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Review

Another link between archaeology and anthropology: Virtual anthropology ☆

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A R T I C L E I N F O

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A B S T R A C T

Archaeology and *biological anthropology* share research interests and numerous methods for field work. Both profit from collaborative work and diffusion of know-how. The last two decades have seen a technical revolution in biological anthropology: *Virtual Anthropology* (*VA*). It exploits digital technologies and brings together experts from different domains. Using volume and surface data from scanning processes, VA allows applying advanced shape and form analysis, higher reproducibility, offers permanent availability of virtual objects, and easy data exchange. The six main areas of VA including digitisation, exposing hidden structures, comparing shapes and forms, reconstructing specimens, materialising electronic specimens, and sharing data are introduced in this paper. Many overlaps with archaeological problems are highlighted and potential application areas are emphasised. The article provides a 3D human cranium model and a movie flying around and through the virtual copy of a most famous archaeological object: the Venus from Willendorf, Austria.

1. Archaeology and anthropology

Biological anthropology represents one branch of anthropology that deals with the biological variability of us humans, our ancestors, and our closest relatives. This “natural history of mankind through time and space”, as Robert Martin defined it already at the beginning of the last century (Martin, 1914), involves a variety of disciplines such as functional anatomy, physiology, osteology, human evolution, primatology, molecular and population genetics, embryology, demography, systematics, life history, and many others. Frequently, biological anthropology is separated at universities from cultural anthropology (ethnography), linguistics, and archaeology, though all kinds of combinations exist (Stanford et al., 2009). However those teaching curricula and research units might be organised, there is no doubt that the relations between biological anthropology and archaeology are manifold. Let’s imagine a typical example: At a pre-historic excavation site, the archaeologist would take care for the stone tools, the pottery, or remnants of buildings, and involve the biological anthropologist to identify sex and age of individuals, or to assess the taxonomic classification of the hominin remains preserved at the site. They would then together draw a picture of the life and environment of this ancient population. Palaeoanthropology, osteology, and osteopathology are particularly important areas in biological anthropology that create overlap with archaeology.

Biological anthropology as an institutional science is an astonishingly young discipline given the fact that it revolves around our own species. Though many scholars, among them such famous individuals as Adrian von Spieghel (1578–1628), G.L. Leclerc Comte de Buffon (1707–1788), J.F. Blumenbach (1752–1840), often called the “father of anthropology”, or Carl Linnaeus (1707–1778), the founder of the binominal nomenclature, were studying human phenotypic variability and were partly aware of the diversity appearing within and between modern human populations, it was not before the middle of the 19th century when the first chairs and societies were founded (Knumann et al., 1988). The reason for this condensation of ideas and data into established structures might be quite simple. Focusing on biological variability of populations really makes sense if the idea of biological evolution, and connectedly, the changeableness of species and populations, is acceptable. Wallace (1858), Darwin (1859), Mendel (1866), and many others paved the way to depart from a religiously dominated picture of human origin, and consequently opened minds to understand our biological history. In the early days, there was much overlap of knowledge and research interests among comparative anatomists, ethnographers, archaeologists, and anthropologists.

Despite the alliances in history, other links between archaeology and anthropology are present, for instance, the methods employed during field work. The scrutiny of documenting excavation sites layer by layer, the analysis of the resulting stratigraphy, or the wet and dry sieving to detect the smallest fragments of evidence being just a few examples. The newer technologies such

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as remote sensing using satellite images in multispectral modes (Ch'ng et al., 2011) or using ground radar to detect potential sites (Goodman, 2009) connect the two disciplines as well as using mass spectrometry (Prat et al., 2011; Stevenson and Mills, 2013), or GIS (Conroy et al., 2008), or laser-based surface scanning for documentation of material and reconstruction of whole sites (e.g. Milojevic et al., 2005; Paquet and Viktor, 2005; Kampel and Sablatnig, 2006; Grosman et al., 2008; Barton, 2009; Niven et al., 2009; Du et al., 2010; Kuzminsky and Gardiner, 2012; Oliveira et al., 2012; Unver and Taylor, 2012).

The topic of this paper, however, is to demonstrate another field where the research approaches begin to merge and overlaps are becoming more and more visible: Virtual Anthropology – VA (Weber Bookstein, 2011a). Since the 1990s, this new interdiscipline emerged in biological anthropology. Only a few years later, Kirchner and Jablonka (2001) suggested a "Virtual Archaeology" using digital methods. Predominantly for documentation and demonstration purposes (e.g. Pollefeys et al., 2001; Gaitatzes et al., 2001; Guidi et al., 2006; Calori et al., 2009; Aguilera and Lahoz, 2010; Stanco et al., 2012; Trinks et al., 2012) digital data from sites and artefacts were used in the last decade. Nevertheless, the analysis of the object geometry, for instance, or the installation of accessible object data bases are still awaiting broader applications (but see some examples below).

Virtual Anthropology (VA) exploits digital technologies and brings together experts from different domains such as anthropology, biology, medicine, mathematics, statistics, computer science, and engineering. VA, as we define it at University of Vienna, mainly deals with the functional morphology of recent and fossil hominoids. Its methods can, of course, be applied in a much broader sense, e.g. for other primates, mammals, vertebrates and invertebrates, and even plants or tools. The most striking differences to classical approaches in anthropology are the fact that only virtual copies are used (which derive from digitisation processes such as computed tomography or surface scanning), and that they are analysed in 3D or 4D within a computer environment. The crucial advantages are:

(1) the accessibility of the entire structure, including hidden areas such as the braincase, the sinuses, the dentine of teeth, the medullary cavities of long bones, or the heart including its chambers,
(2) the permanent availability of virtual objects (24/7) on hard drives or servers,
(3) the possibility of obtaining high-density data across the whole geometry for powerful quantitative analyses of form and function,
(4) the great range of options for data handling, statistics, visualisation, and data exchange for increasing sample size, and
(5) the increased reproducibility of procedures and measurements, a fundamental requirement of science.

The raise of Virtual Anthropology came along with the computer revolution of the 1970s–1990s. Without the capability of processing vast amounts of data, it simply would be unthinkable. Also the development of the mathematical methods and statistics, which stand behind it, would have been impossible to realise without fast electronic data processing.

2. The six areas of Virtual Anthropology (VA)

Many methods and procedures developed in VA for studying biological remains of our ancestors or to compare living individuals or populations can be used 1:1 in a "virtual archaeology". The paper here will introduce some of VA's major features for the readers of this journal which hopefully will be inspiring for further applications in archaeology, and elsewhere.

We divide Virtual Anthropology into six operational areas:

1. Digitise—mapping the physical world
2. Expose—looking inside
3. Compare—using numbers
4. Reconstruct—dealing with missing data
5. Materialise—back to the real world
6. Share—collaboration at the speed of the internet

All six are described in detail in the first comprehensive textbook of this discipline (Weber and Bookstein, 2011a). A short introduction to each of the six areas will be given below.

2.1. Digitise

Working with virtual copies in a computer environment obviously requires the conversion of the real object at first. There are many technologies available today, some still expensive and sophisticated, others cheap and simple to use. The first question to ask is whether the surface of the object is enough to be analysed, or, if the whole volume of the object is needed. In biological anthropology, many traits such as the labyrinth of the inner ear, the maxillary sinus, the tooth roots or the trabecular structures carry important information with regard to interpretation of functional morphology and taxonomical assessment. Therefore, volume data is frequently required. In archaeology, we may find a lot of applications which would be satisfied using surface data, for instance, when the shape of stone artefacts is measured and compared. In this case, the inner composition might be less important or known, and for the sake of saving time and money, surface scans can be ideal.

For volume scanning, all kinds of "tomographic" procedures are in principle applicable. Computed Tomography (CT), a standard medical imaging procedure usually used for scanning living patients, Micro-Computed Tomography (μ-CT), an industrial imaging routine to examine materials in very high resolution, or Magnetic Resonance Tomography (MRT), a medical routine to image patients without ionising radiation, are common examples. The latter is good for capturing soft tissues but delivers no usable signals from the hard tissues such as bones and teeth. It is used to examine the brain, the heart, the cartilage in joints, and the like in living subjects. Its use for archaeology might be limited to very specific problems, e.g. using a special technique of MRT – Ultrafast Echo Time – for specific problems in mummy research (Siemens, 2008) or standard MRT for hydrated mummies (Shin et al., 2010). In contrast, CT and μ-CT can cope easily with dense and very dense objects like bones, teeth, ivory, antler, shells, stones, and pottery. Like any tomographic method, it delivers a stack of 2D images (slices) that are combined to a 3D volume. Images are based on x-ray technology which means that radiation is emitted by a tube, the rays are partly absorbed by the object which is penetrated, and the remaining x-rays are recorded at a detector behind the object. Since archaeology only deals with dead material, the radiation dose is of low interest here (it might, however, affect preserved DNA).

Each slice of the volume data consists of tiny elements, like those of an electronic image that you produce with your smartphone. While these elements in a 2D photo are called "pixels", we call elements of 3D volume data "voxels" because they get a third dimension, a thickness. Thus they carry information about their individual position in x, y, *and* z – plus a particular value for their colour or grey value. Since different densities of materials lead to differences in the grey values of the voxels, one can detect the inner composition of the scanned object. If that composition is to be expected homogenous, there is no argument of using such a technology. If you suspect, in contrast, to recognise different materials or change of material over space, then this is the appropriate procedure. CT can deliver a resolution of roughly a millimetre down to ~200 μm. Features that are smaller cannot be acquired. μ-CT starts somewhere around 100 μm and can go down to 1 μm, depending on the system and size of the object. However, many μCTs are limited to relatively small sized objects (some centimetres in diameter). Only a few machines can handle large objects of the size of a human skull or femur (e.g. see www.micro-ct.at VISCOM X8060 II).

Surface scanning on the other hand doesn't allow looking even a nanometre below the exterior interface, but, depending on the system used, can digitise the surface in very high resolution too (also in the μm range). Scanners are often based on laser beams or structured light (dark and bright stripes) that are projected over the object. A sensor is measuring the reflected light resp. the pattern of stripe distortion. Since the geometry of the light/pattern emitting and receiving system is known, the object geometry can be computed by means of triangulation. The acquisition of one such "shot" can be very fast (within seconds). But comparable to photography, it represents only one view. Thus, the object has to be rotated and captured again and again, with overlapping areas. Smart routines in the software will stitch together the different views until the whole object surface is recorded in all dimensions. Data sets are rather small compared to volume date (because the objects are "hollow"), and in some cases also texture/colour information can be recorded. This might be an important aspect in archaeology - to keep this kind of information in the analysis (which is not possible with any of the tomographic procedures). Surface scanners are better transportable than CT or μ-CT scanners and much cheaper. Applications in the field are thus feasible (as long as electric power is available). Stereoscopic photography is also an alternative to obtain 3D data from multiple images taken from different views. Recent software packages (e.g., PhotoModeler® http://www.photomodeler.com) assist in calibrating the camera system and to identify overlapping points on images to create a 3D model of the object.

2.2. *Expose*

For surface data, as mentioned above, there is nothing to expose because only the visible surface was recorded. However, working with tomographic data, we can examine the outer *and* the inner structure. The good news, in contrast to invasive techniques such as histological thin sections or grinding, is that the object is not destroyed, not even touched. The interior can be inspected by browsing through the stack of slices (like most radiologists still do with their light box examining CT or MRT scans of patients) or by segmenting structures of interest as a 3D object. Segmentation means to separate particular areas of the image from its neighbourhood and address them as different logical entities. For instance, the brain in a MRT scan is often segmented from the surrounding liquor, meninges, bones, and muscles to be able to work on its morphology. Anthropologists do the same with the interior of the braincase, the only thing left in fossils to infer speculations about our ancestor's cognitive capacities. In a dried skull, and often in fossils, the braincase is filled with air which has a different grey value (black) than the fossilised bone (white). There are semi-automated algorithms available that help labelling the borders between the two without much manual intervention. Once this is done for each slice of the volume, there is a new object that we call "virtual endocast". We can render it on the computer screen and measure the cranial capacity (volume) and surface details like the convolutions or vessel imprints (Fig. 1).

The same procedure can be used for any materials to be distinguished as different entities, e.g. the dentine and the enamel of a tooth, or the muscle and the bone of a face, or the semicircular canals in the inner ear and the embedding petrosal bone. In fossils, we frequently encounter debris adhering to the object of interest. These sediments can be hard as concrete and require removal before the actual geometry of the anatomical structures can be appreciated. Physical preparation endangers the precious original specimen but electronic preparation, which uses filter algorithms to enhance borders between materials and segmentation of the virtual specimen, is touch-less and can be repeated until satisfying results are obtained.

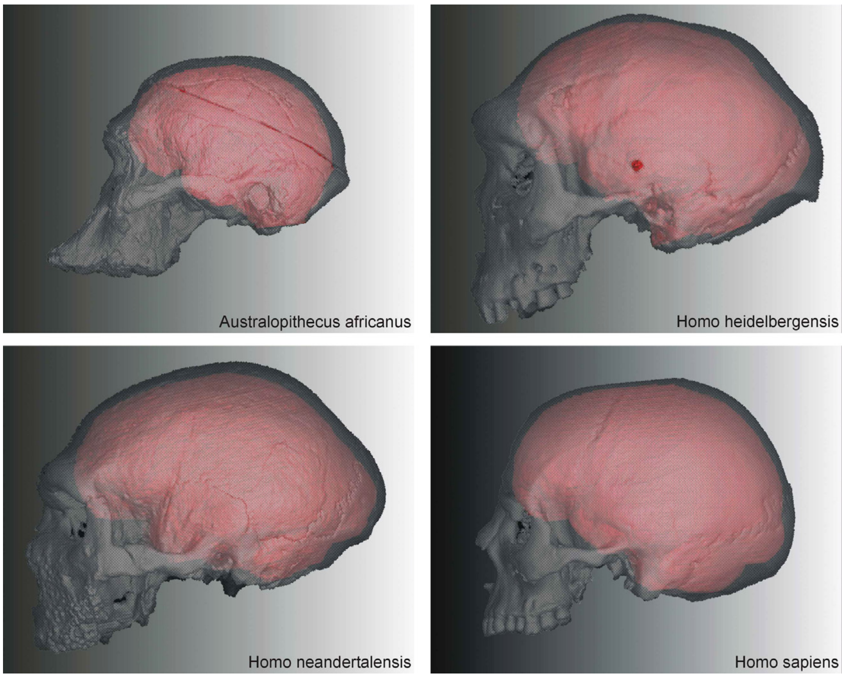
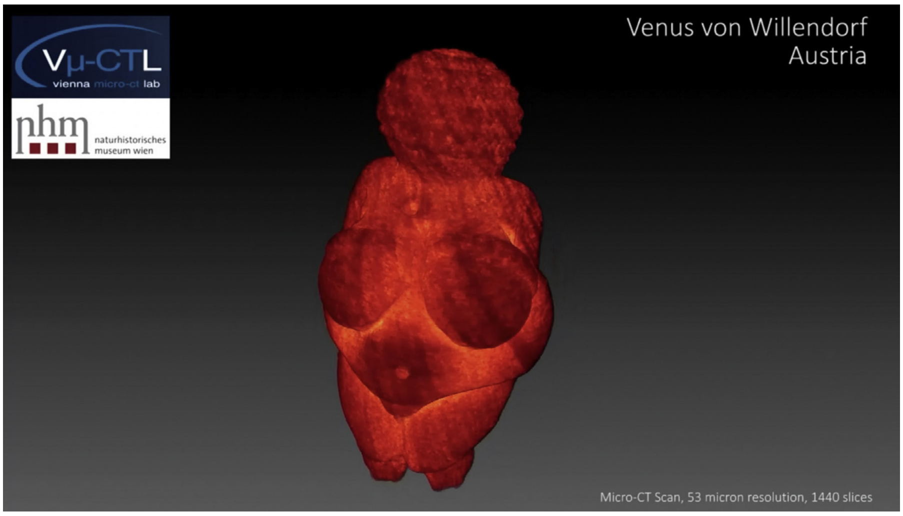


Fig. 1. The interior space of the braincase as a virtual endocast (red) within the transparent skull. Size and shape differences of four hominin species. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



Video S1. The μCT scanning of the Venus from Willendorf (Natural History Museum Vienna). The world-famous figurine (11 cm in height) is unpacked from its original box and securely fixed in a styrofoam container to avoid motion artefacts. The container is then placed in the centre of the rotation platform of the VISCOM X8060 μCT device at Vienna Micro-CT Lab, and the scan performed on Jan 8th 2013 at a resolution of 53 μm. The rotating 3D model in the next sequence is built from the 1440 raw images and represents exactly the outer surface of the figurine. In a further step, volume rendering is used to visualise the internal structures such as the layers of the oolitic limestone. Also, five highly dense inclusions appear. In a zoom to the neck region of the Venus, the porosity and layering of the material is very well visible. One of the five inclusions is segmented as a separate object (blue). Future investigations will show if the type of porosity, the sequence of layers, and the frequency of inclusions per volume unit can be used to identify the quarry site of the raw material for the figurine.

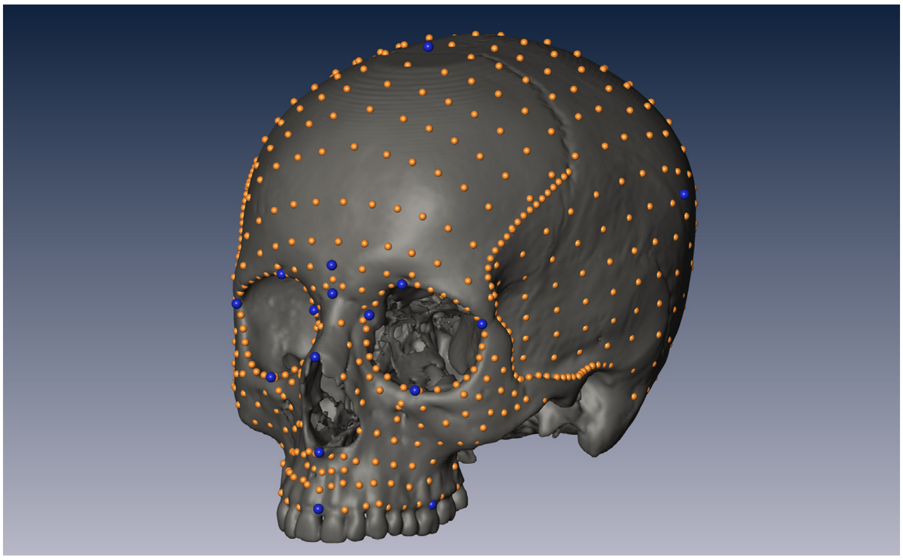
For all archaeological objects consisting of heterogenous materials, "expose" is likely to increase knowledge, for instance about the making of composite artefacts and their tentative functions. Even for an object like the Venus from Willendorf (Soffer et al., 2000) which is made from oolitic limestone, we may learn something from its internal composition because the stone is not as homogenous as initially thought and thus may carry a signal to identify its quarry site (see Video S1). Electronic preparation of matrix, for instance adhering to artefacts, can be equally essential in archaeology as in anthropology. In the same manner, a scan of an excavated block of material containing artefacts inside or the scan of a wrapped mummy (e.g. Jansen et al., 2002) may greatly help the planning of an intervention and avoiding damage if done prior to physical preparation.

2.3. Compare

In biological anthropology, there is a need to quantify the shape and form of objects and to compare individuals or samples to each other. Typical questions are: How does the average form look like? How does form vary in a population around this average? How are two groups differing from each other? What might be the functional meaning of such form differences? Rather than describing different morphologies by words, the aim is to express the shape and form by numbers. This has great advantages, namely to exclude subjectivity as far as possible, and to be able to compare hundreds of traits from hundreds of individuals at once (for a good example dealing with hundreds of crania, see e.g. Gunz et al., 2009a). The human mind is not able to keep the overview for such large data sets and tends to introduce its opinions. Palaeoanthropology has a long history in this sense, and probably also archaeology.

VA is a step towards reproducible results, a fundamental claim of any natural science. There are several techniques to quantify shape and form, for instance outline approaches such as Elliptic Fourier Analysis (EFA, Kuhl and Giardina, 1982) which captures closed contours quite well and is not depending on evenly spaced points or equal number of points across specimens, or Euclidean Distance Matrix Analysis (EDMA, Lele and Richtsmeier, 1991) which is based on distances between landmarks and thus well suitable for already available calliper measurements. In our Vienna lab, we use an approach that is called "Geometric Morphometrics (GM)" to perform quantitative comparisons of the object geometry. The reason is that GM uses multivariate statistics based on 3D coordinate data. Avoiding distances and angles [which have some specific disadvantageous statistical properties such as introducing artifactual covariance structures (Rohlf, 1999) and biased mean estimates (Rohlf, 2003, Slice, 2005)], and orientation problems, GM retains all geometric information contained within the data. A combination of outline and coordinate based approaches would be desirable in some cases (Baylac and Friess, 2005). There are of course many pro's and con's for the individual approaches. However, the space of this review article does not allow for a detailed discussion, but some articles are suggested to get an overview e.g. Bookstein (1991); Rohlf and Marcus (1993); Bookstein (1996); Dryden and Mardia (1998); Lele and Richtsmeier (2001); Slice (2005); Weber and Bookstein (2011a).

GM utilises a particular formal technique, that of landmark/semilandmark points, which enforces one particular rule for keeping comparisons under the control of biological theory: the rule of homology (comparing like to like). Landmarks are specific points on a form or image of a form located according to some rule. There are several types of landmarks corresponding to the method how they are identified. For instance, they can be located at the crossing of bony sutures or at extreme points of curvature or along ridges (see landmark types I–VI in Weber and Bookstein, 2011a). Central to the GM approach are some key elements such as Procrustes Superimposition, Principal Component Analysis, and Thin Plate Spline warping that lead to representations of form by size along with shape coordinates, the reliance on the full mathematical machinery of the statistical theory of shape, and the visualisation not only of single forms but also of comparisons, via the deformation grids that illustrate and formalize shape differences between geometrical objects. Moreover, the way data are represented allows the scientist to compute means and variances of groups at the same time that differences between two specimens or mean configurations are visualised as deformation grids. Importantly, size can be kept in or otherwise be eliminated from the analysis (the message to remember is: form = shape + size).



Video S2. Video of 3D Model 1: 3D model of a CT-scanned human cranium with 25 classical landmarks (biologically homologous measuring points) as blue spheres and 824 semilandmarks (geometrically homologous measuring points) as orange spheres. Almost the complete geometry of the cranium can be captured with this method.

While traditional landmarks are sometimes rare on certain structures (e.g. the braincase), the GM machinery allows to identify so-called “semilandmarks” on curves and surfaces. These points are geometrically homologous (Bookstein et al., 1999; Gunz et al., 2005) and can capture previously unattended regions. The 3D model of the human cranium provided with the online version of this paper (see also Video S2) shows 25 traditional landmarks (blue) like those that are usually applied to conventional studies, and 824 semilandmarks (orange) on curves (temporal line, zygomatic arch, orbita, alveolar rim of the maxilla) and surfaces that capture previously unattended regions. The semilandmark approach obviously considers more information and thus can support more sophisticated statements about shape and form differences between groups or individuals.

What works well with skulls and bones also works with stones and other artefacts. Particularly, the last years have seen the applications of geometric morphometrics in the context of quantitative analysis of lithic assemblages, for instance using landmark-semilandmark approaches (Lycett et al., 2010; Archer and Braun, 2010; Buchanan and Collard, 2010) or surface areas (Lin et al., 2010). Curves derived from tool surfaces even appeared earlier (Loriot et al., 2007), and Bretzke and Conard (2012) have very recently worked with surface scans and measures of convexities on cores and blades. It is not hard to imagine that quantitative data on the geometry of tools could be of immense help to sort out the subtle differences in tool making that appear, for instance, in the Middle Palaeolithic period. A main problem that is not solved yet entirely is the definition of “homologous” measuring points. Here is a very interesting area open for the future with respect to thorough evaluation in the archaeological context.

2.4. Reconstruct

Reconstruction in Virtual Anthropology refers to the form and shape of biological objects, in archaeology to the form and shape of artefacts or buildings. Reconstruction is called for when the present form of an object fails to correspond with its supposed original form. Taphonomic processes, but also damage during excavation or manipulation, can lead to four kinds of disturbances of the biological form (Weber and Bookstein, 2011a). All of these apply similarly to archaeological objects:

(1) An object can be broken but (almost) all pieces are preserved (type 1, e.g., a broken vase that can be fully restored using glue).
(2) some parts of the object can be missing (type 2, e.g., the vase mentioned above - not broken - but with a big hole in it, and no pieces preserved to fill it).
(3) the object can be deformed (type 3, e.g., a metal pot with a large bump in it).
(4) the object is not directly accessible because it is covered by a foreign material (type 4, e.g., a Greek amphora in the Aegean Sea covered by marine organisms).

Of course, all kinds of combinations of these disturbances may exist, and in fact, we rarely find one alone (e.g. there is broken+missing, broken+covered, missing+deformed+covered, etc.). When a disturbance has been recognised and corrected, then we can speak of reconstruction (Weber and Bookstein, 2011a). The types of disturbances introduced here help us thinking about the varieties of reconstruction problems that we will face. Single type 1 and 4 problems can have unique solutions, at least in principle. For most type 2 problems there is no unique solution, and the same is true for type 3 problems (except for those where the deformation forces are known or one half of a symmetric structure is unaffected).

In contrast to biological forms, however, in archaeology we have a good chance to estimate missing or deformed parts from the existing form without using too sophisticated approaches and almost to perfection. The reason is that biological objects, like skulls, do not follow strictly general architectural rules, they show a lot of individual variation. For instance, the form of an upper jaw (maxilla) is of course known in principle for humans, but each human has a slightly different form which is determined by genetic and environmental factors. Bone re-modelling happens during the whole life. A maxilla's form is depending on the inherited general skull form, the individual loadings (related to muscles and diet), the preservation and position of teeth (e.g. some might be lost, some inclined forward or backward), or other behavioural aspects (e.g. teeth might be used as tools or clenched during the night). In anthropology, we can thus reconstruct a particular part only based on a reference data set, and with a particular likelihood. In contrast, if a part of a vase is missing, it could be relatively easy to re-create its initial form because it

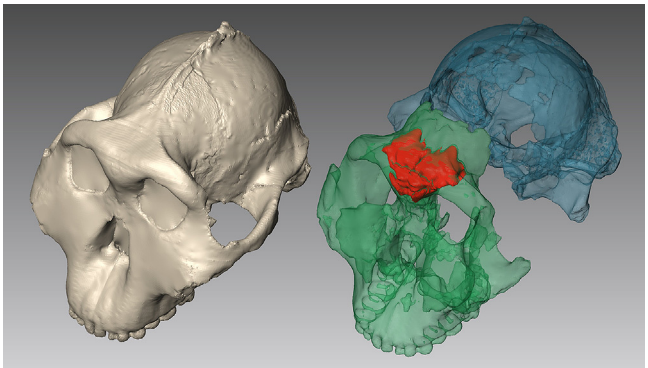


Fig. 2. One of the most famous fossils, OH 5 from Tanzania (*Paranthropus boisei*) consists of a facial (green) and a neurocranial (blue) part. Prior to its morphometric analysis and computation of cranial capacity, it had to be reconstructed (see resulting reconstruction on the left). The detailed steps of the virtual reconstruction, including removing old plaster material, restoring symmetry, estimating spatial positions of parts and interpolating missing areas, are described by Benazzi et al. (2011). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

would follow a pretty strict rule of a smooth surface (especially if done with a potter's wheel). Also the deformation of the metal pot above would be easy to retro-deform according to the remaining unaffected form. When it comes to highly individualised objects, let's say the Nebra sky disk, of course archaeological objects become as difficult as biological ones, or, as in this case, even more problematic because the disk is the only one of its kind (this sometimes applies to fossil specimens as well, e.g., when there is no other finding of the same species).

It is important to bear in mind that a reconstruction can never duplicate the original. It can approximate it. And: reconstruction processes involve assumptions. The advantage of using VA in reconstruction is that these assumptions have to be made explicit. There is no mumbo-jumbo of the expert who pulls out the reconstruction of the hat like a rabbit. Everything is based on numbers and explicit statements are made, e.g. which kind of reference data was used or which geometric constraint (e.g. bilateral symmetry) was applied (Fig. 2). The aim is to reduce subjective influences as far as possible. In lucky cases, the task may boil down to limit the six degrees of freedom (three to translate, three to rotate) to possibly zero when putting pieces together, or to apply a-priory knowledge about the form (e.g. smoothness, radial or bilateral symmetry) during estimation of missing parts. For type 4 problems, we are touching the topic of electronic preparation that we saw already under the heading "expose" above.

A virtual reconstruction, in contrast to a physical one, is not depending on sources of irritation such as gravity, glue, or having only one trial. There are many software packages existing, particularly in the CAD (computer aided design) domain, that allow absolute control over fragment movements and rotations, and also support the process with aiding constructions such as B-splines or NURBS.

Aside this controlled merging of pieces on the screen, which is already an important improvement, we can also use some of the technology introduced under "compare" for estimating missing or deformed parts (type 2 and 3 problems). Thin Plate spline (TPS) interpolation (Gunz, 2005; Gunz et al., 2009b; Weber and Bookstein, 2011a; Senck, 2012) is used for geometric reconstruction. It uses a map of landmarks and semilandmarks from the complete specimen (the "reference") and whatever is observable on the specimen to be reconstructed (the "target"). It is a deformation of the reference that is computed to match the location of the corresponding points on the target, while filling in the rest of the information. Applications range from fossil reconstructions (Gunz et al., 2009b; Benazzi et al., 2011, 2013) to the pre-operative implant planning for large skull defects (Heuzé et al., 2008). TPS should not be used when it is an extrapolation – when the region being reconstructed extends substantially beyond the limits of the region present in the target. But it works particularly well to reconstruct smooth surfaces when landmarks and semilandmarks are sampled densely and is thus of considerable value for archaeological purposes.

2.5. Materialise

Virtual objects can be visualised at any time – as long as a computer is available. For teaching and training purposes as well as for permanent museum display, real models can be more desirable media to create knowledge. But also for the researcher, they provide substantial support to understand three-dimensional relationships of complex structures. If we watch architects, who are certainly among the best trained people with regard to spatial imagination, we recognise that even those people still build real models of constructions to appraise complex interactions of structures. The German word "begreifen", which means both "to touch" and "to understand", clearly illustrates this desire.

Models of digital objects can be produced using Rapid Prototyping (RP) technology which was invented in the late 1980s to facilitate quick and relatively cheap manufacturing of industrial prototypes before mass production. The principle behind all kinds of RP techniques is to build an object layer by layer. This is actually a very old idea if we think about the Great Pyramids of Gizeh and allows to build even hollow spaces and undercuts (which is not possible, e.g. with CNC machinery).

One of the first and still most advanced procedures is stereolithography (STL) which can produce quite accurate models (resolution $\sim$0.1 mm) (Fig. 3). The STL data generated during preparation serve to control a mobile mirror that directs a UV laser beam in accordance with the layer geometry. Where the UV laser beam comes into contact with a photosensitive liquid acrylate or epoxide resin, it hardens. Then the part is lowered

Fig. 3. Transparent stereolithographic model of the Tyrolean Iceman skull (z-werkzeugbau, Dornbirn, Austria). The broken right orbit of "Ötzi" is well visible.

deeper – by the thickness of one layer – into the liquid polymer bath. The surface must be levelled initially by a recoating system and then the next layer is hardened. This process continues automatically until the production of the 3D part has been completed. Other methods use powders rather than liquids (e.g. Z-printing, Laser Sintering) or meltable plastics (e.g. Fused Deposition Modelling) applied through heating nozzles. There are differences in the price, the speed, and as well in the quality of models (see Weber and Bookstein, 2011a for an overview) which demands a decision with regard to the planned application. However, any type of RP model has some advantages over conventional casts in the following respects: (1) there is no mould that is aging (the models itself of course age, but they can be reproduced to 100%), (2) there is no contact to the (possibly fragile) original object, only contactless scanning is required, (3) hollow structures and undercuts are no problem to be realised (and e.g., for skull models, they can be built with a removable skull cap to enable inspection inside the braincase), (4) models can be up- or down-scaled (e.g. a 25%-sized replica). All of these advantages can fully benefit archaeological applications as well. Beside the drawback of some of them being rather expensive, there has to be mentioned the limited resolution of RP models which is somewhere in the 100 μm range (and of course depending on the raw data). Still not widespread, but available to some extent, is micro-stereolithography which can produce models with a resolution between 10 and 20 μm (Weber and Bookstein, 2011a).

2.6. Share

Scientific progress in many cases owes to collaborative work which includes sharing data resources. The larger samples are, the better we understand variation and differences between groups. With the introduction of the Internet we saw a progressively increasing behaviour of sharing information. Open access journals (such as this first issue of DAACH here) are meanwhile widespread and data archives were and are created in any field of research. Palaeoanthropology, however, is a field where the idea of sharing data for the sake of creating knowledge is still not accepted widely. When we installed the first electronic archive of hominin fossils in 1999 (http://www.virtual-anthropology.com/3d_data/3d-archive) and the idea of "Glasnost in Palaeoanthropology" was expressed more than a decade ago (Weber, 2001) it was with the hope that many colleagues would follow the example. The community saw some reviews and conferences on the topic (Gibbons, 2002; Soares, 2003; Delson et al., 2007), and a few archives were established (e.g., NESPOS, EVAN-Society, ORSA, Digimorph, Paleoanthportal, RHOI, AHOB, Visible Human Server). However, many researchers and curators remained reluctant and not much was changed (Weber and Bookstein, 2011b). The digital@rchive of Fossil Hominoids is still the largest data base providing access to a significant number of very important hominin fossils.

Without doubt, there are a lot of difficult questions involved in the problem, for instance, how to protect the legitimate interests of the discoverers who often invested considerable amounts of time and money in the field to make their findings, or how large funding agencies and journals can act to enforce publication of data. It seems reasonable to allocate sufficient time for the discoverers to work on their specimens. Yet, there are large numbers of fossils that are not accessible even decades after their discovery. Moreover, it is a quite essential claim in science that results can be checked by others, particularly if a new taxon is described and established. So there is a reasonable demand also that at least electronic data from specimens should be accessible after publication or, if nothing is published, after a certain number of years.

There is definitely a difference between palaeoanthropology and archaeology with regard to the data sharing issue. Pleistocene archaeological material is much more abundant than hominin fossils, so access regulations might be easier to agree on and include fewer restrictions. For tools, figurines and other artefacts, good quality casts might do a good job in many cases because internal structures, in contrast to biological problems, are often not of such central interest. However, large data bases with 3D digital artefacts would likely also advance the comparative aspect, particularly if quantitative measurements, as introduced above, are included.

In this sense and as a teaser for online artefacts, with the great help of the Natural History Museum Vienna, we can distribute here a movie flying around and through one of the most spectacular archaeological objects of the world, the Venus from Willendorf (see Section 2.2 above and accompanying text). The 3D data derives from a μCT scan of the figurine at the Vienna Micro-CT Lab with a resolution of 53 μm.

3. Technology crossing the borders of disciplines

We have developed a number of new approaches in Virtual Anthropology with the goal to advance the study of human evolution. These developments were based on the interdisciplinary collaboration between different fields such as anthropology, mathematics, statistics, computer science, and engineering. It turned out over the years that some, if not most, of it can be very useful in other areas as well. Palaeontology and zoology, for instance, can use our technology 1:1, just applying it to other animals (e.g., Franzosa and Rowe, 2005; Dockner, 2006; Macrini et al., 2007; Dong, 2008; Knoll et al., 2012; Lukeneder et al., 2013). Medicine can use some of its technologies, for instance, virtual endocasts (Traxler et al., 2002) or measurements based on semilandmarks (Recheis et al., 2004; Bookstein et al., 2006; Heuzé et al., 2008). Biomechanics is using the ability to reconstruct specimens' geometry (Strait et al., 2009; O'Higgins et al., 2010; Wroe et al., 2010) or to find extreme forms in a sample (Smith et al., 2011), and dentists are just about to discover the advantages of working in 3D (http://3d-dentistry.org) rather than using the common 2D cephalometrics for planning interventions.

This new journal here, *Digital Applications in Archaeology and Cultural Heritage (DAACH)*, is the world's first on-line journal with a focus on 3D digital models of the world's cultural heritage sites, monuments, and palaeoanthropological remains (see also *Paleontologica Electronica* for a similar scope with regard to palaeontology or related biological disciplines). I hope the examples and comments above with regard to the overlaps between Virtual Anthropology and archaeology will stimulate more applications in the field, and many new specific articles in *DAACH* and elsewhere.

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Appendix A. Supplementary materials: videos and 3D model

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.daach.2013.04.001.

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