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ANATOMICAL-MORPHOLOGICAL ANALYSIS OF A VOLUMETRIC 3D MODEL OF AN ARCHAEOLOGICAL OBJECT

1. Introduction

Traditional radiology and, after 1975, computed tomography have been used in archaeology since their inception as non-invasive imaging techniques (Huges 2011) for dealing with delicate and valuable artefacts (e.g. mummies, Palaeolithic and ancient remains, papyrus scrolls, wood, metal tools, coins, jewellery, weapons, ceramics, wall paintings, etc.). It was not until the 21st century that microcomputed tomography (μCT) was gradually established as the desired non-invasive technique and method in archaeology. Its use and development are focused on the technological adaptation of industrial μCT recorders to archaeological (e.g. University of Bologna; 37th International Symposium on Archaeometry) and archaeometric treatment (Berdondini *et al.* 2011), as well as non-invasive archaeological analysis of small objects, which could be partially or permanently destroyed or damaged (Morigi *et al.* 2010; Albertin *et al.* 2019). To date, research attention has not been focused on the development of specific algorithms adapted to field or laboratory archaeological work.

In the field of 3D modelling, μCT is still limited to the reconstruction of surface 3D models or the examination of the anatomical structure of an archaeological object (Du Plessis *et al.* 2015; Re *et al.* 2016). There are only rare examples of reconstructing volumetric 3D models from 2D μCT images. This approach could greatly complement archaeological documentation, volumetric treatment and provide high-quality information when planning the use of optimal conservation methods and techniques. There is still a restrained attitude towards the use of μCT in archaeology, although archaeologists acknowledge that the results of microtomographic research are remarkable. This is partly due to the equipment which is still expensive and inaccessible to archaeologists. Therefore, easier, and more affordable 3D modelling technologies are used in virtual archaeology. This was also confirmed by the First CAA-GR Conference in Crete (Reilly, Beale 2015), which was aimed for researchers to exchange experiences on the use of new technological imaging methods in the preservation of cultural heritage based on the guidelines of The London Charter (Denard 2016) and The Seville Principles (Lopez-Menchero, Bendicho 2013). The conference marked the culmination of twenty years of development in the field of virtual archaeology. Currently, archaeologists should standardize the use of new information technologies in the field of cultural heritage (LiDAR, photogrammetry, computer modelling, additive manufacturing, visualization, hypertext, etc.). Archaeological reports in the last five years, despite the official restraint of the profession, confirm the growing interest in the use of micro- and nano computer tomography in archaeological and conservation work.

As sayd by Jeremy J. O'Brien, professor of physics and electrical engineering (Applbaum, Applbaum 2005), it is true that the use of computed tomography in archaeology and in the preservation of archaeological cultural heritage after 1979 was more due to the curiosity and individual interests of the archaeological and Egyptological elite than planned and systematic research work. It is therefore not surprising that a clearly defined interest in rendering surface and volume 3D models from two-dimensional tomographic or microtomographic images has not been expressed in archaeology yet. Somewhat wider interest in the use of computed tomography in archaeology began after 2015.

After 2016, computer scientists and archaeologists began using μCT to investigate the geometric and anatomical features of artefacts. CT and μCT have also become important analytical and diagnostic tools for planning and selecting more appropriate and efficient procedures for the conservation and restoration of archaeological objects. Some French (Introspect Project), British (RTISAD project), American (EDUCE Project, etc.), Canadian, Israeli, Austrian and German university research centres, specialized laboratories of state museums and private companies already use computed tomography as an indispensable part of the regular procedures of conserving and restoring archaeological exhibits.

Only in recent years (Albertin *et al.* 2019) has it become clear that industrial microcomputed tomography, as an advanced non-destructive imaging technique for researching the anatomical structures of various materials, can answer many unexplored questions, enrich archaeological documentation, and contribute to an optimal selection of quality conservation and restoration techniques. Outstanding projects exist, for example, in the X-ray tomography laboratory at the University of Bologna. The research is focused on the development of industrial CT and μCT systems for the needs of archaeological laboratories and museums. Solutions that are adapted to archaeological fields and laboratory work are the beginnings of a qualitative change in the treatment of archaeological objects.

In archaeology, we find isolated examples of reconstructed 3D models from 2D CT or μCT images. To date, no specific need has been expressed for the reconstruction of volumetric 3D models or for the addition of complete replicas of archaeological artefacts from 2D CT / μCT images. Reconstruction of 3D models of archaeological artefacts has so far been limited in archaeology primarily to surface 3D modelling, using photogrammetry, laser recorders, and structured light recorders. Various computer vision algorithms have been used (e.g.: SIFT, ICP, SfM, SfS, SfL, algorithm segmentation, self-learning algorithms, fuzzy clustering algorithm, etc.). In the last few years, deep learning is gaining importance. This is also the reason why the use of information technology in archaeology has focused on virtual archaeology, additive production of copies of artefacts from surface 3D models, and the digitization of basic archaeological documentation.

Due to the indicated peculiarities of the production (photogrammetry and other technologies) of 3D models in archaeology, no special algorithms have been developed for the reconstruction of surface and volumetric 3D models from CT or µCT images of archaeological objects. In the case of computed tomography, commercial algorithms are used for reconstruction and imaging, but they are mostly adapted to the needs of medical diagnostics or quality control of materials in industry. In the reconstruction of tomographic images in medicine, additive manufacturing, material analysis, and industrial control, the filtered feedback projection (FBP) algorithm has been standardized for some time. In recent years, some forgotten iterative reconstruction algorithms have reappeared in industrial tomography.

Their use has become more widespread with the increasing processing power of computers. Comparisons and research have shown some advantages of iterative reconstruction algorithms over the FBP algorithm (AIDR, ASIR and ASIRV, IRIS, SAFIRE, ADMIRE, MBIR, xSPECT, nMERA, etc.). Iterative reconstruction significantly improves image quality and 3D modelling with cyclic processing. New iterative algorithms are already embedded in the latest generations of CT readers (e.g. Siemens, Toshiba, GE Healthcare, Philips, Canon, etc.) and in most cases represent a trade secret.

2. Case study: the Palaeolithic wooden point from the Ljubljanica River

2.1 *The object of the tomographic reconstruction*

The object of tomographic reconstruction presented in in this article is a 40.000-year-old Palaeolithic hunting weapon (Gaspari *et al.* 2011; Kavur 2012). The Palaeolithic wooden point (Fig. 1) was found in 2008 in the Ljubljanica Riverbed near Vrhnika in Slovenia. It is made of yew wood. This wooden point is so far one of only eight known wooden Palaeolithic artefacts found in Europe.

2.2 *Problem*

After the conservation procedure and the last volumetric measurements, the current dimensions of the point are as follows: length 15.01 cm (was 16 cm when found, using traditional measurement method), width 4.9 cm (5.1

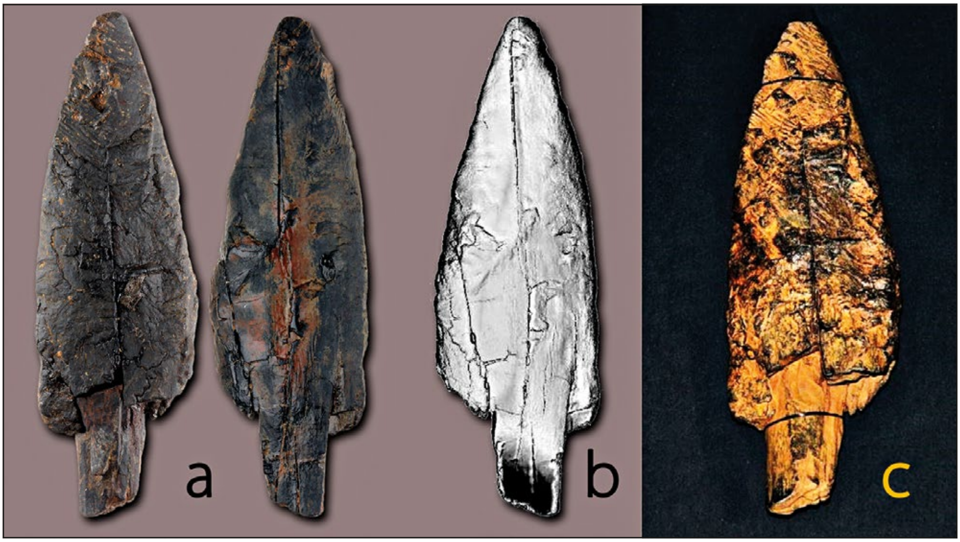


Fig. 1 – The Palaeolithic wooden point from the Ljubljanica River: a) photography of the point from 2008 when it was discovered (Slobodan Olić, Arhos d.o.o); b) 3D model; c) a photography of the exposed point in the City Museum of Ljubljana 2020 (model and photography E. Guček Puhar).

cm), thickness 2.3 cm (2.5 cm). The shape of the point has also changed (there is a strong bend of the lower part and a less pronounced one at the top of the point). Several surface cracks are also visible.

A volumetric comparison of surface 3D models created with the open-source graphical software tool CloudCompare before and after conservation, highlighted unexpected changes. The point changed after conservation its volumetric dimension (Fig. 2). Its volume decreased by almost 18.9 %, length by 5.7 %, width by 3.7 % and thickness by 18.3 %. There was also a visible change in its shape. The lower planting part was strongly and visibly bent. Volumetric comparisons, however, also exposed the bending of the tip point. External changes were identified by volumetric comparison of surface 3D models. These models, which have become widely accepted in archaeology today and the general standard of the signatories of the London Charter and Seville Principles, did not answer the question of what and where the actual (real) causes of external deformations are and in what condition the internal structure of the point is.

2.3 *Hypothesis*

Since microtomographic images of the Palaeolithic wooden point were available after conservation and since previous surface 3D models (Erič *et al.*

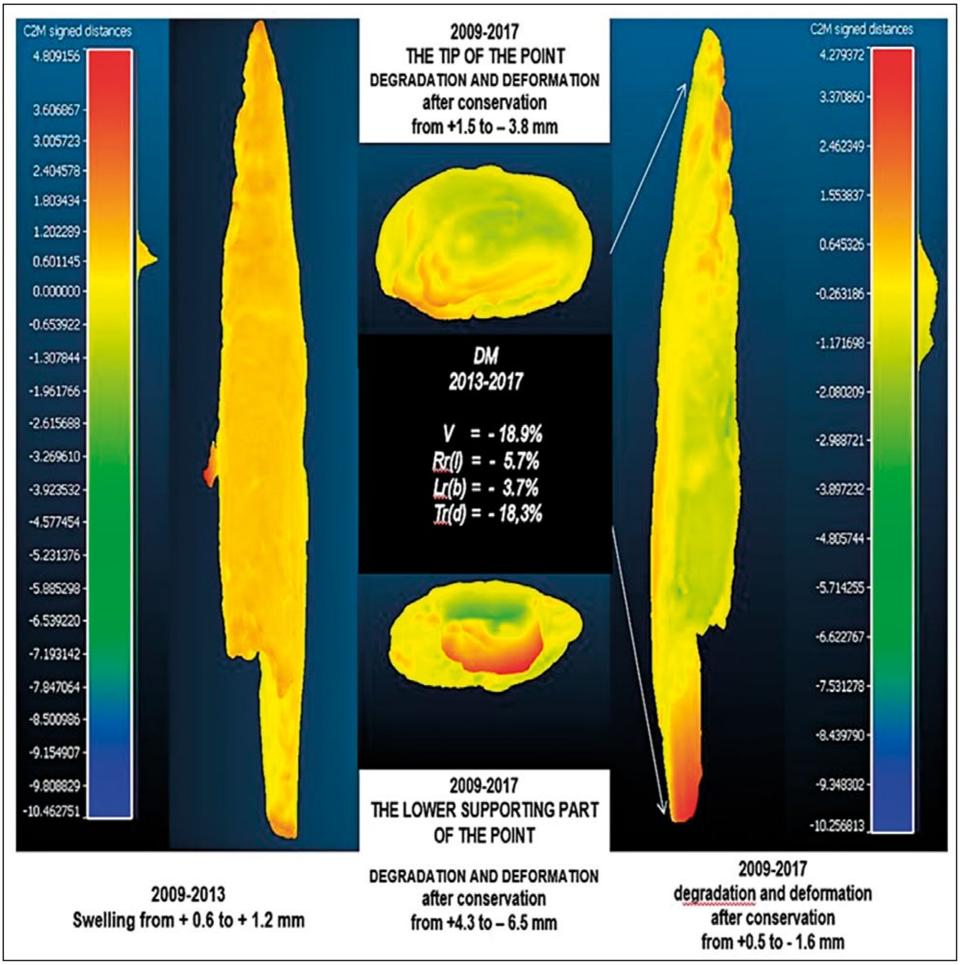
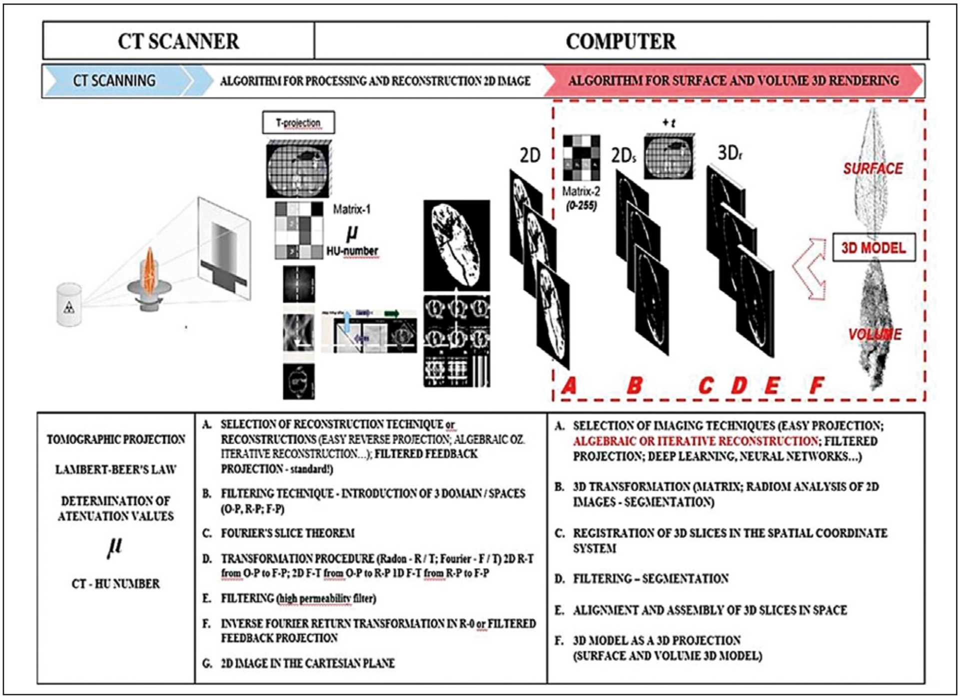


Fig. 2 – Volumetric changes of the surface 3D model of the point after the conservation process (2013-2017).

2018; Guček Puhar *et al.* 2018) did not provide a satisfactory answer to the question regarding the actual state of the artefact, we decided to reconstruct the volume 3D model. This should mainly highlight those anatomical features (cracks, fractures, etc.) of the point that directly or indirectly influenced its morphological, volume and surface changes during the melamine resin preservation phase (intensive soaking and drying).

By hypothesis, we estimated that the surface and volume 3D model of the point could provide archaeologists and conservators with more comprehensive



TOMOGRAPHIC PROJECTION LAMBERT-BEER'S LAW DETERMINATION OF ATENUATION VALUES μ CT - HU NUMBER	A. SELECTION OF RECONSTRUCTION TECHNIQUE or RECONSTRUCTIONS (EASY REVERSE PROJECTION; ALGEBRAIC OZ. ITERATIVE RECONSTRUCTION...); FILTERED FEEDBACK PROJECTION - standard!) B. FILTERING TECHNIQUE - INTRODUCTION OF 3 DOMAIN / SPACES (O-P, R-P; F-P) C. FOURIER'S SLICE THEOREM D. TRANSFORMATION PROCEDURE (Radon - R / T; Fourier - F / T) 2D R-T from O-P to F-P; 2D F-T from O-P to R-P 1D F-T from R-P to F-P E. FILTERING (high permeability filter) F. INVERSE FOURIER RETURN TRANSFORMATION IN R-0 or FILTERED FEEDBACK PROJECTION G. 2D IMAGE IN THE CARTESIAN PLANE	A. SELECTION OF IMAGING TECHNIQUES (EASY PROJECTION; ALGEBRAIC OR ITERATIVE RECONSTRUCTION; FILTERED PROJECTION; DEEP LEARNING, NEURAL NETWORKS...) B. 3D TRANSFORMATION (MATRIX; RADIOM ANALYSIS OF 2D IMAGES - SEGMENTATION) C. REGISTRATION OF 3D SLICES IN THE SPATIAL COORDINATE SYSTEM D. FILTERING – SEGMENTATION E. ALIGNMENT AND ASSEMBLY OF 3D SLICES IN SPACE F. 3D MODEL AS A 3D PROJECTION (SURFACE AND VOLUME 3D MODEL)

Fig. 3 – Workflow of the algorithm for the reconstruction of the volume 3D model from microtomographic 2D images.

information about its condition. The 3D anatomical-morphological structure of the point clearly shows the conditions and risks requiring solutions for a more permanent preservation and protection of the artefact.

2.4 *Methodology*

Surface 3D models do not provide us with complete information about the actual state of an artefact. Only a volume 3D model can provide this information. This was the fundamental reason why we approached the development of an iterative algorithm for the reconstruction of a 3D model from microtomographic 2D images. In the phase of computer processing of microtomographic 3D slices, we developed two algorithms (Fig. 3): a direct algorithm for the reconstruction of a 3D volume model and a segmentation algorithm for the reconstruction of a 3D volume model. Both algorithms were developed using the software package for numerical analysis MatLab. The surface and volume 3D models are rendered with the open-source MeshLab and CloudCompare software.

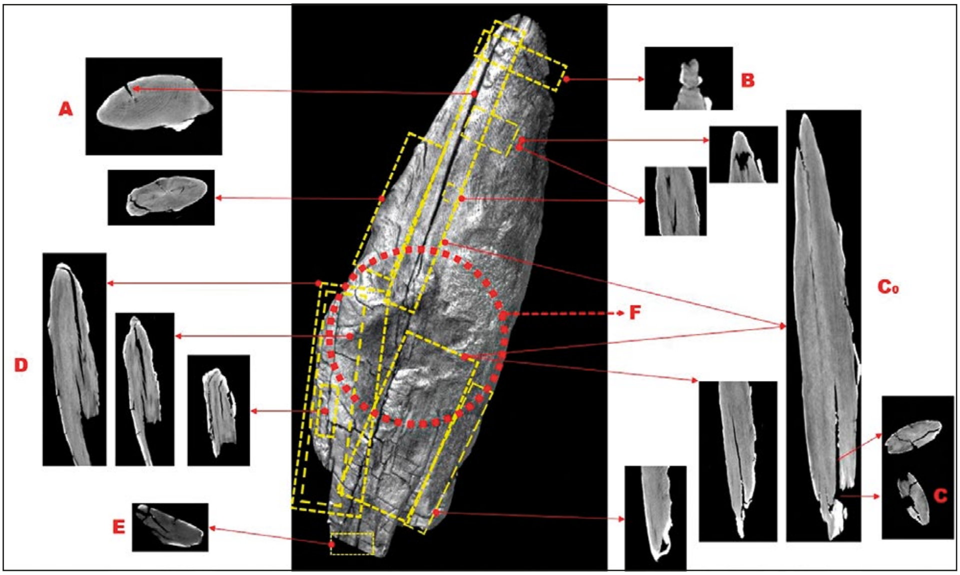


Fig. 4 – Determined volumetric and anatomic-morphological characteristics of the volume 3D model of the point.

2.5 *Results*

With the volume 3D model, we were able to indisputably identify, investigate and document the internal structure of the artefact. Deformation changes (cracks, fractures, decay) are distinctly evident and located (Figs. 4-5). The critical points of the anatomical structure of the artefact are visible and non-invasively located in the volume 3D model (Fig. 5). Two pronounced internal deformations were found: a longer crack (Fig. 5 C_o, A) and a more pronounced fracture (Fig. 5 C_o, C). A crack (Fig. 5 A) with a depth of 2 to 22 mm was found in the upper part of the point. A 9.1 cm long crack runs all the way to the middle of the point along the core band. This crack is not critical if the dynamics of tensile and strain stresses do not continue. It only affects the slight bending of the upper part of the point. 4 mm below the tip of the point (perpendicular to the upper crack) the critical point of the transverse fracture of the object is indicated (Fig. 5 B). Due to internal damage at this point, there is a possibility that the tip of the point (4.2 mm) may break off in the event of careless handling or under the influence of external factors.

If the tendency of the crack to spread continues across the middle of the point along the core strip (Fig. 5 A, F, C_0) in the direction or transversely to the direction of the observed major fracture (note that this crack propagation

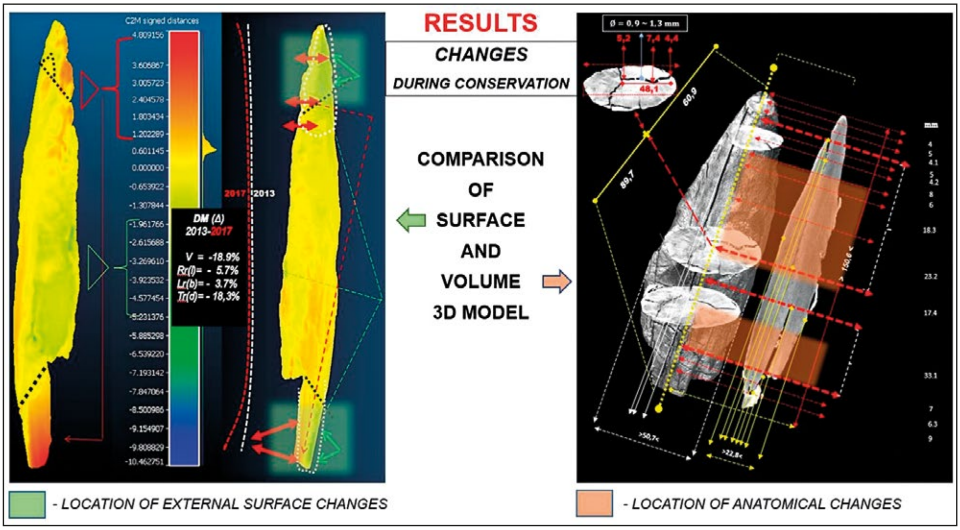


Fig. 5 – Micro locations of anatomical characteristics and deformations (fractures, cracks, openings) of the Palaeolithic wooden point.

tension is currently not detected) to the lower and planting part of the point – which is currently 18 mm away from said crack (Fig. 5 C, C_0, F) – we could face the risk of breakage of the point. A pronounced fracture in the lower part of the point (Fig. 5) runs along the entire width. Its length is 3.3 cm and runs between the planting part and the middle of the point (Figs. 4, 5 C_o, C). This is a critical fracture of the artefact. Numerous cracks have been found on the lower wing parts of the point in the longitudinal direction of the anatomical structure. There is a risk of chipping.

Significant changes found on the surface 3D models in 2009 and 2015 or 2017 may have been the result of various invasive processes to which the point was exposed during the conservation processes (phase of stimulated intensive swelling and heat treatment - drying). The current state of internal dynamic changes indicates that the drying process has slowed down.

3. Discussion

With the volume 3D model, we were able to accurately identify, investigate and document the internal structure of the artefact. Deformation changes (cracks, fractures, decay) are clearly visible and located. The identified critical points (a longer crack extending from the top to the middle of the point and a pronounced transverse fracture in the lower part stand out) have a decisive influence on the external change (deformation-bending) of the top and the lower part of the point. Numerous minor cracks, deviations or even natural changes in the internal texture are also found in the volume 3D model of the point. If data on the internal condition of the point (openings, fractures, deviations, decomposition) were available before conservation, the conservation process could be adapted to the condition of the point or it could be decided to protect it by avoiding its exposition to environmental changes in a special container with a watery environment (aquarium), for example. Undoubtedly, the process of intensive conservation (soaking and especially rapid drying) has influenced the external and internal changes of the point, which will need to be repaired over time to avoid possible disintegration or breakage of the artefact.

Complementing the computer volumetric method of deformation monitoring of 3D models of the considered artefact with both algorithms can provide archaeologists with quality data and information for a comprehensive analysis of the object before and after the conservation procedure. Furthermore, it can provide conservators with the necessary information to select the most appropriate methods, techniques and means to stabilize valuable archaeological objects.

4. CONCLUSION

The volume 3D model together with the surface 3D model provides substantially more information about the state of the original artefact. The model can be successfully for the selection of conservation techniques (VAN GRIEKEN, JANSSENS 2004; JUNGBLUT *et al.* 2013; PAYNE 2013; ERIČ *et al.* 2018), for analysis and evaluation, in the visualization of the spatial representation of the artefact, in additive archaeology (REILLY, BEALE 2015) and in the timely planning of procedures for storage and protection of the artefact. The 3D models supplemented with this information and data will gain in importance in the coming years not only in the field of cultural heritage preservation but also in industry, medicine, etc., as 3D is becoming one of the fundamental standards of the 4th Industrial Revolution (SCHWAB 2017). The importance of 3D models and computer spatial and surface 3D visualizations includes the London Charter, the Seville Principles, and ratified international treaties among the archaeological and cultural heritage protection standards.

A more frequent use of non-invasive computed tomography in archaeology would be appropriate, especially when dealing with sensitive remains and for the production of volume 3D models which should be included into documentary archaeological collections. Spatial and surface 3D rendering from 2D CT images not only expand our knowledge about the screened objects but they also enable further analysis, identification, expansion in the field of archaeometry, enabling better quality 3D rendering and addition.

For archaeologists, conservators, and restorers, computed tomography can provide timely and reliable additional information for the planning, selecting and implementation of more efficient ways to preserve cultural heritage remains. Artificial intelligence, deep learning, convolutional neural networks, and other challenges of computer vision open up the still insufficiently researched possibilities of implementing computed tomography in archaeology and in preserving valuable remnants of cultural heritage.

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ABSTRACT

The article emphasizes the importance of anatomical-morphological analysis of a volume 3D model reconstructed from microcomputer tomographic 2D images for archaeological documentation and treatment, non-invasive archaeological analysis, and a more optimal selection of conservation methods and techniques. The object of µCT reconstruction is a 40,000-year-old Palaeolithic hunting weapon found in 2008 in the Ljubljanica River near Sinja Gorica (Vrhnika, lat.: *Nauportus*, Slovenia). This wooden point (yew; lat.: *Taxus baccata*) is so far just one of only eight known Palaeolithic wooden artifacts found in Europe. Between 2013 and 2017, the point was conserved using a traditional waterlogged wood processing technique with melamine resin. Using computer volumetric analysis of five surface 3D models, taken before, during and after the conservation, it was found out that volumetric changes and deviations of the point have occurred (bending, weight, volume, surface cracks and changes). Surface changes of the 3D models did not answer the question: what are the causes for the resulting changes after the conservation process? Only anatomical-morphological analysis of the internal structure of the point could answer this question. To this end, we developed an

iterative segmentation algorithm adapted to archaeological analysis for the reconstruction of a volume 3D model from microtomographic 2D images. In this way, we successfully supplemented the data of the surface 3D model and confirmed volumetrically and graphically the current and critical state of the internal anatomical structure of the artifact (cracks, fractures, etc.). The case study confirmed the exceptional importance of the use of microcomputed tomography as a non-invasive technique in archaeological analysis and in the planning and selection of procedures for conservation, restoration and storage of sensitive archaeological heritage remains *in situ* or *ex situ*.