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BONES RECONSTRUCTION FROM TOMOGRAPHIC IMAGES USING NUMERICAL AND COMPUTATIONAL METHODS

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Abstract. Tissue Engineering is a highly multidisciplinary science in full expansion, which results from the combination of cell culture and the construction of scaffolds. Basically, it starts from the computer modeling of the defect or missing volume in order to obtain a personalized replacement of the defective or absent biological tissue. The obtained “mold”, coated and/or filled with different biomaterials arranged in special microarchitectures, becomes in a scaffold which is contacted with biological material to start the tissue regenerating process. The main object of this work is to establish a protocol for the numerical and computational modeling of bones and their defects from processing images obtained by computed tomography. The obtained models can be materialized using 3D printers. In addition, they may be used in the simulation of the bones mechanical response by using the Finite Element Method.

1 INTRODUCTION

In the framework of the Tissue Engineering (TE) the replacement of defective or absent biological tissue begins by the computational modeling of the defect or missing volume with the aim to obtain a "mold”. See a.o. the works by Sun et al (2004); Sun et al (2005) and Landers et al (2002).

These molds are coated and/or filled by different biomaterials arranged in particular micro-architectures, resulting in "scaffolds". These are placed in contact with biological material to begin the process of tissue regeneration, see a.o. Damaraju and Duncan (2014).

The computer-aided design (CAD) has been traditionally used to assist in the design, model representation, analysis and manufacturing of many engineering areas but the present advances in technology and biomedicine have developed new CAD applications in Biomedical Engineering, particularly in the field of TE. The CAD modeling of biological pieces to be regenerated provides essential information for the development of scaffolds. Examples of these applications can be found in Sun et al (2005) and Pereira and Bártolo (2014).

In this work a novel method to numerically process computed tomography series corresponding to defective bones is proposed with the aim to obtain a three-dimensional geometry in terms of triangular surface mesh.

In the first sections concepts of TE, digital image processing and 3D computer modeling are includes.

In second place, a computed tomography series corresponding to defective dog humerus is numerically processed using the proposed method.

Three-dimensional triangular surface mesh is shown and compared with original photographic images to demonstrate the capabilities of the developed procedure.

2 TISSUE ENGINEERING

Tissue Engineering (TE) is defined as the application of principles and methods of engineering and biological sciences for understanding the complex relationships between structure and function of tissues, enabling the development of substitutes to restore, improve or maintain the function of these tissues. (Lanza et al, 2007)

This discipline currently offers innovative strategies for implementing biological substitutes in different medical specialties. Major scientific advances in the field of biomaterials, stem cells, growth and differentiation factors and tissue microenvironment knowledge have generated the possibility of "making" tissue in the laboratory by combining extracellular matrices "scaffolds", cells, and biologically active molecules. This affirms Masino (2012).

The development of tissue substitutes requires two basic "ingredients": cells and biomaterials, understanding that these pillars are closely interrelated through complex cell-cell and cell-scaffolds interactions. Moreover the actions of added soluble factors, of both local and systemic origin, are involved in these interactions.

Useful cells may come from different sources: established cell lines (genetically transformed cells), stem cells (undifferentiated cells with high capacity for division in culture and that can result in different types of specialized cells) or primary cells (obtained from enzymatic digestion or mechanical of organ or tissue). They may be classified according to the individual that they originate, as autologous cells (cells from the same patient in which they are implanted), homologous or allogeneic cells (cells from another individual of the same species), or heterologous cells or xenogeneic (cells from an individual of another species).

On the other hand, the choice of biomaterials where cells are often implemented in an artificial structure capable of supporting the formation of tissue becomes very significant. These structures called scaffolds are critical, both in vitro and in vivo behavior. They must be able to summarize the existing environment in vivo and allow cells to influence this microenvironment.

Conceptually, the utilized materials should allow one or more of the following functions:

- cell adhesion and migration
- diffusion of vital nutrients and products expressed by cells
- vascularization
- support of mechanical and biological functions in particular situations

At the present, biomaterials are in its third generation. Materials designed in this generation seek to interact with tissue of specific manner by stimulation at cellular and molecular level combining bioabsorbability and bioactivity properties, closer to the ideal biomaterial. TE is one of the science areas with the most potential in regenerative medicine; see Mano et al (2007).

Novel materials processing techniques for the design and construction of structures and devices on the nanoscale were developed; see a. o. Chronakis (2005). Thus there are numerous production process of biomaterial fibers, such as hauling, phase separation, synthesis by copying, self-assembly, electrospinning, and 3D printing, among others.

2.1 Bone tissue engineering (BTE)

Traditionally bone tissue injuries caused by trauma, osteonecrosis and tumors have been treated by means of the implantation of autologous, allogeneic or xenogeneic grafts; and, in other cases, implementing substitutes.

Regarding main problems such as the shortage of donors, disease transmission, morbidity extraction site and inability of materials to remodel and respond to physiological conditions, the BTE appears as an option to restore, maintain and/or improve function by creating biological substitutes.

As previously explained, in TE three fundamental elements converge: scaffolds, cells, and biologically active molecules in an appropriate physicochemical environment that allows the regeneration of tissue or organ. Whereas for bone tissue scaffolds, according by Estrada et al (2006), the main characteristics are:

- Biocompatibility
- Porosity
- Pore size
- Surface properties
- Osteoinductivity
- Mechanical properties
- Biodegradability
- Radiolucent material

The main characteristic of bone defects results its dimension, with significant influence on the repair. Critical defects are those for which the body cannot effectively promote the repair of bone tissue. Contrarily, non-critical are those for which the body is able to promote comprehensive bone repair without help methods to repair.

3 DIGITAL IMAGES

Regarding an image as a two dimensional function in terms of the pair of coordinates (x,y) which define a single point in the matrix called pixel, the value of the function at one point f(x,y) gives the value of the intensity light at that point. According to the kind of image, a value or a vector define the color of that pixel. Arrays are used to represent an image in computer memory. The number of pixels MxN, defines the resolution of the image. Each pixel is quantified by a number of bits p which indicates the image quality.

3.1 Image processing

The digital image processing consists in a set of techniques applied to digital images in order to improve their quality or facilitate the search of information. Amplification contrast, binarization, filtering and principally segmentation techniques are applied to tomographic images in this work. The enforcement was made by a script of MATLAB (software created by MathWorks®, 2011).

Previously, a pre-processing of .DICOM format files by K-PACS-Lite (license free) has been carried out with the aim to obtain image file formats.

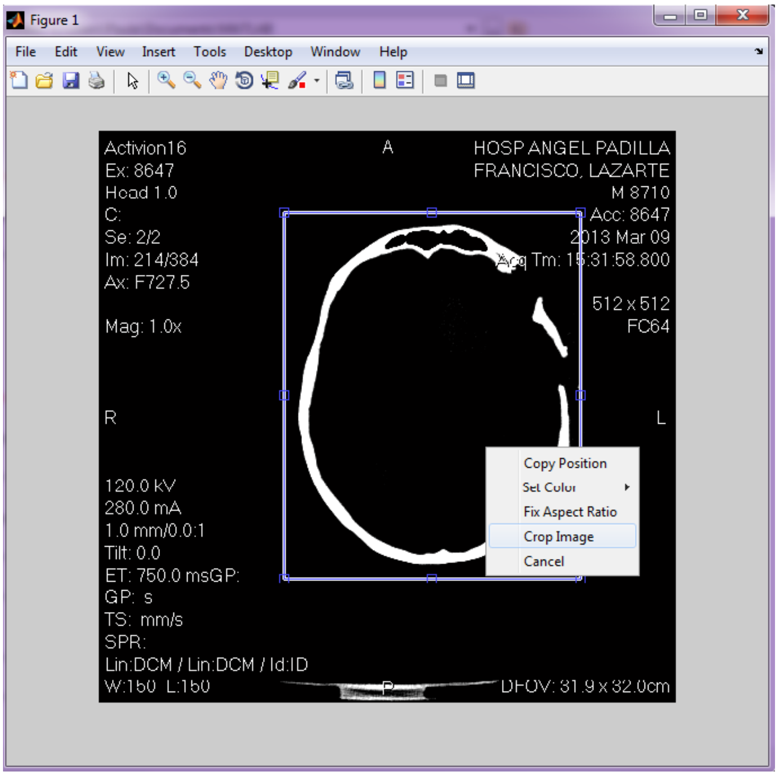

Figure 1: Crop box

Then, images are exported to MATLAB in .TIFF format, suitable for image processing. The bone part to rebuild is selected by a crop box (see Figure 1). The script picks out the parts of the piece by detecting connectivity and applying segmentation by edge detection. There are two possible cases: hollow and solid morphology. Because of this distinction, different types of processing are carried out as can be seen in Figures 2 and 3.

Finally, the contour of each element is obtained. This will be the edge of the resulting three-dimensional model.

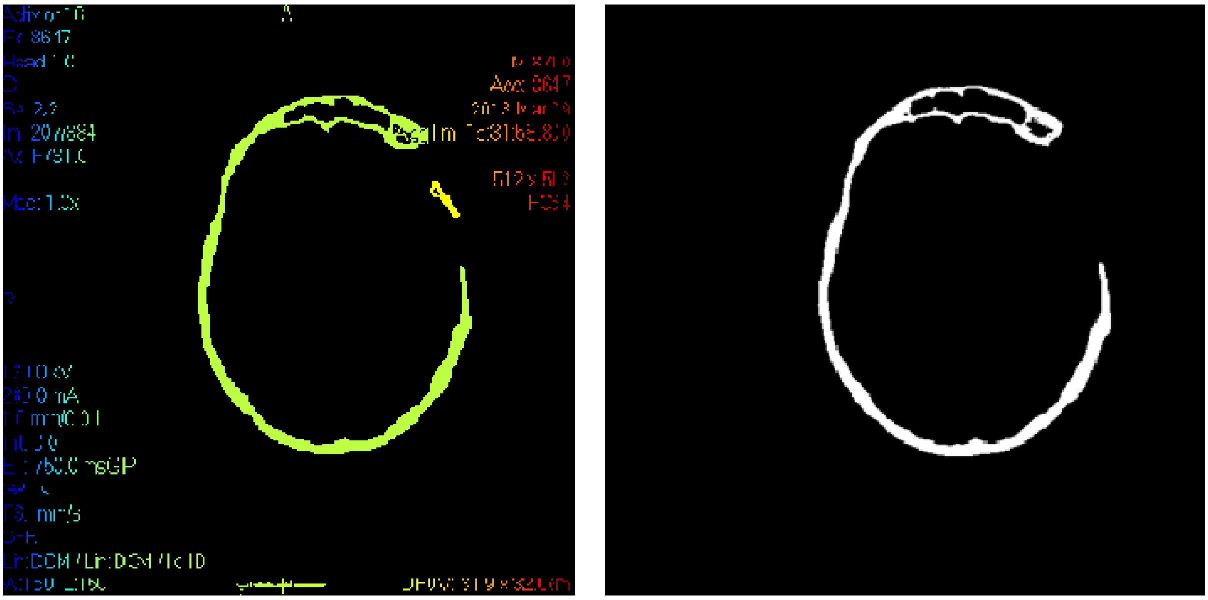

Figure 2: Processing of hollow morphology

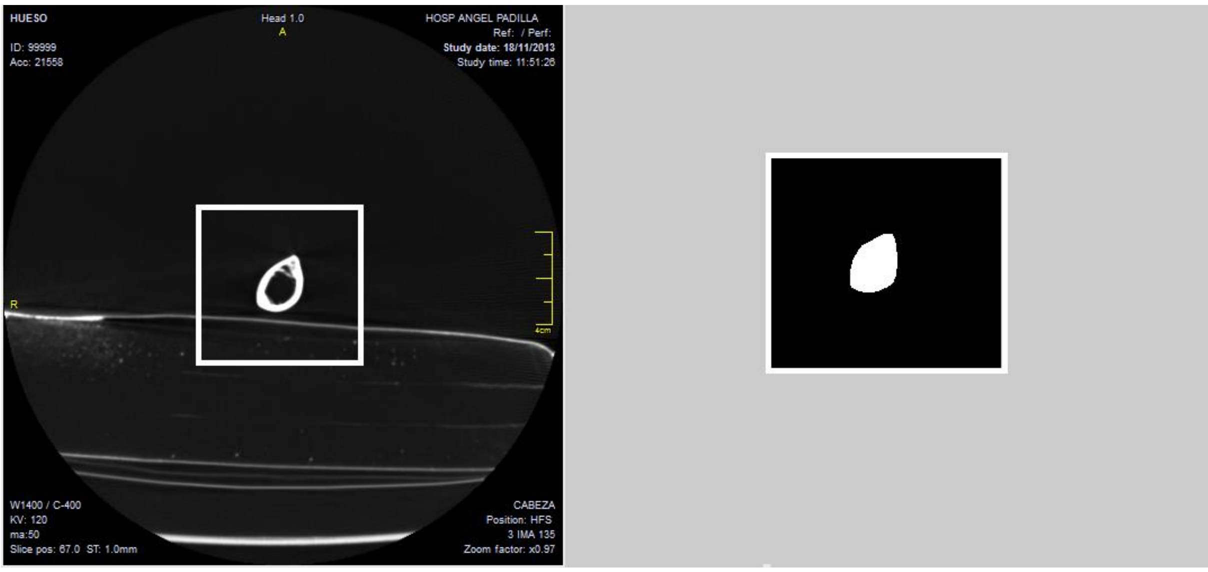

Figure 3: Processing of solid morphology

4 THREE-DIMENSIONAL MODELING

Three-dimensional reconstruction is the process whereby real objects are reproduced in the memory of a computer, keeping your physical characteristics (size, volume and shape). The main object is to achieve an algorithm to connect a set of representative points as surface elements: triangles, squares or simple polygons.

4.1 Point Cloud

A point cloud is a set of vertices in a three-dimensional coordinate system on the external surface of an object. To create the point cloud of one piece, images previously processed are inspected pixel by pixel. Position coordinates of each pixel belonging to the bone piece (white pixel) are saved.

Each recorded pixel corresponding to a point on the edge of the bone will be a point in the point cloud and then, a node in the 3D mesh. A view of the point cloud resulting from the process applied to a dog humerus is shown in Figures 4 and 5.

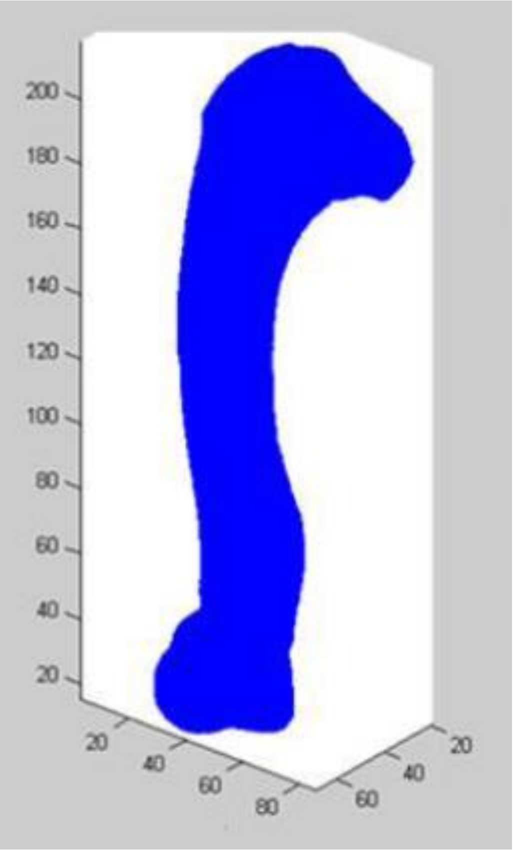

Figure 4: Point cloud of dog humerus

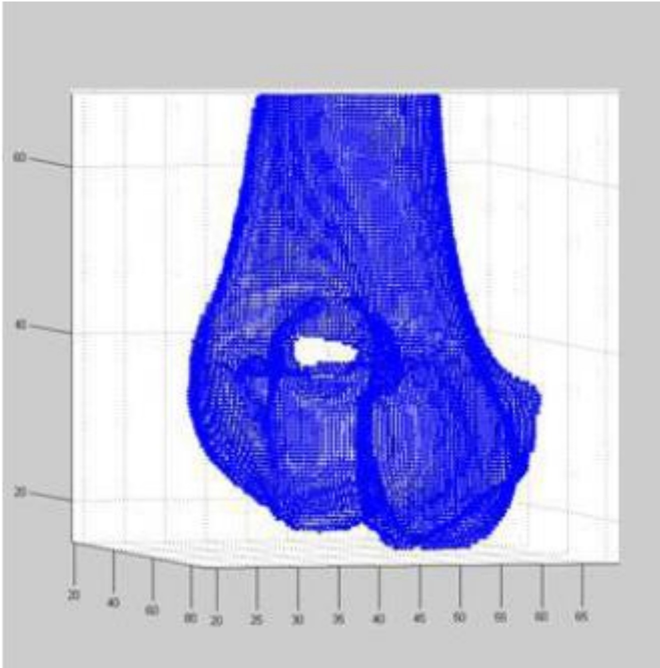

Figure 5: Larger image of point cloud

4.2 Surface reconstruction

The main object of the surface reconstruction can be described as follows. Given a set of points near and/or on an unknown surface S, the approximate surface model S ' is created. Figure 6 shows an example that explains this definition.

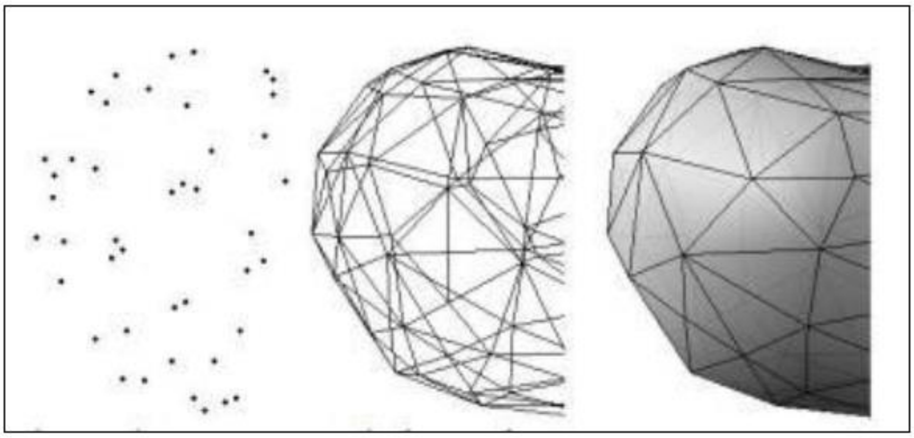

Figure 6: Surface reconstruction

A consistent conversion from point cloud to polygonal surface must be performed, based on the following four steps:

1. Pre-Processing: Erroneous data are eliminated or a sampling is performed to reduce the computation time. In case of bone pieces images, it is advisable do not reduce the number of points to avoid compromising the resolution of the final model.
2. Determination of the global topology of objects surface: This operation typically requires a comprehensive global order with the consideration of possible constraints,

mainly to preserve the special characteristics (such as sides). In case of tomographic images, the points have a global order given by the tomographic slices.

3. Generation of the polygonal surface: Triangular or square meshes are created satisfying some requirements, such as limit size of mesh elements. In case of tomographic slices, it is recommended that the limit size of mesh elements is not much greater than the tomography spacing.
4. Post-Processing: When three-dimensional models are created, edit operations to refine and perfect the polygonal surface are usually applied.

The generation of elements from a point cloud is a fundamental part of reconstruction programs. The triangulation converts a given set of points in a consistent polygonal model, named mesh. This operation partitions the input data and usually generates vertices, edges and faces.

The Ganapathy triangulation method consists in the construction of convex closures from contours points. In first place, a contour as a set of points that share one of the three coordinates in space must be defined, see Figure 7. In the case of tomography, point cloud is sorted by the z axis.

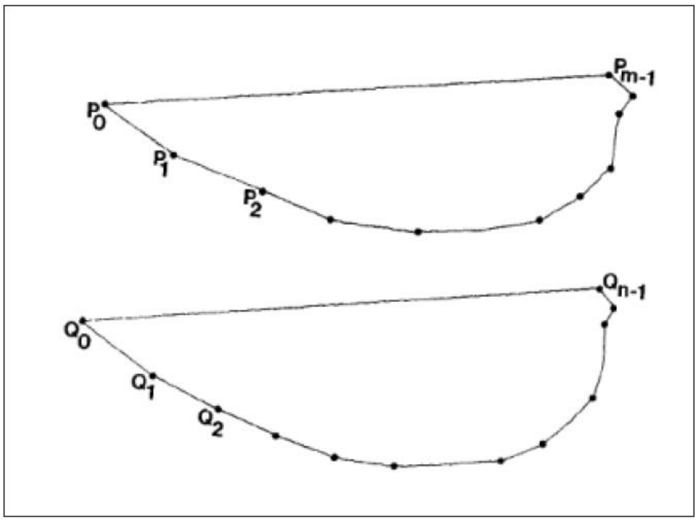

Figure 7: Examples of contours

With the contours sorted, the Ganapathy method proposes connect two consecutive closures with a row of triangles to build the object in three dimensions, as shown in Figure 8.

In the developed subroutine, segments connecting two nearby points on z planes are first generated. These lines will be one of the sides of each triangle of the surface, the algorithm completes the third point of a triangle in the plane immediately superior. Connectivity of segments and triangles are saved in matrix form.

Finally, using matrices information, bone piece surfaces can be plotted and printed in three dimensions.

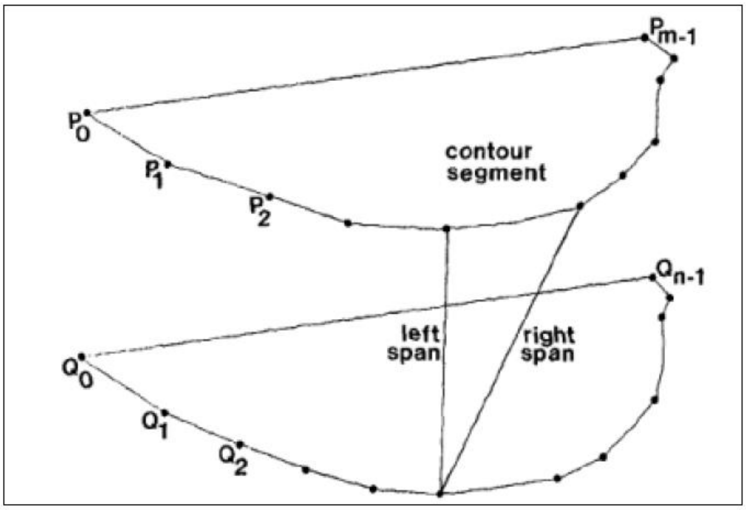

Figure 8: Example of closures

4.3 Numerical analysis

In order to evaluate the capabilities of the proposed numerical method to reproduce defective bones and demonstrate the resolution achieved, different sizes and shapes of defects have been made with a dental lathe in a dog humerus.

In Figure 9 the resulting three-dimensional mesh of the workpiece with a rectangular defect is compared with actual pictures.

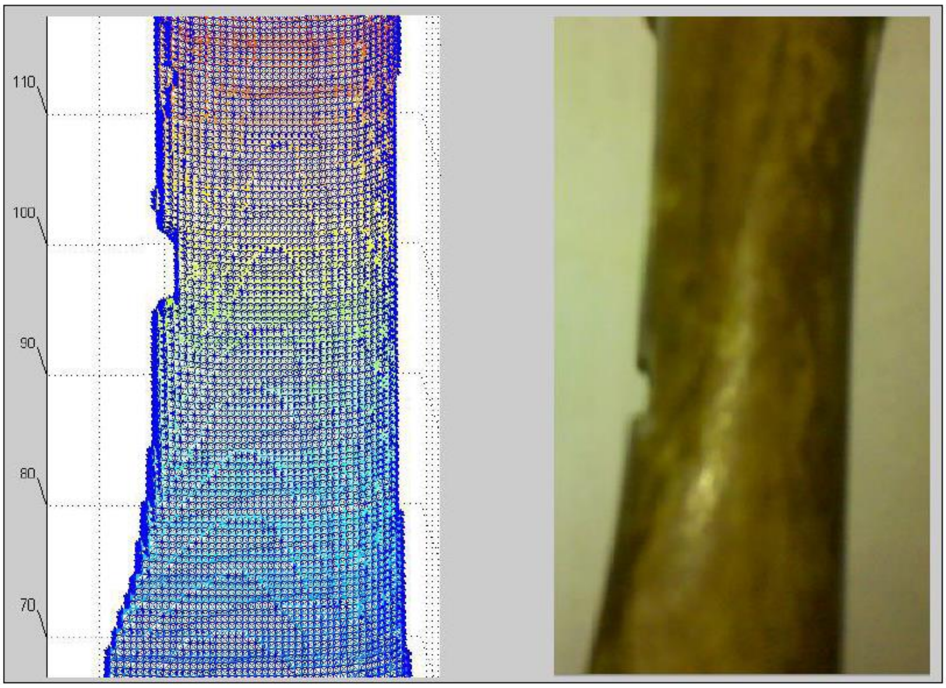

Figure 9: Three-dimensional resulting mesh of a defective bone in comparison with the real part. [Scale in mm]

5 CONCLUSIONS

An optimal platform for computational modeling of defective bone structures from tomographic images has been obtained. It represents a useful tool for personalized replacement of defective bone tissue and for the subsequent development of scaffolds with correct morphology.

The developed method has demonstrated that tomographic images provide the necessary information for generating three-dimensional numerical models of bone structures.

From a single set of tomographic images a three-dimensional bone reconstruction that efficiently approximates the real surface has been obtained, without the need of additional operations (such as manual editing). The obtained files can be easily converted to .STL format to achieve three-dimensional printing.

A general protocol suitable to be applied to bones of any geometry has been generated. The obtained three-dimensional model reproduces bone defects in the order of millimeters, with certain restrictions and possible improvements.

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