doi 10.4436/jass.90004

JASs Invited Reviews
Journal of Anthropological Sciences
Vol. 90 (2012), pp. 7-31

Scratching the surface? The use of surface scanning in physical and paleoanthropology

Martin Friess

Département Hommes, Natures, Sociétés, Museum national d'Histoire naturelle, 57, rue Cuvier, CP 140, 75231 Paris, cedex 05, France
e-mail: friess@mnhn.fr

Summary - *As virtual anthropology is becoming more and more ubiquitous, so are the means to acquire, process and analyze 3D data. Among these means, surface scanners have gained a prominent place for a variety of reasons that make them useful to anthropologists. While surface scanning has several advantages over other 3D devices (digitizers, volume scanners etc.), it does come with one obvious drawback – internal structures remain invisible. Still, surface scanning is emerging as a convenient tool for anthropometric and especially paleoanthropological research. It extends our ability to quantify phenotypic variation, its non-destructive nature contributes to specimen conservation, and it can become an integral part of virtual anthropology, thus doing more than just "scratching the surface".*

Keywords - *Virtual anthropology, 3D scanning, Morphometrics, Conservation.*

Introduction

The last 25 years have witnessed an increased use of three-dimensional image capture and analysis in many areas of anthropological research. During these two and a half decades, coordinate digitizers and medical/industrial CT scanners have become the most widespread instruments for capturing 3D information. More recently, surface scanning technologies based on non-ionizing radiation (e.g. visible light) have been added to the anthropologist's toolbox. Today's surface scanning is largely a development from analog 3D photogrammetry, of which anthropological applications can be found sporadically over the course of the last fifty years (Savara, 1965; Teaford, 1982; Ashizawa *et al.*, 1985; Coblentz *et al.*, 1991). In general, such applications have remained relatively rare until the 90s, when digital imaging and signal processing became available and computing power more affordable. Medical applications and anthropometric surveys on living subjects were the first domains to benefit from 3D scanning (Vannier *et al.*, 1993; Vannier & Robinette, 1995; Bush & Antonyshyn 1996; Linney *et al.*, 1997; Robinette *et al.*, 1999), before paleontologists and (paleo)anthropologists discovered its potential (Jones & Rioux, 1997; Rioux, 1997; Aiello *et al.*, 1998; Lyons *et al.*, 2000). Thus, while analog photogrammetry has a rather long history in anthropology, and neighboring fields have begun using digital variants early on, 3D scanning is a relatively recent tool for the study of human evolution and variability.

Tocheri (2009) offers a practical introduction to surface scanning and gives an example of how to extract quantitative data relevant to functional morphology. The present paper provides an overview of current applications in (paleo)anthropology and engages in a more detailed discussion of some important technical aspects, with the intent to help future users assess the potential of surface scanning for their specific research goals.

Surface scanning: how it works, and what is relevant to the user

Surface scanning refers to optical systems that measure objects through visible light (i.e.

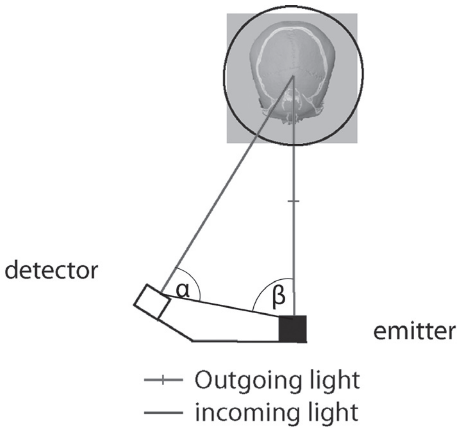

Fig. 1 - Close-range scanners operate according to the triangulation principle, where the position of emitter, detector and object are defined by known angles α and β, and their distance (triangulation base). The triangulation principle causes parts of the object to remain "invisible" for the scanner. In the case of a human skull (seen from above), the apex of the orbits are often missed.

non-ionizing radiation) and generate dense 3D polygonal meshes. The resulting data are restricted to the outer shell of an object, which distinguishes surface scanning from volume scanning (CT, synchrotron, MRI, Terahertz, infrared). Surface and volume data can be used for morphometric analysis, archiving, visualization, rapid prototyping, and other purposes. While technical details of available scanners are subject to constant technological progress and market evolution, and therefore of limited life expectancy, some general aspects are likely to remain valid for the anthropological end-user and the successful application to a given question.

Current scanner models can differ significantly by light source, field of view, resolution, and measurement principle, but they all have in common the use of visible light as opposed to x-rays or synchrotron radiation for the 3D reconstruction. Volume and surface scanning are both non-contact methods, and therefore respond to increasing requirements in conservation, cultural heritage or repatriation programs. The absence of ionizing radiation makes surface scanning also a non-destructive/non-invasive measurement tool (see below).

3D imaging systems can use passive image capture (photogrammetry) or active light projection. Digital photogrammetric systems continue to be used, e.g. for medical applications (Lane & Harrel, 2008; Maal *et al.*, 2010; Wei *et al.*, 2011), but systems that actively project one or multiple light sources (typically laser or white light) have become more and more common. A major distinction is made with respect to the underlying principle of computing xyz coordinates, the most common being time-of-flight and triangulation.

Time-of-flight (TOF)

Scanners of this type measure the time required by a light source to be reflected back to the point of origin. A light source (typically laser) is projected onto the object/area of interest, and its reflection is captured by a detector. Such a system functions as a range finder, or electronic distance measurement for single points. By changing the position of the light source (e.g. through mirrors) the number of measured points is multiplied (tens of thousands per second), thus allowing for a large area to be captured in a relatively short time. Because the underlying measurement principle depends on the ability to accurately measure the time/distance travelled by light (approximately 3.3^{-9} seconds for 1m), such long-range scanners are often used for large to very large areas of interest, for instance in archaeology (González-Aguilera *et al.*, 2009).

Triangulation

Medium-sized to small areas of interests, such as a primate skull, are more accurately measured by triangulation-based scanners. Triangulation-based scanner systems emit light and capture its reflection by one or more cameras. A software algorithm triangulates the xyz- coordinates of the light reflection on the basis of the known distance and angle between light source and detector(s) (Fig. 1). A triangulation-based scanner emits a light line, rather than a point. Repositioning of either the scanner or the object allows for a more or less complete capture of the visible geometry.

Laser vs. structured light

Triangulation-based scanners typically operate with laser or structured light (Fig. 2). The former somewhat restricts its usability in anthropometry: laser light is classified on the basis of its wave length and energy, and its use on human subjects is regulated by the IEC 60825-1 standard (IEC, 2001). Only class 1 and 2 laser light sources are considered eye-safe and thus suitable for living subjects without any restriction. The higher the maximum permitted exposure (i.e. the higher the class) the higher the risk of eye and skin damage. Industrial applications constitute an important segment of the surface scan market, which explains the relative abundance of class 2 or higher lasers. Laser scanners generally operate better in an environment where other light sources, especially daylight, cannot be controlled. Their optical resolution and accuracy depend, among other factors, on the diffraction and wavelength of the laser, especially when phase shift is used (Fangi *et al.*, 2001; Beraldin, 2004).

White light causes no known harm for soft or hard tissue, its use with human subjects is therefore unrestricted. On the other hand, it does require a stricter control of environmental light, because surface scanners will tend to capture the entire visible light spectrum, including unwanted sources.

Most commonly, structured light scanners use fringe (Moiré) projection and/or phase shift technology. Moiré patterns are a series of non-random linear projections onto the surface of the object. Multiple captures of the same pattern, slightly shifted, improve the measurement accuracy, but increase acquisition times (Bathow *et al.*, 2010).

White light scanners are sometimes considered to operate slightly faster than laser scanners (Lane & Harrel, 2008), but this claim is difficult to assess in reality, given that several parameters, such as area of interest and optical resolution, affect the overall acquisition time.

Both laser and white light scanners are routinely and without restriction used on skeletal material and even cartilage (Gu *et al.*, 2008), but are of limited use for dark objects or translucent/reflective structures such as tooth enamel (Slizewski *et al.*, 2010). Several manufacturers now offer systems that use blue light, as the shorter wavelength tends to not only overcome these limitations but also increase the resolution (e.g. Breuckmann, David-laserscanner, GOM, Steinbichler).

Fig. 2 - Laser – versus fringe projection scanner. Scanners using a class 1 or 2 laser are considered eye-safe and can be used on live subjects. The Colour version is available online at JASs web site.

Surface scanning: step by step

The simplified processes involved in surface scanning can be summarized as follows:

1) Acquisition (involving triangulation of multiple images)
2) Aligning and merging of acquired images
3) Fusion
4) Noise reduction filtering
5) Gap-filling

Steps 2 and 3 can be loosely seen as processing of scan images, while steps 4 and 5 fall under

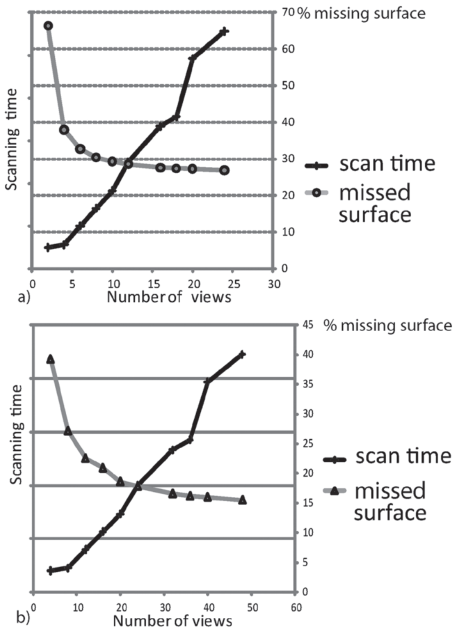

Fig. 3 - Efficiency of surface scanning. Every additional scan in the same orientation adds less surface data than the previous one. A) Single orientation efficiency curve b) dual orientation efficiency curve. Note that the curve patterns remain identical, but the % of missed surface becomes smaller. The Colour version is available online at JASs web site.

post-processing of the final model. Noise reduction can be performed repeatedly and at various stages of the scanning process, and it may be implemented without operator control. Gap-filling is optional and typically more efficient if performed as last step. It requires detailed knowledge of the scanned object. Depending on the manufacturer, processing and post-processing steps can require operator interaction or can be automated, and thus greatly affect duration of the entire process. Compared to CT-scanning, where acquisition times are very short and post-processing (segmentation) relatively time-consuming, acquisition with a surface scanner tends to be longer, post-processing shorter.

Regardless of the light source and computational principle, a single acquisition of any surface scanner is ultimately a very dense 3D point cloud representing the geometry "as seen" in the current field of view. Because surface scanners are more akin to photography, and because a point in space can only be measured if it is "seen" simultaneously by the emitter and the detector, any surface scanner yields, by design, incomplete data. Undercuts and shadowed areas (self-occlusions), as well as areas that exceed the current field of view must be acquired by subsequent views and fitted to previous ones. However, very deep/narrow structures may remain "invisible" if they are beyond the triangulation angle. In a primate skull, this is often the case for the inside of the nasal aperture, or the apex of the orbit (Fig. 1, additional online material).

This raises the issue of efficient use of surface scanning, especially when compared to volume scanners. More acquisitions generate more surface data, but also increase acquisition and post-processing times, especially in the absence of automation (e.g. a rotary table). The non-linear relation between the number of acquisitions and non-redundant data quantity follows a curve known in economics as the law of diminishing returns (Turgot, 1767; Cannan, 1892): the relative gain in captured geometry becomes smaller and smaller as views are added (Fig. 3). The crux of the problem can be somewhat alleviated, but not fundamentally altered, by reorienting the specimen, or by multiplying the number of cameras (simultaneous acquisitions). Multiple cameras can be found in some models, for instance in scanners that are specifically designed to measure living subjects (faces and whole bodies, e.g. Breuckmann, Cyberware). In these applications inadvertent movement between acquisitions is of additional concern, and very fast acquisition times are required. Multiple cameras may come at the expense of portability and, thus, are less likely to benefit those paleoanthropological applications that require multiple scanning locations (e.g. museums). In practice, when scanning large numbers of objects with similar geometry, it may be useful to determine the optimal ratio between the number of acquisitions and the resulting object coverage (Fig. 3), and balance it in relation to scientific goals. The best strategy will also depend on the degree of automation: a fully programmable rotating/tilting table will provide greatest latitude for a variety of objects. In the absence of such a device, or when only constant rotation angles can be programmed, a more intuitive approach (Tocheri, 2009) may be more efficient. Under such circumstances, experience in using a surface scanner will influence efficiency and data quality.

Depending on manufacturer/model and associated software features, fitting two or more views ("aligning", "matching", "registering" according to some manufacturers' terminology) is either done automatically, or by manually selecting at least three corresponding points. Automatic matching is typically achieved through the use of a tracking system (e.g. Handyscan, Polhemus,) or the above mentioned rotary platform, which is controlled by the scan software and moves the object by defined angles. Other automated solutions require the use of reference points inside the measurement volume, sometimes attached to the object itself, which is often incompatible with conservational needs in paleoanthropology. The final match of two or more views (fusion) involves some variant of the iterative closest point algorithm (Besl & McKay, 1992; Rusinkiewicz & Levoy, 2001), which uses the overlapping geometry between two views to align the point clouds.

In sum, the typical surface scanning process consists of oversampling the object of interest through multiple views, matching the views, eliminating redundant points and then fusing all views into a single point cloud object. This point cloud can then be converted into a polygonal mesh (a triangulated point cloud) and rendered as a visible/measurable surface. Because raw data include redundant points as well as variable amounts of noise, some degree of post-processing is required. Some post-processing steps are controlled by the scanner software, and, depending on manufacturer/software capabilities, some can be controlled by the operator. Some manufacturers provide proprietary software solutions, while others opt for third-party packages, in which case much of the post-processing between scanners by two different manufacturers becomes somewhat comparable. The most common commercial software solutions are Geomagic Studio®, Polyworks®, and Rapidform®. Meshlab is freeware and offers many tools for (post-) processing surface scans.

Regardless of what post-processing software is used, the triangulation of the initial xyz coordinates, which is essential to accuracy and precision, is specific to each manufacturer.

Among the most common user-controllable post-processing steps are decimation, smoothing, and gap-filling. Depending on the ultimate purpose of the 3D models, these steps are not strictly necessary but will improve data management and analysis.

Decimation is a process by which the total number of polygons in a mesh is reduced while the original geometry is preserved as much as possible. The major benefit of decimating a mesh is a significant reduction in file size, thus speeding up all subsequent processing and easing archive management. Decimation is lossy by design, i.e. actual data points are removed permanently from the file. The question then is the same as in other areas of data compression (audio, video): at what level does the difference become noticeable? The answer depends, as does the outcome of decimation, on the native resolution, the algorithm and number of iterations used, and most pertinently on what one intends to do with the data: if the purpose is a virtual gallery accessible on the web, then very high decimation/low detail is probably desired or unavoidable. If the purpose is to identify/measure features in the submillimeter range, such as dental wear facets or certain craniofacial sutures, then even small amounts of decimation may be detrimental. Decimation should be tested for a given dataset and purpose. For instance, in the case of human crania, scanned at 0.26 mm resolution, decimation rates of 25-50% are virtually without effect for landmark extraction. Using the same setup and object, loss of detail can be seen when point clouds are reduced to 10% of their original size (Fig. 4).

There are many applicable clean/repair filters for polygonal meshes. Smoothing is one of them,

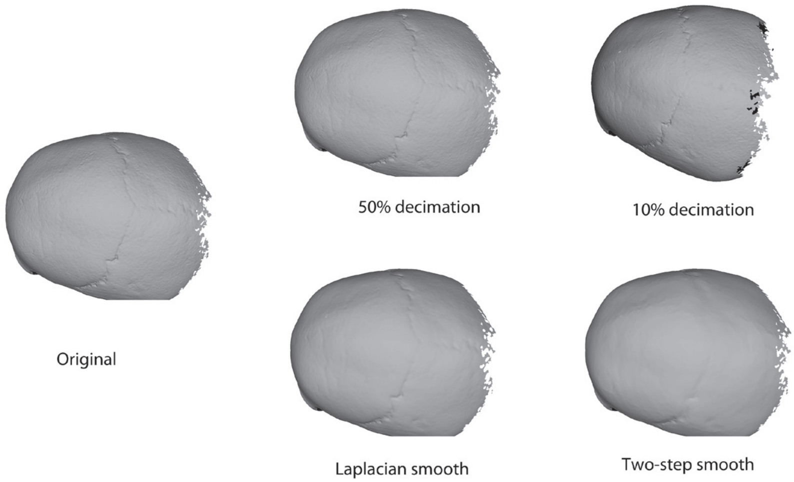

Fig. 4 - Effects of decimation and smoothing on mesh quality. Percentages indicate the amount of preserved original vertices. Note the successive loss of detail in the bregma region and along the sagittal suture. All operations performed in Meshlab.

and it is sometimes part of the automatic post-processing routine, for it results in an apparently cleaner surface and can remove scanner noise. Surface scan data are considered noisy, in the sense that the triangulation algorithm will connect points to triangles in a way that can result in uneven edges, intersecting faces, reversed orientations, holes, and other artifacts. A smoothing filter will reduce some of this noise by moving vertices based on the position of neighboring points, thus recreating meshes with more even edges (Freitag & Ollivier-Gooch, 1997; Amenta *et al.*, 1999; Jones *et al.*, 2003). One possible risk, at least with earlier smoothing filters, is the reduction or loss of real edges (features) and absolute volume. Some smoothing algorithms (e.g. Laplacian) will preserve the connectivity (triangulation), but all alter the shape, which may be considered undesirable in most anthropological applications. In the case of CT-scan data, however, some smoothing is necessary to eliminate the stair-stepping effect (see Olejniczak *et al.*, 2010).

Most post-processing steps, especially when combined, will have an impact on mesh quality and accuracy, some beneficial, some detrimental. The more control the software offers, the smaller the risk becomes. A sound strategy is to keep a copy of the unprocessed mesh for reference and to compare it to the processed mesh after each step before defining a standard operating procedure.

Performance of surface scanners

A critical step in deciding which scanning device to pick for which purpose can be filed under 'performance evaluation'. Such evaluations are often part of a certification process according to industry standards (Luhmann & Wendt, 2000; Rautenberg, 2000), which is beyond the scope of this paper. From the anthropologist's perspective, evaluating the performance of a 3D scanner should take into account the specifics of anthropological objects and the use that will be made of the 3D data. The list of parameters that are most relevant for the end-user should include measurement volume, resolution, accuracy/precision, portability, acquisition speed, and cost.

All of these parameters are more or less closely interrelated, though cost is probably more independent and therefore more variable than others.

Measurement volume, or field of view (FOV), determines the size of the object that can be acquired in a single pass. It is defined by the dimensions of the field of view of the camera(s). Objects that are larger than this field of view can still be scanned by moving the scanner or the object and rescanning, but this may lead to a significant multiplication of acquisitions, and therefore to decreased efficiency.

There is no standard set of FOV among scan manufacturers, but image diagonals of 100-300 mm are common, and quite suitable for most primate skeletal elements. Several models can be equipped with a FOV below 100 mm, which is suitable for teeth, while whole-body scanners have diagonals up to 2500 mm. Several models come with interchangeable lenses, thus offering a range of FOV (e.g. Breuckmann, GOM, Minolta).

The resolution of a surface scanner is usually a function of pixel size of the camera, a charge-coupled device (CCD), i.e. the number of pixels per millimeter of the field of view. Thus, the dimensions of the FOV and the resolution are intimately related: the smaller the FOV the higher the resolution for a given CCD. The typical pixel size ranges for medium to small objects vary between 500 and 20 microns, though better and worse exist. For most anthropometric applications, these resolutions are probably sufficient.

A first critical step is to determine the FOV size required for the objects one intends to scan. The next step is to decide whether the resolution that the scanner yields for this FOV is sufficient for the measurements/features that are sought. One should bear in mind though, that the pixel size only determines the theoretical resolution of a system, which in practice is rarely obtained. The reason for this is that in the case of an optical scanner, the parameters accuracy and precision will add error to the data, thus effectively increasing the size of distinguishable features.

Accuracy and precision of optical measurement systems are less obvious performance parameters, and a lack of internationally recognized standards has contributed to some uncertainty in this area. In metrology, accuracy is defined as the closeness between a measured and a known quantity, while precision describes the closeness between repeated measurements (JCGM, 2008). Thus, accuracy refers to the deviation between measurement and true value, whereas precision measures the consistency, or repeatability, of the generated measurements regardless of their accuracy. Accuracy is often expressed by the mean difference between a known and measured quantity, while precision is measured by the standard deviation or other measures, such as variance or coefficient of variation (but see Kohn & Cheverud, 1992). Repeatability can also be used to measure the difference between two devices. Manufacturers variably use resolution, accuracy and/or precision to characterize their systems, without always making clear how these were defined or assessed. Overall accuracy and precision of surface scanners depend on a number of components, including the pixel size, lens quality, support structure (tripod, articulated arm, a coordinate-measuring machine etc.), triangulation and matching algorithm. Their assessment usually targets the end result of the entire system (Rautenberg, 2000). Several difficulties with applying existing standards for optical systems to surface scanners have been identified (Bathow *et al.*, 2010): scanners differ vastly in volume and resolution, they measure more than one point simultaneously, can be moved between acquisitions, and the number of acquisitions and the lenses used are the operator's choice. One existing standard that provides specific protocols for assessing acceptance and verification for optical 3D scanners is the VDI/VDE 2634/3 (VDI, 2008), but it is not internationally recognized. Tests under this standard involve the ability to correctly determine the radius of a sphere, the distance between two spheres, and the flatness error of a certified plane. To make different measurement volumes comparable (from teeth to whole bodies) and performance certifiable, the errors are evaluated as a percentage of the FOV. Spec sheets provided by manufacturers, however, often give performance measures in absolute values, which are also more intuitive for end-users. Regardless of what performance values are considered, chances are, they have been obtained on calibrated/certified, machined objects that are uniform and without texture. As a consequence, different scanner specs are not easy to compare, and may not say much about a scanner's ability to operate well with organic samples. The seriously interested buyer will be best off testing different models on his/her material before making a final decision.

A number of papers have investigated the suitability of a specific scanner for specific anthropometric tasks, and these studies provide some valuable insight. Since accuracy can only be evaluated through the use of a calibrated object (of certified/known dimensions), a biological organism is unsuitable for such studies. Studies referring to 'accuracy' of body measurements consider caliper measurements as the gold-standard and test how closely they are matched by 3D measurements. This is more akin to testing precision/repeatability, which should not be confused with accuracy. Repeatability/precision studies are particularly useful for landmark-based linear measurements ('classic anthropometry'). As any user will realize immediately, locating landmarks on a real object and on a computer screen can be two different things, especially when these points are located on soft tissue. Precision studies on hard tissue therefore tend to yield results that differ from studies involving living subjects, where actual contact (and possibly movement) changes the position of the point through compression.

Aldridge *at al.* (2005) observe high degrees of precision and repeatability in facial dimensions taken from a 3D photogrammetry system, but do not compare their data to caliper measurements. Conversely, Weinberg *et al.* (2006) report significant differences in precision between three measurement techniques (calipers and two 3D systems). They also note significant differences in 9 out of 12 linear dimensions. However, all reported differences are below 1 mm. Kovacs *et al.* (2006b) report an average difference of 1.3 mm and a standard deviation of 5.7 mm for digitally versus manually taken facial measurements. This would indicate, according to the authors' terminology, 'fair' consistency between manual and 3D measurements, but poor precision within 3D. A similarly designed study using a dummy head (Kovacs *et al.*, 2006a) unfortunately does not provide mean or standard deviation, leaving the question of soft tissue as source of such poor precision unanswered.

Ghoddousi *et al.* (2007) compared manual, 3D photogrammetry (as well as 2D photogrammetry, not considered here) facial measurements and report a mean difference of 0.23 mm (14 dimensions on 6 subjects), which would suggest high consistency between calipers and 3D data. The question whether error within each technique is similar, was not addressed. Comparable differences have been reported by Fourie *et al.* (2011), for CT, surface scan and 3D photogrammetry of cadaver heads (7 individuals, 15 landmarks). The small sample sizes in both these studies may account in part for such small differences. At least one study (Enciso *et al.*, 2004) has yielded significant differences in head dimensions between 3D images and coordinate digitizers, while Gornick (2011) reports high "accuracy" between the two, which suggests that they are highly precise.

Still within the realm of the living, the picture for large-scale dimensions (whole-body anthropometry) is much bleaker, though not necessarily less ambiguous: several studies (Lu & Wang, 2010; Kouchi & Mochimaru, 2008, 2011) on whole body data demonstrate significant differences between calipers and 3D measurement techniques, as well as different degrees of error within each technique. They are not conclusive as to what causes these differences, though it seems likely that soft tissue (compressible landmarks) is a major source of error, as suggested by Ma *et al.* (2009).

More relevant to paleoanthropology, Sholts *et al.* (2010a) compare surface scan-derived and microscribed cranial landmark precision and conclude that the former exhibit slightly lower precision for type 1 landmarks (*sensu* Bookstein, 1991), but slightly higher precision for type 3 landmarks. Based on their results, the precision of surface scan data of human skulls is around 1 mm, thus matching the standard permissible error in craniometrics (Bräuer & Knußmann, 1988). Interobserver error was also investigated and found to vary by device, but not by experience.

Finally, Guidi *et al.* (2007) compare precision of three different scanners, two of which are common among paleoanthropologists (Nextengine®

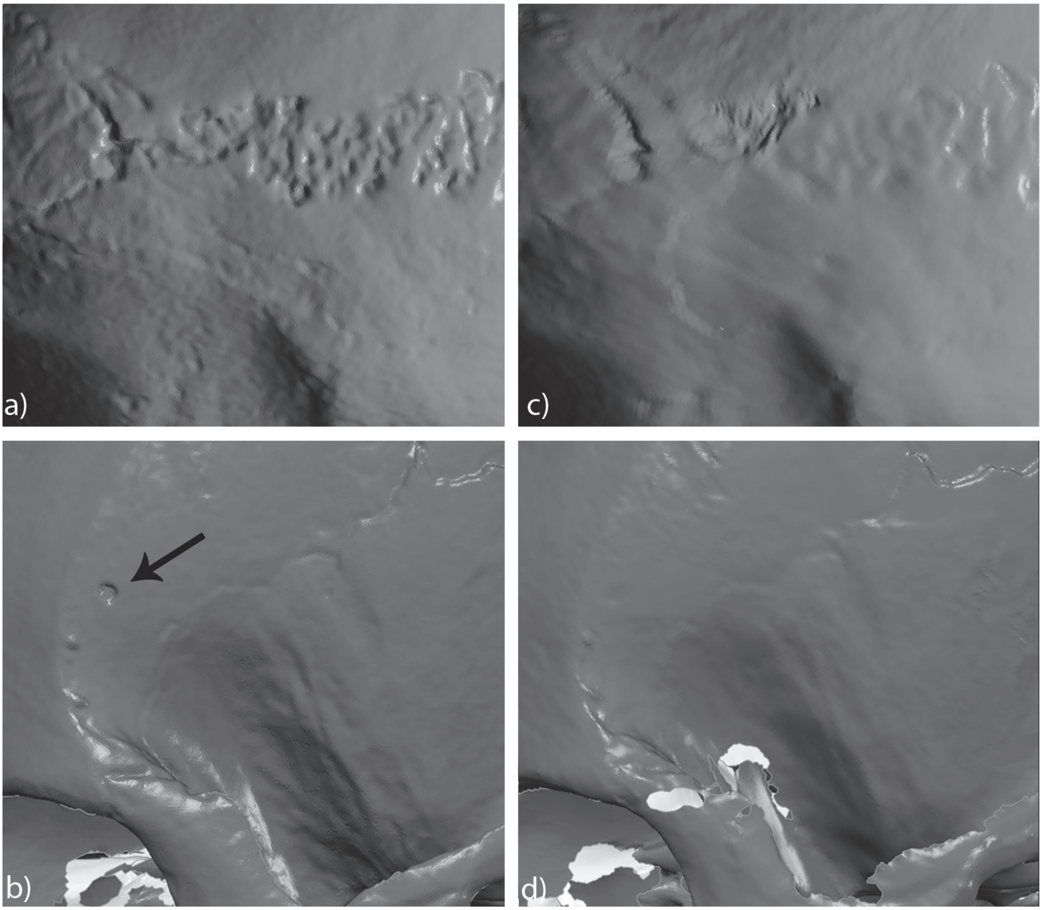

Fig. 5 - Differences in mesh quality generated by different scanners: left asterion-region of the same skull scanned with a Breuckmann smartscan (a) and a Nextengine (c). frontotemporal region by Breuckmann (b) and a nextengine (d). Note the surface noise in c (center-left below the lambdoid suture) and the filled hole in b (arrow).

and Minolta Vivid 910®). While their conclusion seems to encourage potential users to pick the more affordable device and is borne out by the reported standard deviations of around 0.05 mm, they do point out noticeable differences in the mesh quality of the three models. Similar mesh degradations were observed by Slizewski *et al.* (2010) and by the present author (Fig. 5). The key question is whether the resulting meshes are good enough for the purpose at hand, which must be addressed for each case. As previously stressed, no surface scanner generates meshes that are perfectly suitable for all purposes. The tests performed by Slizewski *et al.* (2010) suggest that at least the tested high-end surface scanners can yield extremely precise surfaces even for very small objects (teeth and foot bones).

Klaas *et al.* (2011) address the impact of different alignment algorithms (photogrammetry, adhesive targets, best-fit alignment) on the quality of the resulting surface model and conclude that a photogrammetric alignment yields best

Tab. 1 - Schematic summary of current surface scanner capabilities*.

RANGE	SCANNERS	RESOLUTION (MM)	FOV (MM)	PRICE RANGE (EUROS)
Low-cost	david-laserscanner, nextengine	0.06-0.8**	160-500	<5000
Mid-range	Breuckmann smartscan, handyscan uniscan, Polhemus fast-scan	0.06-0.3	75-680	20-50,000
High-end	Breuckmann stereoscan, Gom, Minolta range 7	0.02-0.6	46-1500	>50,000

****resolution depending on specific FOV and CCD (see text for further information), price ranges reflect information gathered in the author's location in 2011.***
*****For david-laserscanner, this may depend on the user's choice of a web-cam.***

results, followed by best-fit alignment. Most scanners and third party algorithms use best-fit alignment strategies.

Intra- and inter-observer error in surface scan data has been investigated by Sholts *et al.* (2010b) and found to be negligible: intra-observer error was less than 0.3% for surface area and volume measurements, and around 2% between observers. Of course, intra-observer error on non-calibrated objects should be considered separately from device precision, since it is an additional source of noise.

Thus, it appears that, compared to standard allowable errors in anthropometry, surface models replicate anthropological (hard tissue) objects with sufficient precision, but that the human operator remains the biggest source of error when it comes to extracting linear measurements or Cartesian coordinates. Machine-dependent and human error (precision) are subject to object scale (the bigger the object the bigger the absolute error), and measurement type (curvature maxima vs. tissue intersections). The precise location of tissue intersections depends more on resolution than do curvature maxima. The potential impact of measurement error on biological interpretations remains to be investigated thoroughly (cf. Simonis-Sueur *et al.*, 2009).

Many surface scanners are portable, making them very useful for a variety of environments, and responding to a frequent necessity in paleoanthropological research: working in multiple locations. Portability also allows surface scanning to be used outdoors, e.g. in excavation sites, caves etc. (but see lighting requirements above). A collections manager, on the other hand, with the need to archive all or parts of a collection will not be concerned with, nor will he/she benefit from portability. Non-portable devices generally benefit from a more stable setup, which improves accuracy and precision. As Bathow *et al.* (2010) demonstrate, fixed installations that align views through a coordinate-measuring machine, yield the most accurate models. This solution, however, is not suitable for many paleoanthropologists. Similarly, rotary tables improve automation, but generally do so by significantly reducing portability. Some systems with a rotary platform are still transportable. Finally, a new generation of fixed systems, composed of multiple cameras ('multi-camera, multi-projector domes'), offers much faster acquisitions and alleviate self-occlusion issues, again at the expense of portability (Weinmann *et al.*, 2011).

Acquisition speed of triangulation-based scanners can range from less than one second to around one minute for a single pass. Speed has an incidence on the suitability of scanners for a given object. It also impacts long-term economics of data acquisition. In general, laser scanners need more time, because the laser line has to travel across the entire FOV. Structured light scanners, on the other hand, project their patterns simultaneously onto the entire FOV, which can be considerably faster. However, if phase-shift technology is added, the projection time becomes longer.

Living objects require very fast acquisition, to avoid noise from sudden movement. For instance, face scanners typically complete acquisitions in a few seconds or less. For this type of application multiple views with movement in between should generally be avoided, by using either multiple camera systems (e.g. Breuckmann) or systems that perform a full rotation (360 degrees) around the object (e.g. Cyberware). Certain designs can achieve higher acquisition speeds only at reduced resolution. A full-scale test scan is the only way to reasonably estimate the time required to complete a given scan project.

Cost considerations are an important part of acquiring a 3D scanner, but rather volatile, so that discussing them thoroughly within the scope of this review is unrealistic. Still, a quick and informal survey of available models in 2011 (Tab. 1) does confront the potential buyer with an apparent conundrum: the price range extends over three orders of magnitude (roughly \$200 to \$200.000), and is not very well correlated with resolution, the second most looked at specification. Owners of a web cam and a laser can even perform scans with a free software (david-laser-scanner), though they are in this case restricted to low resolution. It should be clear from the previous section that, while pixel size is one limiting parameter for system performance, it does not drive cost as much as does the quality of the optics and the software that operates the scanner and performs basic processing. User-friendliness, while entirely in the eye of the beholder, also tends to increase with system cost.

Costs are subject to constant market evolution and technological development. While typical retail prices are significantly below those of medical/industrial CT scanners, the high-end market segment makes the notion that surface scanners are more affordable quite relative (see Tab. 1). Significant additional costs can incur with the purchase of a 3rd party software license for post-processing.

Why use a surface scanner…

…when medical and industrial CT scanning is becoming more and more ubiquitous? This frequently asked question is in my view misleading in that it construes a polarity that hides an obvious truism: rather than considering the two technologies as alternatives, they should be seen as complementary means of archiving and measuring samples. Clearly their strengths and weaknesses are complementary:

Volume-scanners based on x-rays or synchrotron radiation provide:

- Internal structures, but no texture
- A high degree of automated acquisition, but also a high amount post-processing
- Resolution down to nanoscale

Surface scanners provide:

- Non-destructive/ non-invasive measurements
- Rapid generation of dense point clouds and polygon meshes (low post-processing)
- Texture (not applicable to all models), but no internal structures
- High degree of mobility
- High to very high resolution
- Affordability

As pointed out elsewhere (Friess, 2010a), if external morphology/morphometrics is the sole goal, CT scanning may not be the most efficient way of achieving it. For instance, in the case of a hominin fossil this requires finding a local facility (unless the fossil-housing institution owns a CT scanner), transporting the fossil to the facility and back, and time-consuming post-processing (HMH protocol, cf. Spoor *et al.*, 1993) of each slice. If aDNA extraction is anticipated down the road, exposure to ionizing radiation may be seen as taking an unknown risk.

More recent volume-scanning technologies based on terahertz radiation (Öhrström *et al.*, 2010; Fukanaga *et al.*, 2011) or infrared images (Gopinath *et al.*, 2005) may eventually offer alternatives to x-rays, at least in cases where ionizing radiation is to be avoided (living subjects, preservation of aDNA).

Adverse effects of ionizing radiation on dead tissue are, at best, unknown (Rühli *et al.*, 2007; Kullmer, 2008; Öhrström *et al.*, 2010), but preliminary investigations of such effects on bones and teeth have raised some concern (Grieshaber *et al.*, 2008; Horton *et al.*, 2010). Among the effects observed in these studies were increased fragmentation of DNA sequences and long-term discoloration of dental tissue. Fragmentation renders amplification of aDNA more difficult, but to which extent this can further degrade already fragmented hominin material is unclear (O'Rourke *et al.*, 2000, Grieshaber *et al.*, 2008). Recommendations for invasive sampling in paleoanthropology warrant "photography, high-resolution molding and/or microCT" prior to any destructive investigation, "if proven risk-free" (Hublin *et al.* 2008, p.757). If radiation were to reduce the amount of amplifiable aDNA, then CT-scanning would not qualify as preventive measure, and should be avoided prior to DNA-extraction. Rather, DNA-extraction should be attempted before exposure to x-rays, as suggested by Grieshaber *et al.* (2008). In this sense, guidelines issued by the National Museums of Kenia (Mbua, 2011), are more proactive, since they favor photographing and physical casting before any destructive sampling (including DNA extraction). Therefore, pending further studies, curators might consider CT scanning as potentially destructive and consider surface scanning a safer alternative and include it in their invasive sampling protocols.

Applications

Current use of surface scan data in physical and specifically paleoanthropology mainly reflect their potential for archiving and morphometrics, rather than for visualizing previously invisible features. The latter is more likely to be gained from very high resolutions and/or ionizing radiation through microCT and synchrotron techniques. The range of resolutions commonly used in surface scanning makes this technology more suitable for measuring external macromorphology, possibly with improved precision (but see Baab *et al.*, 2003). Here, the most obvious advantages stem from the ability to measure dimensions/features that are inaccessible by conventional measuring tools (calipers etc.), and to do so in a virtual environment.

The prospect of measuring without contact is beneficial to the preservation of fragile specimens, and is possible even when the actual specimen is not at hand. This is a direct result of the archiving nature of surface scanning, which makes it possible to easily extract additional measurements without having to re-access the actual specimen/object. Digital archiving also plays an increasing role in cultural heritage programs, by providing a permanent record of unique or fragile objects (Bruner & Manzi, 2006; Rüther *et al.,* 2009). Archaeologists use 3D imaging technologies for documenting excavation sites and even entire monuments the size of the Egyptian pyramids (Neubauer *et al.*, 2005). An example of surface scanning as a means of documenting and preventing degradation of archaeological objects is the digital survey of the Easter Island Moai (Kersten *et al.*, 2009). Other examples demonstrate successful applications of surface scanning to lithics, ceramics, and even textiles (Lin *et al.*, 2008; Sumner & Riddle, 2008 and further references therein).

In anthropology, surface scanning becomes a primary tool for constituting virtual databases, such as CAESAR, PRIMO, NESPOS and others (Reddy *et al.,* 2002; Kullmer, 2008; Delson *et al.*, 2002, 2011). Similar efforts to build digital archives have been undertaken by means of CT scanning at the Universities of Vienna, Pennsylvania (cf. Weber, 2001; Schoenemann *et al.*, 2008), and Kyoto. Surface data are being used for scientific visualization and educational purposes (Allen *et al.*, 2003; Cerney *et al.*, 2003; Wiley *et al.*, 2005; Godil & Ressler, 2006; Li *et al.*, 2008; Yin *et al.*, 2009), as well as for web-based knowledge transfer (Potts *et al.*, 2011).

The increasing number of institutions equipped with surface scanners and databases that are being constituted, whether publicly or not, inevitably raises the question of data sharing. The historical vagaries in accessing paleoanthropological specimens have been comprehensively discussed in a number of contributions (e.g. Weber, 2001; Tattersall & Schwartz, 2002; Mafart, 2008).

Snow *et al.* (2006) stress similar issues pertaining to archaeological data. 3D imaging technology, at least in theory, could play a key role in overcoming resistance, by tremendously facilitating shared access, and by minimizing direct contact (Weber, 2001; Delson *et al.*, 2007). Whether these are major reasons to now share (more) what was previously not shared (as much), remains debatable (Bruner, 2009). More than a decade after Weber's call for Glasnost in paleoanthropology (2001), existing data repositories are not even close to containing the "nearly complete fossil record" he had hoped for. While this may be in part due to their recent debut, questions of primacy and property, raised in several papers (Weber, 2001; Tattersall & Schwartz, 2002; Mafart, 2008), have been extended from the actual specimen to its virtual copy, thus clearly perpetuating the reluctance to open access (Bruner & Manzi, 2006). In fact, several authors (Delson *et al.*, 2007; Mafart, 2008; Sumner & Riddle, 2009) do accept or advocate some level of control over access, which underlines disagreement or at least unsolved issues about Glasnost in paleoanthropology. A novel concept to manage access to digital data, by means of licensing, has been proposed by Sumner & Riddle (2009). Another important incentive for researchers to share digital data may be to make them citable publications, as discussed at the Wenner-Gren workshop on databases and data access in paleoanthropology (Delson *et al.,* 2007). Until an agreeable concept for sharing exists, that is until paleoanthropology has rid itself of one of its "original sins" (Bruner, 2009), 3D data remain a theoretical cornerstone of shared digital archives and virtual anthropology, but fall short of their potential (Sumner & Riddle, 2009).

When it comes to using scan data quantitatively, two basic approaches can be distinguished:

- Standard landmark-based morphometric studies
- Advanced morphometrics based on new dimensions previously inaccessible (e.g. volumes, areas, surfaces and curvatures)

Conceptually, the first approach attempts to replicate traditional anthropometry, with the added benefits of non-contact and ease of repeat access/databasing mentioned above, while the latter focuses on gaining new types of data. Both are reasonable ways of putting surface scans to anthropological use, and the fact that it allows actually both to be pursued fairly easily is a frequent motivation to choosing surface scanning for data acquisition.

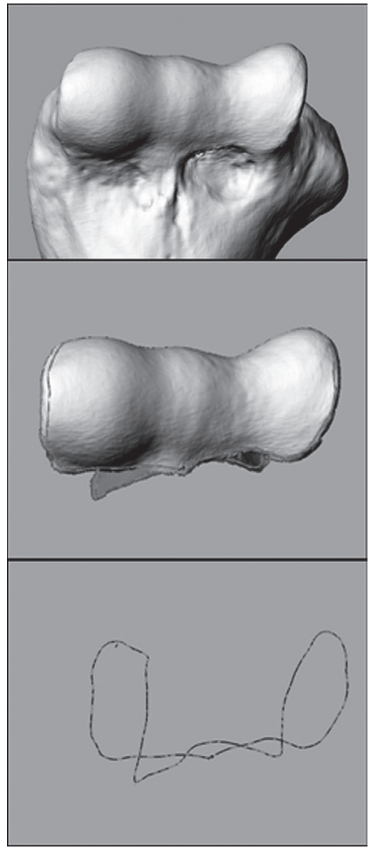

Fig. 6 - Curve extraction from a surface scan, illustrated by the distal articular surface of a human humerus (Friess, 2004).

As stressed above, non-contact and repeat access are major arguments in favor of using surface scans, rather than 3D digitizers (e.g. Microscribe®), for landmark-based morphometrics (but see Tocheri, 2009). While most surface scanners are somewhat less portable and more expensive than a Microscribe®, there are noticeable exceptions (e.g. Nextengine®, david-laser-scanner®). Coordinate digitizers do have at least

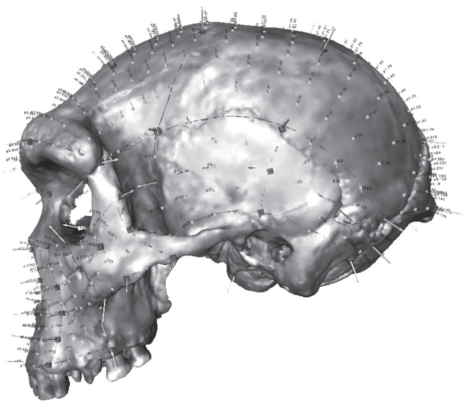

Fig. 7 - Surface patching in landmark editor (Wiley, 2005). In this example, taken from Friess (2010a), the face and the neurocranium of the fossil hominin from Kabwe is covered by quadrilateral patches of variable density. The Colour version is available online at JASs web site.

one short-term advantage: acquiring "just" landmark data is faster, as it would be relatively inefficient to use a surface scanner if standard landmarks are all one wants. This must be weighted against medium- to long-term benefits of having a digital copy of all specimens, which allows to add data in a follow-up, or to engage in entirely new studies by multiple researchers without having to return to wherever specimens are housed. When living subjects are measured, the permanent record of a 3D scan is extremely valuable in that it offers unlimited access to the subject's virtual representation and a long-term record of physical traits at a given point in time (for ontogeny studies, see Kau & Richmond, 2008).

Among the early adopters of surface scanning were ergonomists (applied anthropometry) and surgeons (Linney *et al.*, 1989; Kohn *et al.*, 1995; Rioux, 1997; Jones & Rioux, 1997). In fact, the potential for generating large 3D data bases and extracting quantitative data was recognized already in the late 80s/early 90s, when available technologies were mainly variants of photogrammetry, not yet transposed to fully digital optical systems (Rioux 1997; Linney *et al.*, 1997). Examples of such early anthropometric data bases can be found in Vannier *et al.* (1991) and Linney *et al.* (1992).

Medical applications, especially maxillo-facial and plastic surgery, are numerous and beyond the scope of this paper. Some early examples are Hiritz *et al.* (1986) and Linney *et al.* (1989). The current use of surface scanning in surgical context is discussed by Hoffmann *et al.* (2005).

Historically speaking, strictly paleoanthropological applications appear late, and until now remain limited in number, especially when compared to CT-scanning. Aiello *et al.* (1998) are the first to recognize the benefit of surface scanning for the study of fossil hominins. The authors compare the articular surface geometry of two elements (tibia and fibula of OH 35) to assess the question of their congruence. This is achieved quantitatively through the extraction and analysis of 2D cross section curves. Interestingly, they scanned casts rather than the original hominin remains, whereas the non-contact nature and portability of surface scanning make it particularly suitable for measuring original specimens. It illustrates the potential gain of quantitative data that are difficult if not impossible to obtain otherwise.

Among the many data contained in surface scans and not measureable with traditional tools are surface areas and volumes. Examples of such measurements and their use in paleoanthropology are studies by Friess *et al.* (2002), Kullmer *et al.* (2003), Friess (2009), Raichlen *et al.* (2010), and Sholts *et al.* (2010b).

Analyses based on conventional landmarks from 3D surface scans have been performed in a number of studies on topics ranging from general anthropometry (Robinette & Daanen, 2005; Park *et al.*, 2006), to sexual dimorphism (Hennessy *et al.*, 2005; Friess, 2006), to facial reconstruction and identification (Claes *et al.*, 2006, 2010; Lynnerup *et al.*, 2009; Kustár *et al.*, in press). Several studies attempted automatic identification and extraction of standard landmarks (Pargas *et al.*, 1997; Lewark, 1998; Kohno *et al.*, 2005; De Menezes, 2010; Romero, 2010), with variable outcome.

Curve extraction and analysis (Fig. 6) is another approach to quantifying geometry in a

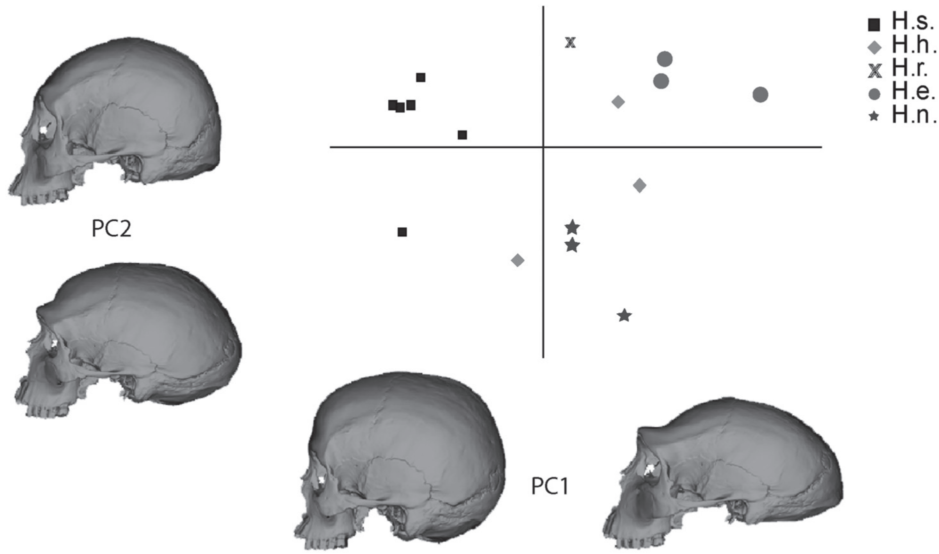

Fig. 8 - Generalized Procrustes Analysis of surface semi-landmarks and surface warping along axes of interest (see Friess, 2010a). Scatterplot of a Principal Components Analysis (PCA) showing* Homo sapiens *(H.s.) on one end of PC1, versus* Homo heidelbergensis *(H.h.),* Homo. rhodesiensis *(H.r.),* Homo erectus *(H.e.), and* Homo neanderthalensis *(H.n.), separated along PC2. A surface model derived from a 3D scanner is warped along these principal components to visualize 3D shape differences between these hominin groups.

way that is impossible with calipers (Delson *et al.*, 2002; Friess *et al.*, 2004; Hsiao *et al.*, 2009; Sholts *et al.*, 2010a). The idea here is to virtually digitize a 2D or 3D curve along the surface of an object and to use the coordinates for various shape analytical comparisons, in these cases based on elliptic Fourier descriptors (Kuhl & Giardina, 1982). While 2D curves can be obtained easily by photographs, drawings etc, Sholts *et al.* (2010a) illustrate the possibility to extract curves in constructed planes, as they are typically available only in 3D modeling software.

Tocheri *et al.* (2002) extract mean curvature values from human pubic symphyses in an attempt to use if for age determination of adult skeletons according to the Brooks-Suchey method (Brooks & Suchey, 1990).

A number of studies have focused on teeth and tooth wear, despite technical limitations of surface scanners with respect to dental material. In all these studies, this limitation is circumvented by scanning casts rather than the actual teeth. Ungar & Williamson (2000) and Ungar & M'Kirera (2003) extract quantitative variables, such as surface area, slope and angularity, from great ape molars in order to relate patterns of tooth wear with dietary profiles. Benazzi *et al.* (2011a) use a combination of microCT and surface scan data on hominin teeth and casts to measure a set of linear dimensions (diagonals, diameters). They argue that these dimensions, when taken with calipers, are subject to personal judgment, and claim that their virtual protocol results in higher reproducibility.

Among the less traditional uses of surface data are a series of dental studies referred to as occlusal fingerprinting (Ulhaas *et al.*, 2004; Kullmer *et al.*, 2009; Fiorenza *et al.,* 2009, 2010, 2011a,b,c; Benazzi *et al.*, 2011b). This approach is based on identifying wear facets on occlusal surfaces, fitting surfaces to them and computing angles between these surfaces.

A similar methodology is applied by Tocheri *et al.* (2011) to gorilla metatarsals. By segmenting articular and non-articular surfaces, and by fitting surfaces to the segmented areas, they are able to determine angles between surfaces in addition to relative surface areas and curvature. These metrics are then compared in relation to functional aspects of locomotion. Previously, Tocheri (2007) and Tocheri *et al.* (2003) have pioneered this approach on a relatively large sample of hominin hand bones and successfully applied it to the case of *H. floresiensis* (Tocheri *et al.*, 2007).

A major advantage, and thus motivation for surface scan data is the relatively rapid access to entire surfaces, which cannot be captured by means of traditional anthropometry. While Gunz *et al.* (2005) use a Microscribe® to digitize the entire neurocranial surface, this device is probably more efficient at a smaller scale, such as the infra-orbital region (e.g. Maddux & Franciscus, 2008). Even most studies involving 3D meshes do not actually use the full data set contained in a surface scan, but rather focus on a subset (standard landmarks), or on a well-defined set of linear or angular dimensions. Several research papers have emerged that attempt to exploit the density of point clouds derived from surface scans, and thus quantify variation of the surfaces themselves. Harcourt-Smith *et al.* (2008) and Friess (2010a, b) use NURBS surfaces to define quadrilateral patches of equidistant points on surfaces (Fig. 7). These points are treated as semi-landmarks and subjected to geometric morphometric analyses (Mitteroecker *et al.*, 2005; Alcantara *et al.*, 2007), which allows for a visual depiction of variability across the entire surface (Fig. 8). A similar approach to the quantitative analysis of entire surfaces is applied by Berar *et al.* (2006) in order to improve facial reconstruction from cranial remains, while Claes *et al.* (2011) compute Euclidean distances between very dense point clouds to assess facial asymmetry. As noted previously, shape statistics like these can be obtained from any surface, whether they are based on CT- or surface scans, though not necessarily with the same efficiency.

Concluding remarks

The ascension of virtual anthropology generates advanced analytical tools and allows exciting new insights into human variation. Surface scanning constitutes a rapid, relatively affordable means to contribute in this area, and it provides tremendous benefits for conservation and cultural heritage programs. Metric databases have long been an important part of anthropology (Menk, 1979), but by design constitute a selection of measurable features. Virtual copies of entire specimens will lift these restrictions almost completely. Ongoing scan projects will dramatically increase the size of existing 3D databases/archives, which, when and if openly accessible, will further transform the way paleoanthropological research is conducted. Traditional approaches to morphology can be more or less directly transposed into a virtual environment, and probably should be for fossil specimens, which are heavily solicited and in some cases bear the traces of a century of caliper-based anthropometry. Future PhD students may not go through the “rite de passage” that is the manipulating of a key fossil for the first time, though several authors have expressed regret at this outlook (Elton & Cardini, 2008; Sumner & Riddle, 2009). On the plus side, they may not have to write as many travel grants anymore, provided current issues in data sharing are solved. Osteology classes will likely continue to make use of real specimens, invasive sampling for aDNA extraction, isotope analysis or chronometric dating must continue to do so (but see Bolnick *et al.*, 2012). The greatest analytical potential of surface scans, in my view, does not lie in virtually replicating what can be easily, more rapidly and cheaper accomplished on a large sample of actual specimens, but in the assessment of dimensions and/or specimens that are not accessible otherwise, be it for functional morphology or phylogenetic analysis. Serious limitations to scanning are largely a matter of technological improvements concerning resolution, multiple camera-use, and different light sources for specific surfaces (e.g. teeth). Whether anthropologists will successfully exploit this potential, or fall back to “just” accumulating (and keeping) data, remains to be seen.

Info on the web

Manufacturers

http://prism.engineering.asu.edu/resources/index.php

provides links to numerous manufacturers

Data and databases

http://plum.museum.upenn.edu/~orsa/Welcome.html
http://www.hec.afrl.af.mil/cardlab/CAESAR/index.html
http://www.nycep.org/primo
http://www.nespos.org
http://www.virtual-anthropology.com/3d_data/3d-archive

Stereophotography

http://www.vision.caltech.edu/bouguetj/ICCV98/
http://www.anything3d.com/product/software/builders.php3

Miscellaneous

http://www.qualitydigest.com/inside/cmsc-article/state-3-d-imaging-standards.html
http://www-graphics.stanford.edu
http://www.3d-conversion.com/index.html
http://digiscan3d.fr/
http://www.impactstudiostv.com/laser_scan_site/htm/technology.htm
http://www.digisens.fr/en/

Acknowledgements

I would like to thank Emiliano Bruner for inviting me to provide this review and for his helpful comments on an earlier version of this manuscript. I am indebted to Eric Delson, Patrick Semal, and two anonymous reviewers for their valuable input. This is NYCEP morphometrics contribution number 63.

References

Aiello L., Wood B., Key C., & Wood C. 1998. Laser Scanning and Paleoanthropology. In E. Strasser, J.G. Fleagle, A.L. Rosenberger, & H. McHenry (eds): *Primate Locomotion: Recent Advances*, pp. 223-236, Plenum Press. New York.

Alcantara D., Carmichael O., Delson E., Harcourt-Smith W., Sterner K., Frost S., Dutton R., Thompson P., Aizenstein H., Lopez O., Becker J. & Amenta N. 2007. Localized Components Analysis. In N. Karssemeijer & B. Lelieveldt (eds): *Information Processing in Medical Imaging, Proc. IPMI 2007, Lecture Notes in Computer Science vol.* 4584, pp. 519-531. Springer, Berlin.

Aldridge K., Boyadjiev S.A., Capone G.T., DeLeon V.B. & Richtsmeier J.T. 2005. Precision and Error of Three-Dimensional Phenotypic Measures Acquired From 3dMD Photogrammetric Images. *Am. J. Med. Genet.,* 138A: 247–253.

Allen B., Curless B. & Popovic Z. 2003. The space of human body shapes: reconstruction and parameterization from range scans. *ACM T. Graphic. (SIGGRAPH 2003),* 22(3): 587–594.

Amenta N., Bern M. & Eppstein D. 1999. Optimal point placement for mesh smoothing. *J. Algorithm.,* 30: 302-322.

Ashizawa K., Kuki T. & Kusumoto A. 1985. Fringe patterns and measurement on dorsal moiré topography in Japanese children, aged 13 and 14. *Am. J. Phys. Anthropol.*, 68(3): 359-365.

Baab K.L., Ting N. C., Capellini T. D., Hagell S. E. & Delson E. 2003. Precision in 3D landmark data collection for geometric morphometrics. *Am. J. Phys. Anthropol.*, Suppl. 36: 61.

Bathow C., Breuckmann B. & Scopigno R. 2010. Verification and acceptance tests for high definition 3D surface scanners. In: A. Artusi, M. Joly-Parvex, G. Lucet, A. Ribes & D. Pitzalis (eds): *The 11th International Symposium on virtual reality, archaeology and Cultural heritage (VAST),* pp. 9-16.

Benazzi S., Coquerelle M., Fiorenza L., Bookstein F.L., Katina S., & Kullmer O. 2011a. Comparison of Dental Measurement Systems for Taxonomic Assignment of First Molars. *Am. J. Phys. Anthropol.*, 144:342-354.

Benazzi S., Fiorenza L., Katina S., Bruner E. & Kullmer O. 2011b. Quantitative Assessment of Interproximal Wear Facet Outlines for the Association of Isolated Molars. *Am. J. Phys. Anthropol.*, 144:309-316.

Beraldin J.A. 2004. Integration of Laser Scanning and Close-Range Photogrammetry - The Last Decade and Beyond. *XXth International Society for Photogrammetry and Remote Sensing (ISPRS) Congress*. Commission VII, pp. 972-983. Istanbul, Turkey. July 12-23, 2004. NRC 46567.

Berar M., Desvignes M., Bailly G. & Payan J. 2006. 3D Semi-Landmarks-Based Statistical Face Reconstruction. *J. Comp. Information Technol.,* 14: 31-43.

Besl P.J. & McKay N.D. 1992. A Method for Registration of 3-D Shapes. *IEEE T. Pattern Anal.,* 14: 239-256.

Bolnick D.A., Bonine H.M., Mata-Míguez J., Kemp B.M., Snow M.H. & LeBlanc S.A. 2012. Nondestructive Sampling of Human Skeletal remains Yields Ancient Nuclear and Mitchondrial DNA. *Am. J. Phys. Anthropol.*, 147(2): 293-300

Bookstein F.L. 1991. Morphometric *tools for landmark data. Geometry and Biology*. Cambridge University Press, Cambridge.

Bräuer G. & Knußmann R. 1988. Grundlagen der Osteometrie. In R. Knußmann (ed.): *Anthropologie. Handbuch der vergleichenden Biologie des Menschen. Band I, 1. Teil*, pp. 129-159. Springer, Stuttgart.

Brooks S. & Suchey J.M. 1990. Skeletal age determination based on the os pubis: A comparison of the Acsádi-Nemeskéri and Suchey-Brooks methods. *Hum. Evol.,* 5: 227-238.

Bruner E. 2009. New tools and old perspectives in the management of the fossil resources. *J. Anthropol. Sci.,* 87: 227-228.

Bruner E. & Manzi G. 2006. Digital Tools for the Preservation of the Human Fossil Heritage: Ceprano, Saccopastore, and Other Case Studies. *Hum. Evol.,* 21: 33–44.

Bush K. & Antonyshyn O. 1996. Three-dimensional facial anthropometry using a laser surface scanner: validation of the technique. *Plast. Reconstr. Surg.,* 98: 226-35.

Cannan E. 1892. The origin of the law of diminishing returns, 1813-1815. *Economic Journal,* 2: 53-69.

Cerney M.M., Adams D.C. & Vance J.M. 2003. Image Warping of Three-Dimensional Body Scan Data. *Proceedings of the SAE Digital Human Modeling Conference*. Montreal, Canada. 2003-01-2231.

Claes P., Vandermeulen D., De Greef S., Willems G. & Suetens P. 2006. Statistically Deformable Face Models for Cranio-Facial Reconstruction. *J. Comput. Inf. Technol.,* 14: 21–30.

Claes P., Vandermeulen D., De Greef S., Willems G., Clement J.G. & Suetens P. 2010. Computerized craniofacial reconstruction: Conceptual framework and review. *Forensic Sci. Int.,* 201: 138-145.

Claes P., Walters M., Vandermeulen D. & Clement J.G. 2011. Spatially-dense 3D facial asymmetry assessment in both typical and disordered growth. *J. Anat.,* 219: 444-455.

Coblentz A., Mollard R. & Ignazi G. 1991. Three-dimensional face shape analysis of French adults, and its application to the design of protective equipment. *Ergonomics,* 34:497-517.

Delson E., Friess M., Marcus L.F. & Reddy D. 2002. Assessment of quantitative characters in the distal humerus among hominids (great apes and hominins). *Am. J. Phys. Anthropol.,* Suppl. 34: 61.

Delson E., Harcourt-Smith W.E.H., Frost S.R. & Norris C.A. 2007. Databases, Data Access, and Data Sharing in Paleoanthropology: First Steps. *Evol. Anthropol.,* 16: 161-163.

Delson E., Ford E., Friess M., Frost S.R. & Harcourt-Smith W. 2011. Organizing, administering, and sustaining an open-access database, examples learned from PRIMO. *Am. J. Phys. Anthropol.,* Suppl. 52: 123.

Elton S. & Cardini A. 2008. Anthropology from the desk? The challenge of the emerging era of data sharing. *J. Anthropol. Sci.,* 86: 209-212.

Enciso R., Alexandroni E.S., Benyamein K., Keim R.A. & Mah, J. 2004. Precision, repeatability and validation of indirect 3D anthropometric measurements with light-based imaging techniques. *Proceedings IEEE Int. Sym. Biomed. Imag.*: Nano to Macro, 2004, vol 2, pp.1119-1122.

Fangi G., Fiori F., Gagliardini G. & Malinverni E.S. 2001. Fast and accurate close range 3D Modelling by Laser Scanning system. In J. Albertz (ed): *Proc., XVIII CIPA Symposium, Potsdam – 18-21 Sept. 2001*. http://cipa.icomos.org/POSTDAM.html.

Fiorenza L., Benazzi S. & Kullmer O. 2009. Morphology, wear and 3D digital surface models: materials and techniques to create high-resolution replicas of teeth. *J. Anthropol. Sci.,* 87:211–218.

Fiorenza L., Benazzi S., Tausch J., Kullmer O. & Schrenk F. 2010. Brief communication: identification reassessment of the isolated tooth Krapina D58 through occlusal fingerprint analysis. *Am. J. Phys. Anthropol.,* 143:306–312.

Fiorenza L., Benazzi S. & Kullmer O. 2011a: Para-masticatory wear facets and their functional significance in hunter-gatherer maxillary molars. *J. Archaeol. Sci.,* 38(9): 2182-2189.

Fiorenza L., Benazzi S., Tausch J., Kullmer O., Bromage T.G. & Schrenk F. 2011b. Molar macrowear reveals Neanderthal eco-geographic dietary variation. *PLoS One,* 6, e14769.

Fiorenza L., Benazzi S.,Viola B., Kullmer O. & Schrenk F. 2011c. Relationship Between Cusp Size and Occlusal Wear Pattern in Neanderthal and *Homo sapiens* First Maxillary Molars. *Anat. Rec.,* 294:453-461.

Fourie Z., Damstra J., Gerrits P.O. & Ren Y. 2011. Evaluation of anthropometric accuracy and reliability using different three-dimensional scanning systems. *Forensic Sci. Int.,* 207: 127-134.

Freitag L.A. & Ollivier-Gooch C. 1997. Tetrahedral Mesh Improvement Using Swapping and Smoothing. *Int. J. Numer. Meth. Eng.,* 40:3979–4002.

Friess M. 2004. The articular surface in the distal hominid humerus: 3D shape analysis using Elliptic Fourier descriptors. *Abstracts of the Annual meeting of the 2004 Paleoanthropology Society, Montreal, Canada*.

Friess M. 2006. The study of craniofacial growth patterns using 3D laser scanning and geometric morphometrics. In: B.D. Corner, P. Li & M. Tocheri (eds): Three-Dimensional Image Capture and Applications. *P. SPIE IS&T Elect. Im.*, Vol 6056. doi: 10.1117/12.654898

Friess M. 2009. Climate and craniofacial shape variation among major human populations: a geometric morphometric approach. *Am. J. Phys. Anthropol.,* Suppl. 48 : 130.

Friess M. 2010a. Calvarial shape variation among Middle Pleistocene hominins - An application of surface scanning in paleoanthropology. *C. R. Palévol,* 9: 435-443.

Friess M. 2010b. Parietal expansion during later hominin evolution, and the validity of *H. heidelbergensis* – A quantitative approach. *Bull. Schweiz. Ges. Anthropol.,* 16: 55-62.

Friess M., Marcus L.F., Reddy, D.P. & Delson E. 2002. The use of 3D laser scanning techniques for the morphometric analysis of human facial shape variation. In B. Mafart & H. Delingette (eds): *Three-Dimensional Imaging in Paleoanthropology and Prehistoric Archaeology. Proceedings of the XIVth UISPP Congress, 2001.*

British Archaeological Reports, S1049, 31-35. Archaeopress, Oxford.

Friess M., Rohlf F.J. & Hsiao, H. 2004. Quantitative assessment of human body shape using Fourier analysis. In B.D. Corner, P. Li & R. P. Pargas (eds): Three-Dimensional Image Capture and Applications. *P. SPIE IS&T Elect. Im.*, Vol 5302, pp. 117-124.

Fukanaga K., Cortes E., Cosentino A., Stuenkel I., Leona M., Duling III I.N. & Mininberg D.T. 2011. Investigating the use of terahertz pulsed time domain reflection imaging for the study of fabric layers of an Egyptian mummy. *Journal of the European Optical Society (RP),* 6, 11040: 1-4.

Ghoddousi H., Edler R., Haers P., Wertheim D. & Greenhill D. 2007. Comparison of three methods of facial measurements. *Int. J. Oral Max. Surg.,* 36(3): 250-258.

Godil A. & Ressler S. 2006. Retrieval and Clustering from a 3D Human database based on Body and Head Shape. *SAE Digital Human Modeling conference*, 02 July to 4th August, 2006, Lyon, France.

González-Aguilera D., Muñoz-Nieto A., Gómez-Lahoz J., Herrero-Pascual J. & Gutierrez-Alonso G. 2009. 3D Digital Surveying and Modelling of Cave Geometry: Application to Paleolithic Rock Art. *Sensors,* 9: 1108-1127.

Gopinath A., Caroll J.J. & MacIntosh D. 2005. Human Body Modeling and Tracking using 3D Voxel Data from Infrared Images. *SAE Transactions,* 114, part 6: 2942-2949.

Gornick M.C. 2011. *Digital three-dimensional photogrammetry: accuracy and precision of facial measurements obtained from two commercially-available imaging systems*. Masters thesis, University of Pittsburgh, School of Dental Medicine.

Grieshaber B.M., Osborne D.L., Doubleday A.F. & Kaestle F.A. 2008. A pilot study into the effects of X-ray and computed tomography exposure on the amplification of DNA from bone. *J. Archaeol. Sci.,* 35: 681-687.

Gu D., Chen Y., Dai K., Zhang S. & Yuan J. 2008. The shape of the acetabular cartilage surface: A geometric morphometric study using three-dimensional scanning. *Med. Eng. Phys.,* 30: 1024-1031.

Guidi G., Remondino F., Morlando G., Del Mastio A., Uccheddu F. & Pelagotti A. 2007. Performance evaluation of a low cost active sensor for cultural heritage documentation. In: A. Gruen & H. Kahmen (eds): *VIII Conference on Optical 3D Measurement Techniques*, Vol.2, pp. 59-69, July 2007. Zurich, Switzerland.

Gunz, P., P. Mitteroecker, & Bookstein F. L. 2005. Semilandmarks in Three Dimensions. In D.E. Slice (ed): *Modern Morphometrics in Physical Anthropology*, pp. 73–98. Kluwer Academic/ Plenum Publishers, New York.

Harcourt-Smith W.E., Tallman M., Frost S.R., Wiley D. F. & Delson E. 2008. Analysis of selected hominoid joint surfaces using laser scanning and geometric morphometrics: a preliminary report. In E.J. Sargis & M. Dagosto (eds): *Mammalian Evolutionary Morphology: A Tribute to Frederick S. Szalay*, pp. 373-383. Springer, Dordrecht.

Hennessy R.J., McLearie S., Kinsella A. & Waddington J.L. 2005. Facial surface analysis by 3D laser scanning and geometric morphometrics in relation to sexual dimorphism in cerebral–craniofacial morphogenesis and cognitive function. *J. Anat.,* 207: 283-295.

Hiritz R.J., Thomas T.T. & Merchant R. K. 1986. Delineation of craniofacial abnormalities of the fetal alcohol syndrome by close range photogrammetry. *Proc. American Society for Photogrammetry and Remote Sensing*, pp. 101-109.

Hoffmann J., Westendorff C., Leitner C., Bartz D. & Reinert S. 2005. Validation of 3D-laser surface registration for image-guided craniomaxillofacial surgery. *J. Cranio. Maxill. Surg.,* 33: 13–18.

Horton C.F., Richards G.D., White T.D., MacDowell A., Jabbour R.S. & Nasiatka J. 2010. Color centers induced in dental enamel during synchrotron microrcomputed tomography; Phase I assessment. *Am. J. Phys. Anthropol.,* Suppl. 50: 132.

Hsiao H., Friess M., Bradtmiller B. & Rohlf F.J. 2009. Development of sizing structure for fall arrest harness design. *Ergonomics,* 52: 1366-5847.

Hublin J.J., Pääbo S., Derevianko A.P., Doronichev V.B., Golovanova L.V., Friess M., Froment A., Hoffmann A., Kachahce N.E.J., Kullmer O., Lordkipanidze D., Moncel M.H., Potts R., Radovcic J., Rak Y.Z., Richards M., Mendez J.R., Rosas A., Schmauder M., Schmitz R.W., Semal P., Smith T., Tafuri M.A., Tattersall I., Tournepiche J.F., Toussaint M., Vassiliev S., Vialet A., White T. & Ziegler R. 2008. Suggested guidelines for invasive sampling of hominid remains. *J. Hum. Evol.,* 55: 756-757.

International Electroctechnical Commission 2001. Safety of laser products Part 1. IEC 60825-1 Edition 1.2: http://www.iec.ch.

Joint Committee for Guides in Metrology (JCGM) 2008. International Vocabulary of metrology – basic and general concepts and associated terms (VIM). Sèvres, France. http://www.bipm.org/en/publications/guides/vim.html.

Jones P.R.M. & Rioux M. 1997. Three-dimensional surface anthropometry: Applications to the human body. *Opt. Laser. Eng.,* 28: 89-117.

Jones T.R., Durand F. & Desbrun M. 2003. Non-iterative, feature-preserving mesh smoothing. *ACM T. Graphic. (SIGGRAPH 2003), 22(3):* 943–949.

Kau C.H. & Richmond S. 2008. Three-dimensional analysis of facial morphology surface changes in untreated children from 12 to 14 years of age. *Am. J. Orthodont. Dentofac.,* 134: 751-760.

Kersten T.P., Lindstaedt M. & Vogt B. 2009. Preserve the past for the future – Terrestrial laser scanning for the documentation and deformation analysis of Easter Island's Moai. *Photogramm Fernerkun*, 1: 79-90.

Klaas E., Kropp J. & Mongon B. 2011. The impact of different alignment strategies on the overall performance of a white light scanner according to sphere spacing error specified in VDI 2634. In J.A. Beraldin, G.S. Cheok, M.B. McCarthy, U. Neuschaefer-Rube, A.M. Baskurt, I.E. McDowall & M. Dolinsky (eds): *P. SPIE IS&T* Elect. Im., Vol 7864, http://dx.doi.org/10.1117/12.876643.

Kohn, L & Cheverud, J. 1992. Anthropometric imaging system repeatability. In M. Vannier, R. Yates & J. Whitestone (eds): *Proceedings of the cooperative working group in electronic imaging of the human body, CSERIAC, Dayton, Ohio*, pp. 114-123.

Kohn L., Cheverud J., Bhatia G., Commean P., Smith K. & Vannier M. 1995. Anthropometric optical surface imaging system repeatability, precision, and validation. *Ann. Plas. Surg.*, 34:362–371.

Kohno Y., Yahara H., Fukui Y., Mochimaru M. & Kouchi M. 2005. Automatic landmarking in 3D human head scans. *SAE Technical Paper*, doi: 10.4271/2005-01-2731.

Kouchi M. & Mochimaru M. 2008. Evaluation of Accuracy in Traditional and 3D Anthropometry. *SAE Digital Human Modeling for Design and Engineering Symposium, June 2008, Pittsburgh, PA, USA.* doi: 10.4271/2008-01-1882.

Kouchi M. & Mochimaru M. 2011. Errors in landmarking and the evaluation of the accuracy of traditional and 3D anthropometry. *Appl. Ergon.*, 42: 518-527.

Kovacs L., Zimmermann A., Brockmann G., Baurecht H., Schwenzer-Zimmerer K., Papadopulos N.A., Papadopulos M.A., Sader R., Biemer E. & Zeilhofer H.F. 2006. Accuracy and precision of the three-dimensional assessment of the facial surface using a 3-D- laser Scanner. *IEEE T. med. imaging*, 25: 742-754.

Kovacs L., Zimmermann A., Brockmann G.,Guhring M., Baurecht H., Papadopulos N.A., Schwenzer-Zimmerer K., Sader R., Biemer E. & Zeilhofer H.F. 2006. Three-dimensional recording of the human face with a 3D laser scanner. *J. plast. Reconstr. Aes.*, 59: 1193-1202.

Kuhl F.P. & Giardina C.R. 1982. Elliptic Fourier features of a closed contour. *Comput. Graph. Im. Proc.*, 18:236-258.

Kullmer O. 2008. Benefits and risks of virtual anthropology. *J. Anthropol. Sci.*, 86:205-207.

Kullmer O., Schrenk F. & Doerrhoefer B. 2003. High resolution 3D-image analysis of ape, hominid and human footprints. *Cour. Forsch. Senck.*, 243: 85-91.

Kullmer O., Benazzi S., Fiorenza L., Schulz D., Bacso S. & Winzen O. 2009. Technical Note:

Occlusal Fingerprint Analysis: Quantification of Tooth Wear Pattern. *Am. J. Phys. Anthropol.,* 139: 600-605.

Kustár Á. Forró L., Kalina I., Fazekas F., Honti S., Makra S. & Friess, M. 2012. FACE-R – 3D database of 400 living individuals' full head CT- and face scans for the craniofacial reconstruction. *J. Forensic Sci.* (in press).

Lane C. & Harrel W. Jr. 2008. Completing the 3-dimensional picture. *Am. J. Orthod. Dentofac.,* 133: 612-620.

Lewark E.A. 1998. *Automated techniques in anthropometry using a three dimensional laser scanner*. Master's thesis, Ohio University, College of Engineering and Technology, Athens.

Li P., Corner B., Paquette S., & Carson J. 2008. Generating Average or Targeted Head Models from Three-Dimensional Scans. *SAE Technical paper* 2008-01-1883. doi:10.4271/2008-01-1883.

Lin S.C.H., Douglass M.J., Holdaway S.J. & Floyd B. 2008. The application of 3D laser scanning technology to the assessment of ordinal and mechanical cortex quantification in lithic analysis. *J. Archaeol. Sci*., 37: 694-702.

Linney A.D., Campos J. & Richards R. 1997. Non-contact Anthropometry using Projected laser Line Distortion: Three-dimensional Graphic Visualisation and Applications. *Opt. Laser. Eng*., 28: 137-155.

Linney A.D., Grindrod S.R., Arridge S.R. & Moss J.P. 1989. Three-dimensional visualization of computerized tomography and laser scan data for the simulation of maxillo-facial surgery. *Med. Inform.,* 14:109-21.

Linney A.D., Tan A.C., Richards R., Coombes A.M., Gardener J. & Lees W.R. 1992. The acquisition, visualisation and applications of threedimensional data on the human body. *Proc. Electronic Imaging of the Human Body Workshop, Dayton, Ohio, 1992*, pp. 38-48.

Luhmann T. & Wendt K. 2000. Recommendations for an acceptance and verification test of optical 3-D measurement systems. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences,* Vol. XXXIII, Part B5: 493-500. Amsterdam.

Lynnerup N., Clausen M.-L., May Kristoffersen A. & Steglich-Arnholm H. 2009. Facial recognition and laser surface scan: a pilot study. *Forensic Sci. Med. Pathol*., 5:167–173.

Lyons P.D., Rioux M. & Patterson R.T. 2000. Application of a three-dimensional color laser scanner to paleontology: An interactive model of a juvenile Tyosauraus sp. basisphenoid-basioccipital. *Palaeont. Electron.*, 3 art. 4.

Lu J.-M. & Wang M.-J.J. 2010. The evaluation of Scan-Derived Anthropometric Measurements. *IEEE T. Instrum. Meas.,* 59: 2048-2054.

Ma L., Xu T. & Lin J. 2009. Validation of a three-dimensional facial scanning system based on structured light techniques. *Comput. Meth. Prog. Bio.*, 94: 290-298.

Maal T.L.L., van Loon B., Plooij J.M., Rangel F., Ettema A.M., Borstlap W.A., Bergé S.J. 2010. Registration of 3-Dimensional Facial Photographs for Clinical Use. *J. Oral. Maxil. Surg.,* 68: 2391-2401.

Maddux S.D. & Franciscus R.G. 2008. Allometric scaling of the infraorbital surface in Homo. *J. Hum. Evol.*, 56: 161-174.

Mafart, B. 2008. Human Fossils and Paleoanthropologists: a complex relation. *J. Anthropol.Sci*., 86:201-204.

Mbua E. 2011: Guidelines on Invasive Sampling for NMK Prehistory Collections, http://www.museums.or.ke/component/option,com_docman/task,doc_details/gid,110/Itemid,61/

De Menezes M. 2010. *Three-dimensional facial anthropometry*. PhD thesis Univ. Milan, Faculty of Medicine and Surgery.

Menk R. 1979. Data banks in historical anthropology: the material infrastructure for interdisciplinarity. *Arch. Suisses d'Anthropol. Gén.* (Genève), 43: 331-342.

Mitteroecker, P., Gunz P. & Bookstein F.L. 2005. Heterochrony and geometric morphometrics: a comparison of cranial growth in *Pan paniscus* versus *Pan troglodytes. Evol. Dev.*, 7:244-58.

Neubauer W., Doneus M., Studnicka N. & Riegl J. 2005. Combined High Resolution Laser Scanning and Photogrammetrical Documentation of the Pyramids at Giza.

In S. Dequal (ed): *Proc. XXth International Symposium CIPA, Torino. The International Archives of Photogrammetry, Remote Sensing and Spatial information Sciences,* Vol. XXXVI-5/C34/1: 470-475.

Öhrström L., Bitzer A., Walther M. & Rühli F.J. 2010. Terahertz imaging of ancient mummies and bone. *Am. J. Phys. Anthropol.*, 142:497-500.

Olejniczak A.J., Gomez-Robles A., Prado-Simon L, Bermudez de Castro J.M. & Martinon-Torres M. 2010. Quantifying the impact of mesh decimation and smoothing on the accuracy of three-dimensional enamel-dentine junction topographic models. *Am. J. Phys. Anthropol.,* Suppl. 50: 180-181.

O'Rourke D.H., Hayes M.G. & Carlyle S.W. 2000. Ancient DNA studies in physical anthropology. *Ann. Rev. Anthropol.,* 29: 217-242.

Pargas R.P., Staples N.J. & Davis J.S. 1997. Automatic Measurement Extraction for Apparel from a Three-dimensional Body Scan. *Opt. Laser. Eng.*, 28: 157-172.

Park H.K., Chung J.W. & Kho H.S. 2006. Use of hand-held laser scanning in the assessment of craniometry. *Forensic Sci. Int.*, 160: 200-206.

Potts R., Tocheri M.W., Tryon C.A., Kovarovic K., Campisano C.J., Walton N., Halvorsen B., Bjorkevoll L.& Hodnefjell A. 2011. The Smithsonian Institution's Human Origins Program Database: development, accessibility, and goals for research and education. *Am. J. Phys. Anthropol.,* Suppl. 52: 242.

Raichlen D.A., Gordon A.D., Harcourt-Smith W.E.H., Foster A.D. & Haas Jr. W.R. 2010. Laetoli Footprints Preserve Earliest Direct Evidence of Human-Like Bipedal Biomechanics. *PLoS ONE, 5 e9769*. doi:10.1371/journal.pone.0009769.

Rautenberg U. 2000. *Untersuchungen zur Zertifizierung photogrammetrischer Messsysteme nach VDI 2634, Blatt 1 mittels Einsatz von Längennormalen*. Dipl.-Arbeit Univ. Hannover, Inst. Photogrammetrie und Ingenieurvermessung.

Reddy D., Frost S., Friess M., Marcus L.F. & Delson E. 2002. An interactive database for primate morphometric studies. *Am. J. Phys. Anthropol.*, Suppl. 34: 129.

Rioux M. 1997. Colour 3-D Electronic Imaging of the Surface of the Human body. *Opt. Laser Eng.*, 28: 119-135.

Robinette K., Daanen H. & Paquet E. 1999. *The CAESAR Project: A 3-D Surface Anthropometry Survey.* In Proceedings of the Second International Conference on 3-D Digital Imaging and Modeling, 1999, pp. 380-386. IEEE Catalog Number: PR00062. IEEE: New Brunswick, N.J.

Robinette K. & Daanen H. 2005. Precision of the CAESAR scan-extracted measurements. *Appl. Ergon.*, 37: 259-265.

Romero M. 2010. *Landmark Localisation in 3D Face Data*. PhD thesis, University of York, Dept. of Computer Science.

Rühli F.J., Nielles-Vallespin S., Böni T. & Speier P. 2007. Clinical Magnetic Resonance Imaging of Ancient Dry Human Mummies Without Rehydration. *J. Am. Med. Assoc.,* 298: 2618-2620.

Rüther H., Chazan M., Schroeder R., Neeser R., Held C., Walker S.J., Matmon A. & Horwitz L.K. 2009. Laser scanning for conservation and research of African cultural heritage sites: the case study of Wonderwerk Cave, South Africa. *J. Archaeol. Sci.*, 36: 1847-1856.

Rusinkiewicz S. & Levoy M. 2001. Efficient variants of the ICP algorithm. *IEEE Computer Society Proceedings 3rd international conference on 3D digital imaging and modeling,* pp. 145-152.

Savara B.S. 1965. Applications of photogrammetry for quantitative study of tooth and face morphology. *Am. J. Phys. Anthropol.,* 23: 427-434.

Schoenemann P.T., Monge J., Glotzer L.D. & Campana M. 2008. The open research CT scan archive. *British Institute of Radiology Newsletter, Spring Issue*: 13-15.

Sholts S.B., Flores L., Walker P.L. & Wärmländer S.K.T.S. 2010a. Comparison of Coordinate measurement precision of different landmark Types on Human Crania using 3D laser Scanner and 3D Digitiser: Implications for Applications of Digital morphometrics. *Int. J. Osteoarchaeol.*, 21: 535–543.

Sholts S.B., Wärmländer S.K.T.S., Flores L.M., Miller K.W.P. & Walker P.L. 2010b. Variation in the measurement of cranial volume and surface area using 3D laser scanning technology. *J. Forensic Sci.*, 55: 871-876.

Simonis-Sueur C., Friess M. & Detroit, F. 2009. Skull shapes, maps, and microscribes. *Am. J. Phys. Anthropol.*, Suppl. 48: 240.

Slizewski A., Friess M. & Semal P. 2010. Surface scanning of anthropological specimens: nominal-actual comparison with low cost laser scanner and high end fringe light projection surface scanning systems. *Quartär*, 57: 179-187.

Snow D.R., Gahegan M., Giles C.L., Hirth K.G., Milner G.R., Mitra P. & Wang J.Z. 2006. Cybertools and Archaeology. *Science,* 311: 958-959.

Spoor F., Zonneveld F. & Macho G. 1993. Linear measurements of cortical bone and dental enamel by computed tomography: applications and problems. *Am. J. Phys. Anthropol.*, 91: 469-484.

Sumner A., & Riddle A.T.R. 2008. A virtual Paleolithic: Assays in Photogrammetric Three-Dimensional Artifact Modelling. *Paleoanthropology, 2008*: 158-169.

Sumner A., & Riddle A.T.R. 2009. Remote Anthropology: Reconciling Research Priorities with Digital Data Sharing. *J. Anthropol., Sci.* 87: 219-221.

Tattersall I. & Schwartz J.H. 2002. Is Paleoanthropology Science? Naming new Fossils and Control of Access to Them. *Anat. Rec.,* 269: 239-241.

Teaford M.F. 1982. Differences in molar wear gradient between juvenile macaques and langurs. *Am. J. Phys. Anthropol.*, 57: 323-330.

Tocheri M.W. 2007. *Three-dimensional riddles of the radial wrist: Derived carpal and carpometacarpal joint morphology of the Genus Homo and the implications for understanding the evolution of stone tool-related behaviors in hominins*. PhD thesis, Arizona State University, Tempe.

Tocheri M.W. 2009. laser Scanning: 3D Analysis of biological Surfaces. In C.W. Sensen & B. Hallgrímsson (eds): *Advanced Imaging in Biology and Medicine: Technology, Software Environments, Applications*, pp. 85–101. Springer, Berlin.

Tocheri M.W., Razdan A., Dupras T.L., Bae M., & Liu D. 2002. Quantitative Analyses of Human Pubic Symphyseal Morphology Using Three Dimensional Data: The Potential Utility for Aging Adult Human Skeletons. *Proceedings of the American Academy of Forensic Sciences. Atlanta, Georgia*. Vol 8, p. 235.

Tocheri M.W., Marzke M.W., Liu D., Bae M., Jones G.P., Williams R.C. & Razdan A. 2003. Functional capabilities of modern and fossil hominid hands: 3D analysis of trapezia. *Am. J. Phys. Anthropol.*, 122: 101–112.

Tocheri M.W., Orr C.M., Larson S.G., Sutikna T., Jatmiko Wahyu Saptomo E., Awe Due R., Djubiantono T., Morwood M.J. & Jungers W.L. 2007. The primitive wrist of *Homo floresiensis* and its implications for hominin evolution. *Science*, 317: 1743–1745.

Tocheri M.W., Solhan C.R., Orr C.M., Femiani J., Frohlich B., Groves C.P., Harcourt-Smith W.E., Richmond B.G., Shoelson B. & Jungers W.L. 2011. Ecological divergence and medial cuneiform morphology in gorillas. *J. Hum. Evol.*, 60:171–184.

Turgot A.R.J. 1767. Observation sur un Mémoire de M. de Saint-Peravy. In G. Schelle (ed): *Œuvres de Turgot et Documents le Concernant*, vol. 2, p. 644. Librairie Felix Alcan, Paris.

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 P.S. & M'Kirera F. 2003. A solution to the worn tooth conundrum in primate functional anatomy. *Proc. Natl. Acad. Sci. U.S.A.*, 100: 3874-3877.

Ungar P.S. & Williamson, M. 2000. Exploring the effects of tooth wear on functional morphology: a preliminary study using dental topographic analysis. *Palaeontol. Electron.,* 3 art. 1.

Vannier M.W., Pilgram T.K., Bhatia G. & Brunsden B. 1991 Facial surface scanner. *IEEE Comput. Graph.*, 11: 72-80.

Vannier M.W., Pilgram T.K., Bhatia G., Brunsden B., Nemecek J.R. & Young V.L. 1993. Quantitative three-dimensional assessment of face-lift with an optical facial surface scanner. *Ann. Plast. Surg.*, 30: 204-11.

Vannier M.W. & Robinette K.M. 1995. Three dimensional anthropometry. IEEE Computer

Society Press *Proceedings '95 Biomedical Visualization, October* 1995, pp. 1-8.

VDI 2008. VDI/VDE 2634/3. *Optical 3D-measuring systems – multiple view systems based on area scanning*. Beuth-Verlag, Berlin.

Weber G. 2001. Virtual Anthropology (VA): A call for Glasnost in Paleoanthropology. *Anat. Rec.,* 265: 193-201.

Wei R., Claes P., Walters M., Wholley C. & Clement J.G. 2011: Augmentation of linear facial anthropometrics through modern morphometrics: a facial convexity example. *Australian Dental Journal*, 56: 141–147.

Weinberg S.M., Naidoo S.R.N., Govier D.P., Martin R.A., Kane A.A. & Marazita M.L. 2006. Anthropometric Precision and Accuracy of Digital Three-Dimensional Photogrammetry: Comparing the Genex and 3dMD Imaging Systems with One Another and with Direct Anthropometry. *J. Craniofac. Surg.*, 17: 477-483.

Weinmann M., Schwartz C., Ruiters R. & Klein R. 2011. A Multi-Camera, Multi-Projector Super-Resolution Framework for Structured Light. In M. Goesele, Y. Matsushita, R. Sagawa & R Yang (eds): *Proceedings of 3D Imaging, Modeling, Processing, Visualization and Transmission (3DIMPVT), 2011 International Conference,* pp. 397-404. IEEE Computer Society's Conference Publishing Services.

Wiley D.F. 2005. *Landmark v 3.0.* Institute for Data Analysis and Visualization, University of California, Davis.

Wiley D.F., Amenta N., Alcantara D.A., Ghosh D., Kil Y.J., Delson E., Harcourt-Smith W., Rohlf F.J., St. John K. & Hamann B. 2005. Evolutionary morphing (extended abstract and associated video presentation). *IEEE Visual,* 2005: 1-8.

Yin, X., Razdan A. & Corner B.D. 2009. EARS: A System for Geometric and Anthropometric Evaluation of Human Body Scans. Computer-Aided Design and Applications. *Proceedings of CAD Conference*, 6: 431-445.

Associate Editor, Emiliano Bruner