moment, expressed through two lateroretrusive (4 and 8) and three medioretrusive (9, 11, 12) oriented facets. In contrast, the well developed facets 2, 3, 6, and 7 give evidence of a dominant lateroprotrusive direction. A distinctive mesial position of the lower jaw in maximum intercuspation, describes an Angle's class III occlusion relationship. This is indicated by lacking facets 1.1, and 5, and the distally positioned facets 4 and 8.

The combination of large and steep facets on the occlusal surface signifies a strong vertical component during chewing with a precise contact fitting in a balanced occlusal relationship.

DISCUSSION

The OFA method described and quantifies the occlusal wear pattern of tooth surfaces based on two angles, the area, and perimeter of wear facets (Table 1). The 3D occlusal compass (Fig. 3e–h) images the dip direction and the dip of wear facets, and therefore draws the major pathways of occlusal movements. It is possible to interpret the occlusal relationship of teeth from the individual OFA results, since in a normal Angle class I occlusal situation the expected facet pattern is known (Fig. 1).

TABLE 1. Measurements obtained from wear facets and vectors of the best-fit planes on the lower left molar in the example dentition

Facet	Perimeter (mm)	Area (mm^2)	Dip angle (°)[a]	Dip direction angle (°)[b]
Facet 2	10.46	6.01	36.5	40
Facet 3	10.04	5.79	25	49.6
Facet 4	6.19	1.89	32.6	116.5
Facet 6	8.91	4.66	25.6	38.9
Facet 7	6.45	2.85	34.9	17.4
Facet 8	9.7	6	27.4	149.6
Facet 9	14.46	8.67	33.2	247.5
Facet 10	9.72	4.34	30.6	267.1
Facet 11	6.97	1.86	32.9	230
Facet 12	5.4	1.65	32.2	228.2
Facet 13	8.87	2.26	21.5	284.5

[a] Angle between vector and vector projected onto the reference plane.
[b] Angle between Reference vector (Rv) and vectors projected onto the reference plane.

An Angle class III occlusion is inferred from lacking contact facet 5 in advanced wear. The color-coded vector graph of the 3D compass confers direct information about the relative movements (Fig. 3). The quantification augments the evaluation of the vertical and the lateral components of the occlusion. Additionally, the correlation between facet directions and dip angles may reflect the mechanical properties of foodstuff processed (Lucas, 2004; Lucas and Luke, 1984). In dental anthropology and paleontology conclusions about the food composition are drawn from dental wear (e.g., Crompton and Hiiemae, 1970; Molnar, 1971, 1972; Crompton, 1971; Butler, 1973; Kay, 1973; Kay and Hiiemae, 1974; Maier and Schneck, 1981; Teaford, 1983; Janis, 1984, 1990; Maier, 1984; Strait 1993a,b; Ungar and Williamson, 2000; Ungar and M'Kirera 2003, M'Kirera and Ungar 2003, Ulhaas et al., 2004, 2007). Nevertheless, the role of food particles in generating wear is still a matter of debate (Lucas, 2004), because the development of wear facets is described as a multicausal phenomenon (Lussi, 2006). Behavioral, biological, and chemical factors responsible for the loss of enamel on the tooth surface are in discussion (Lussi, 2006).

We assume the specific wear pattern of our vegetarian volunteer recorded by OFA of the first molar is providing information about nutrition and daily eating behavior. The quantitative results about size and steepness in combination with the qualitative description of the edged margins in the prominent wear facets demonstrate that a high lateral reaction force must be present to shape such areas. Following simple mechanical principles, this indicates a higher cutting and shearing capability at the wear facets compared to crushing and grinding conditions, which would create much flatter surfaces with higher vertical reaction forces. In our case, the daily vegetarian diet of the individual consists mainly of raw and cooked vegetables, lettuce, apples, citrus fruits, seeds, and nuts. Additionally, fresh fruit juice is consumed daily. We conclude that the individual wear pattern in our example contains dietary information. It suggests that the chewing of mainly raw vegetarian food materials, such as cabbage, celery, carrot, kohlrabi, and apple, led to a distinctive wear pattern. One can expect that a large portion of hard and brittle materials such as grass leaves and grains *etc.* in the daily diet would produce more plateau-like and fused wear facets with less inclination and varying dip directions due to more crushing and grinding activities. A larger amount of elastic and soft foods such as cooked meat probably would reduce sharp margins of wear facets on the occlusal relief due to polishing effects. We predict that meat would produce intermediate inclined facet patterns depending *inter alia* on its preparation techniques. This is not observable in our example dentition.

These assumptions about the relationship of OFA and diet need to be tested by comparing several vegetarians' occlusal fingerprints with those of non-vegetarians. The OFA, as described in this study, introduces an objective approach for the comparison of occlusal wear patterns. The method provides the opportunity for functional interpretations to evaluate the composition of food, e.g., in historical and fossil anthropological samples. This will help to quantitatively compare occlusal differences, i.e., between vegetarian and nonvegetarian populations. The application of OFA in paleoanthropological samples will encourage studies in dental functional morphology investigating the evolutionary changes in dental food processing and tool use for food preparation. Furthermore, forensic investigations can benefit from utilizing OFA for the identification of tooth associations in an assemblage of isolated tooth crowns.

Generally, in modern Homo sapiens societies tooth wear seems to be less distinctive, since foodstuffs are usually softened through cooking and other preparation processes. Especially in industrial countries progressive tooth wear is usually interpreted as a pathological phenomenon resulting from neuromuscular occlusal reaction and non-masticatory effects mainly occurring during sleep (Ohayon et al., 2001). Accurate knowledge of the processes of change in the dentition, associated with the development of attritional occlusion is necessary to truly understand how a reduction of wear in modern societies is affecting our oral health (Kaifu et al., 2003). Obviously, the use of teeth in *H. sapiens* has changed dramatically, at least since industrialization has virtually eliminated natural selection pressure on efficient dentitions.

The OFA method provides a new quantitative tool for comparative studies to understand the causes and importance of tooth wear, a dental phenomenon observable in almost all mammalian dentitions.

Mechanically, teeth are to be regarded as tools for food ingestion and breakdown, and numerous studies show a clear correlation between the efficiency of the dentition and the shape and relief change on its occlusal surfaces (Lucas, 2004). The morphology of antagonists is adaptable because of attrition and abrasion of enamel particles caused by various factors, observable through the comparison of complementary facets fitting exactly at a certain stage of occlusion. Future studies will investigate how beneficial the OFA method can be, e.g., for the determination of individual age, the association assessment of isolated teeth, or the evaluation of the dietary spectra in ancestral populations. Further research will also help to determine if OFA can be useful for modern dentistry.

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LITERATURE CITED

Butler PM. 1973. Molar wear facets of early tertiary North American Primates. In: Zingeser MR, editor. Craniofacial biology of primates, Vol. 3, Symposia of the Fourth International Congress of Primatology. Basel: Karger. p 1–27.

Crompton AW. 1971. The origin of the tribosphenic molar. Zool J Linn Soc (50 Suppl. 1):65–87.

Crompton AW, Hiiemae KM. 1970. Functional occlusion and mandibular movements during occlusion in the American opossum. Didelphis marsupialis. L Zool J Linn Soc 49: 21–47.

Douglass GD, DeVreugd RT. 1997. The dynamics of occlusal relationships. In: McNeill C, editor. Science and practice of occlusion. Illinois: Quintessence. p 69–78.

Janis CM. 1984. Predictions of primate diets from molar wear pattern. In: Chivers DJ, Wood BA, Bilsborough A, editors. Food acquisition and processing in primates. New York: Plenum. p 331–340.

Janis CM. 1990. The correlation between diet and dental wear in herbivorous mammals, and its relationship to the determination of diets of extinct species. In: Boucot AJ, editor. Evolutionary paleobiology of behaviour and coevolution. Amsterdam: Elsevier Science. p 241–259.

Kaifu Y, Kasai K, Townsend GC, Richards LC. 2003. Tooth wear and the "design" of the human dentition: a perspective from evolutionary medicine. Yrbk Phys Anthropol 46: 47–61.

Kay RF. 1973. Mastication, molar tooth structure and diet in primates, dissertation. Yale: Yale University.

Kay RF. 1977. The evolution of molar occlusion in the Cercopithecoidea and early catarrhines. Am J Phys Anthrop 46:327–352.

Kay RF, Hiiemae KM. 1974. Mastication in Galago crassicaudatus, a cinefluorographic occlusal study. In: Martin RD, Doyle GA, Walker A, editors. Prosimian biology. London: Duckworth. p 501–503.

Kordaß B, Velden P. 1996. Der individuelle okklusale Kompaß. Computer- gestützte Aufzeichnungen der okklusalen Bewegungsfunktion für die Aufwachstechnik nach Polz und Schulz. Dental Lab 44:1595–1601.

Kullmer O, Huck M, Engel K, Schrenk F, Bromage T. 2002. Hominid Tooth Pattern Database (HOTPAD) derived from optical 3D topometry. In: Mafart B, Delingette H, editors. Three-dimensional imaging in paleoanthropology and prehistoric archaeology. Liege, Acts of the XIVth UISPP Congress, BAR Int. Ser. 1049. p 71–82.

Lucas PW. 2004. Dental functional morphology—how teeth work. Cambridge: University Press.

Lucas PW, Luke DA. 1984. Chewing it over: basic principles in food breakdown. In: Chivers DC, Wood BA, Bilsborough A, editors. Food acquisition and processing in primates. New York: Plenum. p 283–301.

Lussi A, editor. 2006. Dental erosion—from diagnosis to therapy. In: Whitford GM, series editor. Monographs in oral science, Vol. 20. Basel: Karger.

Maier W. 1984. Tooth morphology and dietary specialization. In: Chivers DJ, Wood BA, Bilsborough A, editors. Food acquisition and processing in primates. New York: Plenum. p 303–330.

Maier W, Schneck G. 1981. Konstruktionsmorphologische Untersuchungen am Gebiß der hominoiden Primaten. Z Morph Anthrop 72:127–169.

M'Kirera FM, Ungar PS. 2003. Occlusal relief changes with molar wear in Pan troglodytes troglodytes and Gorilla gorilla gorilla. Am J Primatol 60:31–41.

Molnar S. 1971. Human tooth wear, tooth function and cultural variation. Am J Phys Anthropol 34:175–190.

Molnar S. 1972. Tooth wear and culture: a survey of tooth functions among some prehistoric populations. Curr Anthropol 13:511–526.

Nakajima J, Hideshima M, Takahashi M, Taniguchi H, Ohyama T. 2001. masticatory mandibular movements of different foods textures related to onomatopoetic words. J Med Dent Sci 48:121–129.

Ohayon MM, Kasey KL, Guilleminault C. 2001. Risk factors for sleep bruxism in general population. Chest 119:53–61.

Schulz D. 2003. NAT—Die Naturgemäße Aufwachstechnik. Teil 1: Der anteriore Bereich. Fuchstal: Teamwork Media.

Schulz D. 2008. NAT—Die Naturgemäße Aufwachstechnik. Teil 2: Der posteriore Bereich. Fuchstal: Teamwork Media.

Schulz D, Winzen O. 2004. Basiswissen zur Datenübertragung. Fuchstal: Teamwork Media.

Smith BH. 1984. Pattern of molar wear in hunter-gatherers and agriculturalists. Am J Phys Anthropol 63:39–56.

Strait SG. 1993a. Differences in occlusal morphology and molar size in frugivores and faunivores. J Hum Evol 25:471–482.

Strait SG. 1993b. Molar morphology and food texture among small-bodied insectivorous mammals. J Mamm 74:391–402.

Teaford MF. 1983. The morphology and wear of the lingual notch in macaques and langurs. Am J Phys Anthrop 60:7–14.

Ulhaas L, Kullmer O, Schrenk F. 2007. Tooth wear diversity in early hominid molars—a case study. In: Bailey S, Hublin JJ, editors. Dental perspectives on human evolution: state of the art research in dental anthropology. Dordrecht: Springer. p 369–390.

Ulhaas L, Kullmer O, Schrenk F, Henke W. 2004. A new 3-d approach to determine functional morphology of cercopithecoid molars. Ann Anat 186:487–493.

Ungar PS, M'Kirera F. 2003. A solution to the worn tooth conundrum in primate functional anatomy. Proc Natl Acad Sci USA 100:3874–3877.

Ungar PS, Williamson M. 2000. Exploring the effects of tooth wear on functional morphology: a preliminary study using dental topographic analysis. Paleont Electron 1. Available: http://www-odp.tamu.edu/paleo/2000_1/gorilla/main.htm.