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GEOMETRICAL MODELS OF MANDIBLE FRACTURE AND PLATE IMPLANT

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Abstract. *In the oral and maxillofacial surgery, there is a requirement to provide the best possible treatment for the patient with mandibular fractures. This treatment presumes application of reduction and fixation techniques for proper stabilization of the fracture site. The reduction of the bone fragments and their fixation is much better performed when geometry and morphology of the bone and osteofixation elements (e.g. plates) are properly defined. In this paper, a new healthcare procedure, which enables application of personalized plate implants for the fixation of the mandibular fractures, is presented. Geometrical models of mandible and plate implants, presented in this research, were created by means of the Method of Anatomical Features (MAF), which has been already applied to the creation of accurate geometrical models of various human bones, plates and fixators. By using such geometrically and anatomically accurate models, orthopedic and maxillofacial surgeons can better perform pre-operative tasks of simulating and planning the operation, as well as an intraoperative task of implanting the personalized plate into the patient body.*

Key Words: *CAD, Orthopedic, Mandible, Fracture, Plate, Parametric Models, Method of Anatomical Features*

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1. INTRODUCTION

In the maxillofacial surgery for the treatment of mandibular fractures, reduction and fixation techniques are used [1, 2]. The reduction of the bone fragments and their fixation is better performed when geometry and morphology of the bone and osteofixation material (plates, screws, rods, pins, etc.) are properly defined [3]. In order to accomplish this goal, it is of great importance to clearly define geometrical properties and morphometric parameters of the mandible bone and to establish proper correlations between them [4-6].

The mandible (lower jaw) is the largest and the strongest bone in the face and its shape is very complex [7, 8]. Mandible fractures are common facial injuries treated by the oral and maxillofacial surgeons as described in [1, 2]. These fractures can be grouped into the broad categories which are defined as unilateral fractures (double or multiple unilateral), bilateral fractures, fractures with contralateral condyle compromise, and bilateral condyle fractures with symphysis/anterior body compromise [9]. Reduction and fixation process of mandible fractures should provide biomechanical stability to the assembly of fractured mandible, bone fragments and adequate implants (e.g. mini-plates, screws) as stated in [10]. Biomechanical stability is often analyzed by the use of numerical simulations in adequate software packages (Abaqus, Ansys, etc.) [10]. In order to conduct such analysis valid geometrical models are required. If the geometry and morphology of the models are better defined, then the Finite Element Analysis (FEA) will provide more reliable results, and the process of reduction and fixation will be improved.

Fixation of the assembly is performed by the use of different kind of plates. In general, they can be divided into two general groups: Locking plates and Non-locking plates [9, 11]. Locking plates provide better stability of the assembly and do not require pre-contouring of the plates. Non-locking plates require pre-contouring, and they can interrupt and destroy the periosteum of the bone [9, 12]. In both cases, it is important to properly adjust shape and position of the plate(s) in accordance with mandible geometry.

The geometrical models which conform to the anatomy and morphology of the mandible can be created by the use of volumetric imaging methods (e.g. Cone Beam Computerized Tomography – CBCT, Computerized Tomography – CT or Magnetic Resonance Imaging - MRI), 2D methods (X-ray, 2D Ultrasound), and predictive methods (based on predictive models). Volumetric methods provide 3D models, which can be used for measuring morphometric parameters and initial placement of implants in medical software (e.g. Materialize Mimics) [8, 13]. These models do not have proper geometrical definitions and correlations between anatomical entities, so they do not have the ability to change and adapt to various requirements. 2D models acquired from 2D scanning methods do not provide enough information about geometrical properties in 3D space. Various transformations can be applied [14], but the resulting models still lack anatomical and geometrical definitions, especially in comparison with volumetric methods. Predictive methods enable the creation of bone geometrical models by using various types of parametric (statistical) models. These methods can provide valid geometrical models, but they are limited by the input set of the bone samples, type of the applied method, and by the number and type of the parameters involved [15-17].

In this paper, the procedure for the treatment of patient with mandibular fracture(s) is presented. This procedure encapsulates the whole process from scanning the patient to the implantation of an adequate plate implant. The essential parts of this procedure are processes in which accurate geometrical models of the mandible, mandible fracture, and plate implants are created. To construct such models the Method of Anatomical Features (MAF) is applied. The main goal of this research study is to achieve a complete geometrical definition of the mandible, mandible fractures, and plate implants in order to enable the orthopedic surgeons to adequately prepare and perform orthopedic interventions.

2. Anatomy of Mandible

The lower jaw (mandible) is the biggest and the most massive bone in the face, which is connected to the skull bones through the temporomandibular joint. It represents the biggest odd bone in the face or the viscecranial bone, which participates in construction of the only mobile head joint. It consists of a mandible body and two rami [18, 19].

The mandible body is of complex shape and represents its horizontal part. It consists of two sides (external and internal) and two edges. The first edge is defined as alveolar part of the mandible which corresponds with inferior dental arch (Latin: arcus alveolaris) whereas the second (lower) edge is defined as mandible basis (Latin: basis mandibulae). Ramus is roughly of a rectangle shape, which is located upward and backward in relation to the mandible body. It forms an angle of 90°–140°, most commonly 120°–130°, to the mandible body. Ramus has two sides, external and internal. It also has four edges, upper, lower, anterior, and posterior. The upper edge has two processes: coronoid process (Latin: processus coronoideus) and condylar process (Latin: processus condylaris) [18, 19].

3. Method of Anatomical Features and Its Application

MAF is created by the authors of this research study whose objective is to enable the creation of various types of geometrical models of the human bones and osteofixation material [17]. One of the most important outcomes of the MAF application in medical imaging is the creation of a generic parametric model of the specific human bone. In general, parametric model can be defined as a model whose geometry can be changed by the application of different parameters values, while its topology remains the same. In the cases of human bones (in this case mandible), the parametric model is defined as a set of functions, whose arguments are morphometric parameters, whose values can be measured in medical images. Morphometric parameters are geometrical dimensions, which are defined individually for each bone in human body [16]. They are used in order to customize the parametric model to the specific patient [15-17]. By the application of measured values, the parametric model transforms into a 3D personalized geometrical model of the specific human bone. “Personalized” means that model geometry, shape and anatomy correspond to the patient bone. The main benefit of this model application is in its possibility to create a complete 3D geometric model of the patient bone, even in the cases when input data acquired from medical images are incomplete. The reasons for lack of data can be single, or not enough 2D image(s) (not enough data for 3D reconstruction), inability to perform CT scanning (patient must not be subjected to radiation, medical institution does not have CT device), too much noise in medical image, etc. The personalized model of the human mandible created in this manner can be used for preoperational planning and simulation in orthodontics and maxillofacial surgery, the creation of customized plates and other types of implants and fixators, for educational purposes, etc. In this research, the parametric model of the human mandible is used for the creation of a fracture parametric model, and the personalized model of the human mandible with a fracture is used for the creation of a personalized model of the plate implant.

4. Process Description

The main research goal was to create an improved healthcare procedure in maxillofacial surgery and orthopedics, which will enable the surgeons to improve on their performing of surgical interventions. The presented procedure covers the whole process from the diagnostic to the implantation of the plate. It is important to describe the proposed procedure of the implant placement because only in that way can it be understood why it is important to have accurate geometrical models of the mandible fractures and plate implants. Treatment of mandible fractures was chosen as an example of the process because these kinds of fractures are very common [1, 2] in today's clinical practice.

The main process is described by using the Structured Analysis and Design Technique (SADT) notation. SADT is a methodology that uses diagrams to describe process functionality [20]. The basic elements of SADT are: input elements, resources, control elements, output elements and various types of arrows and connection elements [20]. The process of fixator customization is presented in Fig. 1 and in the SADT notation it is defined as A0 process with the following elements:

- Input elements: volumetric or 2D image of the patient bone, parametric models of the mandible fracture
- Control elements: anatomical knowledge about human bones, medical image analysis knowledge, anatomical and morphological rules, rules defined in MAF
- Resources: doctor, designer, software packages (Medical imaging software, CATIA)
- Output elements: geometrical model(s) of the customized plate implant.

The context diagram A-0 is broken down at the level A0 into the subprocesses as shown in Fig. 2. In this diagram, the whole procedure for the creation of the customized plate is visually presented. The procedure can be divided into the four sub activities described below:

- A1 - Analysis of the medical image – In this the activity analysis of the acquired medical image is performed. Doctors (radiologist, orthopaedists, etc.) use created image of the patient bone to determine the type of fracture, its position and orientation, and to decide which plate implant will be used for fixation of the mandible. One important part of this activity is to measure values of morphometric parameters. These values are used to adapt parametric model of the mandible and fracture to the geometry and shape of specific patient - to create Personalized Model of the Mandible and Fracture (PMOMF). Values are measured by using technical features of the applied medical software (e.g. Vitrea). All of this knowledge represents output from the process and it is defined as "Collected knowledge about mandible fracture".

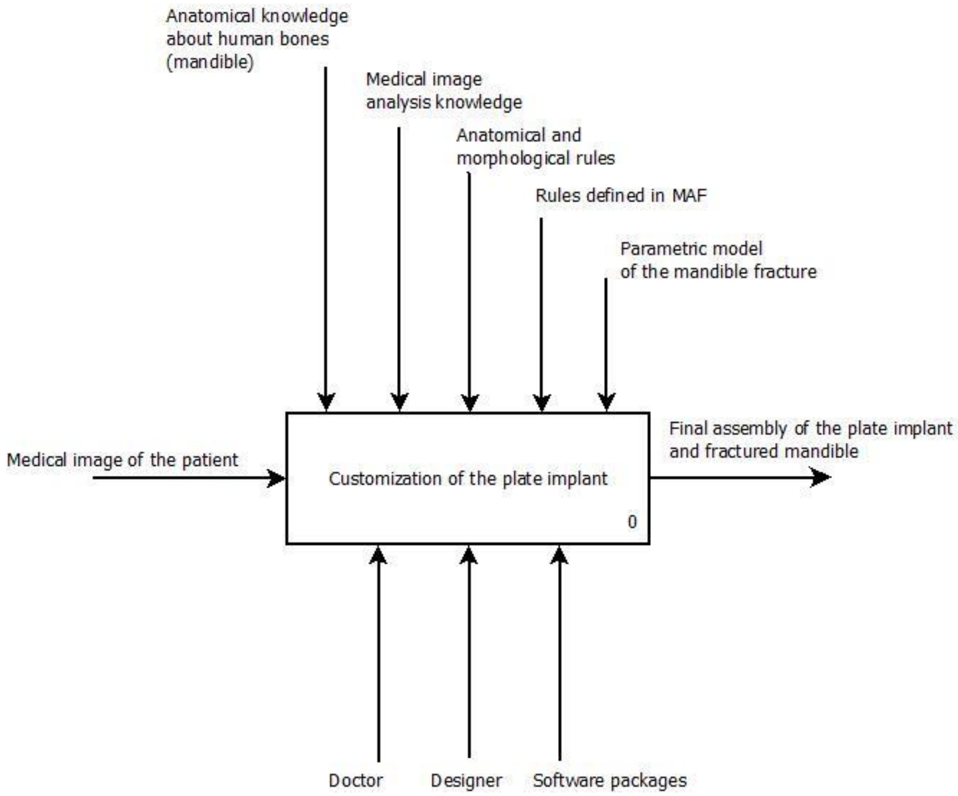

Fig. 1 Creation of the geometrical models of the plate implant and mandibular fracture – context diagram A-0

- A2 - Application of the measured data in CAD software – Measured values of morphometric parameters are applied to the parametric model of the adequate entity (mandible, fracture), and personalized models are created. This activity consists of two main sub activities and they are:
  1. Creation of the polygonal model of the mandible with fracture. This model is based on the parametric model of the mandible, which has already been created and described in [17]. The position of the fracture is defined by the measurements conducted in medical image analysis process – it is conditioned by the values of the morphometric parameters.
  2. Creation of an adequate solid model of the plate implant by following recommendations and procedures defined in literature [21].

  It is possible that the resulting models can have some geometry and topological errors, but they can be fixed by using technical features of CAD software, e.g. correction and optimization of the model in a sense of number of triangles, orientation of triangles, triangles reduction, filling holes, etc. These correction steps are very important because only valid closed polygonal models can be later converted to the solid models for the purpose of creating assembly.

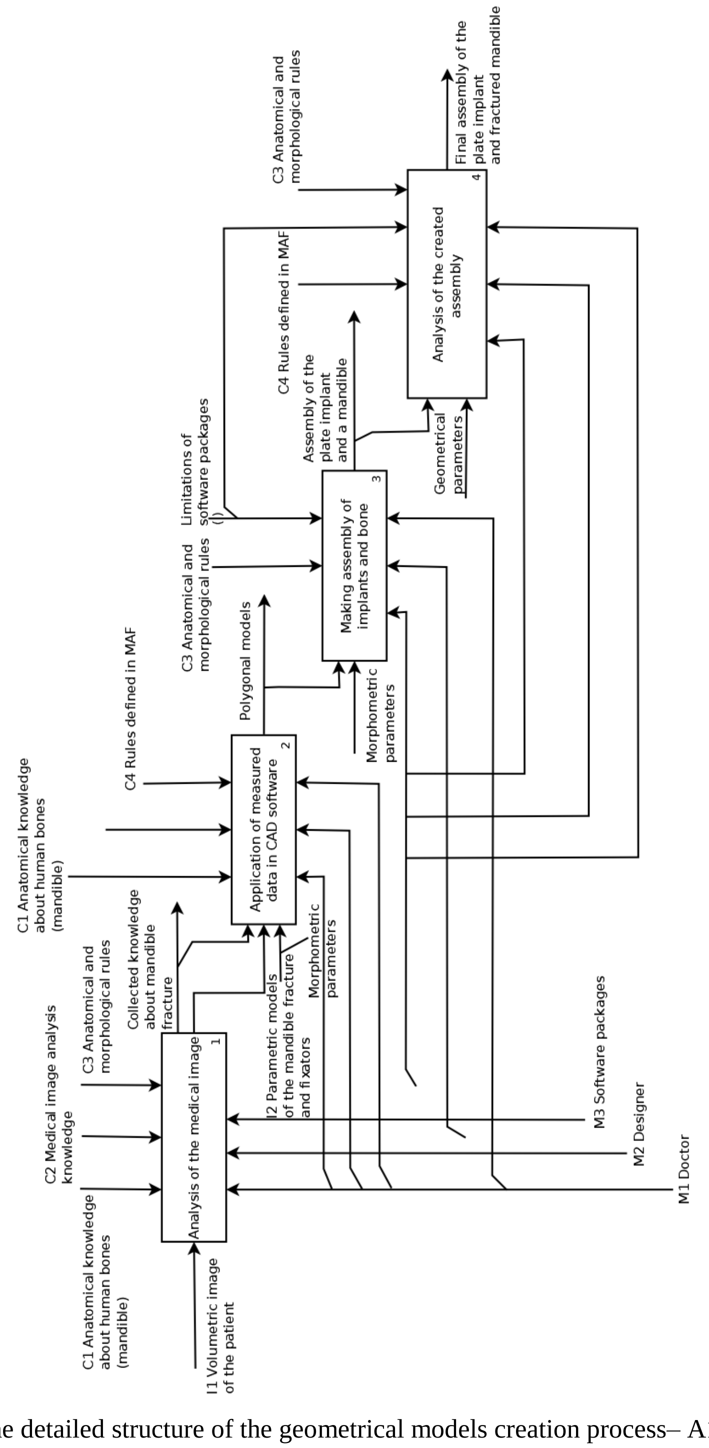

Fig 2. The detailed structure of the geometrical models creation process– A1 process

- A3 - Making assembly of fixator and a bone – A polygonal model of mandible with fracture is converted into a solid model by using technical features of the CAD software (e.g. CATIA closed surface technical feature) and an assembly of the mandible with fracture and plate implant (fixator) can be created.
- A4 - Analysis of the created assembly - In this activity, anatomical, morphological, and geometrical analysis of the created assembly of the mandible with fracture and plate implant is performed. Anatomical analysis presumes that all the anatomical entities important for the proper positioning of the fixator are present. This means that if some crest exits in a real physical model, then the same crest must exist in a virtual model. Morphological analysis presumes that shape of the anatomical entities must be preserved. This means that if the crest exists, then the shape of that crest model should be the same as the shape of the real crest. Geometrical analysis implies that if the crest model exists and it has the same shape as the real crest, then dimensional deviations between the real crest and its model must be in the minimum range defined by the orthopedic surgeons. If all the conditions are fulfilled then the assembly is ready for other activities (e.g. testing biomechanics, surgery preparation) and the process is finished.

It is important to note, that described procedure can also be used in the clinical cases of massive mandible fractures. In such cases, it is possible to add scaffold [22] component to the assembly of bone and plate, in order to enable better tissue growth, and thereafter, faster recovery of the patient.

5. Parametric Models and Their Applications

The essential elements of the defined procedure are geometrical models of the mandible with fracture and plate implant. In order to present the whole process of their creation, a specific use case is defined and shown in this paper. The use case represents a clinical situation where fracture type B is formed on the patient mandible bone. To provide stability of the mandible bone with such fracture, tension band plate with four holes is chosen [9]. Medical data used in this case are acquired from CT scanner (64-slice CT MSCT, Aquilion 64, Toshiba, Japan) positioned in the Clinical Centre, Niš, Serbia. This data was already used for the creation of the parametric model of the human mandible in previous research [17]. In the following text, methods for the creation of parametric models of the mandible body with fracture type B and solid model of the tension band plate implant will be demonstrated.

5.1. Parametric and personalized model of the mandible with fracture

It is important to distinct the parametric model of the mandible with fracture and PMOMF. The parametric model is a virtual mathematical model, while PMOMF is a concrete geometrical model of the specific patient bone with fracture (surface or solid).

The parametric model of the mandible with fracture was created by the use of points included in the parametric model of the mandible [17]. As stated in [15, 16] the parametric model of the human bone is a geometrical model defined as point cloud. Coordinates of points included in the point cloud are defined by parametric functions, as described in [16, 17]. Parameters are defined for each bone, and for mandible there are ten defined morphometric parameters [17]. To define the geometrical model of the mandible body fracture it is necessary to select proper points in point cloud set. Proper points were selected based on standard classification of mandible fractures described in [9]. For the use case defined in this research, the fracture is classified as B fracture type, so adequate points were chosen and presented in Fig. 3.

PMOMF is created by the application of the parameters values measured on CT scan of the specific patient (or any other source of data), in parametric functions. The created point cloud was tessellated and the polygonal model of the mandible with fracture was created. The Surface model of the mandible with fracture was created by the use of technical features of the CATIA software (automatic surface, multisection surface, etc.), and it is presented in Fig. 3. In order to create the most precise model possible, some adjustments were performed: cleaning and healing of the acquired point cloud, finer tessellation, and optimization of the surface model (e.g. softening, points adjustments).

5.2. Plate implant

Based on the created PMOMF and the defined procedure for the mandible body fracture reduction and fixation described in [21], a solid model of the tension band plate implant was created (standard 4-hole mandible plate 2.0 with centre space - plate thickness 2 mm), and presented in Figs. 4a and 4b.

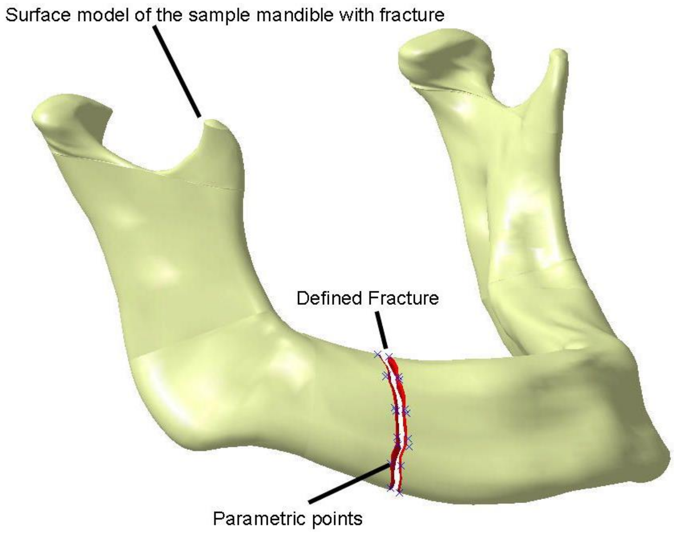

Fig. 3 Surface model of the mandible with defined fracture model and parametric points

The created solid model of the plate implant can be called personalized because its geometry and shape are adapted to the specific patient. The procedure for the creation of geometry model of the personalized plate implant contains three important steps:

- Creation of the tangent (base) plane - The tangent plane is defined on the surface model of the mandible with fracture. The position and orientation of this plane is determined by the part of the surface near the fracture and ramus surface, Fig. 4a.
- Construction of the outer contour of the plate - The outer contour of the plate model is created in the tangent plane and projected on the surface of mandible model. The thick surface technical feature (thickness 2mm) is used on the projected contour and a solid model of the fixator is created, Fig. 4b.
- Final modifications - Screw holes are created on the solid model of plate implant by the application of the hole technical feature. Position and number of holes are defined in accordance to specification defined in [21].

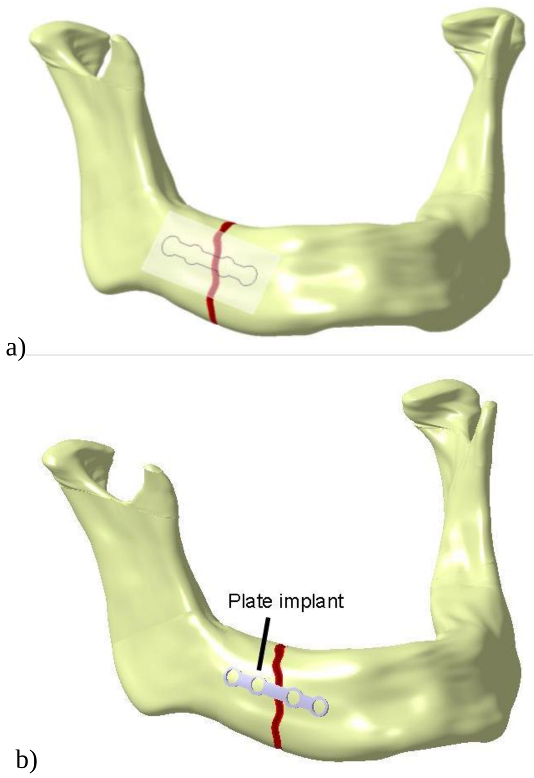

Fig. 4 Construction process of the personalized plate implant: a) Construction plane and outer contour of the tension band plate; b) Solid model of the tension band plate implant with 4 holes

The geometry model of the personalized plate can be used to produce the real implant by the application of additive or conventional manufacturing technologies. In this way orthopedic surgeons can do pre-operative tasks of simulating and planning the operation with geometrically accurate models of mandible with fracture and plate, and intraoperative task of implanting the personalized plate into the patient body.

6. CONCLUSION

In this paper, an improved healthcare procedure for the implantation of plate implant for the fixation of mandible fractures is presented. The procedure is based on a newly developed method for the creation of personalized geometrical models of the mandible with fracture and plate implant.

Personalization of the models is achieved by the application of the parametric model of the human mandible. Geometry and morphology of the presented models can be customized to the specific patient, by applying the parameters values acquired from the medical images (CT or X-Ray). The geometrical and anatomical precision of the parametric and other geometrical models is already determined and published in previous research studies [16, 17].

By applying the proposed procedure, maxillofacial and orthopedic surgeons can greatly improve pre-operative planning (precise geometrical models can be used), intra-operative procedures (pre-contouring is already performed) and post-operative recovery of the patient (faster and of better quality).

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