3D Reconstruction of Patient-Specific Dental Bone Grafts by Application of Reverse Engineering Modeling

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Abstract*— Three-dimensional (3D) reconstruction of free-form physical shapes, which are present in patient-specific dental bone grafts, can be produced by application of reverse engineering modeling. After the loss of the tooth, the effect of bone resorption or loss of bone density caused by periodontal disease or other disease or trauma can occur. Effective implantation of dental implants however requires a firm and strong bone base. This paper presents the methodology of 3D reconstruction of patient-specific dental bone grafts using reverse engineering modeling. Initially, cone-beam computer tomography (CBCT) scans of the jawbone 3D model reconstruction was used. After that, by application of additive manufacturing using binder 3D printing technologies, a physical model was made. Oral surgeon is then manually adding material similar to clay which formed the desired shape of the bone graft at the predefined area. On the next step, 3D digitization by close-range photogrammetry (CRP) was used, to get the outer geometry of the bone graft. As a result, with the use of Boolean subtraction of jawbone 3D model and CRP 3D model with designed bone graft, 3D model of completed bone graft was reconstructed.

I. Introduction

Teeth are organs that cannot be regenerated. Within the first year of tooth loss, study shows that up to 25% of bone density can be lost in that particular area [1,2]. Despite this information, placement of dental implants requires certain conditions regarding their placement on the human jawbone, and those are volume and density of the surrounding bone tissue [3]. Dental implants look and function like natural teeth, but require sufficient jawbone density to anchor the implant. The bone augmentation process enables patients the opportunity to obtain the adequate supporting bone structure required for implantation. Implants are used to reconstruct bone damage or defects caused by trauma or disease. Traditionally, implants have been manually bent and shaped, either preoperatively or intraoperatively, with the help of anatomic solid models [4]. Due to the development of 3D technologies, production of patient-specific bone grafts has dramatically expanded [5,6]. With recent additive-manufacturing, that is, 3D-printing, custom-made prosthesis can be created by laser-melting metal powders layer-by-layer [7]. Computer-aided bone augmentation today plays a vital role as it presents a new field of multidisciplinary approach where the need for cooperation between engineers and surgeons is emphasized. If the bone is not suitable for implantation due to bone resorption, it cannot support the implant, thus there is a high possibility that the implant surgery will fail. This is very important precondition since the bone loss presents a crucial factor for implant longevity [8].

II. Related Work

The importance of shape and size of bone graft is also very significant. According to Seibert alveolar crestal defects can be divided into three classes [9]. In class I ridge defects there is horizontal bone loss with adequate height, which leads to insufficient bone volume for successful placement of regular diameter implants. Class II refers to vertical bone loss with adequate width, which leads to insufficient bone volume for proper positioning of regular length implants in the correct prosthetic corono-apical position. The most complex defects are stored in class III where is a vertical and horizontal bone loss that prevents placement of successful implants in all spatial dimensions [10]. During the operational procedure, only minimal corrections on the manufactured bone graft can be made, however, the purpose of the digitally designed and manufactured patient-specific bone grafts is that the designed and manufactured graft fits perfectly on its intended place. Namely, there are several techniques to differentiate and regenerate the alveolar bone defect. These include, but are not limited to, the use of barrier membranes for guided bone regeneration, particulate grafting materials, block grafting techniques, distraction osteogenesis, ridge split techniques, the current applications of growth factors to accelerate the rate of bone formation, and enhance the quality of bone formed especially in severe defects [11].

Designing and manufacturing patient-specific bone implants before surgery improves accuracy, and also reduces surgery time, hence improving the quality of surgery, but also the quality of life of the patient [4]. Fabrizia Luongo et al [12] presented a computer-assisted design/computer assisted manufacturing (CAD/CAM) technique for the design, fabrication, and clinical application of custom-made synthetic scaffolds, for alveolar ridge augmentation. Also using CAD/CAM techniques for preparing hydroxyapatite scaffolds may increase graft stability and reduce surgical operating time [13]. An approach that is based on application of modern computer-aided systems and methods which enable minimization of the errors during modeling and placement stages was proposed by [14]. They confirm that the grafts base surface, which is in direct contact with the bone of the patient, plays an essential role in the success of the surgical procedure and patient recovery.

III. Materials and Methods

Reverse engineering modeling (REM) presents a process of 3D model reconstruction based on 3D digitization of a physical object [15]. The proposed methodology of 3D reconstruction of dental bone grafts is shown on Fig 1.

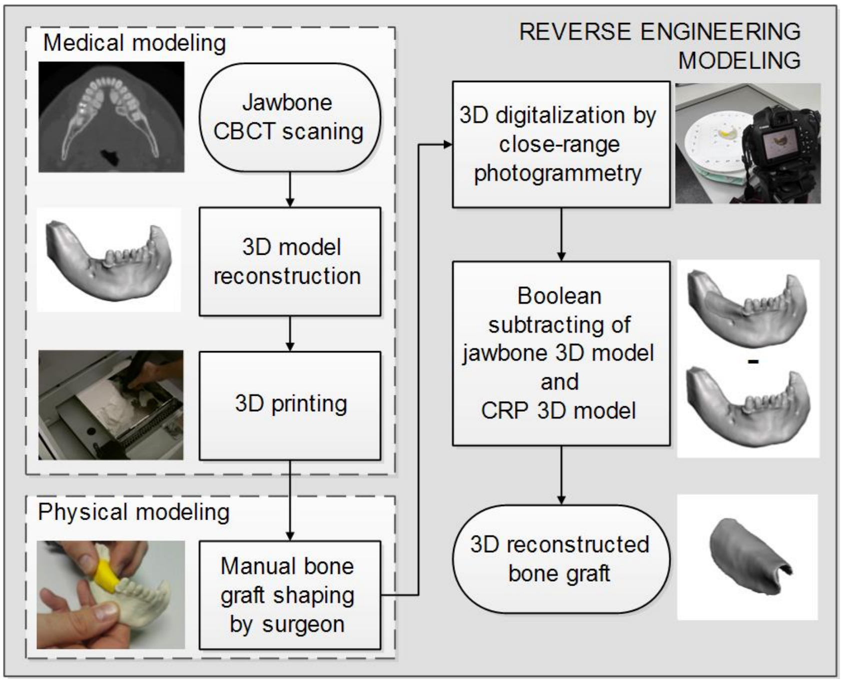


Figure 1. The proposed methodology of 3D reconstruction of dental bone grafts

This straight forward oriented methodology doesn't have loop or iterator elements. Within this methodology two sub-phases can be emphasized:

- medical modeling and
- physical modeling.

The term "Medical modeling" is used to describe the creation of highly accurate physical models of human anatomy directly from medical scan data. This process involves capturing human anatomy data, processing the data to isolate individual tissues or organs, optimizing the data for the manufacturing technology to be used, and finally building the model using additive manufacturing technologies [16].

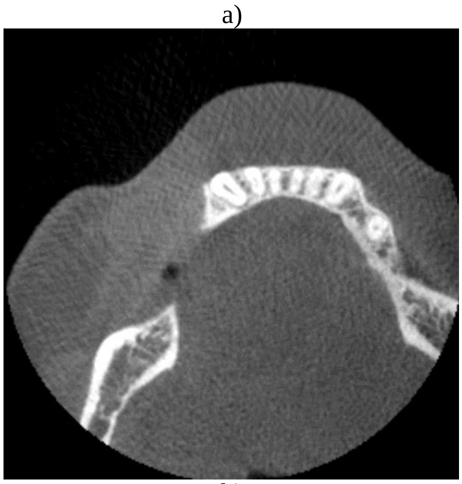
Physical modeling was addressed to manually design a missing bone structure at the particular area on the 3D printed model by the surgeon. This stage is of utmost importance for 3D reconstruction.

3D digitization by close-range photogrammetry (CRP) was the next step. As a result, a 3D model (further referred as CRP 3D model) with a defined outer geometry of bone graft was obtained. By overlapping CRP and jawbone 3D model, the Boolean subtracting conditions were created. Finally, when subtraction was done, 3D models of the patient-specific bone graft was completely reconstructed.

A. *Medical modeling*

The first step includes CBCT jawbone scanning were set of DICOM images is acquired containing total of 124 DICOM images at 250x250 image resolution and with 0.4 mm pixel size (Fig. 2a). From there DICOM dataset was imported in 3D DOCTOR v4.0 software, specifically used for medical image processing. Within this software, segmentation is performed in order to reconstruct a surface 3D model of the lower jaw (Fig. 2b). Selection of optimal parameters used for segmentation was crucial since slight offset of parameters to higher or lower values could result in over- or under-segmentation. For this particular case, the min. and max. segmentation parameters that are used were 1234 and 4096, respectively.

a)



b)

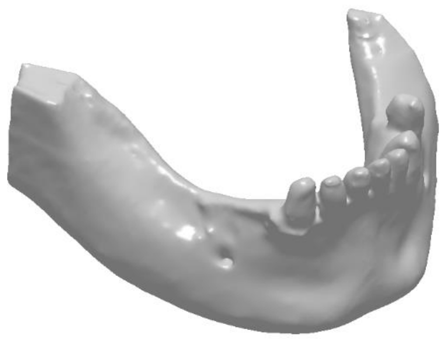


Figure 2. Showing a) single DICOM images and b) 3D model of the reconstructed jawbone

The next step included 3D printing stage where Monochrome 3D printer Z310 plus (3D systems - former Z corporation) was used. Printed physical model of the jawbone is shown on Fig. 3

Figure 3. 3D printed jawbone

B. Phsical modeling

3D printed jawbone in scale 1:1 was used as an anatomy model on which oral surgeon or dentist manually by hands and other clay modeling tools (knifes and spatulas) created a missing bone graft (Fig. 4). Two-component material used for modeling is similar to clay and can stay easily deformable for around 15 min. After that time the material is transferred to a solid state and can separated from 3D printed model.

Figure 4. Manually model bone graft

Within this approach surgeon (along with dentist) have full control in designing a shape an size of a further dental bone graft. Another big advantage is that during physical modeling stage surgeon can plan surgery, and also can easily spot problematic areas, check the thickness of bone graft and make corrections.

C. 3D Digitization by Close-Range Photogrammetry

One of popular and widely used 3D digitization method is CRP. This image-based method uses two-dimensional (2D) images of an object captured from different viewpoints. After image processing, simultaneously 3D points and camera positions were estimated. In this case, 2D images were captured with digital single-lens reflex (DSLR) camera Canon 1200d with adjustable 18-55mm lens posted on a tripod. This semi-pro camera have advanced photo system type-C (APS-C) sensor with crop factor 1.6. Photos acquisition setup is shown on Fig. 5. 3D printed jawbone model with manually modeled bone graft was placed in the center on a turntable while reference markers were positioned and glued on the top side of the turntable plate, to establish a proper object scale. The camera was adjusted according to object size and light condition, as well as distance to an object, obtaining an appropriate depth of field (DOF). Photos acquisition strategy (number of photos), photo resolution, as well as visual texture of an object are direct linked to final 3D reconstruction quality. Therefore photos were captured in three levels forming ring around an object.

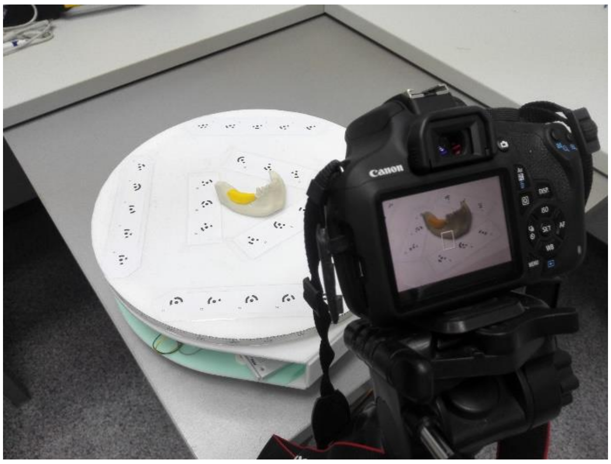


Figure 5. CRP photos acquisition setup

The first ring had 18 photos equally distributed in a 360 degree circle, while optical and turntable axes have approximately 90 degrees between each other. In the second ring 12 photos were captured, while the camera optic axis and turntable axis have 60 degrees to each other. The angle in the final ring between the optical axis and the turntable axis was about 30 degrees. In the final ring, only eight photos were captured. This spherical strategy enables good photo overlap and fast image processing. Images were processed with Agisoft Metashape Profesional 1.5 software [17]. This software in the first stage generates a sparse point cloud and estimate camera positions. In the second stage is applied the dense matching algorithm and as a result, was obtained dense point cloud. After that, on basis of a dense point cloud, a polygonal mesh 3D model was created. The total error of the CRP 3D model can be expressed over (1):

$$CRP\ model_{\ err} = 3D\ print_{err} + CRP_{err} \qquad (1)$$

where:

- $CRP\ model_{\ err}$ is total error of obtained CRP 3D model,
- $3D\ print_{err}$ is error generated during 3D printing process,
- CRP_{err} is error generated during CRP 3D digitization.

In our previous work we investigated and came to a conclusion that accuracy of obtained CRP 3D model was in range ±0.4mm [18].

D. *Boolean subtracting and dental bone graft 3D reconstruction*

CBCT and CRP 3D model contain information about sculpted dental bone graft. Further postprocessing by Autodesk Meshmixer software was performed [19]. Overleaping these two 3D models using the fest-fit method and applying Boolean subtracting, all differences will be extracted. The obtained result is dental bone graft with bottom surface kept from CBCT 3D model and top surface taken from CRP 3D model (Figure 6.). Some minor postprocessing was also required at the connection point of top and bottom surface in order to create a watertight 3D model.

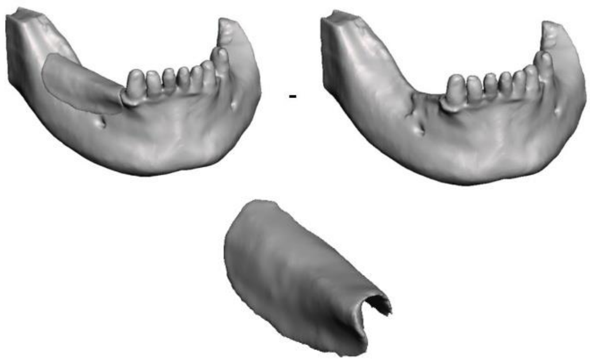


Figure 6. Boolean subtracting of CBCT and CRP 3D model

IV. CONCLUCONS

Every person presents a special individual in its own way, shape, and form. With that in mind, modern medicine is striving towards patient-friendly directions and requires that more attention is dedicated to patient-specific implants, bone grafts, medical devices etc. Today's modern technologies and interdisciplinary knowledge enable the development and application of patient-specific approach that significantly increase the lifespan and ease of life of the patients. 3D reconstruction of patient-specific dental bone grafts by application of reverse engineering modeling approach presented in this paper has several benefits, but the key one is the ability of physical modeling of adequate bone graft shape by the surgeons and dentists.

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