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THREE-DIMENSIONAL DOCUMENTATION OF DOLNÍ VĚSTONICE SKELETAL REMAINS: CAN PHOTOGRAMMETRY SUBSTITUTE LASER SCANNING?

ABSTRACT: Creating digital replicas of unique biological findings or archeological artifacts has become a desirable task, which enables to spare original integrity and enhance accessibility of valuable objects to a wide range of experts as well as public. In recent years, specialized scanning devices have been challenged by performance of photogrammetry software tools capable of processing unstructured image sets and providing three-dimensional digital models in return. Simplicity, portability and affordability predetermine photogrammetry to be the method of choice if three-dimensional documentation is to be conducted at remote facilities and outdoor locations.

The present paper tests technical limitations of two 3D documentation techniques – close range photogrammetry carried out in Agisoft PhotoScan software and laser scanning conducted with MicroScribe/MicroScan scanning unit while documenting pelvic bones and sacra from the Upper Paleolithic triple burial of Dolní Věstonice, Czech Republic. For photogrammetry, two different approaches to generate closed textured 3D models were confronted – alignment of partial polygonal meshes and joint processing of multiple image sets.

Our results showed that photogrammetry provided high-resolution 3D models appended by photorealistic texture. In terms of depicted details, the photogrammetry-generated models were comparable to those of laser scanning. However, the robust performance of the employed algorithm was achieved at the expense of extensive time and labor demands, which for many experts may be difficult to justify. In conclusion, photogrammetry should be considered a suitable substitute for surface scanners only if conducted for occasional and/or out-of-lab documentation tasks.

KEY WORDS: Photogrammetry – Laser scanning – Three-dimensional documentation – Skeletal remains – Paleoanthropology – Dolní Věstonice

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INTRODUCTION

Unique skeletal findings represent valuable items of natural history attracting attention of experts and public. Given their scientific value encouraging never-ending revisions and re-examinations, they are prone to irreversible damage (Balzeau *et al.* 2010). Nowadays, three-dimensional digital documentation represents a widespread procedure that facilitates both preservation and accessibility of such skeletal remains by creating display-worthy copies (Kullmer 2008, McPherron *et al.* 2009, Kuzminsky, Gardiner 2012, Hublin 2013) and by generating outcomes abundant in a variety of scientific data (Freidline *et al.* 2012, Pan *et al.* 2014, Jurda *et al.* 2015).

With the recent extensive development in 3D technologies, three-dimensional digital surface models can be generated rapidly and easily using laser or optical devices. Both are accessible and affordable in many forms (Friess 2012, Tzou *et al.* 2014). In addition to surface scanning computed tomography or microtomography are capable of creating 3D digital copies of biological or non-biological objects (Bruner, Manzi 2006, Abel *et al.* 2011, Brough *et al.* 2014, Dedouit *et al.* 2014), although neither provides information about surface coloring. As a low-cost alternative to 3D surface or volume scanning, single camera photogrammetry has gained a momentum during the last decades (El-Hakim *et al.* 2005, Chandler *et al.* 2007, Fourie *et al.* 2011, Koutsoudis *et al.* 2013, Katz, Friess 2014, Maté González *et al.* 2015).

In the current state-of-the-art, photogrammetry represents a highly accessible and versatile technique for surface data acquisition (Ducke *et al.* 2011) which employs automated software tools capable of processing unstructured image sets and providing three-dimensional digital models in return (e.g., 123D Catch, PhotoModeller, PhotoScan etc.). It became particularly popular among anthropologists and archaeologists due to the increasing performance of digital cameras and personal computers, enabling to generate high-resolution models within an acceptable timeframe (Mathys *et al.* 2013, Moraes *et al.* 2014, Jurda, Urbanová 2015, Quinto-Sánchez *et al.* 2015, Urbanová *et al.* 2015).

In 2012, following the current trends in the field it was decided that the human skeletal remains originated in the infamous triple burial from Dolní Věstonice (Klíma 1987, Svoboda 2006) would be digitized in order to preserve their form, integrity and to make them available, at least in the digital form, to a wider range of research-oriented and educational projects. Since their discovery in 1986, the remains have been housed close to the discovery site, at the Paleolithic and Paleontology Research Center in Dolní Věstonice, Czech Republic. The facility has limited local lab equipment, which makes it difficult to carry out the study without external technical resources. In addition, the tremendous historical value and hardly countable, still costly, insurance coverage complicates or virtually rules out transferring the remains for an out of place examination or documentation.

Generally, conducting documentation at a remote location is burdened with many technical, spatial and time-related limitations. Its high portability and low demands on working conditions make photogrammetry an excellent candidate for documentation tasks carried out under less than optimal circumstances (Doneus *et al.* 2011, Barratt 2013, De Reu *et al.* 2013, Forte 2014, McCarthy 2014). However, photogrammetry is usually not regarded as the first choice when digitalization of human remains is desired due to its unpredictable performances (Slizewski, Semal 2009, Weinmann *et al.* 2011). Although numerous studies have reported reliable performance of the photogrammetric algorithms when confronted with human artifacts (Pierrot-Deseilligny *et al.* 2011, Chandler, Fryer 2013, Dellepiane *et al.* 2013, Galeazzi 2016), adequate information concerning documentation of human skeletal remains is sparse (Katz, Friess 2014, Moraes *et al.* 2014). Similarly, novel techniques outlining how to generate closed models that depict the entire outer surface of a digitalized object, e.g., fusion of partial polygonal meshes (Moraes *et al.* 2014) or joint processing of multiple image sets (Katz, Friess 2014), are yet to be embraced by the scientific community and confronted with other skeletal parts than typically used human crania.

The present paper aims to address issues of quality control and practical limitations of 3D documentation if a single camera photogrammetry performed using commercial yet affordable software (Agisoft Photoscan) and laser scanning are confronted with human remains under unfavorable documentation conditions. In order to validate the usability for out-of-lab or fieldwork both techniques were applied to selected skeletal elements of the renowned Upper Paleolithic skeletal remains of Dolní Věstonice.

MATERIAL AND METHODS

All documented skeletal elements originated in the early Upper Paleolithic triple burial of Dolní Věstonice (southern Moravia, Czech Republic, Klíma, 1987), uncovered at the Dolní Věstonice II site, and dated to approximately 27,000 years BP (Svoboda 2006). The skeletal remains belong to three individuals, two were determined as males (referred as DV13 and DV14 specimens) and one (DV15 specimen), labeled as enigmatic, shows a mixture of male and female, possibly pathological, characteristics. To date, all morphological examinations in regards to individual's sex have been inconclusive (Novotný 1992, Vlček 1992, Formicola *et al.* 2001, Trinkaus *et al.* 2001).

For the purpose of the study, only pelvic bones and corresponding sacra were documented. These elements have been repeatedly scrutinized and re-evaluated in order to provide a conclusive sex diagnosis for DV15 specimen and eventually to bring a better understanding and more plausible interpretations of the whole burial (Novotný 1992, Vlček 1992, Formicola *et al.* 2001).

At the time of the survey, all skeletal elements were well-preserved, but exhibited a number of artificial interventions. Damaged and missing parts were completed using several materials distinctive in color and texture. Surface was impregnated with an unknown substance, possibly acrylic resin, which now forms a glossy partly scratched coating. Shortly after the discovery, the pelvic bones and the relevant sacrum corresponding to DV 13 specimen had been assembled into a complete bony pelvis and such 3D documented. Originally, the pelvic bones and sacra corresponding to DV 14 and DV 15 specimens had been also completed accordingly (Novotný 1992). Since then, however, the bones were dismounted and at this state available for 3D recording.

The 3D models as provided by different methods were displayed side by side in Meshlab v1.3.3 application and compared visually.

Photography

The bones were photographed using Nikon D7000 digital camera equipped with Nikon 60mm f/2.8G ED AF-S Micro lens mounted on a tripod. A paper metric scale was added along each bone in order to size-adjust final digital models. To ensure that photography covered each pelvic bone completely a set of approximately 30 images were taken while the bone was facing the camera with its superior side and then the same procedure was repeated with the opposite, i.e., inferior side (*Figure 1*). Attributed with more complex and irregular morphology the sacra were documented with three sets of digital images.

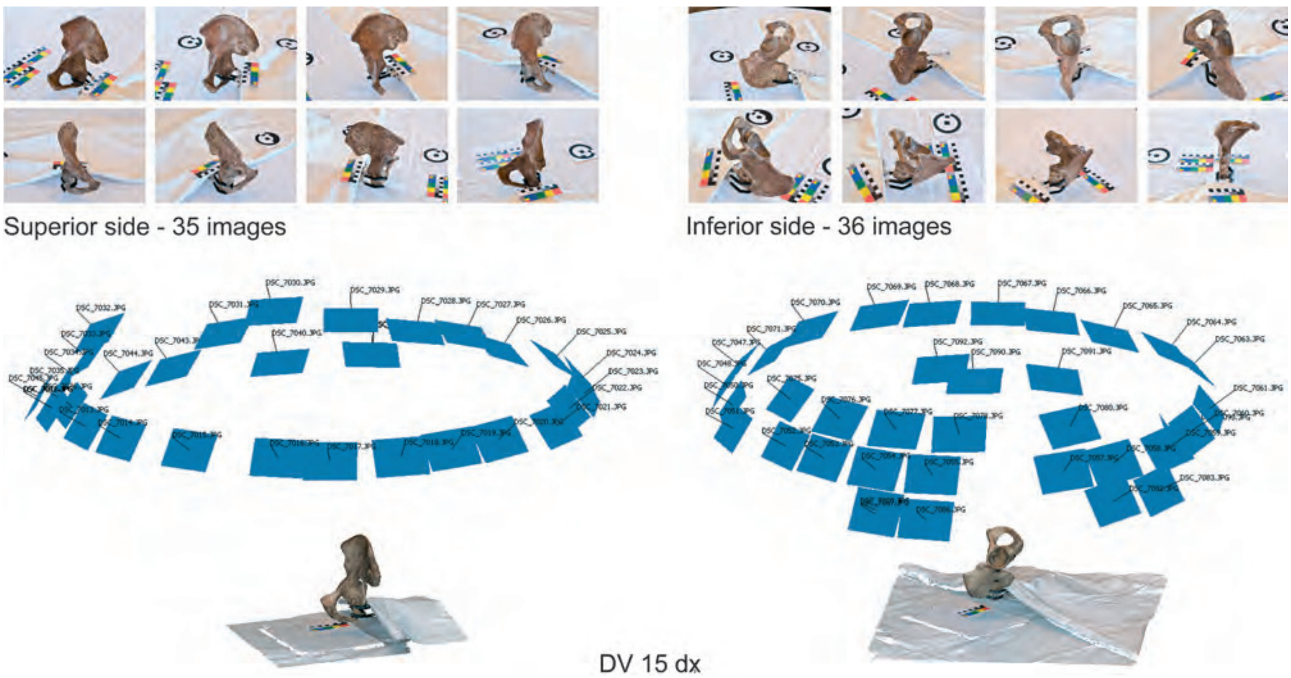

FIGURE 1. Two sets of photographs documenting the right pelvic bone of DV15 specimen. Examples of the images are shown in the upper part, their positioning in relation to the digitalized bone is depicted below. Note the higher density of images covering the area of acetabular fossa.

Photogrammetry

For each studied bone, a digital model was generated using PhotoScan 1.0.3 software set to the "High accuracy" option for both alignment and dense cloud generation functions. During the polygonization, i.e., joining of adjacent vertices by edges into a polygonal mesh, the point-clouds were reduced to approximately 300,000 vertices per separate bone and 900,000 vertices for the complete pelvis. Once finished the meshes were appended with textures generated using "Average" mapping mode. The texture consisted of three image files, each with resolution of 4096×4096 pixels. Prior to processing all input images were pre-calibrated using camera calibration data as provided by Agisoft Lens 0.4.1, lens calibration freeware.

In order to generate closed 3D models two different approaches were utilized (*Figure 2*). In the first, the sets of images acquired for each side or position were processed separately. This produced two or, in case of sacra, three partial unclosed models that were subsequently scaled, trimmed of unwanted background noise and aligned using MeshLab software (v1.3.3, Visual Computing Lab - ISTI - CRN n.d.). The partial meshes were aligned manually using a three-point alignment algorithm followed by an automated processing employing the point to point variant of Iterative Closest Point (ICP) algorithm. The aligned meshes were then merged into a single model using the Poisson remeshing algorithm. The filter parameters were set to preserve the highest level of details for model geometry (Octree Depth set to 12, Solver Divide set to 10). Using such settings the algorithm provided meshes which consisted of approximately 400k vertices. Ultimately, the newly generated mesh was attributed

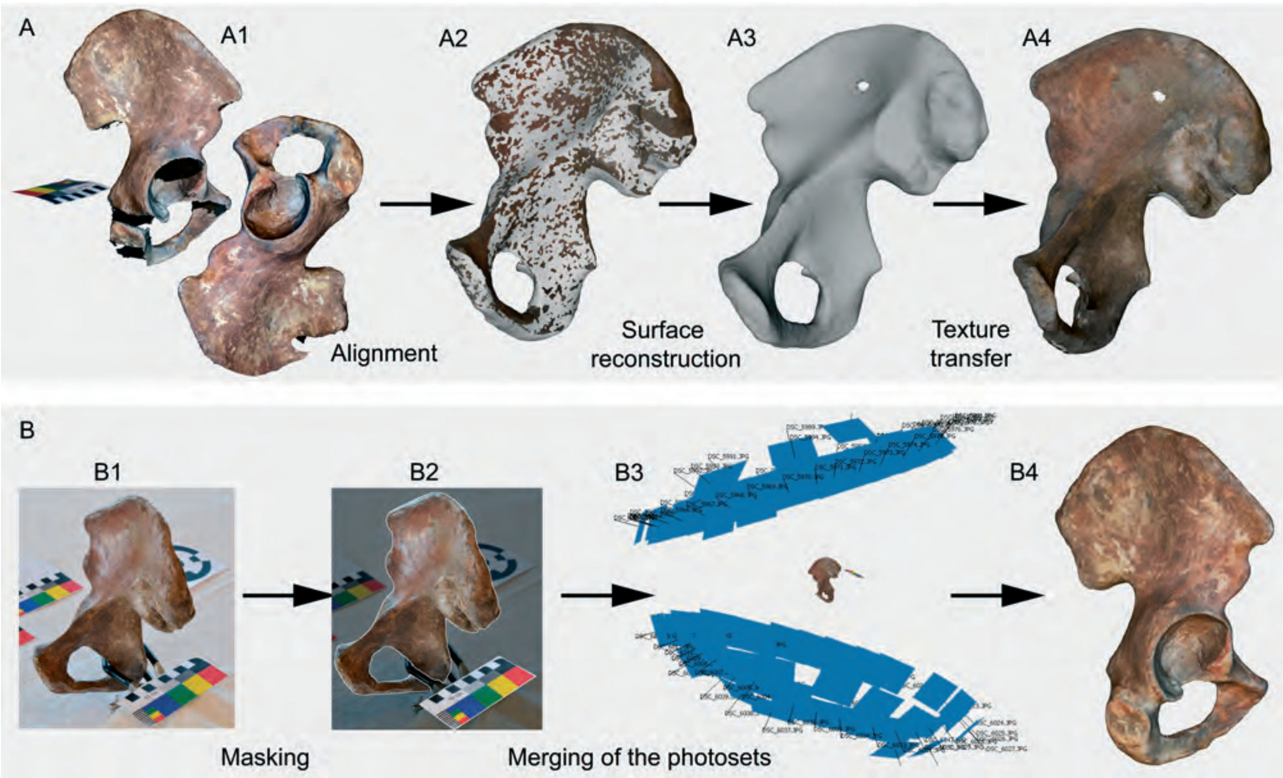

FIGURE 2. Scheme displaying two approaches utilized to build closed 3D models. The first approach (A) consisted of processing relevant series of images separately. This eventually produced partial, unclosed models (A1), which were combined (A2–A3, A2 – superimpose inferior model is displayed in white) using editing tools included in MeshLab application. Prior to being merged, separate scans were trimmed of unwanted background noise and scaled to real units. Manual and automatic ICP-based algorithms were used to aligned separate scans, a new textured polygonal mesh was generated with Poisson filter and texture transfer (A3). The second approach (B) composed masking out unprocessed parts of the images and combining relevant sets of photographs using *Chunk tools* available in PhotoScan application. This enabled the software to generate a closed model (B4) while processing all the available photos at once.

with texture coloring using Vertex-Attribute-Transfer filter, which allowed transferring original color information onto created vertices.

In the second approach, a closed 3D mesh was built by processing the total number of images recorded for each bone all at once using Chunk tools and Masking functionalities available in PhotoScan software (*Figure 2*). The Chunk tools function allows compartmentalizing larger projects into several inter-related components. This is equally beneficial if the intentions are reversed, i.e., multiple sets of images that depict an object in different positions are to be combined into a single project (*Figure 1*). The approach requires for a depicted object be cut out using the Masking tools. The corresponding chunks were first aligned using automatic point-based matching algorithm and subsequently merged. Ultimately, a new dense point cloud was computed using the complete set of images and processed into a closed textured model. As a result, only scaling and trimming was further required for the outcomes.

While digital photography was carried out entirely on location, the photogrammetric processing and editing of the resulting data included was conducted later under standard lab conditions using a personal computer equipped with 8 GB RAM, 1 GB discrete graphics and 7th generation Intel processor.

Laser scanning

Still on location the studied skeletal remains were additionally scanned with MicroScan 3D, a laser head. If combined with a 6-degree MicroScribe digitizer the laser head forms a handheld scanning unit. The MicroScribe arm system provides the laser head with mobility and allows scanning objects from different perspectives without losing mutual spatial correspondence. Therefore, as long as a bone remains fixed in one position partial scans, so-called sweeps are aligned and merged automatically in real-time. Once the bone is repositioned to be scanned from a different side, a different set of sweeps must be registered and then aligned manually. The skeletal elements in study were scanned at least in three separate positions.

The post-processing, conducted afterwards in the lab, included the alignment of partial scans, cleaning, remeshing and reduction of mesh resolution. In all cases, the scans were aligned using a 3-point alignment function, then adjusted automatically and eventually merged into a raw 3D model. The raw models were then converted into point clouds, trimmed of a background noise, smoothed (with density set to 0.15 mm), remeshed into open 3D models and finally reduced to approximately 200k vertices for pelvic bones, 100k vertices for sacra and 500k vertices for the complete DV 13 pelvis. In all cases, the post-processing was performed using MicroScan Tools program. Since the device is not equipped with an optical system and therefore incapable of recording information on surface color, the models were not appended by texture and artificial coloring was used for visualization.

RESULTS AND DISCUSSION

A researcher conducting an investigation at a remote location or in the field must deal with unpredictable, sometimes highly varying working conditions, limited workspace as well as time restrictions. In the present study, the out-of-lab digital data acquisition was carried out at an adequate, yet clearly out of date research facility. At our disposal was a small windowed conference room, spacious enough to accommodate photography and scanning equipment needed for image data acquisition featuring direct physical contact with the studied skeletal remains, two researchers operating the devices and additional two conducting unrelated tasks. The out-of-lab phase was being carried out in the course of two days. In spite of the effort to maintain the starting conditions, the available equipment allowed us to regulate lighting in the room only to an extent. Therefore, during 3D documentation procedures lighting shifted as the daylight progressed.

Under these conditions, the tripod-mounted Nikon D7000 digital camera combined with macro lenses provided sharp images, which captured the skeletal remains in high details. Our previous experience had shown that sharpness and regular, evenly distributed brightness were crucial image properties that ensured high quality of resulting 3D models (Urbanová *et al.* 2015). To control stability of brightness in images under the given conditions the photography was conducted in the full manual mode. The aperture was set to f/22 ensuring that the depth of field encompassed the entire scene. Under standard lighting conditions, an aperture this small requires that the exposure time be stretched to several seconds. This makes the use of a tripod essential. Altogether, the time needed for capturing a single bone counted approximately 30 minutes. These time requirements may seem as unreasonably long, but together with the rest of suggested guidelines, they provided optimal prerequisites for subsequent photogrammetric processing.

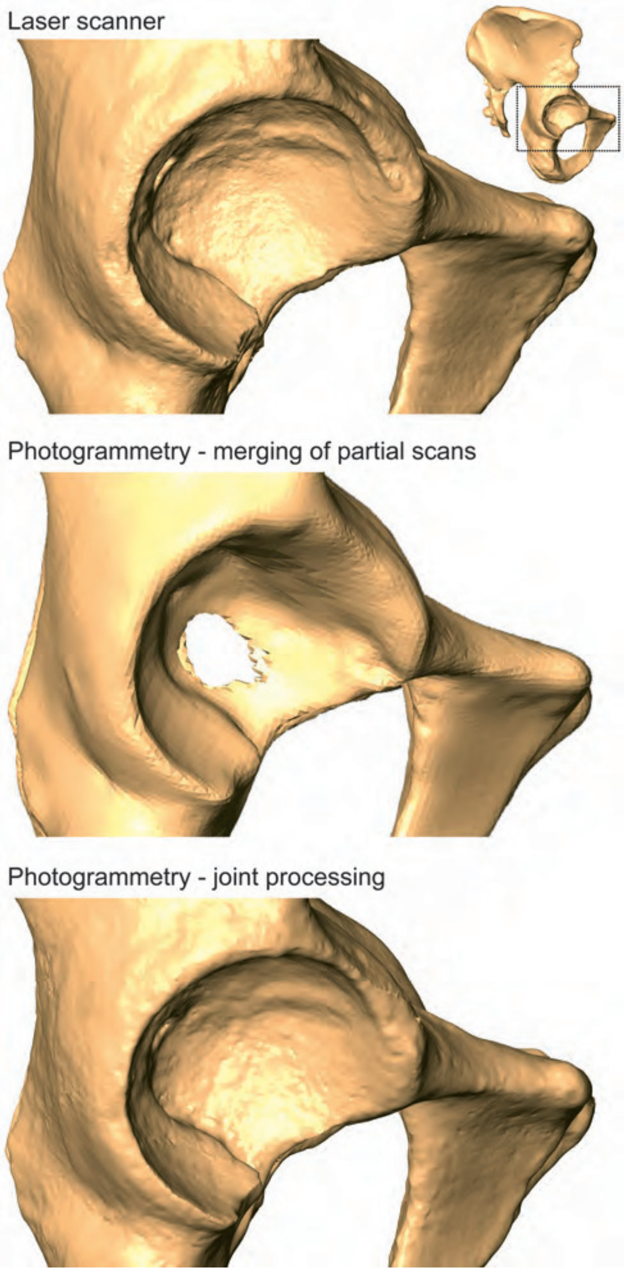

FIGURE 3. Comparison among 3D models corresponding to DV13 specimen as provided by different procedures. Models were rendered using artificial coloring.

The two approaches employed in the post-processing of digital images varied substantially in quality of the outcomes and overall processing time. The straightforward approach generated partial scans, which were yet to be merged using external editing software. In our case, the editing phase took approximately two hours for separate pelvic bones and sacra (DV14 and DV15 specimens) and three hours for the reconstructed pelvis (DV13 specimen). While trimming and aligning using Meshlab tools was conducted easily and rapidly, merging and colorizing in order to create closed, textured meshes turned out to be rather problematic steps. Of the employed tools, the Poisson remeshing algorithm was the most challenging task to provide an optimal result. The procedure often resulted in defective models and in order to produce realistically looking meshes, the process had to be repeated multiple times until optimal input-specific settings were met. Even then, the tools often yielded extensively smoothed meshes that contained localized defects, most typically hole-filled regions, such as those located in depressions of illiac fossae (*Figure 3*) and acetabula, and/or numerous defects in texture coloring (*Figure 4*), such as presence of unicolor regions of several centimeters in size or misplaced texture patterns.

These rather unsatisfactory results are in contradiction to Moraes et al. (2014) who, using the identical approach, were able to produce 3D models of human skulls in superior quality. It is unclear whether in attempts to reproduce their approach we failed due to the larger complexity of human pelvic bones and sacra in comparison to skulls, higher sensitivity of the technique to prehistoric chemically and otherwise treated skeletal remains, or it was simply caused by lacking advanced operational skills. However, had the complexity of pelvic bones been an obstacle to more satisfactory results the second approach employing the masking and chunk tools program would have been equally affected. Here, the techniques provided compact 3D models that lacked any defects in geometry unable to register surface only in areas that lied beyond the reach of optical system, specifically inner walls of sacral foramina or ventral rims of the acetabular fossae. It should be noted that the approach is rather laborious and time-consuming. This may present an obstacle to a wider more general usage. In our case, it took upon several hours to demarcate the objects on images from the background. The masking process can be speed up by the employment of automated masking tools featured in PhotoScan application. Our performance tests, however, showed that he automatically generated masks require additional manual editing, which may add up to several minutes to the already stretched time requirements. Therefore, even though the masking process reduces substantially the time needed for the subsequent post-processing it may be difficult for a researcher to justify such unnecessary extension.

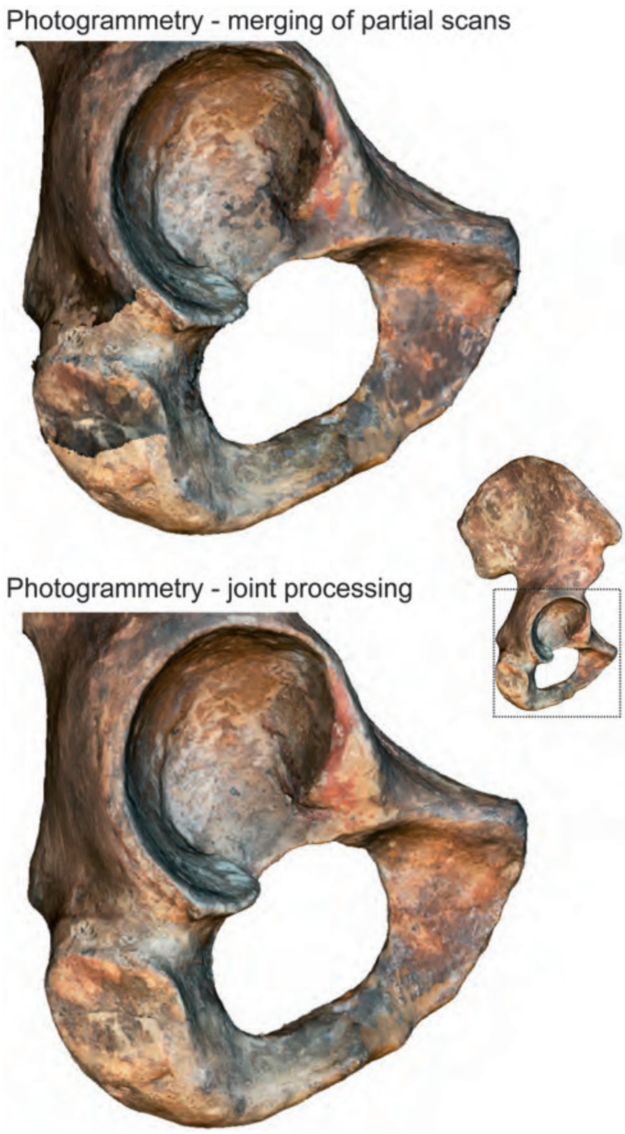

FIGURE 4. Surface textures resulting from the two photogrammetry-based approaches.

Processing digital images in Agisoft PhotoScan application proved to be a robust approach capable of dealing with the fact that majority of photographs were affected by daylight shifts, irregular lighting, shadows and reflections from ambient light on glossy skeletal surface and other inconsistent technical noise. In result, these unfavorable conditions induced only subtle texture defects of few centimeters in size, e.g., discontinuities in brightness and blurred regions. These conclusions are in concordance with De Reu *et al.* (2013) who emphasized the stability of the algorithm employed by Agisoft PhotoScan while documenting archaeological excavation sites and also appear to be more promising than those by Barratt (Barratt 2013) who documented archaeological features via 123D Catch, an alternative photogrammetric application.

All 3D photogrammetry-generated models were appended with high-resolution photorealistic texture, which informative value was comparable to photographic records. The artificial interventions and restored areas of the bones were clearly distinguishable and so were various surface abrasions and scratches – evidence of taphonomic history. The ability to register surface coloring in such high quality favors the method particularly in tasks where an external appearance is as informative as a geometry, e.g., documentation of color-decorated human remains (Martínez-Abadías *et al.* 2009) or taphonomy-induced color changes (Mann *et al.* 1998).

In contrast to photography and image processing, laser scanning with MicroScan-MicroScribe unit proved itself fast, robust and efficient surface scanning technique usable at a remote location. The device represents a relatively portable solution with low demands on workspace and operator's experiences. In comparison to photography, scanning is generally more restrained in regards to sizes of documented objects as many smaller portable scanning devices are bounded by limited measuring volumes. Two-part MicroScribe-MicroScan unit takes advantage of a long yet articulated arm and a small-sized scanning head. These features allowed us to scan the complete pelvis just as well as the disassembled bones. In order to scan an object the sensor head of the scanner has to be moved manually to face scanned surface. For this reason, recording cannot be achieved automatically as accustomed in cases of other laser scanners. Nevertheless, the principle becomes highly time-effective because it is the user who controls which parts of a scanned object are added to or omitted from the digital record.

For the skeletal elements in study, the actual scanning did not exceed 30 minutes. The post-processing back in the lab was still relatively time-demanding and laborious, in particular, since an appropriate setting for each step was, sometimes, met at any but the first trial. However, it was far less exhausting than the photogrammetric procedures. Still, given the varying lighting some laser scanning-based models contained localized artifacts of few centimeters in diameter. The scanning environment setting allows adjusting certain parameters for scanning. However, they were rarely adjusted in between the tasks.

Accuracy and precision of employed documentation techniques is paramount, especially for cases where 3D models are expected to serve as a source of scientific data (Decker *et al.* 2011, Urbanová 2011, Jurda *et al.* 2015). According to the specifications provided by the manufacturer, the MicroScan device is designed to scan with accuracy of 0.2 to 0.3 mm. For the tested photogrammetric software, no quality control data are available. Generally, quality of 3D photogrammetry-generated models is a function of almost infinite number of factors, including resolution of input images, camera network design, photogrammetric algorithm settings and surface properties of digitalized objects (El-Hakim *et al.* 2008, Ducke *et al.* 2011, Koutsoudis *et al.* 2013). The visual confrontation of the tested approaches showed that both provided detailed 3D models, depicting subtle structures of the surface relief. Still, it was observable that the photogrammetry-based models were attributed with smoother surface. This characteristic was particularly evident in small-sized structures such as foramina. In larger surface, it was less noticeable or even absent. However, it is worth emphasizing that the photogrammetry-generated models were created using not the best, but the second most accurate option available in the program. That being said, the created models do not reflect the maximum achievable quality, and it is likely that setting the algorithm to the high-quality option would have a positive effect on the observed sharpness. The models should be rather seen as reflections of the trade-off between the optimal quality achievable and reasonable computation time and power requirements.

CONCLUSION

Close range single camera photogrammetry successfully captured morphology of the Upper Paleolithic skeletal remains from Dolní Věstonice triple grave in quality that was at least comparable to those recorded with the portable laser scanner. The tested photogrammetric Agisoft PhotoScan (1.0.3) application processed generated 3D models that lacked substantial defects in both geometry and texture. We may conclude that due to high demands on time, labor and computational performance photogrammetry should not be considered a direct rival to specialized automated or semi-automated scanning devices, particularly if a large number of objects are recorded under ideal in-lab condition and on a daily basis. However, in occasional cases of out-of-lab 3D documentations it may serve as an appropriate substitute.

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