Reconstruction of the missing part in the human mandible

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***Abstract*— The reconstruction of the missing part of the human mandible is a significant challenge in orthodontics and surgery, especially when the shape of the missing part is not known prior to operation. Creation of geometrical model of specific patient is being become an expected treatment. The one of the greatest challenges within this procedure is related to efficient designing the geometry and anatomy of a particular human bone. In this paper, method of the reconstruction of missing part the human mandible is presented. The reconstruction was performed by using the parametric model based on Method of Anatomical Features (MAF). The 3D parametric model is defined as point cloud, where coordinates of points are described by parametric functions, whose components are morphometric parameters (dimensions which are read on medical images). The main benefit of this model is ability to adapt model to the specific patient, by applying patient specific values of morphometric parameters. The resulted model may be used for preoperative planning and for surgical simulation. The main idea of the research was to present patient-specific reconstruction method which will provide the surgeon more control over the treatment, decreases the risk of surgical errors and reduces the operating time.**

I. Introduction

Computer-assisted surgery (CAS) defines a set of methods that use computer technology for planning, performing and/or assessing surgery. The important components which influence on the outcome of CAS procedures are accurate geometrical models of the human bones. Geometrical and anatomical accurate geometrical models can improve preoperative and postoperative procedures. Benefits of geometrical models' application can be creation of personalized bone implants, scaffolds and fixations. Mandibular reconstruction using computer-assisted surgery involves planning, modeling, surgical simulation. It was developed to improve conventional treatment methods [1]. The reconstruction of large continuity defects of the mandible is a challenging task, especially when the shape of the missing part is not known prior to operation. For that reason, application of geometrical model of specific patient is being become a regularly expected treatment.

Several patient-specific reconstruction methods of the human mandible based on medical images are described in the literature [2-7]. Most of these methods base on a training set of bones from which a statistical model is constructed. A bone samples used as a training set are processed from medical images and reconstructed mandible geometries is mapped onto a common reference shape to identify corresponding points thus allowing the representation of each surface model in a common vector space. These methods are used to create statistical shape model. This model can predict the intermediate form of the model, including all its variations based on the input data set. The knowledge about shape variation was used to estimate the missing parts, in the reconstruction mandibular dysplasia, determination of sex differences in anatomy of human mandible, for 3D medical image segmentation [2,4-6]. Possible disadvantages of this approach are the inability to predict shape variations and geometry of the bone outside the input set.

Mirroring the affected to the unaffected side has been used as a gold standard for the facial reconstruction [8]. Based on fact that the face represents a symmetrical structure, the injured area is virtually resected, and the healthy part is mirrored to the injured site. As described by different authors, results of this approach indicate an unsuccessful reconstruction [7,8]. Disadvantage of this approach are the inability considers asymmetric and individual properties of the skull.

The major challenge is to develop a reconstruction method based on limited available medical data to create geometrical model of a specific patient. For that reason, in this paper reconstruction method for the creation 3D geometrical model of missing part of the bone is presented. The geometrical model will aim to encompass the patient's individual geometrical features, including shape and dimension of the bone.

II. Method of Anatomical Features and its Application

Method of Anatomical Features is enabling the creation of various types of geometrical models of the human bones in the skeletal system of a man, even in cases when the information about the patient's bone are incomplete [9]. Two different types of output models can be created by MAF.

The first type of output model is 3D geometrical model (polygonal, surface and solid), created by the application of standard CAD software packages. The process for creating such models consists of processes: CT scanning of the patient, segmentation of medical data, transformation of geometrical data to an appropriate format for CAD, importing 3D model into CAD software, definition of the Referential Geometrical Entities, creation of anatomical points and creation of an adequate 3D model. The process is described in more detail in [10]. Such model allows the creation of fixators of human bones adapted for the patient, while also improving the preparation and simulation of surgical interventions.

The second type of output model is predictive (parametric) model. Parametric model of human bone is defined as model whose geometry can be changed by the application of different parameters values (measured in medical images by using adequate software) while its topology remains the same. They are defined as a set of parametric equations (functions), whose arguments were morphometric parameters [11]. Morphometric parameters are specific dimensions which are defined for each bone in human skeletal system. They are used to describe the configuration of the human bone.

The main benefit of parametric model application is in its possibility to used in clinical cases when 3D data of human bone are missing. Due to the bone illness, fracture or some other trauma, the input data of a patient's bone are not complete. In that cases, available values of morphometric parameters are read from medical images and applied in parametric equations. As the result of this process, complete 3D geometrical model of specific patient is created, despite the lack of input data. Geometrical model may be a less accurate, but it will be personalized model.

A. Parametric model of the human mandible

For the geometrical analysis of the human mandible, 22 mandible samples were scanned. The samples were made by 64-slice CT MSCT, Aquillion 64, Toshiba, Japan according to the standard protocol recording.

The process of creation of parametric model of human mandible by using MAF is presented in previous research in detail [12].

As already state, parametric model of the human mandible is a geometrical model defined as point cloud. Point cloud consists of 156 anatomical points. The anatomical points represent some topological and anatomical landmarks on the model. For each anatomical point, the values of the distance from coordinate system in three directions X, Y and Z were measured. Planes of coordinate system is presented in Fig. 1 and described in [6]. The measured values of coordinates of these points were used as the input data in the statistical analysis.

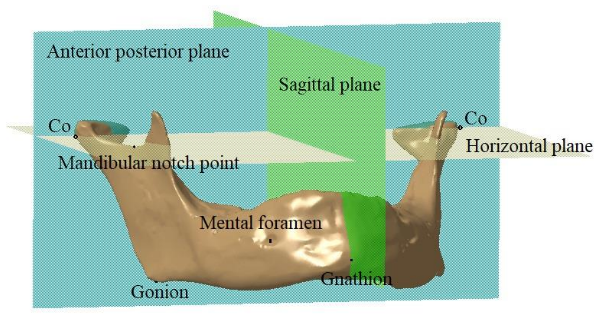


Figure 1. Coordinate system

On each individual model of mandible, the values of morphometric parameters were also measured. According to the literature [13], configuration of the mandible can be accurately perceived with the help of the 10 basic central and bilateral mandibular morphometric parameters. Morphometric parameters of the human mandible are presented in the Fig. 2.

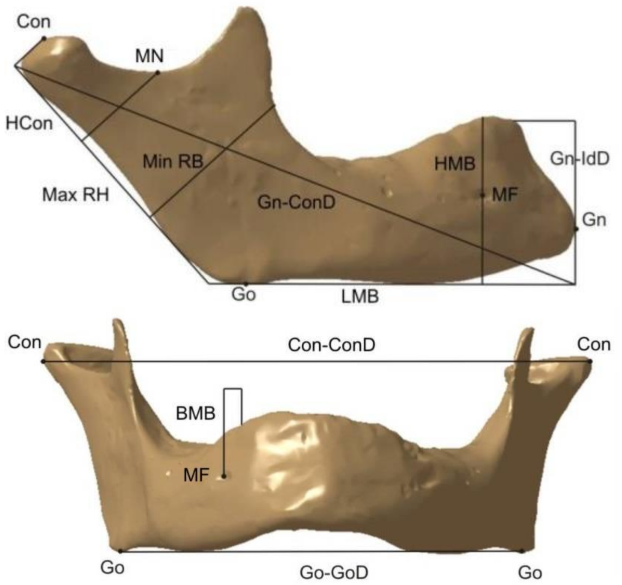


Figure 2. Morphometric parameters of human mandible

The measured values of coordinates of anatomical points and morphometric parameters represent the input data in the multiple linear regression. The main objective of this analysis was to obtain the functions that describe the relationship between the coordinate of the anatomical points (dependent variable) and values of morphometric parameters (independent variables). As a result of the analysis et of parametric equations (functions) are obtained. The resulting model is cloud of calculated anatomical points. The example of equation for the Y coordinate of one point is presented in (1):

$$C=22.0-4.52C_1+0.414C_2+0.221C_3+4.15C_4+0.034C_5+0.578C_6-1.58C_7-0.054C_8-0.172C_9-0.030C_{10} \quad (1)$$

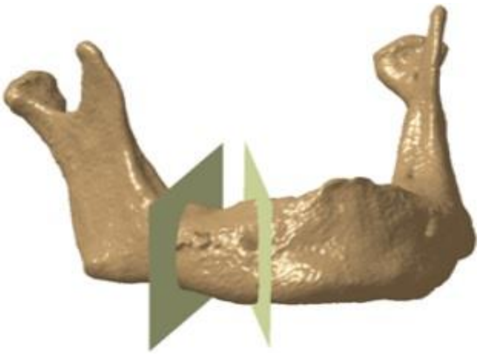
where: C - dependent variable (variable response), C_1-C_8 - is an independent variable (explanatory variable). In our case, C_1, C_2, ..., C_{10} represent the values of morphometric parameters measured in all samples of the mandibles.

Geometrical accuracy of the obtained surface models was tested by the application of the deviation's analysis in CATIA software. Maximum surface deviations of the surface model of human mandible created by the use of parametric functions from the input surface model of original mandible specimens is 2.25 mm.

III. Application of the Parametric Model of Human Mandible

In this section of the paper, application of parametric model of the human mandible in reconstruction of missing part of the bone is presented. By the application of measured values, the parametric model transformed into a 3D personalized geometrical model. On that way, model geometry, shape and anatomy correspond to the patient bone.

In order to present the whole process of creation of geometrical model of personalized bone implant, a specific case is defined and shown below. The use case represent a double unilateral fracture formed on the patient mandible bone. The complex fracture is created according to the AO classification defined for mandible fractures, with the assistance of the medical practitioner involved in this research. The process for the creation of complex fracture on the body of the human mandible is presented in the Fig. 3.



a)

b)

Figure 3. Complex fracture on the body of the human mandible,
a) position of constructive plane on the mandible body b) mandible body fracture

Medical data used are acquired from CT scanner (64-slice CT MSCT, Aquillion 64, Toshiba, Japan). The CT scan was collected using the resolution of 512 x 512 px and slice thickness of 0.5 mm.

In the following text, methods for creation of personalized implant will be demonstrated.

A. Personalized model of implant

The personalized model of human implant was created by the use of anatomical points included in the parametric model of the mandible.

In point cloud set anatomical points were selected. The anatomical points were used to fully characterize the shape of the missing part of mandible. In this case, 27 anatomical points were selected and defined, Fig. 4.

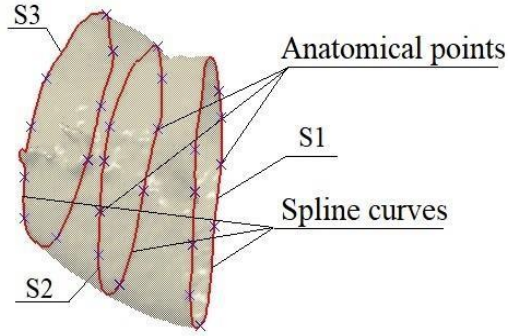


Figure 4. Anatomical points on the part of the human mandible

Geometrical model of personalized implant is created by the application of the parameter's values in parametric functions. In this specific case, only 8 morphometric parameters were read from the medical images. Complex fracture on the mandible body is affected the inability to read values of two morphometric parameters, Gn-ConD and LMB. The inability to read morphometric parameters from the medical images caused the re-formation of parametric equations according to the available input data, but without data that could not be reached. The morphometric parameters were measured on mandible sample and incorporated into new regression functions. The multiple linear regression algorithm which is applied. The example of matrix equation for the coordinate of one point defined in Matlab is presented in (2):

$$C=-23.5-0.115C1-0.101C2+0.133C3-0.030C4+0.196C5-0.0720C6-0.132C7+0.053C8 \quad (2)$$

where: C1-C8 - represent the values of morphometric parameters measured in all samples of the mandibles.

The construction of the surface model of personalized implant is based on the obtained prediction values of the coordinates of the 27 anatomical points. Surface model was created by the use of spline curves though the calculated anatomical points in CAD CATIA software, Fig.5.

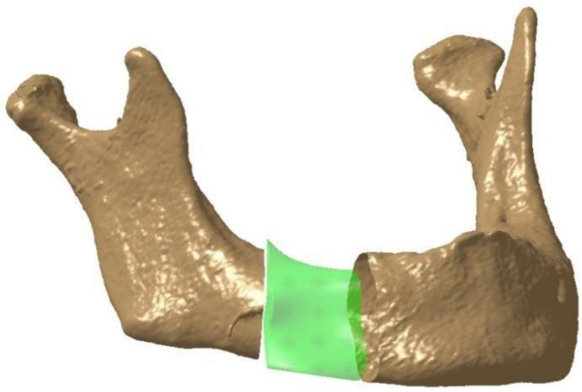


Figure 5. Geometrical model of personalized implant

IV. Results and Discussion

The geometrical accuracy of the obtained surface model was tested by the application of the deviations analysis in CATIA software. The deviations analysis was performed between the input and resulting model, (Fig.

6). As we expected, the result is a less accurate 3D model. A maximal surface deviation of the surface model of personalized implant is 5.11 mm.

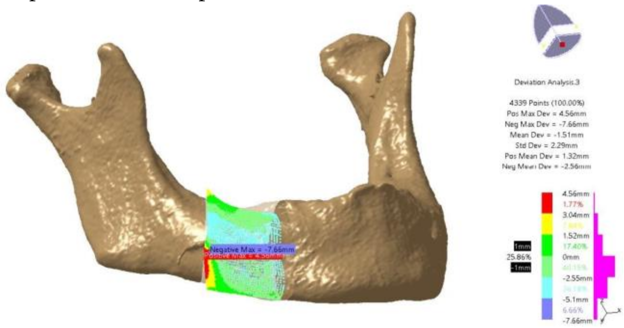


Figure 6. A deviations analysis between the input and the resulting model

V. Conclusion

Approach presented in this research enables creation of personalized implant customized to the geometry, morphology and anatomy of the specific patient. The customization is performed by the application of values of morphometric parameters (measured in medical images) in the parametric functions.

The preliminary claim about geometrical model of personalized implant, geometrical accuracy and anatomical correctness can be stated as satisfactory for the prototype model.

In order to obtain reliable response of the geometrical model of implant, more detailed analysis must be performed:

- the number of samples should be increased,
- parameters influence on the individual points should be examined,
- application of statistical or artificial intelligence methods on the set of bone samples should be used.

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