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APPLICATION OF COMPUTER MODELLING FOR PLANNING MAXILLOFACIAL SURGERY

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S u m m a r y

The article describes application of reverse engineering techniques for modeling the appearance and the planning of correction of mandibular prognathism and FEM numerical analysis process components designed to perform anastomoses condylar fracture.

Keywords: CAD, reverse enginering, medicine

Zastosowanie modelowania komputerowego do planowania zabiegów chirurgii szczękowej

S t r e s z c z e n i e

W artykule przedstawiono zastosowanie technik inżynierii odwrotnej dla modelowania wyglądu i planowania zabiegu korekcji progenii. Przeprowadzono proces analizy numerycznej MES elementów przeznaczonych do wykonania zespoleń wyrostka kłykciowego.

Słowa kluczowe: CAD, inżynieria rekonstrukcyjna, medycyna

1. Introduction

Medicine is a very promising area for reverse engineering applications, which usually are used for modeling the bones and surgery planning. This was due to biomedical engineering, which through a combination of achievements of sciences such as mechanics, chemistry, computer science, electronics and medicine, allowed the introduction of innovative engineering solutions. An example is the possibility of mapping of the internal structures of the object/patient using reverse engineering techniques and to conduct virtual simulation procedures such as correction of mandibular prognathism and treatment of fractures of the mandible.

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A need to analyze the states of the biomechanics of the human mandible in recent years was crucial, that show the large number of publications on this subject. The main issues in the field of maxillofacial surgery, interesting from the point of view of engineers are to assess the state of stress in the jaw with chewing function, overloading of bone structures arising from strikes. The assessment of the phenomena occurring in the bones of the merge and the reconstruction and analysis of the implant after surgery osteosynthesis and reconstruction also in terms of the design of new components and optimalization existing ones. Another group consists of models with operational planning, particularly with regard to orthognathic. Both of this problems are shown in this article.

2. Development of methods for planning one- and two-jaw osteotomies

Mandibular prognathism is a morphological malformation of the facial skeleton. It is characteristic of the forwarded position of the jaw which is the result of excessive growth within its stem and / or branch, which is seen as excessive forward protrusion of chin looking at the person from the profile. This distortion covers the entire cranial-facial unit.

Epidemiological research carried out in the last half century in Poland among children and adolescents showed that the percentage of anterior malocclusion increases [1]. Studies show that the basis of this defect can be both skeletal disorders and dental. The National Health Programme (NHP) developed project for the period 2006-2015 in wich malocclusion were included in the most common diseases and developmental disorders of children and young people of school age. Treatment of morphological irregularity of the mandible is mainly aimed at improving the aesthetics and function, but also a correct bite, correct facial proportions [2].

The development of computer systems has a huge impact on the success of surgeries and patient satisfaction. Currently available specialized software to enable the reconstruction of medical data to build virtual 3D CAD model (eg, Amir, Analyze, Biobuild, Mimics and sliceOmatic), which gives the surgeon dimensional imaging of structures that the tomographic image can be seen only in the form of cross-sections. The virtual model can be used to design and simulate the surgical procedure and, if necessary, can be made one of the methods of rapid prototyping. The most important is the fact that models obtained in this way are fully functional, which means that they can be subjected to modification depending on the needs [3-6].

The procedure for three-dimensional modeling of the patient's tissues, and surgery simulation with the final comparison of the actual changes in the appearance of a patient based on Mimics program is shown on Fig. 1.

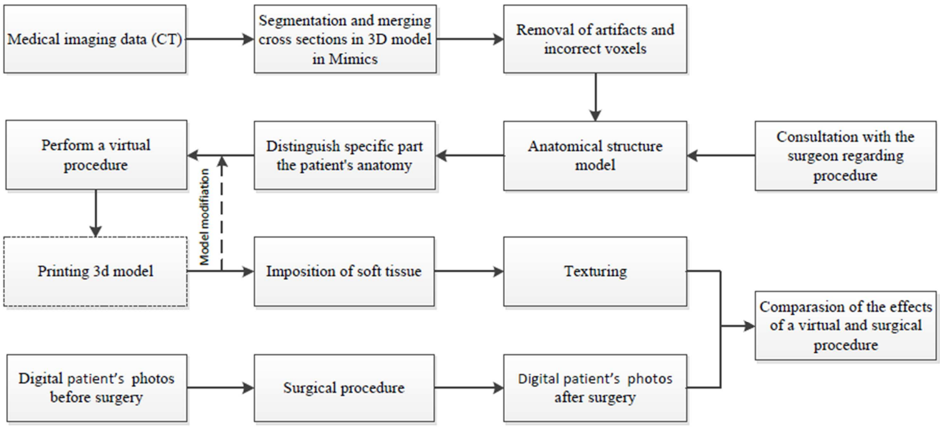


Fig.1. Scheme of data processing in the planning and simulation procedure and comparing the obtained result with the real effect

3. Data preparation to the virtual protruding jaw surgery

The processed data are tomographic examination of 23-year-old patient (Fig. 2), diagnosed with the protruding jaw resulting from overgrowth of the lower jaw and the underdevelopment of the upper jaw – visible asymmetry. As a result of the medical examination the patient was qualified for the orthodontic-surgical treatment. Correction of defects required to carry out double surgery – lower left side of the upper and the lower jaw of 5 mm and preform jaw retraction of 3 mm. The study material included 384 tomograms with a resolution of 512x512 pixels.

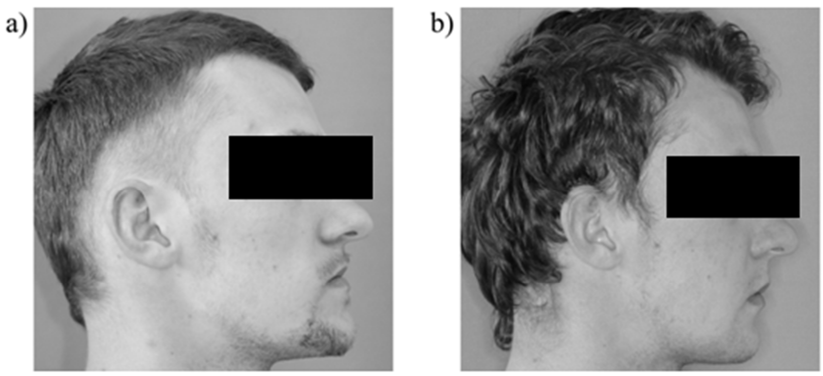


Fig. 2. Patient's face photography – a shot in profile, a) before surgery, b) after surgery

All operations were performed in the Mimics, based on the patient tomograms made in the Department of Radiology, Jagiellonian University in Cracow using spiral CT apparatus 16 row Siemens Somatom Sensation.

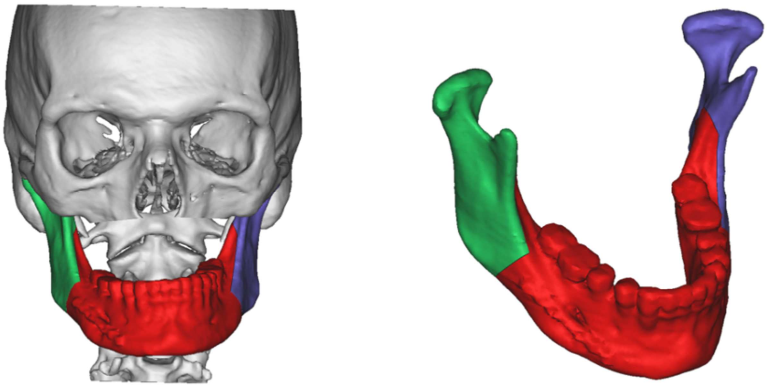
Creation a model of the skull was started with importing data from computer tomography. The first step in the processing is to extract interesting data structures. Sets of voxels are extracted by the command, consisting of the separation of the entire model of all voxels with values from a specified range. In the neighborhood of that voxel or a set of extracted voxels are those which have a value close to the specified value, while fragments separated from the selected structure or the individual pixels are removed. During a 3D modeling of the skull, there was a difficulty due to the presence of dental braces in the patient's body, which led to the creation of artifacts in the form of visible flares. Such distortions of information can also be caused by metallic implants, amalgam fillings, etc.

In the next stage the mandible was separated from the 3D model skull. As a result of these activities a three-dimensional model of the skull of a separate jaw was obtained, which then was used to plan the surgery correction of mandibular prognathism.

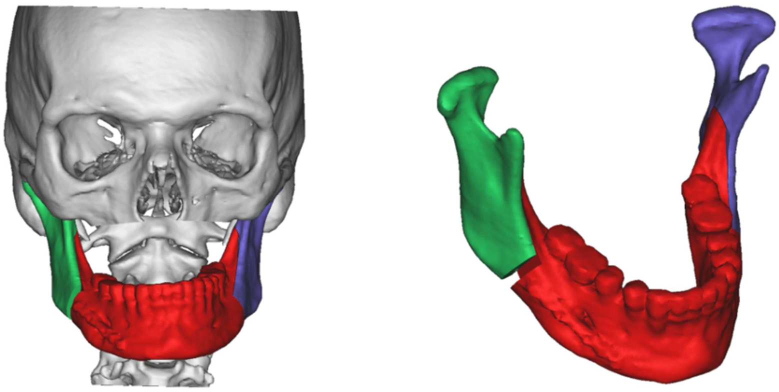
In the next step, the cutting plane of the upper jaw was determined, the upper jaw osteotomy was performed and the jaw was separated from the rest of components. This was followed by reduction of the left side of the upper jaw of 5 mm. In the subsequent step cutting planes were determined and mandibular osteotomies was performed on both sides of the jaw. To adjust the jaw in the correct position relative to the maxilla, mandible were separated into three parts – two branches and the corpus and measured and excised the right fragment of 3 mm lengths. This was followed by retraction of the mandible by 3 mm (Fig. 3).

The orthodontic-surgical treatment of maxillofacial defects is important not only to achieve stable skeletal and occlusal relations, but also to obtain the best aesthetic result. This effect is clearly visible immediately after surgery, revealed in changes in the appearance of the face. Hence, there is a great need for modeling soft tissue. Changes in the patient's soft tissue profile, following surgical correction due to skeletal disorders have been made.

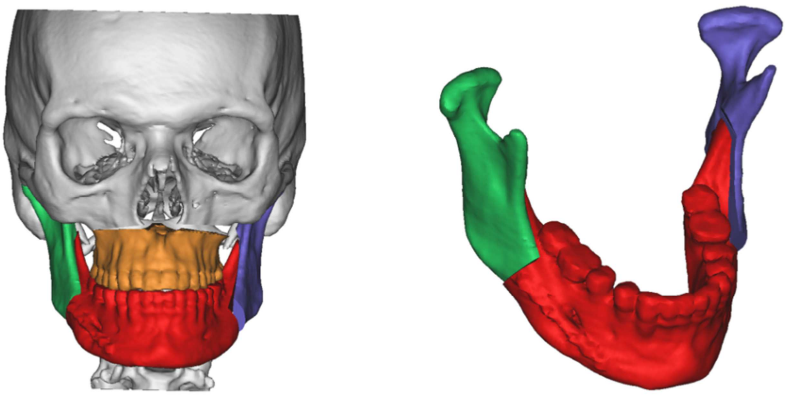
The next step was to model the external appearance of the patient after the surgery. For this purpose the digital images of the patient's head, taken before surgery were used to apply texture on a virtual model of the patient's soft tissue reconstructed and performed simulations of changes in the tissue according to the new position of hard tissues (Fig. 4). To the final bone structure after surgical intervention has been defined and soft tissue on which the simulation was performed were indicated. As a result of the activities carried out the animation was obtained, showing the size and the nature of the changes in the facial appearance after the surgery.



Mandibular osteotomy



The removal of the fragment of the mandible



Mandible withdrawal by 3 mm and its proper alignment with the upper jaw

Fig. 3. The stages of conducting virtual prognathism correction – en face view

The final step was the preparation of medical models using 3D printing machines and presentation of the relations of anatomical regions of the skull after surgery, which were checked and modified if needed by the surgeon. Unlike virtual models, the real model enables the actual planning adequate treatment procedure directly on the model. As a result, there is the possibility of introducing corrections, which significantly increases safety for both the surgeon and the patient. The big advantage is to reduce the treatment time and what goes with a reduction in its cost.

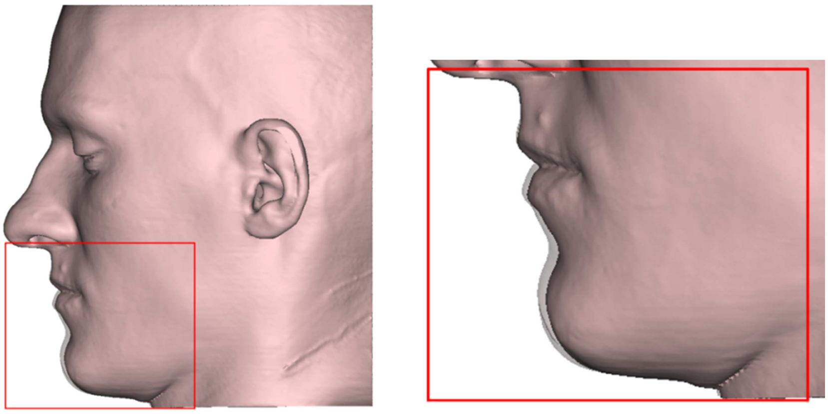


Fig. 4. The magnitude of changes in facial appearance after surgery

4. Simulation of change of the patient's appearance in the context of the planning of surgical procedures

In recent years there have been several attempts to demonstrate the enormous potential of a 3D modeling and rapid prototyping in the medical practice. Particularly promising areas of development is the correction of facial-maxillary defects because of the very high aesthetic requirements, so can be more frequently to meet with the planning of this type of surgery.

Described pattern of practice has not only an illustrative character but it is used in conjunction with specialist knowledge and experience of the surgeon also has a practical application in planning surgery. It can help the surgeon in selection of appropriate treatment, early procedure plan, for example, the line cuts, etc. In the future, it can help patients make decisions related to the submission to the surgery. Virtual simulation of the appearance of a patient after surgery, and the final result may have a positive motivation for the patient's psyche by showing him what changes can be expected.

The presented methodology of processing and modification acquired spatial models of anatomical structures can be successfully used in the design and simulation of the effects of treatment not only protruding jaw, but also other maxillo – facial – occlusal defects, and even many other diseases of surgical treatment.

Application of reconstructive engineering in medical applications improve the overall quality, speed and accuracy provided medical services and make it possible to match it individually to patient. However, consciousness of occurrence of error is a must. Reconstructive engineering and virtual reality are undoubtedly a powerful tool for the development of new paths and new opportunities.

5. Numerical analysis FEM of 3D Rhombic plates fixation for condylar fracture

Treatment of the mandible fractures is one of the most important problems in maxillo-facial surgery. A result of the fracture is, disturbance of muscle equilibrium, which causes displacement of bone fragments. This causes changes of the bite and the traumatic jaws occlusion, that can make breathing impossible. Disorder of the facial features occurs and instability of bone fragments make their union impossible.

In clinical practice different fixation systems are introduced. For all of them the most important is to provide fixation of the stability during treatment. However, each system is based on different basis of biomechanic, the aim of all is to restore the structure and the functional unity of the fracture site until such time as then a new bone can transfer the stresses arising during mastication [7, 8]. The plate osteosynthesis provides stability of bone fragments, allows further functional treatment, without the use of maxillomandibular fixation and significantly reduces the treatment time.

This method restores faster correct breathing, chewing of food, not destroys the periodontal and shortens time of the hospitalization.

The criterion of the proper treatment includes assessment of bone union (mainly based on the radiological diagnosis) and arising complications such as malocclusion, the plate denudation, or fracture of unit element. The cause of these complications can be incorrect match of plates to the surface of the bone or use not sufficient number of plates, causing secondary displacement of the bone fragments.

Condylar is the one of the areas of fractures of the mandible, for which a lot of discussion about the correct osteosynthesis are running. Based principles of treatment are aimed at improving the mandible as soon as possible in order to restore undistorted function of temporomandibular joints. Continual improvement of the operational methods by the application of new types of union elements and the introduction of modern biomaterials, does not give the expected results in the subject of the optimal osteosynthesis techniques.

The numerical analysis of computer models can be useful for surgeons. Those analisys enable a preliminary assessment of bone union and the risk of complications caused by failure of biomechanical equilibrium of the stomatognathic system. The finite element method (FEM) presented in this work, allows an analysis of repeatedly hyperstatic systems with complex shapes, complex nonlinear mechanical properties, with complex boundary conditions, with the possibility of modeling a complex load. FEM analysis enable the evaluation of biomechanical aspects of the stabilization of fractures of the mandible, helping in the proper surgical procedure planning by rational choice of fixation elements (shape, quantity, placement method alongside of fracture lines).

Aim of numerical simulations is to determine to what extent the method of implantation of the mandible is changing the stress distribution in the fixation elements and strain in hard tissues of the mandible. However, it is necessary to compare the obtained solution with clinical observations.

6. Materials and methods

Analysis of the fixation condylar fracture with the use of titanium plate 3D Rhombic from Martin was performed using the existing numerical model of the mandible, whose creating process has been described by Kromka M. and Milewski G. [9-11] (Fig. 5a, b).

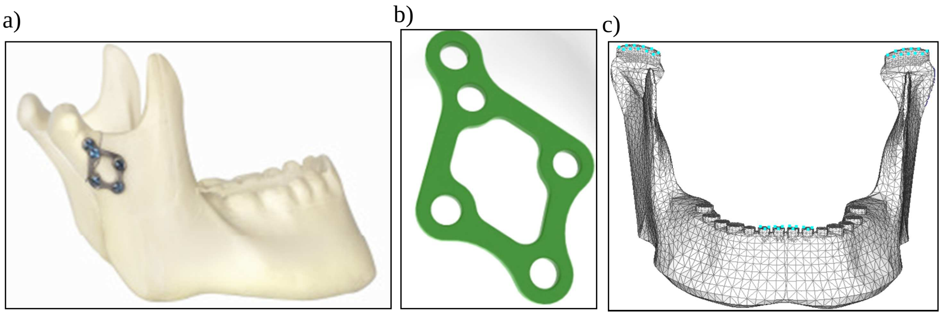


Fig. 5. 3D Rhombic plate (a) and (b) and the numerical model of the mandible with complex boundary conditions (c)

The numerical model of the mandible reproduced the anatomical structure, the activity of muscles and mobility in the temporomandibular joint (TMJ) (Fig. 5c). The simplifications:

- material properties – mandible is treated as an isotropic material (this simplification is usually sufficient in the early stages of modeling and analysis, and is often used by the authors) [5, 11-17],

• assumed loads schema, account of the recommendations concerning the possibility of postoperative food intake ie loading of bone structures by incisors; the four muscle groups were taken into consideration: masseter, temporal, medial pterygoid and lateral pterygoid, the value of the applied load in the region of the incisors was 100 N.

To simulate the bone union an element of the material properties of callus was introduced. Assumed material constants are shown in Table 1.

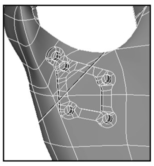
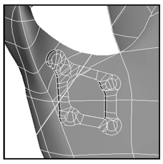
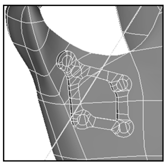
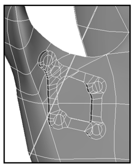
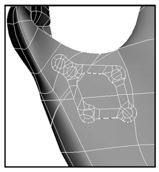
Two cases positioning 3D Rhombic plates were analyzed (Table 2). To the first case the analysis of changes in the course of fracture lines was introduced.

Table 1. The material constants assumed for the calculations [4, 18-20]

Material constants	**Mandible**	**Callus***	**Disc of TMJ**	**Temporal bone**	**Dentine**	**Periodontium**	**Plate**
***E*, MPa**	18000	200	50	15000	18600	67	108000
ν	0.32	0.4	0.45	0.32	0.31	0.47	0.3

* callus value in the final weeks of treatment

Table 2. Analyzed cases of plates positioning and the course of fracture lines

					
Designation of case	Ia	Ib	Ic	Id	II
Description	The first position of plates on condylar. The course of fracture lines - variants.				The second position of plates on condylar.

Changes occurring in hard tissues of the mandible and in the fixation union were evaluated on the basis of selected strength parameters. As accepted by the majority of authors, the effort of plates was defined using the values of the von Mises stress (σ_{HMH}). The effort of mandibular hard tissues was determined based on the values of strain ε_1. Changes in strain distribution are the most important factor to stimulate adaptive responses of the bone tissue associated with mechanical deformation field [20].

7. Results

The distributions the of von Mises stress [MPa] in the fixations plate for all the cases were compared. The effort of plates that could result of the destruction of the implant was defined.

Figure 6 shows the stress distribution for the case of Ia and Ib. In other cases (Ic, Id, II) stress distribution is regular, similar to Ia, Ib and the same area of effort is observed. Only for the case Ia the area of effort is the region of the hole near the edge of the upper fragment of the bone (this is the case when the fracture lines is the lowest). For all cases, the stress values are less than the value for which plates damage can occur (Fig. 7).

a) b)

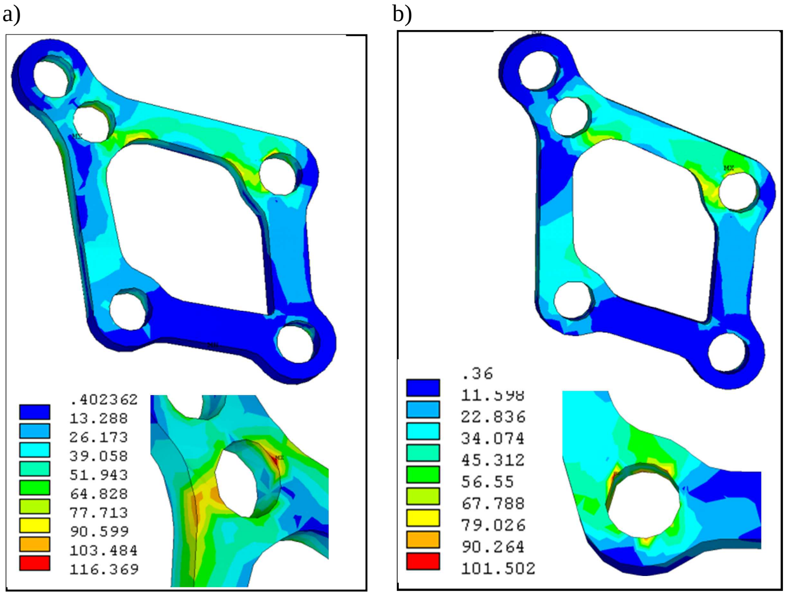


Fig. 6. Distribution of von Mises stress [MPa] for the cases: a) Ia, b) Ib

For the analysis of hard tissues of the mandible strain values are assumed. In the analysis of cases of osteosynthesis most frequently principal strain ε_1 is taken into consideration. Based on the hypothesis of mechanical stimulator of bone remodeling, it is possible to assess the future effects of treatment (bone union or non-union).

According to the range of values presented in the literature [14] for strain 20-40 x 10^{-4}, the response of the bone tissue is an increase of mineral phase. Above this value the resorption of bone and microcracks occurs. Values below 2 x 10^{-4} means the underload, the result of which is decrease of the mineral phase of the bone tissue and the bone atrophy.

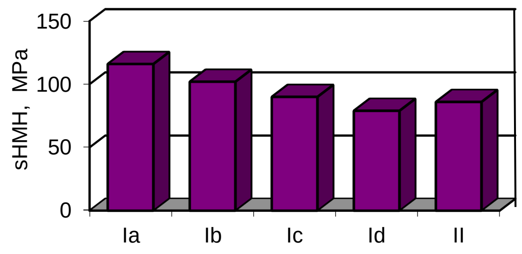


Fig. 7. The maximum values σ_{HMH} of the stress in the plate

In the analyzed cases, in the areas of fracture lines, the value of ε_1 is 10.03 – 14.47 x 10^{-4} for the upper fragment of bone and 3.56 – 14.32 x 10^{-4} for the lower fragment of bone corresponds to the range of physiological equilibrium (Fig. 8). The higher values of strain occur on the upper fragment of bone (it is pressed). Only for case II the value of the of strain is similar in both fragments of bone.

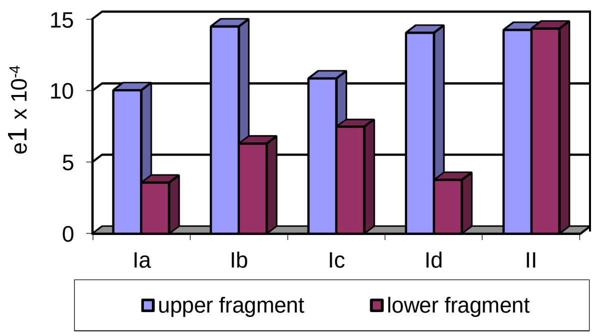


Fig. 8. The maximum values of the principal strain ε_1
in the areas of fracture lines for the analyzed cases

For cases Ib, Ic and Id places of effort are areas of lines of fracture (Fig. 9). For the case Ia and II these are places near the screw holes. In these cases, the maximum value of strain ε_1 is 18.38 x 10^{-4} for the case Ia, and is located in the hole of screw where it was areas of effort in the plate and 15,05 for case II x 10^{-4}.

In order to compare the stability of the bone fragments in the analyzed cases, the summary and axial displacements values were determined.

For all cases, the analysis of displacements showed the same tendency in the movement of bone fragments. Figure 8a shows the distribution of the axial displacements (along the *x* and *z* axis) for the case Ib. Axial displacement U_x of smaller fragment of bone at the bottom, has value -0.077 mm in the direction of the outside (buccal). The head of condyle moves to medially to the value of 0.03 mm.

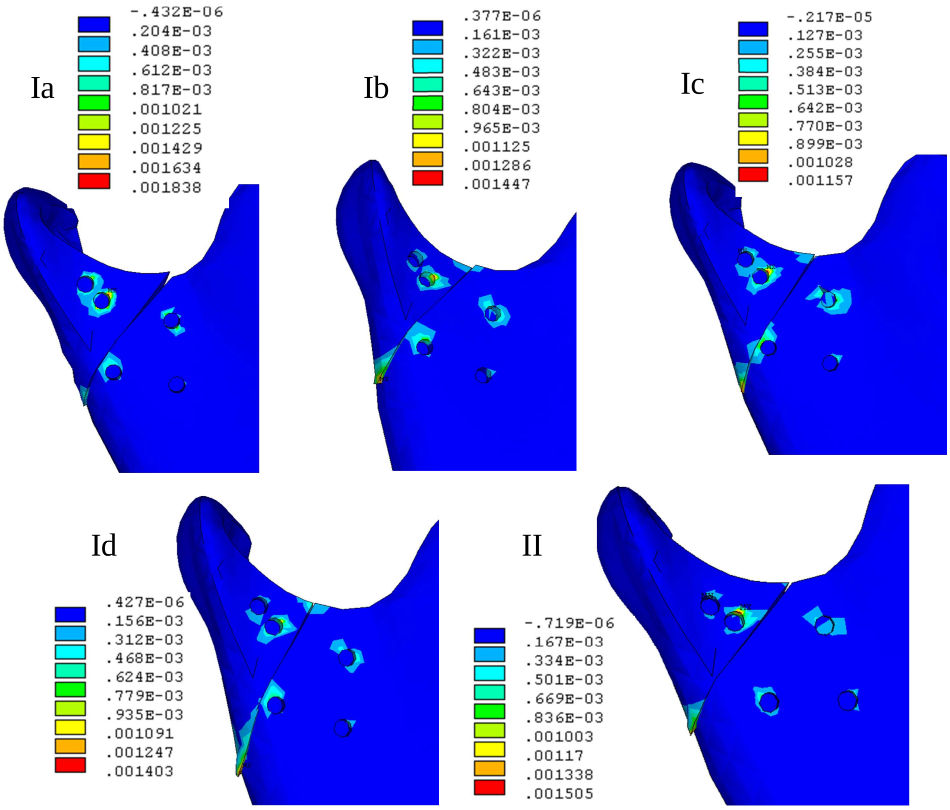


Fig. 9. Distribution of the principal strain ε_1 in the bone of the mandible

Analyzing the movement of the bone fragments along the axis z (direction: back of-front of), coronoid displacement anteriorly is visible in all cases (range 0.111-0.062 mm) (Fig. 10b). For cases Ib and Ic the displacement of the bottom piece of the smaller fragment of the bone can be observed, but it is 2.5 times lower. The effect of this movement may be a small enlargement of fractures line of bone fragments.

In all analyzed cases, the maximum displacement value does not exceed 0.15 mm. However, studies have been performed for the final stage of treatment (after a period of about 6-8 weeks), when the value of the elastic modulus of callus shall be assumed as E = 200 MPa.

Figure 11 shows the comparison between the axial displacements for the analyzed cases.

Comparing the values of displacements U_{sum} for the analyzed cases and the case of the fixation of condylar fractures with two plates 2.0 [11, 21], can be observed that they are similar, especially for the case of Id (Fig. 12). It seems that the analyzed 3D Rhombic plate can provide a similar stabilization of bone fragments. However, for a full evaluation the analysis with assumptions on the initial phase of treatment should be performed.

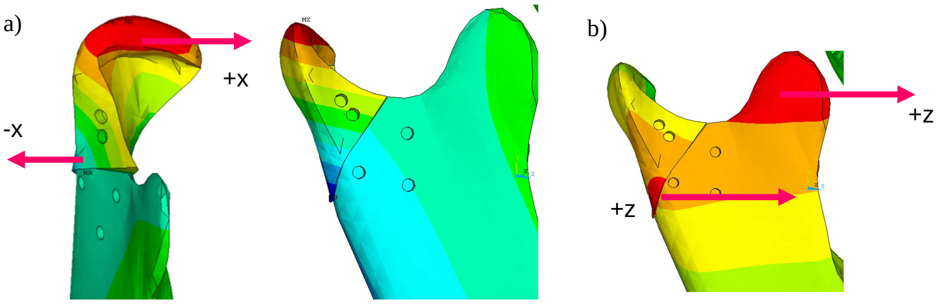


Fig. 10. Displacements: a) U_x and b) U_z for cases Ib

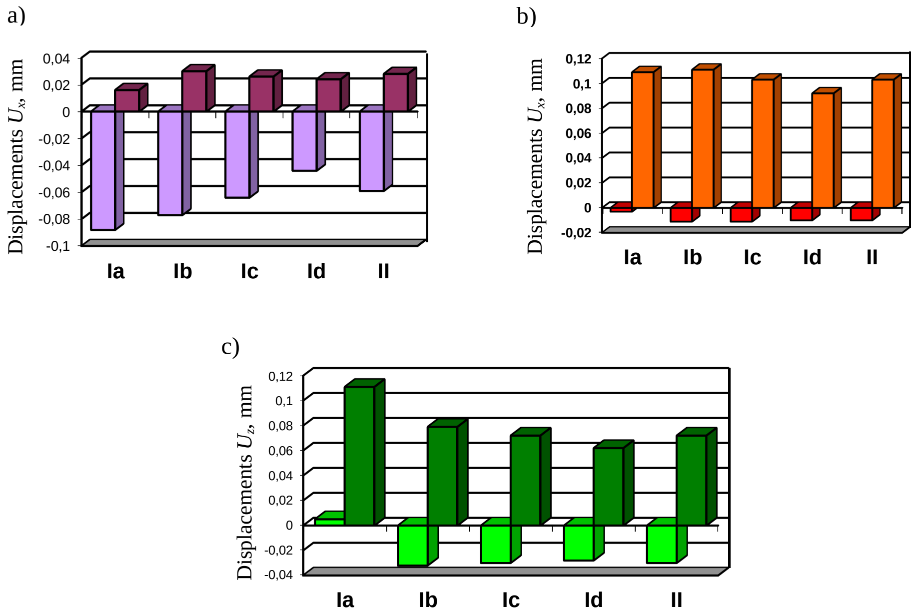


Fig. 11. Comparing the values of axial displacements: a) U_x, b) U_y and c) U_z for the fixation of the condylar fracture

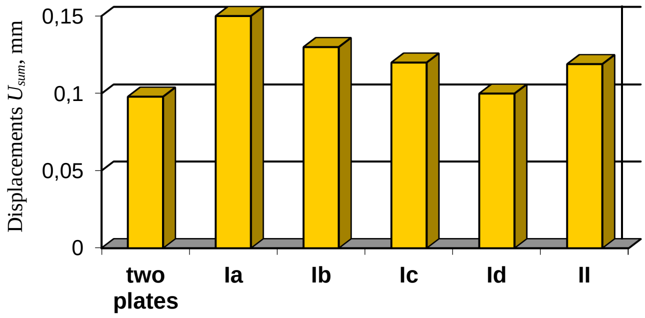


Fig. 12. Comparing the values of displacements U_{sum} for the fixation of condylar fractures

8. Summary

In recent years there have been several attempts to demonstrate the enormous potential of virtual modeling and rapid prototyping in the medical practice. Particularly promising area of development is the correction of facial-maxillar characterizing of very high aesthetic requirements. Thanks to the assessment of the state of stress in the jaw with chewing function, overloading of bone structures arising from strikes, the assessment of the phenomena occurring in the bones merging and reconstruction and analysis of the implant after surgery osteosynthesis and reconstruction is common. Also in the aspect of the design of new components and optimize existing inclusive planning of this type of surgerys.

Described in the article workflow not only has visualization purposes. Used in conjunction with specialist knowledge and experience of the surgeon also has practical applications in planning surgery. It can also help the surgeon to decide on the selection of the appropriate treatment and early surgery planning. In the article there is presented an example of tomographic reconstruction in maxillofacial surgery planning surgical correction of mandibular prognathism and obtained simulation of patient's appearance. That reflects very well the actual changes in the appearance of the patient, which would appear after the surgery. In the future, it can help patients to make decisions related to the submission to the surgery. Virtual simulation presented the appearance of a patient after surgery, and the final result may preferably motivate the patient's psyche by showing him what changes can be expected.

The development of computer technology has increased the possibility of using them for modeling, numerical simulation and stress analysis. Today they are one of the main tools in the evaluation of the states of biological structures.

Numerical methods are repeatable, and in addition cheaper and more effective, also in terms of time relation to clinical.

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