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Advances in virtual archaeology: research, preservation, and dissemination

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Abstract **– The archaeological and palaeontological record (including human skeletal remains) often bears crack, damage and deformations. The recent rapid development of the diagnostic potentials of "virtual archaeology" has provided innovative tools to manage, study and preserve cultural and natural heritage. These tools include, among others, CT-scans, Laser-scanning, photogrammetry, 3D imaging and rapid prototyping. This approach can contribute to any archaeological context from its discovery to research, preservation, and dissemination. 3D imaging techniques, for instance, substitute physical intervention with a virtual protocol aimed at restoring the original shape of an archaeological item or a fossil specimen. In a similar way, the recovery of digital morphological information can be gathered using data preserved even on a deficient finding through the use of 3D comparative samples. Here we present an extended and updated review about the most innovative protocols applied in virtual archaeology and palaeontology.**

1. INTRODUCTION

The possibility of an archaeological find to unravel its full set of historical and scientific information is strictly dependant upon the combination and coordination of many different skills involved in every stage of its discovery, study, conservation and disclosure. For what concerns skeletal remains, the circumstances of their preservation (as fossils, sub-fossils, mummies or else) are often occasional, and typically undergo various processes of diagenesis that alter (to various extent) their original morphology. Very often, these findings represent the only source of information available on important, or even crucial, phases of human evolution, diffusion and civilization. Hence, it becomes extremely important to gather as many information as possible, restoring their original state and studying their features extensively while preventing interventions that could potentially damage the skeletal elements in an irreversible manner [1-4].

The development of computerized technologies based on X-rays, structured-light and photogrammetry, allow us to acquire, record and process digitally, many relevant aspects of the morphology of important and, sometimes, unique remains. Further analytical tools, based on statistical and multivariate methods for the study of skeletal variability, made it possible for the disciplines of palaeontology and paleoanthropology to gain a new analytical dimension with regards to evolutionary, functional and ecological processes associated with these remains [5]. Sophisticated digital techniques, such as computerized tomography, laser scanning, 3D-imaging, allow us to 'operate' in a totally virtual environment on unique and precious remains, while favouring their conservation and fruition by a larger audience.

The development of 3D imaging techniques entailed the implementation of digital acquisition procedures and the definition of protocols addressed to the virtual restoration of damaged human remains [1, 6-8]. The 3D digital acquisition not only decreases the possibility of damages performed on the original specimens during the phases of study, but can undergo reproducible protocols of virtual restoration aimed at repairing damaged or deficient regions [9, 10]. The digital versions of physical objects can be used to restore morphologies and to reproduce the original in an indefinite number of copies as detailed physical casts by using 3D printer (rapid prototyping). This issue is central for research purposes as well as sharing information, preservation, conservation and museum exhibits [11].

The traditional method of cast processing entails the production of two valves composing a negative print of the specimen; successively they can be used to obtain a positive cast by filling the inner cavity with plaster or plastic resins [12]. This approach can be invasive both for undesired physical damages and genetic contamination. This latter factor can affect ancient DNA analysis. A specimen can be subject to the making of casts of the inner cavity (e.g. endocast) through the introduction of silicon resins inside the specimen; as for the previous case, also in this one the risk of causing damages is high.

A physical restoration consists in the reassembling and immobilization of fragments adjacent and not through the apposition of fixing material. Furthermore, an archaeological specimen can undergo further restoration works, which might burden the specimen with additional physical and chemical stresses. The operations of restoration on a physical object are restricted to the portions preserved, on the contrary, working on the its digital version make it possible to perform other procedures such as the retrodeformation and the addition of missing parts cut-out from a similar specimen and adapted to the target sample [4, 13, 14].

3D printing is one of the latest technology making inroads in archaeology and in palaeontology. Nowadays it is possible to recreate duplicates of fossils, also in different scales, without damaging sensitive collections and "print" virtually restored specimens. Replicas can be used both in scientific research as testing models and in dissemination activities such as museums or temporary exhibitions. They can also play a crucial role as teaching support at different levels, especially for disabled persons [15].

In the last years, digital acquisition and editing techniques have undergone a reduction of costs. Photogrammetry requires low cost equipment and software (e.g. Agisoft). Many editing softwares (e.g. Meshlab) and informatics libraries (e.g. vcg library) are open access, making it possible to modify the source code for any implementation [16-18].

Throughout this paper we demonstrate how all of the techniques described have the potential of yielding a context of archaeological or palaeoanthropological interest with little intervention on its original. While providing a full set of reproducible information and guaranteeing immediate valorisation and dissemination, such techniques are still under applied in cultural heritage studies.

In particular, we considered data acquisition, digital restoration, digital printing techniques and their improvements in recent years by means of some examples in the field of palaeoanthropology and archaeology.

2. DIGITAL ACQUISITION AND VIRTUAL RESTORATION

a. Digital acquisition techniques

i. Computerized Tomography

X-ray tomography provides a series of 2D cross-sectional images ("slices") spaced by a constant distance (inter-slice distance), which defines the resolution of the CT acquisition. The application of the Marching cubes algorithms (isosurface) allows to extract a polygonal mesh from a 3D-array [19].

ii. Laser scanning

A 3D laser scanner is a device that acquires the surface attainable from a beam laser source. The physical object is thus acquired through a CCD sensor as a points cloud. The scans performed by a number of viewpoints allow a digital reconstruction of the virtual version of the physical object via triangulation. Colouring can also be acquired using this technique.

iii. Photogrammetry

3D reconstruction from multiple images is a method commonly called photogrammetry. With this approach the photographs are aligned producing a points cloud. The specimen is acquired from different angulations so as to reduce the number of blind areas. A detailed texture can be processed from the photographs acquired. Unlike CT-scan and laser scanning the dimension of the 3D model obtained via photogrammetry does not replicate the original scale, hence a metric reference is needed.

b. Editing and virtual restoration techniques

i. Geometric Morphometrics (GM)

This analytic methodology is based on the concept of geometrical/anatomical "homology" meant as correspondence between two related forms in accordance with ontogenetic or phylogenetic criteria [20]. The biological configurations in related specimens are acquired as a series of "points" (landmarks) presumed to be "homologous" and comparable in all their histological and topological characteristics [21]. In addition to landmark acquisition more topological information can be reached through the acquisition of semi-landmark sets [22]. In detail these configurations consist in a group of geometric points defined on a reference template and superimposed on the target model exploiting the spatial pattern obtained from the Procrustes alignment (GPA) of the landmark configurations belonging to the reference and the target models [23].

ii. Mirroring and digital alignment

A restoration of the overall morphology of a specimen can be performed to restore the deficient side by mirroring of the preserved portion. The first step consists on the definition of the midsagittal plane by 3 landmarks. The complete side can be mirrored along the midsagittal plane and the deficient portions on the other side replaced with those mirrored. Occasionally, the deficient side can be replaced completely with the mirrored side. When an anatomical portion is missing on both sides (e.g. zygomatic arch) digital alignment can be applied [24]. This approach consists in the acquisition on the reference and target models of two (semi-) landmark configurations. The target model, optionally, can be scaled on the size of the reference model. Successively the (scaled) reference model will be aligned on the target model and the deficient portion cut-out and "stitched" on the deficient target model.

iii. Thin Plate Spline (TPS) and surface warping

Specimens are often damaged and with missing portions. In this case it is suitable to apply a geometric reconstruction via interpolant TPS [25] paired to surface warping procedures [26]. Homologous landmark sets on both models (reference and target) are used to superimpose a semilandmark set (built on the reference) on the target specimen. The TPS is performed between the two surfaces using the (semi-) landmark sets as reference. The warped surface corresponding to the damage portions on the reference model can be cut out and merged to the target model.

iv. Retrodeformation

GM can be applied to correct the asymmetry due to taphonomic events in the virtual restoration of digital models. GM protocols exploit the acquisition of two bilateral landmark sets on a specimen to extrapolate the geometrical pattern of asymmetry. Two bilateral configurations can be symmetrized [27] and the digital specimen can be forced to follow the new constraint, intended as landmark symmetrisation, through the application of TPS [25] and surface warping algorithms [28]: this procedure is usually referred to as retrodeformation.

v. 3D printing

3D printing, or more correctly Additive Manufacturing (AM), is the process used to build up a physical object from a digital model by successive addition of material. ISO/ASTM52900-15 defines seven categories of AM processes: Binder Jetting, Directed Energy Deposition, Material Extrusion, Material Jetting, Powder Bed Fusion, Sheet Lamination and Vat Photopolymerization. The most common processes in archaeology and palaeontology are the Material Extrusion and the VAT Photopolymerisation processes. The Fuse Deposition modelling (FDM) process is a material extrusion process. Material is dispensed through a nozzle or orifice, where it is heated and is then deposited layer by layer. The nozzle can move horizontally and a platform moves up and down vertically after each new layer is deposited. The Vat polymerisation uses a vat of liquid photopolymer resin, out of which the model is constructed layer by layer. An ultraviolet (UV) light is used to cure or harden the resin where required, whilst a platform moves the object being made downwards after each new layer is cured.

vi. Digital life appearance reconstruction

Life appearance of fossil specimens are possible to obtain by combining digital illustration and virtual restoration techniques. Once a virtual or 3D-printed model of a restored specimen is acquired, an accurate reconstruction can be made using an illustration software (e.g. Adobe Photoshop, Clip Studio Paint). The layer feature of these softwares allow to set the model as a base reference layer and to paint muscles, soft tissues or hair over it with great precision.

3. CASE STUDIES

a. Altamura man (Altamura, Italy)

The paleoanthropological specimen referred to as "Altamura man", discovered in 1993 within the Lamalunga karst system, near the town of Altamura (Apulia, Italy), might well be the most complete Neanderthal specimen ever discovered. The chronology ranges from 172 ± 15 ka to 130 ± 2 ka [29]. Despite its importance for the knowledge of human evolution during the Middle-to-Late Pleistocene, the specimen is still *in situ*, largely incorporated within a curtain of calcite and coralloid concretions. The skull of the Altamura man is entirely preserved but accessible from two different paths. The partial portions of the face and cranial vault ("front side") are preserved in the so called "Abside dell'Uomo" (Apse of Man), while the cranial base, parts of the cranial vault and of the maxillary anatomical district ("rear side") are only visible by a small chamber behind the Abside.This latter chamber is not accessible with laser-scanner facilities so the rear side has been digitalized via photogrammetry using photographic probes and the GoPro camera the images were processed using the software Agisoft Photoscan (Fig. 1a). The front side of the Altamura skull instead, was acquired through laser scanning (Konica Minolta range7) at a resolution of 40 μm (Fig. 1b). While we wait for the physical extraction of the Altamura skull, thanks to the digital acquisition techniques (Fig. 1a-b), we safely performed the virtual extraction of the skull as reported in the [30].

b. Saccopastore 1 and 2 (Rome, Italy)

The two Neanderthal crania of Saccopastore 1 and Saccopastore 2 were found in 1929 and 1935 respectively within the gravels and sands of a quarry near the city of Rome; these were referred to a Late Pleistocene deposit originally dated about 130 ka [31-35] and recently redated to 250 ka [36]. Saccopastore 1 represents one of the most complete Neanderthal cranium available for comparative analyses. Except for some loss of bony material (e.g. the medial portion of the supraorbital torus) occurred during its discovery in 1929, Saccopastore 1 cranium consists of the whole base, the vault and large parts of the facial complex in place. However, some taphonomic processes affected its morphology, in particular some compressive forces acted across the region of left parietal, portions of mastoid region of the right temporal bone and part of the right side of maxilla. In this way the cranium appear medio-laterally compressed. Saccopastore 2 is more damaged, lacking the whole vault and the left fronto-orbital region [37]. 7

We performed the retrodeformation of the skull of Saccopastore 1 acquiring 86 bilateral landmarks (43 on each side). These landmarks are reflected and relabeled in order to compute a symmetric average of both the original and the mirrored and relabeled set of landmarks. Subsequently, the 3D model is warped to the symmetric consensus using a Thin-Plate-Spline deformation (TPS) [25].

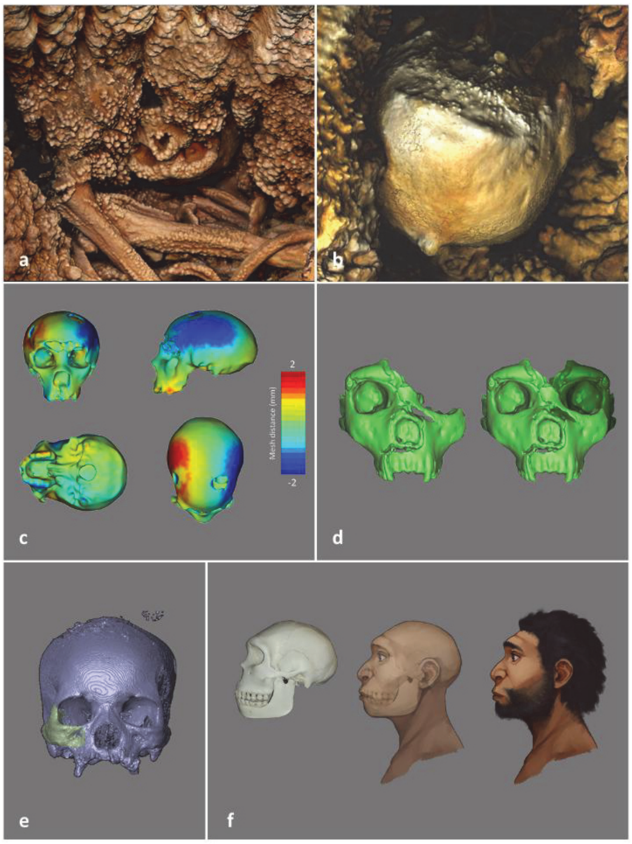

Figure 1. The digital acquisition of the Altamura skeleton by laser scanner (a) and photogrammetry (b). The skull of Saccopastore 1 retrodeformed (c) after TPS transformation. Mirroring of the right portions of the orbital region of Saccopastore 2 on the left side (d). Digital alignment and merging of the mirrored version of part of the left zygomatic bone on the right side of TK RS H1 (e). Picture of the Chimera printed using the WASP Delta 3D printer with facial reconstruction (f).

As shown in figure 1c the principal axes of variation, due to taphonomic processes, crosses the region of left parietal, portions of the mastoid region of the right temporal bone and part of the right side of maxilla, suggesting that a phenomenon of compression occurred during post-depositional processes.

In the case of Saccopastore 2, where facial portions of the skull are preserved asymmetrically we performed a restoration of the overall morphology through a procedure of mirroring (reflected relabeling techniques). If the specimen is not deformed, this correction is desirable. The left missing portions of the skull of Saccopastore 2 had been obtained after the definition of the midsagittal plane. In this way, the preserved portions on the right side of the orbital region have been mirrored along the symmetrical plane and correctly placed on the other side.

c. TK RS H1 (Tadrart Acacus, SW Libya)

TK RS H1 is a naturally mummified human body discovered at Takarkori in the Libyan Acacus Mountains [38-40]. The cranium is almost complete (except for most of the right zygomatic bone) and perfectly preserved.The digital alignment is the protocol developed by Profico and colleagues (2016) to place an anatomical region on a deficient 3D mesh. In particular this tool consists of the extrapolation of the rotation matrix to translate, rotate, and scale a fragment (or bone) using another object as reference. In this case, we applied the digital alignment on the cranium of TK-RS-H1. The placement of the mirrored version of the left zygomatic bone on the right side was performed after the acquisition of two homologues landmark configurations on both sides using the rotation matrix calculated between the coordinates of the bilateral landmark sets.

d. A 3D “Chimeric” skull of *Homo heidelbergensis*

The 3D chimera model of the hypothetical main features of the skull of the European Middle Pleistocene species *Homo heidelbergensis* was performed using a protocol consisting in a series of transformation (TPS warping) starting from a reference 3D model (a skull of *Homo sapiens*). The procedure is landmark-based. On the reference model, sets of landmarks were acquired, with semi-landmarks and the homologous “anatomical points” also acquired on a comparative sample of fossil specimens (a sub-sample of *Homo heidelbergensis*). Via TPS, the reference model was warped into a morphological 3D model consistent with the alleged morphology of the fossil species. All such procedures have been performed in R environment [41]. The chimera model has been printed at the “Fab Lab Frosinone Officine Giardino” using the 3D printer WASP Delta 40x70 (layer thickness 0.2 mm; infill percentage 30%; grid pattern). The printing is in polylactic acid (PLA) and a “post-production” work has been necessary to better refine the chimera. A “paleoartist” sanded, puttied and painted the chimera beside a face reconstruction (Fig 1f). A 2D facial reconstruction of the 3D-printed *H. heidelbergensis* chimera skull has been performed using a digital illustration software (Clip Studio Paint Pro Version 1.5.4) and a graphic tablet (Wacom Cintiq Companion). A clear high-resolution picture of the 3D-printed chimera skull in lateral view has been used as a base layer. Soft tissues have been added on top of the skull picture using the bone anatomy as a guide, and multiple photos of modern humans as reference for both hair texture and skin colour (Fig 1f). The reported examples illustrate the unquestionable advantages of digital acquisition in the study and preservation of specimen of interest in the field of cultural heritage. There would be no real progress or utility for archaeological and paleontological disciplines if virtual objects could not be manipulated and "managed in silico" in order to perform all the operations of restoration, integration and cleaning (separation of the bony elements from the embedding matrix) that would be extremely invasive and even destructive (or even impossible to achieve) if made directly on unique, delicate and irreplaceable specimens. The acquisition by means of CT-scan, photogrammetry and laser scanner allows the full acquisition of morphological information, thereby allowing the specimen to be subject to other. The five case studies reported here stressed the potential of the virtual anthropology jointly with geometric morphometric approach. Most of the techniques discussed are currently being used to acquire and restore virtually human remains. At present, we are witnessing a cost reduction for acquisition and editing techniques.

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