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Digital Zooarchaeology: State of the art, challenges, prospects and synergies

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ABSTRACT

Digital technologies are an increasingly pervasive medium for zooarchaeological scholarship, providing a means to document and preserve fragile zooarchaeological specimens, share primary data, address methodological questions, and spread the information to the wider public. During the last decade, a broad array of digital technologies has been widely applied for the creation of three-dimensional images of animal bones, with a number of freely accessible collections being developed and published online. To be beneficial for academic and non-academic audiences, the creation of these collections requires careful planning, and more attention is needed in order to ensure their longevity in the web as well as their future usability. Drawing on an online workshop, organised by the Science and Technology in Archaeology and Culture Research Center of The Cyprus Institute, titled "Zooarchaeology in the Digital Era", this article aims to provide a snapshot of the current state of art, and the methods and digital tools being employed in the digitisation of animal remains. The article also raises some of the challenges that the international zooarchaeological community is facing in the era of Linked Open Data, including management, archiving, curation, storage, dissemination and communication of digital data to the scientific world and the wider public. In addition, the paper highlights the need for a stronger collaboration between archaeologists and researchers from the Digital Humanities' sector in order to stimulate an innovative discourse and create fertile ground for the production of new scientific knowledge.

1. Introduction

> *By comparison with the earlier conventional methods involving time consuming manual handling of each (bone) fragment by many workers, computer handling is in the long run […] easy to control and needs only one specialist with an assistant. The author claims that in the future (the computer) will be the solution to all archaeological and museum work, as it has been already proved to be in a number of other scientific and public activities (Gejvall 1966: 20).*

More than 50 years ago Gejvall (1966) had put forward a vision regarding how archaeology and museum studies were going to be impacted from the use of computerised methods. The decades since the 1950s have seen extensive and varied changes within archaeology, with the discipline undergoing a series of radical transformations in both its intellectual orientation and its methods. During its long way, the interaction of archaeology with other sciences has experienced important transformations and passed through key stages, including the use of computers (Djindjan 2009), the application of mathematical and

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statistical approaches to archaeological data (1975–1995), the commercial development of Geographical Information Systems (GIS) (Conolly and Lake 2006), and more recently the explosion of digital technologies (Daly and Evans 2005; Huggett 2017; Zubrow 2006). Geographical Information Systems (GIS), Computer-Aided Design and Mapping (CAD/CAM), including Building Information Modeling or Management (BIM), 3D modelling, relational and semantic databases, multimedia web-based visualisation, X-ray Computed Tomography (CT), μCT, virtual, augmented and mixed reality, are all rapidly becoming popular terms in an archaeologist's vocabulary. These technological advancements, contextualised through the sub-field of Digital Archaeology with the associated theoretical approaches, facilitate an increase of capabilities and complexities of archaeological data interpretation, opening up new ways to approach and provide solutions to archaeological problems. Most importantly, digital technologies offer a unique opportunity to archaeological communities worldwide to access information. This has been further facilitated by the Linked Open Data (LOD) movement that revolutionised the way archaeological data is generated, co-created and communicated among different specialists. The rapid growth of the field, the proliferation of dedicated projects, and the emergence of numerous digital repositories now provide a rich offering from which one can choose when setting up a new project. At the same time, the increasing volume of activity leads to an increasing duplication and fragmentation of work as well as potential divergences of approaches, lack of communication and therefore less than optimal use of resources. Some projects are by necessity time and budget-limited, thus resulting in stagnant repositories, and even loss of data after completion of the project. Other issues concern changes in data formats evolving over time, which may render legacy data less accessible (see Lau and Kansa 2018; Kansa et al. 2020), leading to the Digital Dark Age (Kuny 1997).

Recognizing the significance of digital technologies in zooarchaeological research and the many challenges that the discipline will need to address in the near future, a group of several active researchers, including zooarchaeologists, human osteologists, 3D modelers and digital archaeologists, felt that it is time to look at the current situation and identify possible activities and suggestions for the benefit of the wider zooarchaeological community. In late 2020 an online workshop titled *Zooarchaeology in the Digital Era* was organized by the Science and Technology in Archaeology and Culture Research Center of the Cyprus Institute, providing a unique opportunity to these researchers to discuss the role digital technologies have in zooarchaeology. This paper is the main deliverable of the workshop. By using the term Digital Zooarchaeology, the authors neither attempt to introduce a new research agenda nor a new sub-field of zooarchaeology, but rather to present a call to action regarding the need for a stronger synergy between zooarchaeologists and digital archaeologists as well as their equal involvement in the entire lifecycle of Digital Zooarchaeology projects, from the initial conceptualisation to the project's completion. In addition, the paper highlights the need for better coordination among the zooarchaeological community to pursue communication and integration of data with broader projects and initiatives from relevant fields. As Jeremy Huggett (2021) highlights in a recent article "*Digital Archaeology concerns much more than using computers to understand the past and should be better conceived as a spectrum in which archaeologists do not only do research digitally but also do digital research*" (Huggett 2021: 1597). Following Huggett's approach, our work aims to move beyond the commonplace reflections on specific tools, software and hardware. We want to ensure that digital technologies will help to initiate new and innovative ways of approaching past human-animal interactions enhancing established zooarchaeological methods where relevant, and enabling digital technologies to open new research avenues facilitating exciting zooarchaeological discoveries.

2. Practicing zooarchaeology in the digital era

Among the most common category of finds in an archaeological excavation are the remains of animals, which are usually numerous and can be extremely fragile. In a similar manner to other archaeological finds, animal remains are subject to various natural as well as anthropogenic processes that may damage their morphology and internal structure, reducing in this way their potential analytical value. Skeletal remains can be easily damaged during excavation while post-excavation treatment, especially bad handling and storage can also be detrimental factors. Like all other archaeological finds, animal remains (e.g. bone, tooth, antler, horn-core, fish scale, otoliths and all sorts of hard and soft tissues from animals) can be destroyed in human and natural catastrophes, including fires and earthquakes. Thus, primary zooarchaeological material should be protected and preserved in order to be properly analysed in the future and add meaning to archaeological narratives. Digital technologies provide the perfect means towards implementing this goal. During the last two decades, zooarchaeological communities across the world have tremendously benefitted from the proliferation of the Internet, which offered them a unique opportunity to exchange and share knowledge with other colleagues. In addition, the digital era has enabled zooarchaeologists across the world to improve their data recording protocols through the replacement of spreadsheet softwares and flat files (e.g. Microsoft Excel) with relational databases; the latter providing greater analytical flexibility and more potential for organising, communicating, sharing and integrating zooarchaeological data (Jones and Hurley 2011; Keller 2009). This process has been further facilitated by a wide range of technologies, including digital single-lens reflex (aka DSLR) cameras and scanners (both laser and structured light) becoming more affordable, allowing them to fully document animal remains during and/or after excavation. New computational methods, such as Structure from Motion Photogrammetry (SfMP; see below), allow the *in-situ* documentation and examination of animal remains and their spatial proximity with other ecofacts, artefacts or features (Macheridis 2015), providing a unique potential to researchers to measure bones during excavation while also decreasing the conceptual distance between field and lab work (Macheridis 2015:242).

In some cases, digital technologies also enable access to virtual material in remote areas or areas with less accessibility to comparative collections, either due to museum regulations or governmental restrictions (Weber and Malone 2011). More recently, the improved imaging technology provided by μCT imaging and 3D X-ray digital microscopes, two technical tools borrowed from the medical sciences, contributed significantly to taxonomical, osteological, taphonomical and archaeological investigations. These methodologies also allowed us to examine changes on bone microstructure, helping us to better understand the effects of different taphonomic agents, such as burning (Boschin et al. 2015) and butchery (Moretti et al. 2015). In particular, high resolution μCT scanning of human and animal remains provides digital data on morphology, shape, and size, which can be used without having direct access to the actual materials (Teodoru-Raghina et al. 2017). Representing the real-time digital counterparts of physical objects, digital twins are a fundamental concept in zooarchaeological but also in wider archaeological studies, providing endless possibilities to researchers to study an artefact or ecofact, without removing archaeological specimens from the countries of origin. Digital twins may be used for all different types of studies and analyses as the original remains, with the exception of several invasive methods such as ancient DNA (aDNA) analyses, palaeoproteomics, X-ray powder diffraction (XRD), and chemical and isotopic studies. At the same time, they record the characteristics of specimens that are going to be impacted by the aforementioned research practices. One of the major advantages of the use of digital twins in zooarchaeology is that they make it easier to describe spatial structures, opening the door to 3D Geometric Morphometrics, look at inner structures, calculate the thickness of bone walls etc. Most importantly, the study of digital twins can help us to solve methodological problems, relevant to the many inconsistences resulting from inter and intra analysts' variation during bone measurements. Lastly, digital twins can be reused and shared among researchers and have the potential to limit the damage on the physical remains from repeated handling and packaging (Bowron 2001, 2003).

Since animal remains must be identified first in order to provide scientific information to any zooarchaeological study, the most fundamental aspect of zooarchaeology should be the accurate osteological identification, and to species level (sensu O'Connor 2008). One of the most beneficial applications of digital technologies in zooarchaeology is the development of digital reference collections, facilitating animal bone identifications, and applicable for research, education and also for public outreach activities.

3. Zooarchaeological reference collections and their impact in academia

Zooarchaeological reference collections fulfil multiple roles. Primarily, they support the identification of anatomical element, taxon and other data categories, including age-at-death, sex and pathological conditions, but they can also be used to address questions relevant to domestication, history of different animal breeds and all other aspects of human-animal interactions that require the use of comparative anatomy. A satisfactory zooarchaeological reference collection takes many years to build and is never complete, due to the animal kingdom's nearly-infinite diversity. Research needs in zooarchaeology brought about the positive development of proliferation of faunal reference collections, especially during the last three decades. Many of these were developed in university departments to enable efficient teaching and research in zooarchaeology, palaeontology and veterinary science. For this reason, and because of their usually small size compared to those in natural history museums, such collections are tailored to the needs of zooarchaeological studies. The creation and curation of faunal reference collections are painstaking and 'unglamorous' undertakings involving the defleshing of carcasses, cycles of degreasing, and documentation in databases, requiring overall high levels of organisation, planning and maintenance (Betts et al. 2011: 756). In all these procedures, it is of paramount importance to maintain an ethically (e.g. in the acquisition of animal carcasses), legally (e.g. conformation with conservation laws), and environmentally (e.g. in processing and disposal protocols) responsible stance. Although complicated, these issues are still more straightforward to deal with compared to setting up physical reference collections for human osteoarchaeology, as the curation and study of human skeletal remains has many more ethical implications and considerations, with descendant communities, scientists, curators, and the public often having different viewpoints and concerns (DeWitte 2015; Lambert and Walker 2018; Squires et al. 2019).

Faunal collections tend to quickly fall into disarray without curation as specimens regularly need degreasing, marking and remarking, and reorganisation, and their storage and usage environment need to be constantly monitored and improved. It is, thus, true that reference collections require a considerable investment in time, resources, and commitment, especially in their initial development stages. Nevertheless, besides their obvious benefits to zooarchaeological research, teaching and public outreach, those institutions investing in reference collections also seize the opportunity to become regional research hubs and centres of excellence, where zooarchaeologists and other researchers congregate to engage in mutually beneficial activities with the hosting institution. An inevitable drawback of physical reference collections is that they cannot always be accessible due to political and logistical constraints (Nobles et al. 2019: 5706). This fact, combined with research needs for the remote use of old and development of new identification tools, has paved the way for the introduction of digital technologies in zooarchaeology. The digital era ushered in a proliferation of virtual versions of reference collections, from high resolution photographs to 3D digital renderings and physical replicas. These developments have significantly improved the rate and reliability of identifications in the field by removing barriers of access. Below, we present some case studies, where digital technologies have been successfully applied for the creation of zooarchaeological reference collections and for addressing other methodological issues in zooarchaeology and its sister discipline, human osteoarchaeology.

4. Digital reference collections: Case studies, technologies being employed and their impact for the academic community and the wider public

4.1. Case studies from zooarchaeology and its sister disciplines

Today, a good number of reference collections spanning much of the range of archaeological ecofacts, including human, animal and botanical remains exist and are freely available through the web. Such collections have been mainly produced by Natural History Museums, academic researchers and on a smaller scale by amateurs interested in comparative anatomy and the natural world. Even though photographic atlases with two-dimensional (2D) images of animal skeletons have long provided significant assistance to zooarchaeologists working away from their laboratories (e.g. Schmid 1972; Hilson 2012), the advantages provided by the application of 3D technologies are much more numerous. In contrast to 2D images, 3D models of bioarchaeological specimens benefit from interaction, enabling rotation in 3D space and greater scaling with the ability to zoom in to observe the smallest morphological detail. The earliest attempts to digitise animal remains were initiated by zoology museums, in Europe and the United States (e.g. Florida Zoology Museum), in the context of "democratising science" by making scientific knowledge accessible to non-academic audiences (Kleinman 1998).

Among the first digital platforms for human and animal bone identifications is the *eSkeletons*, a digital library created by John Kappelman (Kappelman et al. 2001) to provide a teaching tool for students interested in comparative anatomy and other related fields, as well as visual arts. The platform offers a unique opportunity to viewers and visitors to play with a bone in 3D space or cyberspace, taking advantage of web video and virtual reality player (VRML) applications. Furthermore, the platform includes "clickable" coloured overlays that highlight special aspects and muscle-attachment points for certain bones, a glossary of terms and "mini-windows" displaying in-depth information about animal and human skeletons.

One of the most accurate, useful and functional digital reference collections for zooarchaeology has been created by researchers at the Department of Human Evolution, Max Planck Institute at Leipzig (Niven et al. 2009). Today the MPI's collection includes high resolution digital models of several Late Pleistocene wild and domestic animal species from Africa and Europe, such as equids (*Equus caballus*), reindeer (*Rangifer tarandus*) and gazelle (*Gazella gazella*). Following the MPI's example, several other institutions across the world have started creating their own 3D reference collections. Among them are worth mentioning the University of Nottingham's *Archaeological Fish Resource*, which encompasses over 90 specimens of North Atlantic and Mediterranean marine and freshwater fishes, as well as *Aves 3D* and *Avian Osteology*, both dedicated to the remains of birds.

Funded by the National Science Foundation Office of Polar Programs, the *Virtual Zooarchaeology of the Arctic Project* (VZAP) is a good example of how digital technologies can facilitate zooarchaeological research on geographical regions where access to reference collections is particularly difficult (Betts et al. 2011). Even though the prime aim of the project was to enable, promote, and teach North American zooarchaeology, VZAP's final website also contributes to public participation, through the provision of free access to anyone interested in the zooarchaeology of the Arctic.

Aiming to address a fundamental research challenge in zooarchaeology, the morphological distinction between sheep and goat skeletal elements, and to evaluate the potential of digital resources compared to physical reference collection in teaching and research, the collaboration between a digital archaeologist and a zooarchaeologist resulted in the creation of *Bonify 1.0* (Nobles et al. 2019). To approach the topic of sheep/goat identification, a virtual reference collection was created with a structured light scanner (David-SLS2; see below). Once digitised, the bone scans were visualised using web browser (WebGL) technology (Nobles et al. 2019: 5708) and augmented reality, and were then replicated through 3D printing. Both digital platforms were tested by an expert panel consisting mainly of zooarchaeology post-graduates and professors at multiple institutions and were then evaluated through a questionnaire. The survey demonstrated that digital reference collections can not fully replace physical reference collections. Instead, they are seen as a useful additional resource to the physical material, especially when the latter is inaccessible (Nobles et al. 2019: 5711).

In contrast to osteological reference material, digital reference collections dedicated to the identification of plant remains are rare. This has started changing recently with the development of *Paleobot.org*, an online and open-access resource that is hosting reference collection images and data provided by researchers around the world. Apart from being a palaeobotanist's tool to the identification to archaeological plant remains, the platform represents a dynamic forum for discussion between archaeobotanists (see: Warinner et al. 2011).

In addition to being powerful tools for the development of virtual comparative collections, digital technologies may also contribute to the development of our analytical capacities. 3D models of animal remains can capture and precisely quantify the shape and size of particular bones, which can be of critical interest to identify closely related species, including wild and domesticated relatives, and document the biological features of past animals. Geometric morphometric approaches are commonly employed to visualize and statistically compare shape differences (Bookstein, 2013). This can improve significantly our ability to identify between wild and domesticated relatives, and detect taxonomic signals in bones (Cucchi et al., 2017; Hulme-Beaman et al., 2018). It also helps to discover individuals' biological characteristics (e.g. sex; Manin et al., 2016) as well as to assess the human and environmental impact on populations' physical features (Evin et al., 2016; Pelletier, 2019). Digital technologies, and particularly the increasing use of μCT imaging (see below) on archaeological artefacts, also pave the way to new kinds of investigations using faunal remains with the possibility to examine external and internal structures. Microanatomical studies of the distribution and amount of bone tissue are currently expanding. Bone and teeth inner structure is known to respond to mechanical pressures (Kivell, 2016), thus it constitutes a promising marker of the loadings exerted on the jaw and skeleton during an animal's lifetime, and thus of its lifestyle and activities (Harbers et al., 2020; Shackelford et al., 2013). Similarly, the use of Finite Element Analysis on bone remains is increasingly common in vertebrate palaeontology (Fastnacht et al., 2002). This method, which predicts how structures respond to external forces, uses loads virtually applied on 3D models, avoiding any alteration on the bones themselves (Polly et al., 2016). It demonstrates the potential of digital technologies to get a better grasp of past animals' biomechanics, and through that, of the uses and conditions of captivity of animals in the past, a still poorly known component of human-animal interactions.

With biomolecular analysis becoming more and more widespread in zooarchaeology, 3D models of animal remains have the potential to be used as back-ups and archives before destructive sampling for analyses such as C14 dating, aDNA, XRD, and staple isotopes (Pálsdóttir et al. 2019; Evin et al. 2020). It would be therefore possible to preserve a 3D image of the destroyed element, for instance to conduct multi-proxy studies combining data extracted from the exact same specimens (e.g. morphometrics and ancient DNA; Ameen et al. 2019). Furthermore, the virtual reconstructions of animal remains may be 3D printed to produce actual replica of the bones. Even though printing technology has for long been established in the fields of engineering and industry, it has only recently become widespread in archaeology. 3D printing technology has allowed the export of virtual replicas of equid bones from Syria to Iraq (Weber and Malone 2011), and has facilitated the analysis of human tooth cusp morphology (Niven et al. 2009).

In a similar manner to zooarchaeology, digital technologies applied by zooarchaeology's sister discipline, human osteoarchaeology, also have broader applications than just creating reference collections. These include investigations of anatomy, pathological variations at the macro- and micro-scale, the creation of digital osteological reference collections for remains that are going to be repatriated and/or reburied, and the exhibition of human remains to the public. The research applications of digital human osteoarchaeology are diverse and partly overlapping with those of zooarchaeology (Kuzminsky and Gardiner 2012). In particular, digital models of human bones have been used to capture surface features linked to pathology (Milella et al. 2015; Plomp et al. 2019), taphonomic alterations (Wilhemson and Dell'Unto 2015), and 'occupational' markers (Nikita et al. 2019). 3D technologies also allow to virtually reconstruct fragmentary or distorted skeletal elements, fill in missing parts of the skeleton (Benazzi et al. 2009, 2014; Fantini et al. 2008), and facilitate advanced statistical analysis of biological shapes by means of 3D geometric morphometrics (Kenyhercz et al. 2014; Kuzminsky et al. 2016; Nikita et al. 2012; Perez 2007). At the same time, digital human osteoarchaeology has brought to the surface a series of serious practical and ethical considerations. The former relates to best practices for digitising, storing and sharing bioarchaeological digital data, while the latter pertain to the ownership of the 'dead' in the format of bone digital replicas and the duty of anthropologists to balance the promotion of knowledge with a respect for the dignity of the deceased.

4.2. Tools and technologies being employed

Archaeologists have long been using modern tools and applying techniques designed outside of their discipline, such as digital cameras, total stations, laser scanners and proton magnetometers, among many others. These tools support them in performing several tasks that otherwise would have to be conducted using more laborious and time-consuming methods. Digital devices, including both hardware and software cannot be used in isolation, and researchers should be aware of every single parameter before deciding which digitisation method they will use. Even though several studies refer to cheap and expensive techniques, we feel the need to clarify here that when it comes to digitisation, cost can be very challenging to be defined. A cheap hardware may require an expensive software to process the data and vice versa making things much more complex. The selection of the most appropriate method along with the hardware and software being involved should be made in respect to the project's specific research question and available budget.

In the following section, we briefly present some tools and technologies which have been widely used by zooarchaeologists and human osteoarchaeologists for digital recording of 2D and 3D shapes, including laser and structured light scanners, digital cameras and computed tomography.

i. **Laser and Structured Light Scanners (SLS):** Three-dimensional surface scanning technology is a valuable tool for digitising archaeological, palaeontological and geological specimens. 3D surface scanners are inexpensive and easy to handle; most importantly, they are completely non-destructive to skeletal material (Kuzminsky and Gardiner 2012). Both surface and structured light scanners have been widely used for digitising fossil and modern human and animal skeletal remains for multiple applications, including morphometric analyses, evolutionary biology, comparative anatomy, preservation of fragile or unique specimens, and archiving, without the risk of damaging or destroying the original specimen. The most widely used scanners in zooarchaeology and human osteoarchaeology are the

NextEngine laser scanner as well as the Artec and the DAVID-SLS2 scanners (no longer in production at date of submission of this article), which are structured light scanners. The NextEngine Desktop 3D scanner is a surface scanner using multi-laser technology. It has a 100 μm precision, and its small size and relatively low cost has made it a favored solution for many institutions. The somewhat difficult mounting of specimens and the occasionally inefficient capturing of negative topographic openness features, as well as its software design contribute to relatively slow 3D model production times. The Artec Space Spider scanner is a structured light scanner based on blue light technology. It can capture up to 7.5 frames per second with a 50 μm precision, and its user-friendly software allows for the relatively fast production of high precision 3D models. The accuracy of the models produced, its portability and the minimal setup required, as well as the speed with which models can be produced make it a good choice for institutions wishing to digitise their collections (Zechini 2014). Lastly, the DAVID SLS2 represents a low cost and high detail instrument. Among its main properties is the speed of processing time along with the generation of high resolution and accurate results (Alby et al. 2009). Even though valuable for digitising human and animal bones, laser and structured light scanners have their limitations. In contrast to CT technology (see below), scanning technology captures only the external surface of bones and not the bone inner structure. In addition, the digitization of objects with complex geometry, such as crania, at high resolution can be a time-consuming process. The Light Detection Ranging (LiDAR) scanner, included in the newest Apple devices, is another available choice for digitising animal bones, alongside other archaeological finds. Even though LiDAR scanner is good for large stable items such as building walls and settlement ruins, as well as for capturing excavations with human or animal bones *in situ* it has several drawbacks, especially because its offered software has not yet met the high polygonal count and consequently the level of detail of models produced with other techniques, including Structure from Motion Photogrammetry (see below).

ii. **Structure from Motion Photogrammetry:** Another major revolution in archaeology has been the application of Structure from Motion (SfM) Photogrammetry (Magnani et al. 2020). The application of photogrammetric approaches has grown substantially in archaeology due to their relatively economic equipment and easy to apply methods. Most importantly, the method allows the accurate reproduction of the geometry and colour pattern of real and even complex objects (Fallkingham 2012). SfM Photogrammetry has been widely applied for the study of macro-evolutionary processes (Giacomini et al. 2019). Apart from the creation of 3D models of animals, photogrammetry has also been used to address questions in evolutionary biology and zooarchaeology (Evin et al. 2016).

iii. **Micro Computed Tomography (μCT):** μCT is a computed tomography technique using geometrically cone-shaped beams for reconstruction and back-projection processes (Orhan et al. 2018: 379). Its voxel size is almost one million times smaller than that of standard computed tomography (CT). Thanks to this high-resolution voxel size (1–50 μm^3), μCTs provide outstanding cross-sectional resolutions on bone allowing us to obtain internal structural information often related to the life history of animal remains. So far, μCT has been used to obtain reliable information from burned specimens (Boschin 2015), or for studying the cross-section of cut-marks observed on animal bones (Moretti et al. 2015). The introduction of μCT tomography also opened a venue in developing a novel methodology for the study of complete fish anatomy and osteology (Weinhardt et al., 2018). One of the best benefits of μCT technology is that it is a non-invasive and non-destructive method, providing the ability to inspect rare and unique specimens such as those in museum collections. Moreover, its high resolution enables the study of small size specimens (including embryos) (Ahnelt et al., 2015, Babaei et al., 2016, Brinkmann et al., 2016, Pasco-Viel et al., 2010). The recent development of whole-body automatic segmentation was successfully performed on several species of teleost fish, leading to the establishment of an interactive 3D atlas that permits virtual visualization of body and organs, that was not accessible before (Babaei et al., 2016, Brinkmann et al., 2016, Weinhardt et al., 2018). The μCT technology also enabled researchers to re-examine the evolutionary history of dentition. Fish jaws and teeth demonstrate the relationship between vertebrate evolution, diet, habitat, structure, function, and speciation (Ahnelt et al., 2015, Bruneel et al., 2015, Konings et al., 2021, Pos et al., 2019, Vladykov, 1934, Wautier et al., 2001, Zeng and Huanzhang, 2011, Zohar et al., 2014). Unlike mammals, fish display several distinct dental traits: 1) jaws with teeth that can appear either on the oral cavity (dentary, maxilla, premaxilla, vomer, palatine), or on the pharyngeal cavity (modified 5th ceratobranchial); 2) the teeth are constantly replaced throughout the duration of the animal's life (polyphyodonty); 3) the teeth display a great diversity in number, location, size, and structure (Gobalet, 1989, Golubtsov et al., 2005, Huysseune et al., 1994, Huysseune et al., 2009, Iliado and Anderson, 1998, Zeng and Huanzhang, 2011, Zohar and Biton, 2011). The application of μCT technology provides researchers with an outstanding view of the development of the pharyngeal jaw and teeth, the mechanism of teeth replacement, as well as morphometric data for comparisons between species and within each species from different body sizes (Bruneel et al., 2015, Pasco-Viel et al., 2010). Therefore, when applying μCT technology for taxonomic identification of archaeological and palaeontological remains, it can be performed in a reliable way, regardless of specimen size (Vasilyan et al., 2019).

4.3. Scientific, educational and societal impact of digital zooarchaeological reference collections

Archaeological digital reference collections have the potential to synchronise the communication of research to both academic and non-academic audiences in an effective manner, facilitating the democratisation of knowledge. Anatomically and morphologically accurate replicas of archaeological and modern animal bones can be used to support teaching and learning at all levels, including for primary and secondary school pupils as well as undergraduate students in zoology, zooarchaeology, and veterinary science, and for independent researchers. Digital 3D models, especially when they are disseminated globally as an *Open Access* resource hosted on a dedicated server, improve access to teaching resources and offer important hands-on training in digital humanities, creating new and exciting ways to engage students learning and meet the growing needs of education. In addition to this, the ability to 3D print digital models is crucial, as most of the archaeology-related and educational activities are becoming more attractive and experiential through handling of the object. Technological advancements and their rapid development always create new and exciting ways to engage students learning and meet the growing needs of education (Kalogiannakis et al. 2021: 1). The digital models of skeletal remains of animals are particularly attractive to the current generation of computer-literate students, and digital reference collections of animal skeletons can facilitate learning, develop skills, and increase student engagement while also inspiring teachers' creativity and engagement (Horowitz and Schultz 2012). This is especially the case with Special Needs Educational programs. Similarly, serious games or gamification along with animation provide excellent ways for citizens to get involved in zooarchaeology. Gamification (Tulloch 2014: 317) is an effective tool for student engagement in classroom archaeology, by providing elements of gameplay: rules, rewards, punishments, competition, and narrative.

Gamification has only recently started gaining a position in archaeology (but see: Kontogianni and Georgopoulos 2015). As in many serious games done in the past, gamification principles could easily be applied in interactive applications in archaeology in general and zooarchaeology in particular. An example of such an application could involve a combination of a digital reference collection and a puzzle game, which gives points to users as they recognise an array of skeletal elements or skeletal parts and classify them by taxon or even animal species (or subspecies). The user's points gained could be stored in a database, and as more users from local or global groups are participating, a contest could be held and the winners could acquire prizes. Growing the general crowd accustomed to these gamification principles and by following affordance methodologies in such interactive applications, we can assume that designing serious games to help archaeology students and the wider crowd understand, examine, observe and gain knowledge about zooarchaeology is an opportunity which, as a tool, is missing from current curricula and academia's quiver more generally (but see, e.g. Stockhammer 2020). From desktop to virtual reality applications, the users could experience virtual comparative collections, virtual museums, and narrative-based adventure games, to name a few.

One of the most important challenges for the scientist of the 21st century is public engagement and the promotion of science to a wider, non-academic, audience. Since the early 2000s, official commitment to public engagement has deepened, and public engagement activities have become more institutionalised and professionalised across academic disciplines. Access to online collections will provide researchers and general users with a wide range of opportunities to facilitate knowledge combined with creating and establishing a participatory environment that can promote also knowledge exchange (Flynn, 2018: 14; Borowiecki & Navarrete, 2017; Schlesinger, 2016). Furthermore, the European Commission's 2014 *Green Paper on Citizen Science for Europe: Towards a better society of empowered citizens and enhanced research* highlighted the significance of "citizen science", a relatively new concept that aims to encourage the involvement of citizens in science. Digitisation projects in zooarchaeology might involve citizens interested in zoology and other related fields. For example, private collectors might be invited to offer their collections for digitization, or even learn how to digitise specimens by themselves or as part of community groups, which can be easily performed via photogrammetry that requires minimal equipment (e.g. a smartphone camera).

5. Discussion: Zooarchaeology in the era of Linked Open Data: Prospects and challenges

The Linked Open Data (LOD) community effort has been a cornerstone in the realisation of the Semantic Web (Web 3.0, see Berners-Lee et al. 2001) vision, with huge impact in archaeology as in many other fields. One of the most serious concerns and one of the biggest challenges for zooarchaeology today is the excessive amount of different data formats, produced by different digitisation methods, visualisation and analysis software, resulting in potential data incompatibilities, and highlighting the need for interanalyst variation awareness (Lyman and VanPool 2009; Lau and Kansa 2018). Digital models of animal bones come in a variety of formats, including more common ones (.stl, .obj, .ply or .vrml) as well as a range of proprietary formats which are only readable with specialised (and expensive) software packages, making interchangeability of data and communication amongst different analysts particularly difficult. Today, there is a growing need for data standardisation in order to facilitate communication and interoperability between different data sharing networks. Many digitisation efforts are published only as finished 3D models, with little details on the protocols being used, thus reducing the long-term existence and reusability of the obtained files (Lau and Kansa 2018). One of the biggest challenges of digital reference collections is the fossilisation of their contents, which makes them easily controlled by few and leading to the danger of becoming too authoritative. If this happens, then the reference collection could become a hindrance rather than help the research process. Therefore, caution is needed when we plan a digitisation project. It is very important to state from the very beginning our aims and objectives (whether for research, teaching, or public outreach), define our target groups and long-term potentials, make sure that we are having enough budget, choose the most appropriate digitisation technique, and consider long-term storage and archiving of our 3D models. By employing best practices in the way digital images of animal remains are created, managed, stored and preserved, zooarchaeologists and digital archaeologists will ensure the long-term use and consistency of their projects and justify the investments being made in digitisation projects. A good starting point to bridge the gap between different analysts is through the use of ontologies and data standards, also known as identifiers. As in any other scientific field, ontologies limit complexity and ease communication between different specialists, who organise their data into information and knowledge. Standardisation is not only a matter of data formats; it is also something that can be achieved on other levels, for example by providing 3D information with valuable sets of metadata. Data standards are also necessary as they facilitate interoperability between different data sharing networks. Today, many ontologies and schemas are available which produce standard sets of metadata. A good example of generic standards is the Dublin Core Metadata Initiative, while there are domain specific metadata standards such as the related Darwin Core, an extension of Dublin Core for biodiversity informatics representing a reference for sharing information on biological diversity. One of the most useful standards, created by the museum sector and with increasing use in archaeology and cultural heritage is the CIDOC Conceptual Reference Model and its derivatives (CIDOC CRF; see Crofts et al. 2009). The CIDOC CRM aims to promote a shared understanding of cultural heritage information through the provision of a common semantic framework for evidence-based cultural heritage information integration.

Aiming to mitigate the threat of data loss and help archaeologists to avoid the Digital Dark Age and the loss of a generation of research, a team of specialists, including archaeologists, IT specialists and archivist, have started exploring current policies that determine access to and reuse of data held by digital archaeological repositories in Europe, and to investigate the guidance and support needed to make these repositories and data Findable, Accessible, Interoperable and Reusable (SEADDA project, Geser et al. 2022). This kind of approach should be adopted in more regions of the world, encouraging fruitful collaborations and synergies between archaeologists and data management specialists.

6. Conclusion: Strengthening synergies

Archaeology encompasses various sub-fields which are focused in specific areas of our discipline, each developing their own specific but inter-related theoretical and practical underpinnings upon which practitioners function. These foundations are often developed in line with other sub-disciplines or drawing on those external from the archaeological discipline. In a similar manner, zooarchaeology draws on methods and approaches borrowed from zoology, biology, biochemistry and others. When combining elements between sub-disciplines, it is essential to have sufficient overlap between them, not only on the practical but also on the theoretical level. The success of the digital era in zooarchaeology depends heavily on the quality of faunal reference collections, as these represent the raw material for digital tools. In order to make the most of the opportunities of the digital era, physical reference collections will need to increase in numbers, size and diversity, thus serving as sound foundations for the building of new digital tools that will ultimately enhance and spread their use. For zooarchaeology to benefit to the fullest extent from the digital era, the potential that is on offer must be recognised, not wasted. Most importantly, zooarchaeologists should not view digital technologies only as tools to help them deal with data collection and analysis, but also as a powerful means of addressing important archaeological problems and/or generating new zooarchaeological questions, methodologies, and consequently new data. If we take a transformative approach such as the one applied to the generation of Digital Twins, then the 3D object itself could be the focus of investigation and viewed as having its own agency that is open to study, similar to Reilly et al.'s (2021) approach to the Phygital. While the concept of a Digital Twin originates from manufacturing for understanding the present, and through Machine Learning to predict the future (Kritzinger et al. 2018), there is no reason why such a concept could not be used to better understand the past. It is therefore crucial that cross-fertilisation between the archaeological sub-disciplines and digital archaeology is actively developed, promoted, and embraced; such a synergy will ultimately and inevitably lead to a far better digital zooarchaeology and avoid straying from well-established and validated methodological approaches. Even though there are many potential benefits in the application of digital technologies in zooarchaeological studies through research, education and outreach, we still have much to learn about the effectiveness of these methods. The Wow Factor (Forte 2000, 2014: 116) associated with the many opportunities offered by digital technologies and their sophisticated tools and techniques should not make zooarchaeologists and other specialists neglect the roots of their original work, and the constant methodological advances that it requires. Although broadly beneficial for the zooarchaeological community, advances in digital technologies need not dominate the discipline and replace traditional tools and approaches; rather there should be a demonstrable reasoning why as well as how digital methods can improve and protect the discipline, and digital know-how should complement established methodologies.

A good starting point would be the development of a formal guideline or practical handbook for digitisation in archaeology in general, with special sections on different archaeological materials, providing also consultation on the digitisation of faunal remains in different situations (burial contexts, pits, infills, etc). Such guidelines have started being produced for the sister discipline of human osteoarchaeology (e.g. the compilation of case studies in Errickson et al. 2015) as well as for natural history collections (Brecko and Mathys 2020). Although they are often linked to the ethical implications of relevant initiatives (e.g. British Association of Biological Anthropology and Osteoarchaeology 2019), they are still lacking in zooarchaeology. The need for a broader and more diverse archaeological community engaged with the issues highlighted in this article will hopefully bring fresh approaches and perspectives, new experiments, and more insight into how we can best make use of digital technologies and the data contributions created by us and our colleagues.

CRediT authorship contribution statement

A. Spyrou: Conceptualization, Writing – review & editing, Project administration. **G. Nobles:** Writing – review & editing. **A. Hadjikoumis:** Writing – review & editing. **A. Evin:** Writing – review & editing. **A. Hulme-Beaman:** Writing – review & editing. **C. Çakirlar:** Writing – review & editing. **C. Ameen:** Writing – review & editing. **N. Loucas:** Writing – review & editing. **E. Nikita:** Writing – review & editing. **P. Hanot:** Writing – review & editing. **N.M. de Boer:** Writing – review & editing. **A. Avgousti:** Writing – review & editing. **I. Zohar:** Writing – review & editing. **H. May:** Writing – review & editing. **Th. Rehren:** Conceptualization, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

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