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PHOTOGRAMMETRY FOR 3D REPRESENTATION OF HUMAN REMAINS FROM THE NECROPOLIS KR-N1 IN DHOFAR (SOUTHERN OMAN): DIGITAL TECHNOLOGY APPLIED TO OSTEO-ARCHAEOLOGICAL STUDIES

1. Introduction

The use of photogrammetry for 3D reconstruction in archaeology has increased significantly during the last ten years, becoming a fundamental tool for documentation, study (McCarthy 2014; Campana 2017; Jalandoni *et al.* 2018; Pena-Villasenin *et al.* 2019; Perez-Garcia *et al.* 2019; Valente 2019), protection and public fruition (Richardson 2013; Perez-Garcia *et al.* 2019) of archaeological sites and artefacts (Fiorini *et al.* 2017, 2019; Brandolini *et al.* 2020). If the application of this digital technology for 3D reconstruction of material culture seems to be definitively developed (Pierrot-Deseilligny *et al.* 2011; Dellepiane *et al.* 2013; Fryer, Chandler 2013; Galeazzi 2016; Sapirstein 2017; Brandolini, Patrucco 2019), its employment in the virtual recreation of osteo-archaeological evidence still remains episodic (Katz, Fries 2014; Jurda, Urbanova 2015, 2016a). Nevertheless, despite the scarce number of scientific publications, the importance of photogrammetry in osteo-archaeological studies is now acquired. Its application has been fundamental in recent research concerning the interpretation of bone modification marks caused by cutting (Gonzalez *et al.* 2015) or by taphonomic processes (Yravedra *et al.* 2017), demonstrating its importance also for forensic facial reconstruction (Moraes *et al.* 2014).

The employment of 3D photogrammetric reconstruction is still scarce in the archaeological contexts of Dhofar, the southernmost region of the Sultanate of Oman (Fig. 1). In this context, the pioneering work (Brandolini *et al.* 2020) conducted by the DHOMIAP Project, for the 3D model SfM-photogrammetric reconstruction of a dolmenic cist (D1), in the KR-N1 necropolis at Khor Kori (Lischi 2019; Lischi, Vangeli 2022) is noteworthy. This further confirmed the importance of photogrammetry during archaeological surveys of remote sites. To further expand this methodological test, a 3D photogrammetric reconstruction of a selected sample of human remains was chosen. This test was done with the aim of demonstrating, via a comparison of the results obtained by using two different settings (full-frame DSLR camera with macro lens vs. APS-C DSLR camera with standard zoom lens), the importance of this digital technology for the study, conservation and fruition of osteo-archaeological records in a poor state of preservation.

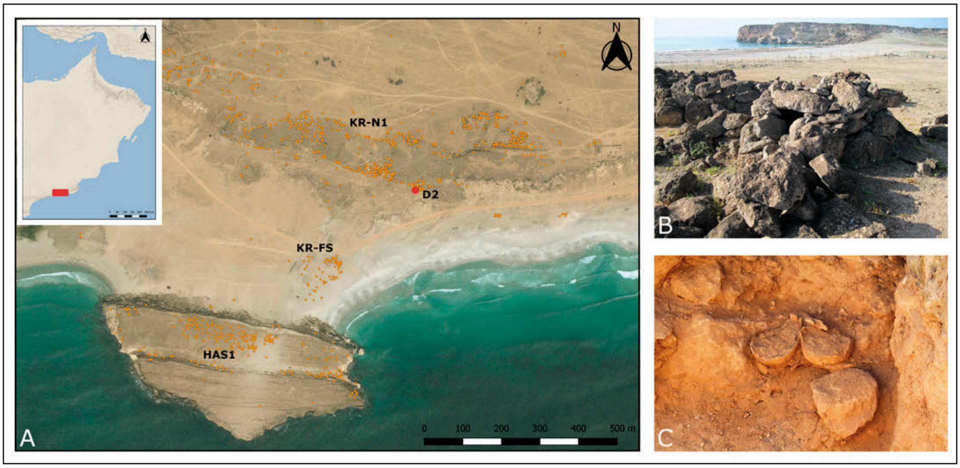

Fig. 1 – General location of the area (top left box), distribution of the necropolis KR-N1 with the location of the tomb under investigation and other archaeological evidence in the vicinity (A). Northeast view of tomb D2 before excavation (B); photo of two of the three skulls found during excavation of the tomb, still *in situ* (C).

The human bones selected for this test were found in one of the dolmenic cists (tomb D2) belonging to the KR-N1 necropolis (Fig. 1), a funerary setting on a promontory facing the sea in the Khor Rori area (Dhofar, Sultanate of Oman), five hundred metres N of the HAS1 settlement (dating from 4th century BC to 2nd century AD) (Lischi 2019, 2022), this being the pilot site for defining the Dhofar Coastal Culture (Lischi 2022). This newly identified culture led to a redefining of the land use and settlement dynamics in the Khor Rori area. Furthermore, it has allowed a new interpretation of the relations between the South Arabians settled in Sumhuram (ca. 2 km from HAS1) and the native inhabitants of the area.

Excavations at KR-N1, started in 2018 (Lischi 2018a, 2018b) by the DHOMIAP project and still ongoing, have determined the grave typologies, their distribution and a preliminary chronology for the use of the funerary structures (Lischi, Vangeli 2022). Three categories of tombs are attested: cairns, multiple cists and dolmenic cists, the latter ones being the most represented within the necropolis. Of the 558 dolmenic cists, only three (D1, D2, and D3) have been excavated. Radiocarbon dates, obtained from human bone fragments from D2, allowed at least to date the use of the necropolis at the beginning of the 4th century BC (Lischi, Vangeli 2022), coeval with the maximum expansion of HAS1 settlement (Lischi 2019, 2022).

After having studied in detail the osteological material from D2, four diagnostic elements have been selected for 3D photogrammetric reconstruction:

a fragment of male cranial frontal bone (specimen IQM18B.US124.HB1), an upper left first incisor (specimen IQM18B.US124.HB3), a calcific lymph node (specimen IQM18B.US124.HB51) and a right infant clavicle (specimen IQM18B.US124.HB21). All the selected specimens were characterised by significant elements. The cranial frontal bone had a subcircular healed injury. This cranial trauma is evidence of blunt force trauma, the origin of which is currently difficult to establish. However, it should be remembered that similar traumas have been found on coeval skeletons from Yemen and have been interpreted as possible ritual punishment (Coppa, Damadio 2005). The calcific lymph node could be the result of tuberculosis or brucellosis infections, the latter being more likely considering the agro-pastoral subsistence lifestyle of the HAS1 inhabitants (Lischi 2019, 2022). Finally, the incisor was affected by enamel hypoplasia and heavy wear, whilst the clavicle indicated a juvenile individual. The determination of the juvenile age of the individual to which the clavicle belonged was possible thanks to the lack of fusion of the medial epiphysis. This was also confirmed by comparing its length with the reference tables (Schaefer *et al.* 2008).

The images of the cranial frontal bone, the incisor and the lymph node were taken using a DSLR camera with a standard lens (referred to as Setting 1), while the images of the clavicle were taken using a full-frame DSLR camera with a macro-lens (referred to as Setting 2). The four selected elements, being part of the whole osteo-archaeological record of tomb D2, were in a poor state of preservation. The application of 3D photogrammetric reconstruction techniques has also provided an opportunity for verifying the efficiency of this method for studying fragile human remains, avoiding further physical manipulation.

2. Methods and tools: image acquisition

Setting 1 image acquisition made use of a DSLR camera (Nikon D3400), operated in automatic mode with a standard zoom lens (DX VR AF-P NIKKOR 18-55 mm 1:3.5-5.6 G) (Tab. 1). Setting 2 image acquisition made use of a full-frame DSLR camera (Nikon D610), operated in manual mode with a macro-lens (AF-S Micro NIKKOR 60 mm 1:2.8 G ED) (Tab. 1).

The time spent to obtain the images with Setting 1 was about 15 minutes per element (for a total of 45 minutes), while 30 minutes were necessary to acquire images with Setting 2. The description that follows is shared by both Setting 1 and Setting 2. To avoid micro-motion effects, a tripod was used to sustain the camera, which was operated using a wireless remote control. The image acquisition was realised by placing the bones on a turning plate inside a cubic box with a black background, and by illuminating it with two external lamps of neutral colour temperature (5560 K). The distance in centimetres between the two sights was used as the metric reference during the creation

	Setting 1	Setting 2
Device	Nikon D3400	Nikon D610
Lens	Standard 18-55mm	Macro-lens 60 mm
Number of elements	3	1
Picture acquisition time (total)	~45 minutes	~30 minutes
Exposure time	1/6 s	1/20 s
Aperture	f/6.3	f/25
Shooting mode	Remote control, 2 s	Remote control, 2 s
Exposure mode	A	M
White balance	A, 5560 K	M, 5560 K
ISO	100	250-400

Tab. 1 – Features used for Setting 1 and 2.

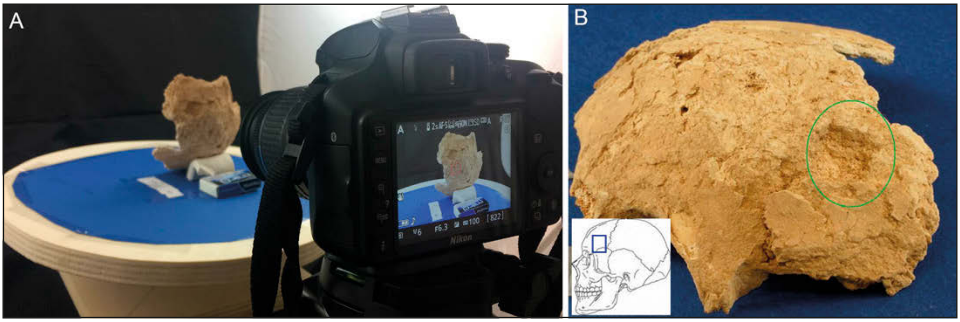

Fig. 2 – A) Camera workstation during the frontal bone image acquisition; B) frontal bone with the lesion highlighted in green and the position of the lesion on the cranial district (bottom left).

of the scale-bar. Several series were made, with the lens at different heights, to obtain as much information as possible about the osteological elements (Fig. 2).

The first series was realised with the lens almost parallel to the plane above which the object was located. The second series was taken with the lens at the same height, while different positioning of the subject allowed documentation of the other parts. For the third series, the lens was set at a greater height and was inclined to the object's plane. The fourth series, only realised with Setting 1, was obtained by changing only the object position. In total, 428 images were taken: 95 for the cranial frontal bone, 76 for the incisor, 98 for the lymph node and 159 for the clavicle. Pictures were saved in RAW format, eventually converting them into TIFF format through the software ViewNX2. Then, the TIFF images were uploaded in a chunk (working folder) of the software Agisoft Metashape Professional (1.7.5 version) to start the desk processing.

3. Methods and tools: desk processing

The desk processing methodology summarised below is common to both Settings 1 and 2. Images were processed through the software Agisoft Metashape Professional (1.7.5 version), using the virtual machine (GPU Tesla T4 2 CPU and 384Gb of RAM 800 GB of disk) kindly made available by Laboratorio MAPPA (Metodologie APPlicate all'Archeologia) of the University of Pisa. The process consists of five operations:

1) Creation of masks. The masks were created with high precision to reduce noise to a minimum. In this process, the chromatic contrast between the colour of the bones (whitish) and that of the cardboard (blue) allowed the application of the 'intelligent scissors' function of the software that speeded up the workflow.
2) Camera alignment and creation of the sparse point cloud. The images were aligned by selecting a high level of proceeding accuracy with the key point limit set to 100,000 and the tie point limit to 4000.
3) Creation of the scale-bar. The error margin for the creation of the scale-bar was set to 0.001 m because of the small dimension of the subjects.
4) Creation of the dense point cloud and creation of the mesh. The dense point cloud, created by setting high quality and medium deep filtering, was used as the source of information for the creation of the mesh.
5) Creation of the 3D model and of the texture. After the creation of the mesh, the 3D model with the texture is created. The texture itself was created by selecting the images as the source of information and setting the ratio texture size/count to 4,096×1. The mapping mode was set to 'generic', and the blending mode to ' mosaic', while the additional parameters (Enable Hole Filling and Enable Ghost Filter) were not added. The parameters described above are summarised in Tab. 2.

4. Pros and cons of Setting 1 and Setting 2

The first setting, as previously mentioned, was accomplished using a Nikon D3400 DSLR camera with an 18-55 mm standard zoom lens set to

3D model and texture creation parameter	
Source of information	Images
Texture size/count	4096x1
Mapping mode	Generic
Blending mode	Mosaic
Enable hole filling	Not
Enable ghost filter	Not

Tab. 2 – 3D model and texture creation parameter.

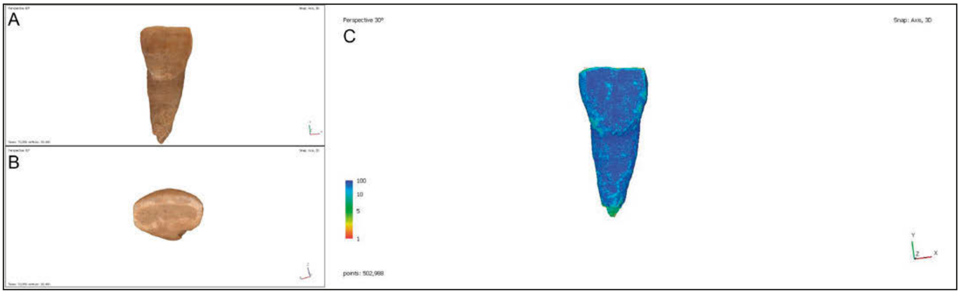

Fig. 3 – Enamel hypoplasia lines and wear on the buccal and occlusal view of the incisor (A, B); high degree of confidence of the incisor dense point cloud (C).

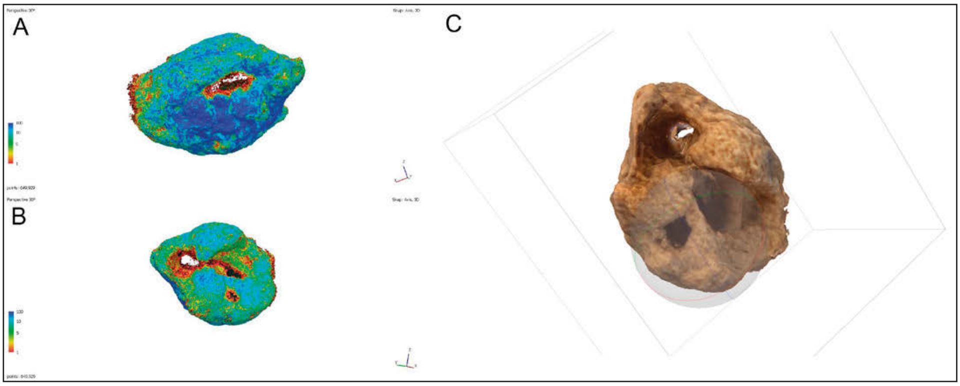

Fig. 4 – Low degree of irregular-shape portion of the lymph node dense point cloud (A, B); undetailed texture of the lymph node result of the low confidence of the dense point cloud (C).

automatic mode. This setting was utilized to capture images of the frontal bone, incisor, and lymph node, and allowed for quick acquisition of the three elements in approximately 45 minutes. The automatic mode eliminated the need to manually adjust exposure and focus settings, and the high depth of the lens expedited the process. A specialized operator was not required to use this setting due to its simplicity and speed.

The standard zoom lens provided detailed images, even capturing barely visible traces on the remains, such as enamel hypoplasia and wear traces, which were clearly visible in the 3D model of the incisor (Fig. 3). The dense cloud confidence was also high, indicating the effectiveness of Setting 1 for 3D reconstruction of small human remains. Additionally, the economic aspect of this process was advantageous as the standard zoom lens is typically included in the basic equipment of any DSLR camera. However, the standard zoom lens

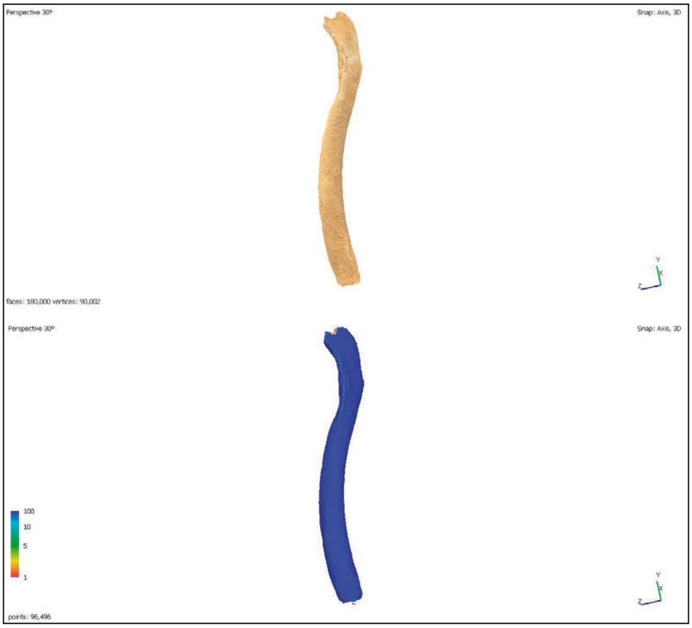

Fig. 5 – High quality of the clavicle texture resulted from the high degree of confidence of the dense point cloud (top); high degree of confidence of the clavicle dense point cloud (bottom).

was not suitable for irregular-shaped and small-sized elements, as demonstrated in the photogrammetry of the lymph node. The dense cloud confidence was low, resulting in a non-detailed texture of those areas (Fig. 4). To avoid losing essential information during osteo-archaeological studies, it is best to avoid using standard zoom lenses for 3D reconstruction of irregular-shaped objects like the lymph node. The pros and cons of Setting 1 are summarized in Tab. 3.

In contrast, Setting 2 utilized a Nikon D610 full-frame DSLR camera with a 60 mm macro lens set to manual mode. The image acquisition of the clavicle was made with this setting, which required manual control of light exposure and focus. This resulted in a longer acquisition time of approximately 40 minutes, and either an operator with photographic skills or an operator willing to invest a lot of time to improve this technique was needed.

Although Setting 2 was more expensive due to the need for a full-frame DSLR camera with a macro lens, its excellent degree of detail was noteworthy. The 3D model of the clavicle showed almost no zones of low confidence in the dense point cloud, which was crucial for the subsequent texture to have colours equal to those of nature (Fig. 5). The pros and cons of Setting 2 are summarized in Tab. 3.

	Setting 1	Setting 2
Pros	- Speed of execution - No need for specialized worker - Not expensive technique - Good detail of small remains - Good detail of scarcely visible traces	- No zone of low confidence in the dense point cloud - Perfect colour texture
Cons	- Not high degree of detail of the "shape anomalies" of small-size elements	- Slowness of execution - Specialized worker request - Expensive technique

Tab. 3 – Comparison between Pros and Cons of Setting 1 and 2.

5. Results and discussion

The results obtained by applying both settings were significant from different points of view, providing valuable insights into the study of osteological samples. The high degree of detail captured in the 3D models allowed for thorough examination without the need for additional physical manipulation. This aspect is crucial not only for the preservation of osteological materials but also for the possibility of studying them remotely, in a different location or country from where they are stored, as was the case in this study. One notable advantage of the 3D models was the exceptional precision of the scale-bar, enabling accurate measurements for anthropometric studies and analysis of morphological variables, as is clearly visible in the case of teeth. Measurements such as clavicle length, the circumference of the frontal bone lesion, mesio-distal and bucco-lingual diameters, and crown and root heights of the incisor (Fig. 6) could all be taken with great precision. A comparison between manual measurements using a digital calibre and digital measurements is presented in Tab. 4.

It can be observed that, in general, the digital measurements are generally higher than those obtained through manual measurement, with a difference ranging between 0.19 and 0.75 mm. Only in one instance did the difference become negative, but it remained well below 1 mm (-0.30 mm). Interestingly, the digital measurements that closely matched the manual measurements were predominantly obtained from the models produced with Setting 1, while the only measurement taken on a 3D model produced with setting 2 differed from the manual measurement by 0.75 mm. Furthermore, the high-quality 3D model of the incisor enabled the measurement of the line of enamel hypoplasia. These lines serve as a permanent chronological record of stressful

Inventory n.	Description	Manual measurements (mm)	Digital measurements (mm)	Deviation % between the two techniques	Setting
IQM18B.US124.HB21	Clavicle maximum length	670	675	+ 0,75	2
IQM18B.US124.HB3	M-D incisor diameter	7,92	7,95	+ 0,38	1
IQM18B.US124.HB3	B-L incisor diameter	4,17	4,18	+ 0,24	1
IQM18B.US124.HB3	Crown lingual height	6,60	6,58	- 0,30	1
IQM18B.US124.HB3	Root lingual height	102,8	103	+ 0,19	1

Tab. 4 – Comparison between manual measurements and digital measurements.

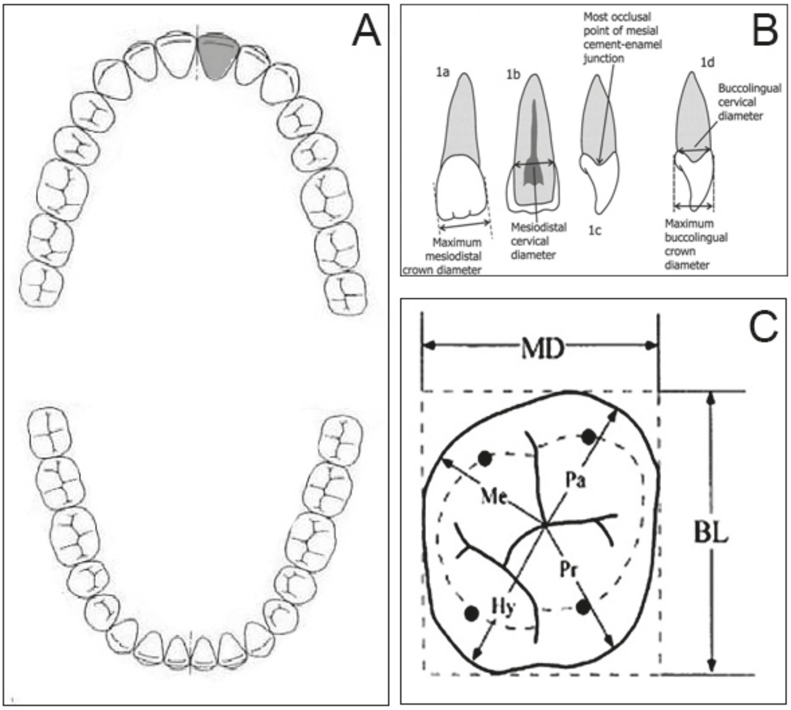

Fig. 6 – Adult teeth scheme with IQM18B.US124.HB3 position highlighted (A); mesio-distal and bucco-lingual crown and cervical diameters (B) (after Hillson *et al.* 2005); diagram showing mesio-distal width and bucco-lingual width (C).

events, often nutrition-related, that occurred during the first seven years of the individual's life (Goodman, Rose 1990). Within tomb D2, four episodes of enamel deposition disruption between the first and third year of the buried individual's life were discovered (Vangeli 2022). One particularly evident line was prominently visible in the 3D model presented in this study (Fig. 3), allowing for accurate measurement and identification of the time when the individual experienced significant nutritional stress, approximately at 1.49 years of age.

The regression equation proposed by Goodman, Rose (1990) allowed the determination of this value. Normally, this type of measurement requires the use of a microscope, which implies the transportation of the material to a laboratory equipped with such an instrument. Unfortunately, this is not always feasible, highlighting the usefulness of creating 3D models in the field. Such models enable the measurement of highly diagnostic elements, like enamel hypoplasia lines, which can be challenging to be accurately measured using portable instruments such as a caliper.

Additionally, within our case studies, as previously described, a 3D model of a calcified lymph node (IQM18B.US124.HB51) was created. This lymph node is believed to be pathognomonic of brucellosis, although it could also be indicative of another infection such as tuberculosis. The definitive assessment of the nature of the infection suffered by the individual requires destructive biomolecular analysis. Therefore, the ability to preserve a 3D model of the fragment becomes crucial as it allows for the continued study of its morphology even after its destruction, enabling researchers to gather additional data about the infection. The results obtained by applying both settings in this study underscored how photogrammetry could serve as a viable alternative to laser scanners, especially when it comes to reconstructing 3D models of small human remains (Jurda, Urbanova 2016a).

From a methodological standpoint, our research focused on testing two different settings (Setting 1 and Setting 2) to compare the effectiveness of basic equipment against more expensive and technologically advanced photographic tools. While there are various other combinations of cameras, lenses, and acquisition modes worth exploring, such as using an APS-C DSLR camera equipped with a macro lens or operating either an APS-C or full-frame DSLR camera with a macro lens in automatic mode, our main objective was to evaluate the potential of the most basic and user-friendly photographic equipment (Setting 1) versus the most advanced and costly equipment (Setting 2), rather than covering all possible combinations and settings.

As previously mentioned, Settings 1 and 2 differed primarily in the devices used while keeping the image acquisition process largely unchanged, except for the additional fourth series in Setting 1. The use of a DSLR Nikon D3400 with a standard zoom lens in automatic mode significantly accelerated the image acquisition process in Setting 1 compared to the manual mode employed in Setting 2. The manual mode required more attention to control lighting and focus on the subject. The resulting 3D models clearly exhibit varying levels of detail. The macro lens used in Setting 2, with its technical specifications, enabled precise focusing at close distances, resulting in highly defined details, as exemplified in the 3D model of the clavicle. However, even the application of a standard lens in Setting 1 yielded a considerable degree of detail, as evident in the rendering of the incisor enamel hypoplasia and wear. Nonetheless, Setting 1 may not be suitable for elements with highly irregular surfaces, such as the documented lymph node, where Setting 2 is undoubtedly more appropriate.

The ability to conduct osteo-archaeological studies without physically handling human remains holds paramount importance for poorly preserved osteological specimens. As highlighted by Mccorriston *et al.* (2012), the inadequate preservation state of human remains is a major obstacle preventing the comprehensive study of many funerary contexts in Dhofar. 3D model reconstruction presents a promising solution to this challenge. Creating 3D models can prevent progressive fragmentation, destruction, and the loss of information associated with skeletal elements, stimulating scholars' exploration of Dhofar's funerary archaeology. Additionally, 3D model reconstruction enables the visualization of osteo-archaeological features without the need for their physical presence, eliminating the necessity of transporting fragile remains across countries for research purposes. Therefore, generating 3D models of osteological elements has the potential to enhance the accessibility and utilization of valuable information in this field.

6. Conclusions

The objective of this paper was to test and compare two different settings for the 3D model reconstruction of human remains, aiming to demonstrate the significance of 3D photogrammetry in studying osteo-archaeological records, particularly those in a poor state of preservation. The findings revealed that Setting 1 offered a balance between good quality and fast execution speed, making it highly relevant for the 3D photogrammetry of *in situ* skeletal remains. This setting proved valuable for describing taphonomic processes, documenting specimens, and capturing different excavation phases (Lussu, Marini 2020). Such documentation is crucial considering the potential damage caused to the osteo-archaeological record during its removal from the ground matrix. Preserving the ability to document the funerary context from which the 3D reconstructed human bones originate is of utmost importance in gaining a comprehensive understanding of their history. This emphasis on contextualization aligns with the principles of modern South Arabian bio-archaeology, which seeks to surpass the traditional approach of isolated laboratory-based anthropological research (Williams *et al.* 2014).

On the other hand, Setting 2 yielded excellent results in terms of capturing intricate details of human bones, but it involved higher costs, increased complexity in operation and longer processing times. Under optimal conditions, Setting 2 proved particularly suitable for more ambitious objectives, such as reconstructing facial morphology or determining sex and ancestry (Jurda, Urbanova 2016b). However, the application of 3D photogrammetry in these specific fields remains relatively limited (Lussu, Marini 2020). The higher level of detail provided by Setting 2 becomes especially valuable when there is a need to produce a 3D printed model of an osteo-archaeological element, particularly irregular-shaped ones (Cole *et al.* 2019).

This comparative test highlighted the advantages and disadvantages of the two different settings, clarifying their specific use adequacy. The optimal quality-speed ratio offered by Setting 1 was deemed sufficient for accurate 3D documentation of human remains and their funerary context. However, it is worth exploring a potential alternative in the future, such as employing a DSLR camera (either APS-C or full-frame) equipped with a macro lens and operated in automatic mode. This setup could potentially eliminate the complexity and slowness associated with Setting 2 while maintaining a high level of image detail. However, it should be noted that the limited depth of field inherent to macro lenses would require capturing more photographs compared to Setting 1, making the latter still the faster option. Despite their specific characteristics and applications, both settings reaffirmed the significance of 3D photogrammetry in the bio-archaeological study of human remains, particularly those in a poor state of preservation.

Matteo Vangeli, Silvia Lischi, Gabriele Gattiglia, Filippo Sala
Dipartimento di Civiltà e Forme del Sapere
Università degli Studi di Pisa
vangelimatteo@gmail.com, silvialischi@msn.com, gabriele.gattiglia@unipi.it
filippo.sala@phd.unipi.it

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ABSTRACT

The poorly preserved human bones discovered during the DHOMIAP Project excavation of the necropolis KR-N1 in the area of Khor Rori (Dhofar, Sultanate of Oman) were an opportunity to apply, for the first time in Dhofar's pre-Islamic funerary contexts, 3D photogrammetry to osteo-archaeological studies. The low economic engagement and the execution speed make this technique essential in the documentation of barely accessible archaeological remains and contexts, as already witnessed by previous studies conducted outside this research area. This paper aims to find a more appropriate method and setting for 3D model photogrammetric reconstruction of human remains, demonstrating the importance of this digital technology for the study of poorly preserved osteo-archaeological remains. For these purposes, the results obtained using two different settings for image acquisition (one with macro and one with standard lens) were compared and discussed.