

DEMONSTRATION OF PROTOCOL FOR COMPUTER-AIDED FORENSIC FACIAL RECONSTRUCTION WITH FREE SOFTWARE AND PHOTOGRAMMETRY

ABSTRACT

Forensic facial reconstruction (FFR) is an auxiliary technique that approximates a face in order to generate identifications. Technological development allows access to open software that can be applied to FFR. The demonstrated protocol has features from creating 3D replicas of the skull to finishing and displaying the reconstruction. PPT GUI is used for 3D scanning, and the resulting point cloud is converted into a 3D mesh in MeshLab. The sculpture is made in Blender, according to the user's preferred technique. The adaptation of the skin layer and finishing of the reconstruction is optimized with the use of templates. In this phase, details can also be hand-carved. Allied to basic training in the software featured in this protocol, the open access to these tools and its independence of imaging hardware other than digital cameras is an advantage to its application in forensic and research contexts.

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INTRODUCTION

In the field of forensic anthropology, forensic facial reconstruction (FFR) is an auxiliary technique to human identification.¹ This method reconstructs a face with its approximate appearance, in order to generate recognition and subsequent identification by forensic analysis.² The technique can also be performed within archaeological or educational contexts, such as in museums and exhibitions.³

Development of different techniques allow different approaches to the procedure, which can emphasize solely anatomically-based features, or those related to the average depth of facial soft tissues (according to assessed sex and ancestry of the skull) or even a combination of both.⁴⁻⁶ The techniques above can be applied to facial reconstructions using plastic or virtual materials, in case of computer-aided facial reconstructions.

Technological development provides technical advances in FFR using digital hardware and software for generating three-dimensional models (3D), like CT scanners, MRI machines, surface scanners and other applications used in 3D animation. The computer-aided FFR methods can be basically divided into manual, which are an adaptation of manual techniques to a virtual environment and automated, in which a database provides parameters for the automatic deformation of a virtual mesh until it fits the skull, without need

for placing virtual pegs that work as references for soft tissue depth.⁷ With a database supported by a significant number of archived CT scans, one can still use other automated computational models to perform various types of reconstruction of a same face, modified according to body mass index (BMI), soft tissue reference table and other features.

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However, the use of this methodology in some forensic units is hindered by factors such as lack of imaging equipment, scanners, specific software and personnel training. This study aims to demonstrate a protocol for computer-aided FFR that uses exclusively open source software without need for complex imaging devices.

MATERIAL AND METHODS

For performing the protocol, a DSLR camera with regular macro lens, photographic tripod, a non-reflective white surface marked with scales measuring 2x2 m and a computer are needed. Basic requirements for computer hardware are Windows or Linux operational system, Intel i3 processor, 1GB RAM memory, with softwares InVesalius,¹² Python Photogrammetry Toolbox with Graphic User Interface (PPT-GUI),¹³ MeshLab¹⁴ and Blender.¹⁵ Notebooks need to be equipped with mouse. Computer-aided FFR with open software goes through three phases: 1) obtaining 3D models; 2) positioning virtual soft tissue pegs and

anatomical modeling; and 3) rendering and finishing.

For this protocol, anthropological examination of skull and/or other bones is considered to be a responsibility of the forensic anthropology team. As their results will guide the facial reconstruction process, the selection of techniques and methodologies are subject to their discretion.

For a better use of the protocol, the user should have basic training in the softwares PPT-GUI,¹³ MeshLab¹⁴ and Blender.¹⁵ Thus, the commands and tools mentioned in this paper can be better understood and their specific operation mastered by the user. As stated above, the purpose of this paper is to demonstrate the use of the protocol developed by the authors, rather than explain in detail the operation of the software at each stage. The demonstration is expected to evidenciate that the digital resources used are sufficient for computer-aided FFR.

OBTAINING 3D MODELS:

In FFR the skull works as an anatomical framework on which the operator performs the modeling in both physical and digital environments. In cases where imaging devices are not available, the alternative is to use photogrammetry. PPT-GUI software¹³ offers the possibility of constructing 3D models from digital photos. A sequence of digital photographs of an object is processed, and

from the detection of coincidence points between them, a 3D point cloud in the shape of the object is obtained, without perspective distortions. This application is a group of softwares (Bundler, PMVS, CMVS, VLFEAT and SIFT), connected by a graphic interface that facilitates operation by non-technical computer users.

A critical step in obtaining 3D models from photogrammetry is the photographic technique. A styrofoam ring with approximately 100 milimeter diameter is used for safe positioning of the skull. A white non-reflective surface with 2 x 2 m, marked with reference points in a cross shape and a metric or volumetric scale (e.g., a cube of known proportions) is used so that the software can detect coincidences in the photos correctly.

Adequate results can be obtained with a DSLR camera equipped with macro lens and regulated to maximize the depth of field, usually by using small aperture and low shutter speed. At a focal length of 60 mm, aperture value of f/32 and definition of 3696 × 2448 pixels, initial parameters for regulating camera shutter speed manually according to the lighting of the room are provided.

With the camera mounted on a tripod (Fig. 1), photos are taken around the skull, in order to obtain pictures in two positions: with the splanchnocranium facing down and then facing up. For the first position, the skull must be placed on the styrofoam ring supported by

its frontal bone, so that the basal and posterior portions can be viewed in the photo frame. The mandible must be articulated in habitual intercuspation. For the first position, photographic register starts with the tripod at approximately 50 cm in height, or at an angle of 45 degrees. Moving around the skull, 30 photos should be taken (one photo every 12 degrees) until a full turn is complete (360 degrees). Then, one more 360 degree turn

should be done with the tripod slightly lower, around 10-15 cm, or at an angle of 35 degrees. Afterwards, the same process is carried out with the skull in the second position. It must be placed on the styrofoam ring supported by its occipital bone, so that the facial and anterior-superior portions can be viewed in the photo frame.

Fig. 1: Flowchart for obtaining a virtual mesh to be used as skull replica

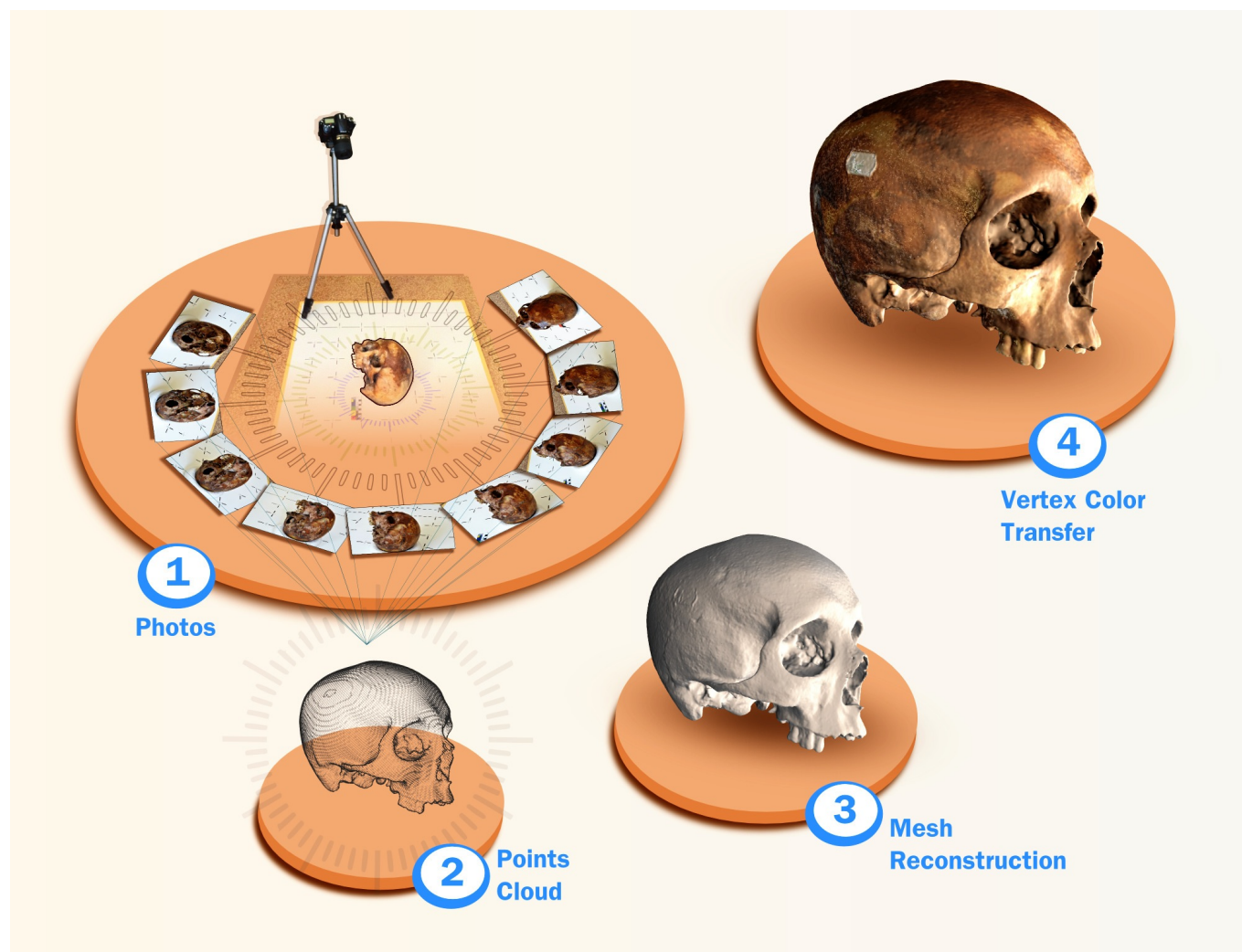


Fig. 2: Areas of transition between green and blue indicate regions with topography up to 1mm deeper than the laser scan mesh, while areas of transition between green and red represent areas up to 1mm shallower. Green areas, the largest ones, represent regions in which the differences are close to 0mm.

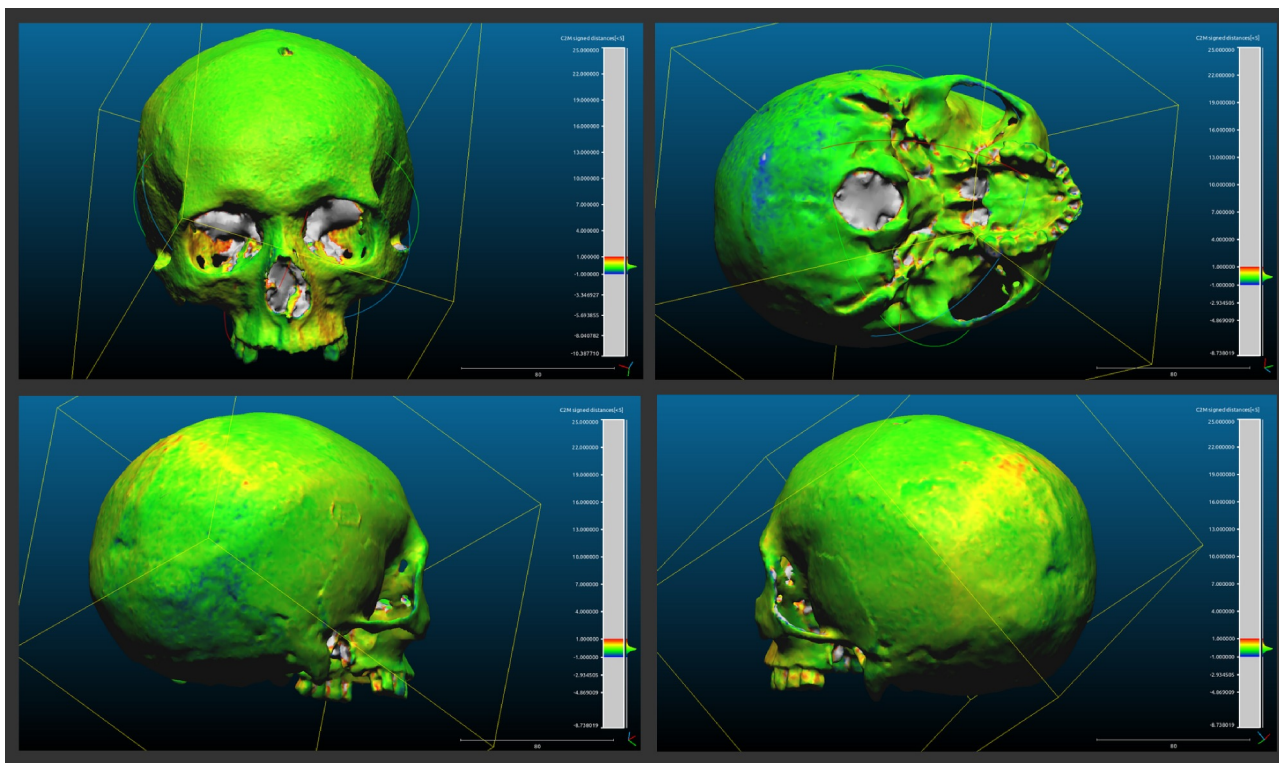


Fig. 3: Upper left and middle: *Empties* positioned on the skull and sketch of the profile; Upper right and lower row: *UVSphere* wrapping the skull and basic muscle modeling.

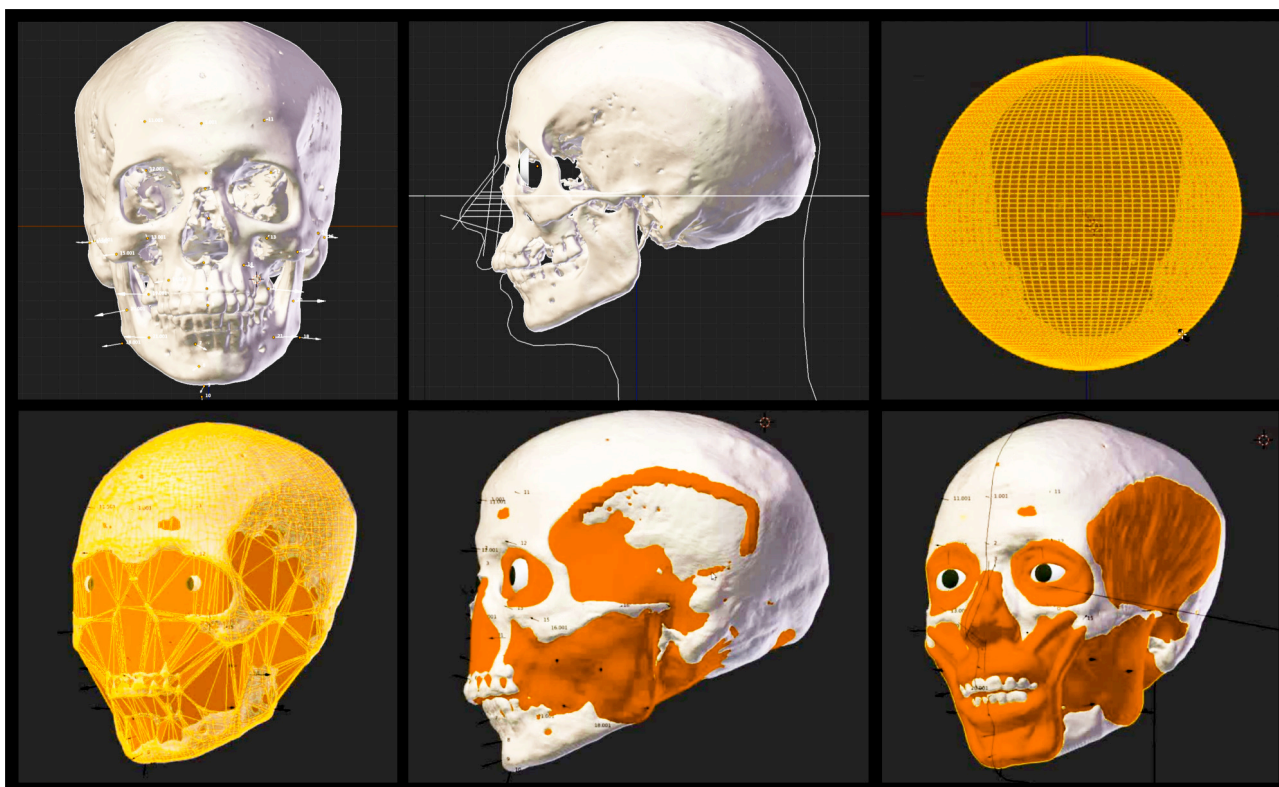


Fig. 4: Upper row: Skin sculpted on the muscle layer. Lower row: Template skin adapted to the sculpted skin. Areas of mouth and ears are not modified and are adapted manually afterwards.

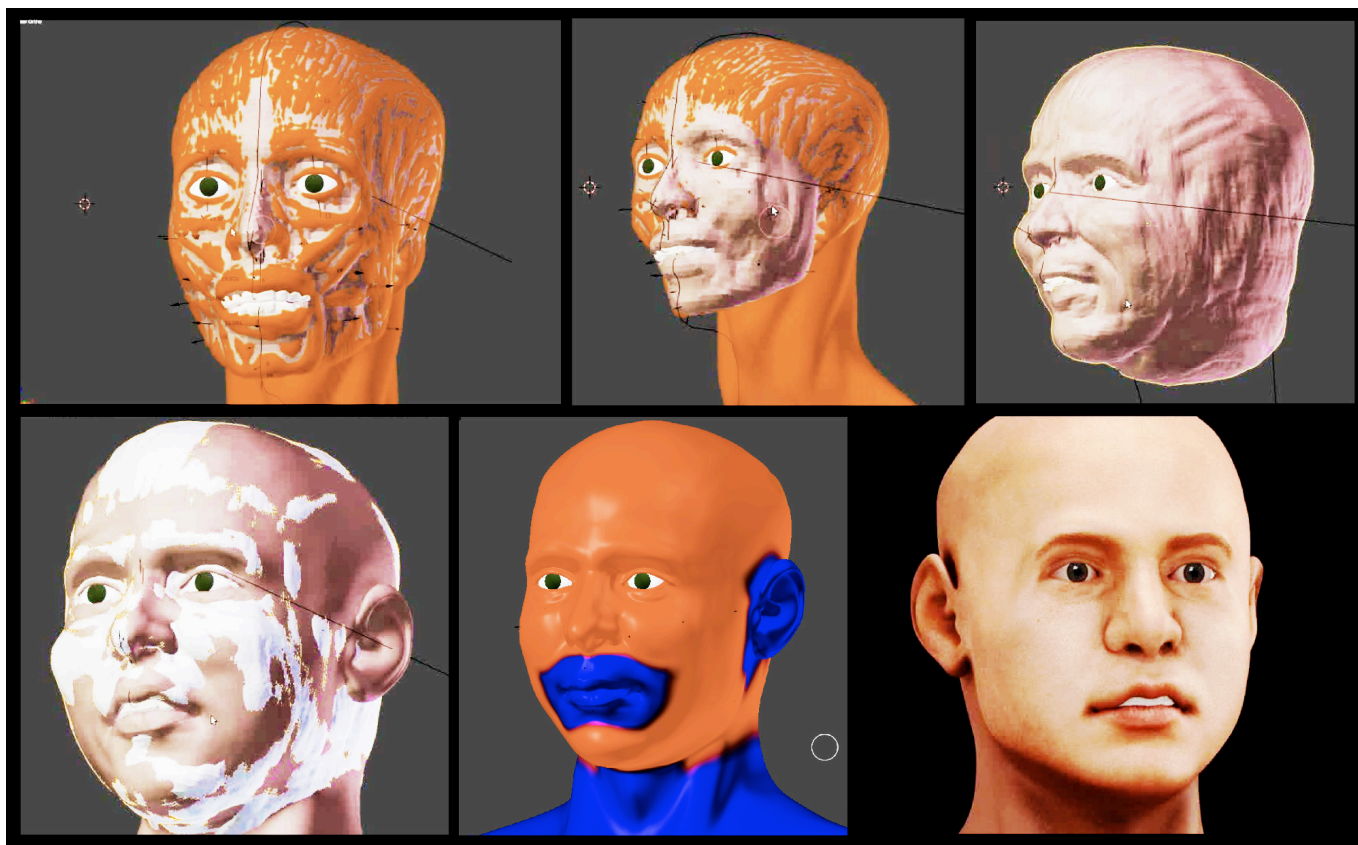
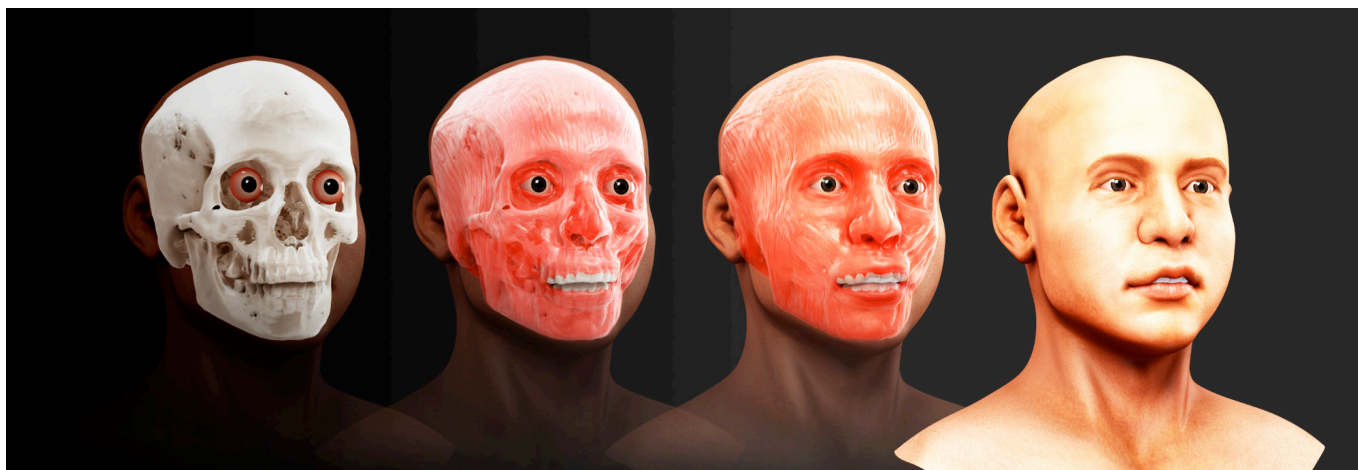


Fig. 5: Final rendered reconstruction can be displayed with transparency between layers.



The graphic user interface of PPT consists of four tabs. In the first tab the user must select the path to the directory where the .JPG pictures are stored. The photographs must be saved in two separate folders, one for

each position of the skull. Thus, two scans will be made, to obtain two distinct point clouds. To prevent errors during the operation of the software, the name of directories and image files must not contain spaces nor special

symbols. For a more precise scanning, original photo dimensions are kept in 1:1 scale, provided this do not go beyond the processing capability of the computer.

Then the user runs the processing and calculations start with the calibration of the camera. If the camera does not appear in the default database of PPT-GUI, the user should refer to its specifications and inform the width of the image sensor when the application's terminal displays the corresponding message. With the camera calibrated, the formation of a sparse point cloud is performed within PPT-GUI by Bundler software. At the end of this process, a message indicating the creation and location of a temporary directory with the sparse cloud is displayed on the terminal log.

On the third tab (run PMVS without CMVS), the address of this temporary directory is pasted and a second processing is ran. Once the calculations finish, a dense point cloud is created within PPT-GUI by the PVMS application. All generated files are stored in a directory in the temporary folder. The point cloud generated is a .PLY file, which is usual in the field of 3D scan.¹⁶ The process must be repeated for the folder with the images of the second position of the skull.

After processing, the two .PLY point clouds are imported into a new project in 3D mesh editor MeshLab.¹⁴ Using the metric/volumetric scales as reference, the two point clouds are resized until they are at a 1:1 scale,

where 1 MeshLab unit equals 1 mm. The scaling factor is calculated as follows: Scale Factor = Real Measure / Current Measure.

Real Measure is represented by measures observed on the metric/volumetric scales and should always be considered in millimeters to facilitate further steps, eventual 3D printing or importing meshes from reconstructed CT scans. Current measure is represented by the measure displayed by MeshLab once the point clouds are imported into the project. The Scale Factor must be calculated for setting MeshLab's scale transformer.

As soon as the two point clouds are resized, they must be aligned with the *Alignment* tool. Each .PLY file is displayed as a layer. The user must select these layers individually, and erase areas that are not related to the skull. Only the areas of interest of the point clouds should be left. Once the top and bottom are cleaned and aligned, the two layers are selected and merged to form a single point cloud.

To convert a point cloud to a 3D mesh, the *Poisson* algorithm is applied and a white mesh is generated. For texturing it with the colors of the scanned images, the modifier *Vertex Attribute Transfer* is applied. This paints the white mesh with the colors of the original point cloud. Preliminary tests with open software CloudCompare¹⁷ were performed to compare meshes obtained from laser scans

versus photogrammetry of a same skull. This application superimposes them and projects the differences in mesh topography as a color map. Results were satisfactory, with high similarity between the two meshes (Fig. 2).

In cases where DICOM images of the skull are available, InVesalius¹² software should be used to set a mask of the bony tissues, to be saved as a 3D surface and exported in .STL format. However, texturing this mesh with color is not possible.

POSITIONING VIRTUAL SOFT TISSUE PEGS AND ANATOMICAL MODELING:

This step is done in 3D modeling and animation open software Blender.¹⁵ The application is a tool for the user to apply whichever technique he or she prefers in a virtual open-source environment. Thus, the preference for the use of techniques that emphasize anatomical modeling over soft tissue population, or vice versa, is irrelevant to the application of this protocol. In this paper, an anatomical modeling technique⁶ was used for demonstration purposes. In possession of anthropological profile information provided by the forensic team, the operator should select the most appropriate soft tissue depth table for the skull, regarding sex, ancestry and age, if available. The .PLY file in 1:1 scale is imported into Blender and positioned on the plane of Frankfurt.

In Blender, soft tissue pegs are represented by 3D elements called *Empties*, type *Single Arrow* and length of each peg is set in the field *Size*. The length is set according to the reference soft tissue data table used. In order to the pegs to be placed at the surface of the skull, the *Snap* command is activated. For the peg to be perpendicular to the triangular face on which it is sliding (normal line) the command *Align rotation with the snapping target* is also activated (Fig. 3).

After placing all pegs, sketch lines to orientate positioning of the eyeballs, reconstruction of the nose, position of lips and eyebrows are also drawn with elements denominated *primitives*. *Primitives* are simple 3D objects that serve as a basis for modeling more complex objects. They can be obtained by an outward projection of the vertexes of the sagittal craniometric landmarks. The projection of the nose can be estimated according to the user's technical preferences.

To demonstrate how the user can apply techniques of his/her preference, in this paper the maximum nose length is estimated according to the Manchester method,¹⁸ the design of the nose profile is estimated by the technique of Lebedinskaya¹⁹ associated with Krogman's technique.²⁰ Once the limits of the nose are estimated, the resulting line is connected along with the *primitives* that sketch the shape of the face in profile (Fig. 3).

Then, the eye globes are added to the reconstruction from pre-shaped templates. These templates were done by the authors and can be downloaded from a repository at the website [http://www.ciceromoraes.com.br/?page_id=1355.21] The reconstruction itself then begins using Blender's *Sculpt Mode*. As a base object for sculpture, a mesh with using the 3D replica with the skull is imported. Using the *Add* command, a *primitive* of the type *UVSphere* with 60 or 100 subdivisions is placed around the skull. This sphere must be larger than the skull, to wrap it. Once it is set, the modifier *Shrinkwrap* is activated. The purpose of the modifier is to move each vertex of the sphere toward the skull mesh and create a 3D volume based on its shape. In other words, the sphere must involve the replica of the skull, so that it can be deformed outwards, originating the reconstruction itself (Fig. 3).

The result is an object with the approximate shape of the skull. This object has a coarse structure with few vertexes, incompatible with the precision needed for sculpture. In order to have this mesh more homogeneous and suitable for sculpting, the *Remesh* modifier is used and set at the value of four. Small divisions are created on the deformed sphere, facilitating the process of sculpture. The next step is to apply the changes made by modifiers in order to make this mesh editable in Blender's *Edit Mode*.

The reconstruction is done on *Sculpt Mode*. It allows one to edit only a previously selected mesh, and also create more subdivisions for a more precise sculpture. By using anatomical knowledge, the major facial muscles are sculpted. If the user wishes to use another technique, like the soft tissue data method,⁵ at this step the deformed sphere should be sculpted outwards to the limit determined by the soft tissue pegs. To sculpt extruding the sphere from inside out, the user selects the size and type of sculpt tool. With the desired *brush*, the user moves the mouse over the mesh pressing the left mouse button and the deformed sphere shape is modified. To create a reverse effect, i.e., to push the shape from the outside to the inside, the same must be done with the CTRL key pressed. To smooth the mesh, the SHIFT key is used instead of CTRL. With these basic commands that simulate the physical modeling, one with basic training in manual FFR can sculpt in a user friendly environment (Fig. 3).

Once the basic musculature is finished, a copy of the mesh of the muscles is made. The aim is to use the shape of this layer as the base to sculpt the skin. In order to the mesh of the skin not to be confused with the mesh of the muscles, it is set with another color.

The skin mesh is then simplified with the *Remesh* modifier. More subdivisions are added so as to facilitate the sculpture. The skin is modeled with the orientation provided by

the two-dimensional *primitive* sketch lines initially drawn and the soft tissue pegs (Fig. 4).

FINISHING AND RENDERING:

Once the skin sculpture is finished, it will hold the basic shape of the face, but without ears and neck. At this point the layer with a template face is activated. The skin of this generic face is adapted to the previously sculpted skin using the *Shrinkwrap* modifier. However, lips, ears and neck areas must not be modified, or else they will adapt poorly to the underlying skin. They must be manually adjusted later in Blender's *Edit Mode*. *Shrinkwrap's* area of exclusion is defined using *Weight Mode*. The parts painted blue have weight zero, and will not be modified. Areas painted red have weight one, implying full modification (Fig. 4).

For basic results, modeling can be finished at this point, now that the skin of the reconstruction set using *Shrinkwrap* modifier. However, if the goal is a face with more evident expression lines and features (e.g., an older adult), one can disable *Subdivision Surface* modifier, enable *Multiresolution* modifier, set a few more levels of subdivision and manually carve the face using *Sculpt Mode*.

Sculpting tools offer a wide range of features for the finishing of the skin layer to be done manually, without the aid of texture mapping for coloring. However, in case this is necessary, the meshes available in the

template come with preset textures, according to ancestry. One can still make adjustments by using Blender's *Texture* mode to recreate particularities estimated by anthropological examination, such as scars on the face.

The skin layer template has a default hair configuration. The user can edit the characteristics of hair, turning them from straight to wavy or curled. To cut, add more hair strings, stretch or comb them, then Blender's *Particle* mode must be used.

The scene of the Blender template project has already multiple cameras and light points strategically placed to emphasize the facial expression lines, without the need for editing by the user. Using the internal renderer *Cycles*, the results can be seen almost in real time by activating the rendering display in *3D View*. To generate an adequate exhibition and display of 2D images of the final reconstruction in forensic contexts, rendered images can be obtained in frontal and lateral views, along with information about the anthropological profile of the individual. For didactic purposes, images of the reconstruction images can be saved progressively (in .JPG or .PNG format), in the same position, displaying dry skull, skull plus deep structures and finished skin. More dynamic views are obtained by applying transparency to the more superficial structures (Fig. 5).

DISCUSSION

The demonstrated protocol aims to promote access to computer-aided FFR to forensic experts with basic training in the software above, working in an unit provided with a basic computer and digital camera, quite common and easy to purchase items. The possibility to obtain 3D models without complex imaging devices is appealing even in cases of comminuted material, where in the image acquisition process can be done in as many parts as necessary for further aligning and merging in MeshLab. Replicas of skulls are created in an economic and minimally invasive manner, opposite to manual techniques, in which handling and application of molding materials can damage the originals, even if carefully conducted. In cases where imaging devices are available, the first part of the protocol can be skipped directly to sculpture.

The user can work with 3D models generated from surface scanners or DICOM files generated from imaging examinations. In case of incomplete or fragmented materials, reconstitution can also be performed in virtual environment (e.g., skulls lacking portions of the calvaria, facial bones, or even the mandible, cases in which methods for estimating its size²⁰ can be applied to templates that are deformed to reach the estimated dimensions).

Three-dimensional models generated by photogrammetry are suitable for use as a framework for anatomical facial modeling.

Comparative analysis of 3D model surfaces of a same skull, generated from photogrammetry versus laser scans show that the differences between the two models is around plus or minus 1 mm (Fig. 2), which ensures the accuracy required for FFR purposes. The simplification of the 3D meshes obtained by photogrammetry does not result in significant differences from the original. The perspective is that it may be possible to view these skeletal 3D models in more simple devices such as smartphones and tablets.

Like any skull replica, however, 3D models generated by photogrammetry have some limitations that makes anthropological examinations not advisable, such as the impossibility to weigh skulls, view some anatomical details (such as suture closing stages), inability to touch and assess their surface or to collect material for laboratory testing. Therefore anthropological examinations should be conducted on the *in situ* material, following the methodology preferred by the forensic team.

Providing templates of eyes and skin (individualized for different ancestries) is a way to make the experience with Blender more dynamic, saving time of the user, who will have less work than if each structure would be modelled from scratch, or each camera or light spots placed individually. Main points to use this protocol as part of a forensic routine is that one becomes familiar with the software

and tools used, besides having adequate knowledge of the anatomy of the head and neck. A previous training in manual FFR is recommended. With these issues addressed, it is possible to combine and transpose techniques intended for manual FFR, into a open access virtual environment.

A differential resource is the application of the *Shrinkwrap* modifier to adapt to the skin of the template to the skin that was sculpted manually. Thus, the shape of the face provided given by the muscles and other structures is maintained and evidenced in the final sculpture. Even though the modeling can be considered complete at this stage, if the user or the anthropological team wishes to put more details on the reconstruction, it is still possible to use manual sculpting tools in Blender and add more individuality and expression in the final reconstruction. It is also possible to correct details in the sculpture after completion if the anthropological team recommend so.

The finalized reconstruction can be viewed in several ways. It can be displayed in front, lateral and perspective views. The lighting of the scene can be adjusted, if necessary. Furthermore, a progressive display with transparency of the layers of muscle and skin over the skull helps the observer to objectively assess the sculpture in relation to its anatomical indicators of position and size.

Storage and sharing of reconstructions is also facilitated by the file extensions used, which are compatible with open source and most of commercial softwares. With the increasing technological advances, one can share the reconstructions via Internet and use a relatively small (virtual and physical) space for storage.

The time taken to complete a reconstruction is also important for assessing the protocol. Photographic register takes approximately 1 hour. The scanning of high resolution photographs in PPT-GUI is the most time consuming process, which can take up to 8 hours. However, the computer is kept available for use and one can continue working normally or perform other reconstructions.

After the two point clouds are generated, the process for obtaining a 3D mesh is relatively fast, up to about one hour. The sculpture and finishing, when done by trained user can take around 5 hours. Thus, it is expected that a FFR, including photogrammetry scanning, can be performed in less than 24 hours. The applicability of the protocol to forensic contexts is an aim for future research.

Exclusive use of open source software also contributes to the use of the protocol in different locations, as well as enables broad access to a technique that can be improved with experience from different users. The independence of licenses and upgrades is a

factor that significantly lowers the cost for using the protocol and contributes to its dissemination. In addition, the open source environment allows software users to suggest improvements in computer programming in order to decrease the occurrence of bugs and errors, increasing the security of virtual work environment.

In this paper, it was demonstrated a protocol for performing computer-aided FFR using exclusively open source software. Further research is recommended to assess its efficiency. Blind tests conducted by independent operators should be performed to reconstruct skulls with ante-mortem data available. Open access to the tools used in this protocol and its independence of complex imaging devices is an advantage to its application in forensic and research contexts.

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