Stress-strain Analysis of the Temporomandibular Joint with Subtotal Prosthesis

Josef Daněk, Taťjana Dostálová, Milan Hubáček, Nima Mahdian, and Jiří Nedoma

Abstract—**The aim of the paper is a stress-strain analysis of the temporomandibular joint (TMJ) with subtotal replacement. The temporomandibular joint is a complex, sensitive and highly mobile joint which works bilaterally so each side influences the contralateral joint and because of this the distribution of the stresses is changed in the healthy joint as well. Detailed knowledge about function these are necessary for clinical application of temporomandibular joint prosthesis and also help us estimate the lifetime of the prosthesis a possibilities of alteration in the contra lateral joint components. The mathematical model of TMJ with replacement is based on the theory of semi-coercive unilateral contact problems in linear elasticity. The numerical solution is based on finite element approximation. The obtained numerical results will be discussed.**

Index Terms—**temporomandibular joint, cysts, prosthesis, finite element method, contact problem.**

I. Introduction

THE temporomandibular joints function symmetrically and this harmony allows biting, chewing and speaking. There are two types of movement: (a) rotary movement, (b) sliding movement. Movements are mostly combined together resulting in the following jaw movements. Because the TMJ is a bilateral joint, function or change of one side influences the contralateral side. In our case the right TMJ is resected and replaced by subtotal prosthesis. During the surgery the medial pterygoid muscle, masseter muscle and temporal muscle were cut off and resutured to the replacement (subtotal prosthesis UNILOC). Temporomandibular disorders (TMDs) is a generic term and may occur for many reasons involve among others pathological processes in condyle of mandible. Temporomandibular disorders (TMDs) are a term embracing a number of clinical problems that involve the masticatory musculature, the temporomandibular joint and associated structures, or both. These disorders are accompanied by pain in the masticatory muscles, in the TMJ, and in the associated hard and soft tissues. Other symptoms include limitation or deviation in the mandibular range of motion, TMJ sounds, and/or headaches and facial pain.

In this case we deal with patient, who underwent surgery because of a large cyst (see Fig. 1a) on the right mandibular

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(a)

(b)

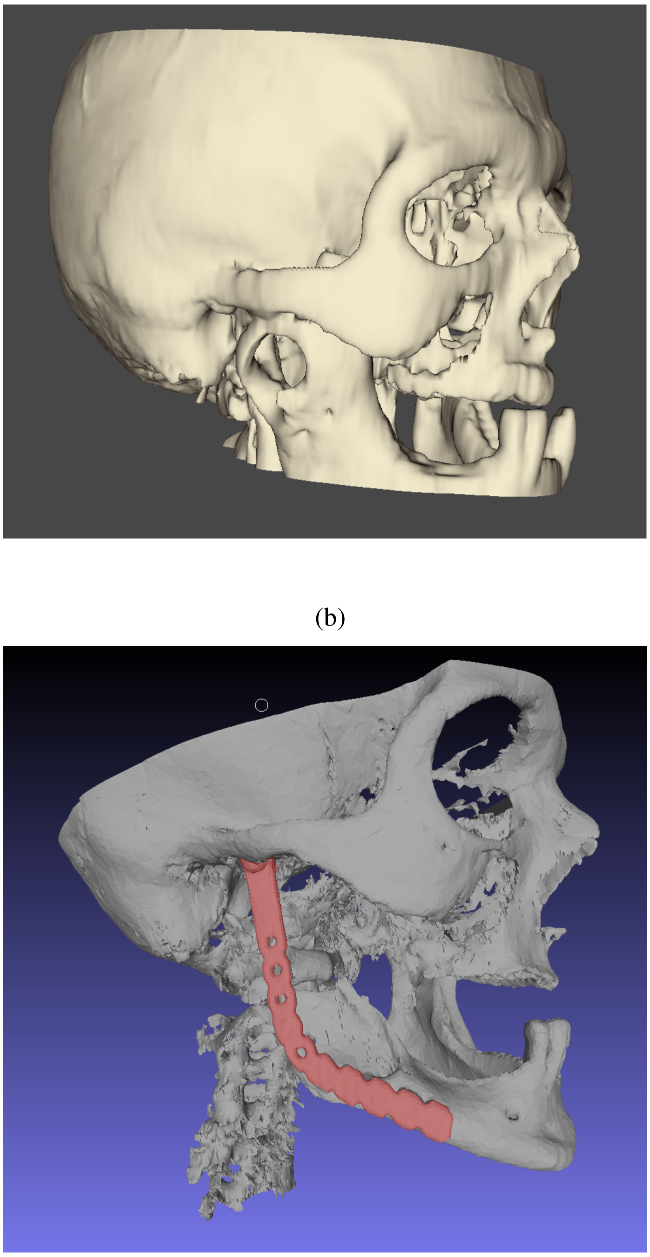

Fig. 1. Comparison of the jaw (a) before and (b) after the surgery.

ramus from the condyle to the angle of the mandible and reconstruction by partial join prosthesis (see Fig. 1b) and as further discussed in the case report, now two years after surgery is the patient with minimal discomfort. Applying the subtotal TMJ replacement biomechanics of the joint system changed. An imbalance will result in a failure of the function and integrity of the TMJ. Therefore, the aim of the mathematical model of TMJ and TMJ prosthesis

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(TMJP) functions is to establish conditions for preventing any imbalance of the harmony and potential destruction of the TMJ and TMJP. TMJ is strained by pressure and traction, the contact surfaces of TMJ lead to separate in the case of traction and to press in the case of pressure action. Therefore, it is important to mathematically simulate and to analyze the different behavior of each joint during jaw movements, and above all, during nonsymmetrical movement after the surgery. Since the mathematical model allow us to evaluate the application of mechanical and biomechanical aspects of TMJ on prosthesis of TMJ (TMJP). The construction of TMJP and its application by surgical treatment must satisfy or be as much as possible close to human physiological biomechanical parameters, only then the TMJP for our patient will function for a long time without great difficulties. This is the aim of our study for the discussed patient with the large cyst of mandible ramus. Since the patients glenoid fossa was in a good condition, the reconstruction of the right TMJ was made by using the subtotal replacement only. Therefore, the object of our study was a patient after implantation of a subtotal TMJ replacement after resection of right mandible ramus due an extensive cyst. We focused on evaluation of the present and future function of her reconstructed TMJ joint. For this reason we first modeled the healthy 3D model of the mandible, the used data were the data set of axial CT. The results were published in [3], [1].

II. The model

The model for mathematical (numerical) analyses of our patient case was constructed on the basis of real geometry, based on the data from the 3D-CT scan of the destructive cyst on the right ramus mandible, and, therefore, it renders it possible to estimate and to evaluate the future function of both TMJ. Such 3D simulation also brings us new views for evaluation of reconstructive performance in facial skeletal system. To fully understand the response of the glenoid fossa to the prosthesis we need to understand, how the internal forces are distributed through the prosthesis to glenoid fossa and how the changes in right side of joint influence contra lateral joint. Here mathematical modeling of movements of TMJ and distributions of stress-strain fields in operated joint can be used for better understanding of TMJ and its artificial replacement, biomechanical aspects, its function and morphology.

TMJ devices are used as endosseous implants for replacement of each part of temporomandibular joint. For a TMJ implant to be successful is important biocompatibility, low wear and fatigue materials, adaptability to anatomical structures, rigidly stabilized components, corrosion resistant and non-toxic nature. TMJ implant devices can be generally divided to subtotal (partial) or total replacement. The first one is consisted just from one component and it depends, if we want to reconstruct the glenoid fossa (the fossa component) or we want to replace the condyle of mandible (the condyle component). The total replacement consists both the fossa and condylar components. In this area underwent great development custom made total joint prosthesis. It is also because of progress in 3D imaging technology and possibility of mathematic modeling of human skeletal system. Thanks to this is possible by using data from 3D computer model make a 3-dimensional plastic model of the TMJ and associated jaw structures and on this model fabricate a custom-made total joint prosthesis conforming to the patients specific anatomical morphology and jaw interrelationships. Using this technology allows also correction of facial deformities, which are often associated with TMJ disease, in the same operation [8].

(a)

(b)

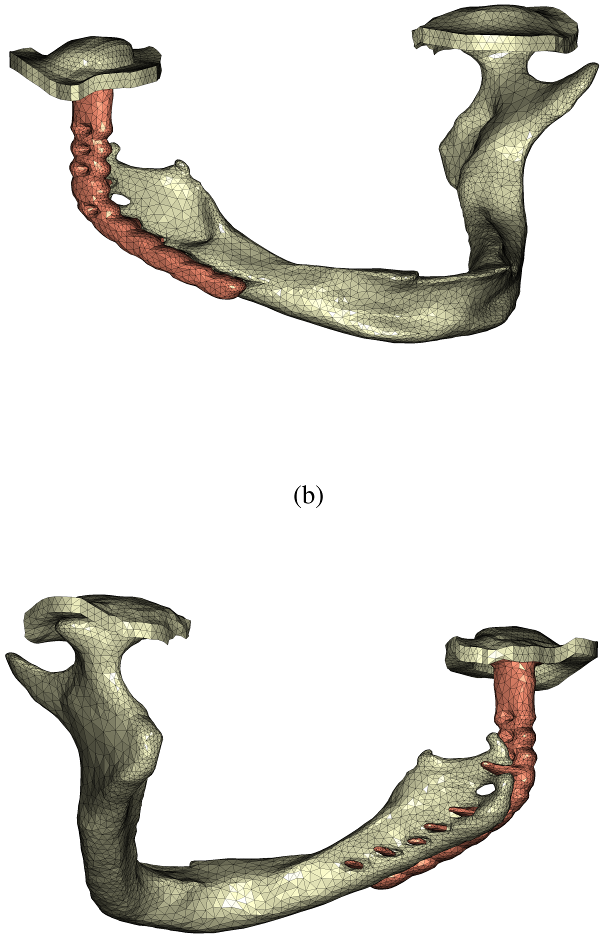

Fig. 2. The finite element mesh.

In our case we used subtotal replacement of condyle and ramus mandible, because the clinical examination and CT scan didn't show any destruction of glenoid fossa. Also the surgery is not so stressful for the patient and rehabilitation after the surgery is easier and faster. Another benefit of the subtotal replacement is possibility of use before of the end of facial skeletal system growth.

The stress-strain analyses of TMJ and TMJP based on several numerical models and methods, namely the finite element method, were studied by several authors [4], [6].

The mandible, the prothesis and the related parts were approximated by the tetrahedral 4-nodes FE elements. The magnitudes of muscle contraction forces (in N) were estimated with the product of the cross-sectional region of the muscle (in cm^2), the averaged activation ratio, which is taken for all muscles the same of the masseter, and the constant $\nu = 40$ N/cm^2 [7]. The FEM model simulates the statically

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loaded mandible in occlusion, where the TMJ is modeled as an ellipsoid-and-socket (or a ball-and-socket) joint. The prosthesis is applied by such a way that the location of the center of rotation is steadily fixed. In the compression with the left (healthy) TMJ any muscle forces are neglected.

The frictional force on the contacts between the loads of TMJ (P) right and light joints are approximated by the given frictional forces based on the Coulombian law of friction. Due to the existence of the synovial liquid (fluid) in the TMJ joint, the coefficient of Coulombian friction is very small, so that the frictional forces can be neglected in special cases.

The mathematical model and its numerical solution is based on the theory of semi-coercive unilateral contact problems in linear elasticity [2], [5]. The contact between the condyles and the joint discs are approximated by the unilateral condition.

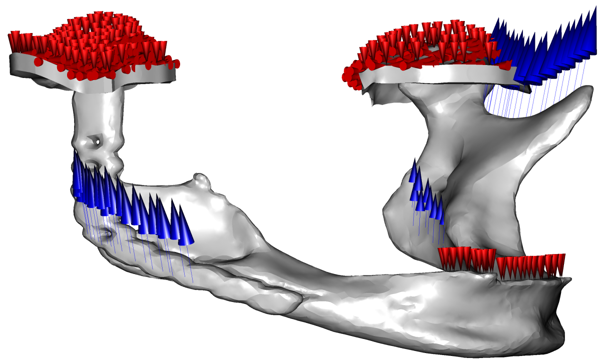
The finite element mesh is characterized by 43107 tetrahedrons with 12006 nodes (see Figs 2a,b)). The contact boundaries between the condyles of the mandible and the glenoid fossa are approximated by 40 nodes. For the numerical model the following boundary conditions are prescribed: (a) the temporal bone, where the sockets of TMJ are located are fixed; (b) at the upper side of the teeth vertical displacements of about 1mm are prescribed; (c) we have (i) functioning masticatory muscles of the left TMJ acting on the head of the mandible of loads of about $[0.9, -0.6, 2.8] \times 10^6$ N/mm^2 for the lateral pterygoid muscle, about $[0.7, -0.6, 2.8] \times 10^6$ N/mm^2 for the masseter muscle and about $[0, -0.5, 1.5] \times 10^6$ N/mm^2 for medial pterygoid muscle are prescribed; (ii) functioning masticatory muscles of the right TMJ acting on the head of the artificial prosthesis of loads of about $[-0.7, -0.2, 2.4] \times 10^6$ N/mm^2 for the m. masseter and about $[0, -0.5, 1.5] \times 10^6$ N/mm^2 for the m. pterygoideus medialis are prescribed, where the m. pterygoideus lateralis was get out during the surgical treatment (see Figs 3a,b). For the realization of the numerical solution the COMSOL Multiphysics with the Structural Mechanics Module were used.

III. Results and Discussion

The main objective of this investigation is to introduce a three-dimensional finite element model to calculate the static loading of the TMJP and to characterize processes in the TMJP during its function. A geometrical model of the TMJP was created using the dataset of axial computer tomography (CT). The values of material parameters are $E = 1.71 \times 10^{10}$ Pa, $\nu = 0.25$ for the bone tissue and $E = 2.08 \times 10^{11}$ Pa, $\nu = 0.3$ for the material of replacement. For the numerical model we set the boundary conditions presented in Figs 3a,b.

At Figs 4 a,b the horizontal displacement components in the directions of the x-axis and y-axis tell us about the movements (due to deformation of the mandible) of the loaded mandible in the horizontal plane, moreover, in the consequence of the operated muscles. We see that their effect is greater in the area of the left TMJ joint. At Fig. 4c the vertical displacement component is given. It is shown that the minimal value of -2.339×10^{-4} m is in the area of both glenoid fossa, vertical part of replacement and dorsal part of mandible ramus on the left (healthy) side and the maximal values are in the area of mandible corpus and coronoid processus of the left side

(a)



(b)

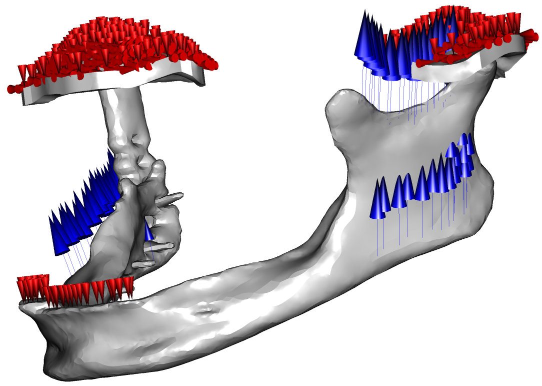


Fig. 3. The boudary conditions.

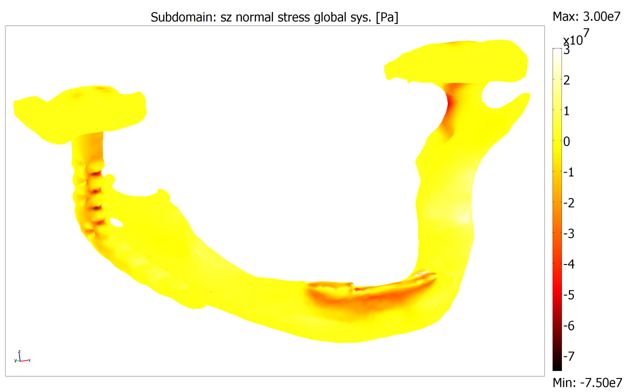


Fig. 5. The vertical stress component.

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(a) (b) (c)

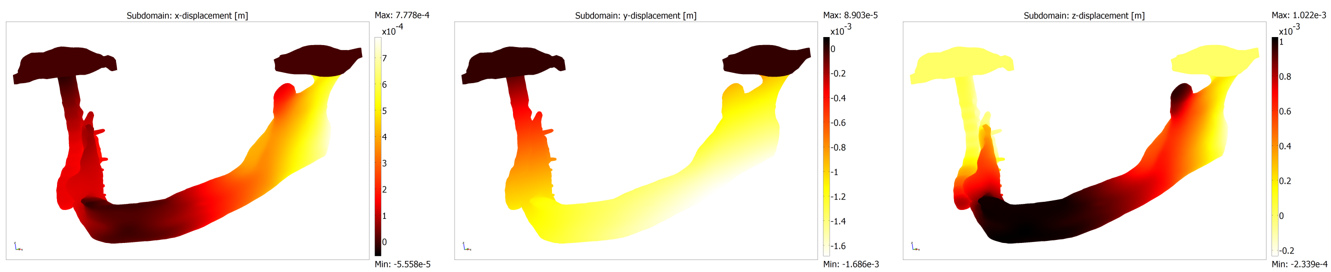

Fig. 4. The displacement components in the directions of (a) the x-axis, (b) the y-axis, (c) the z-axis.

(a) (b) (c)

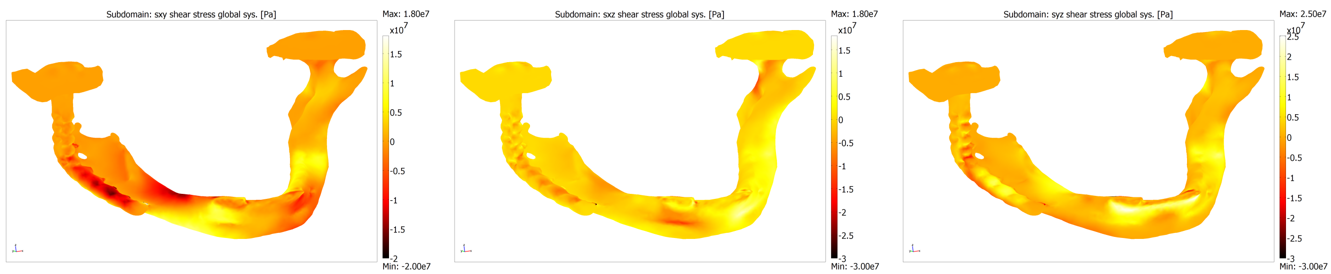

Fig. 6. The shear stress components (a) in the plane xy, (b) in the plane xz, (c) in the plane yz.

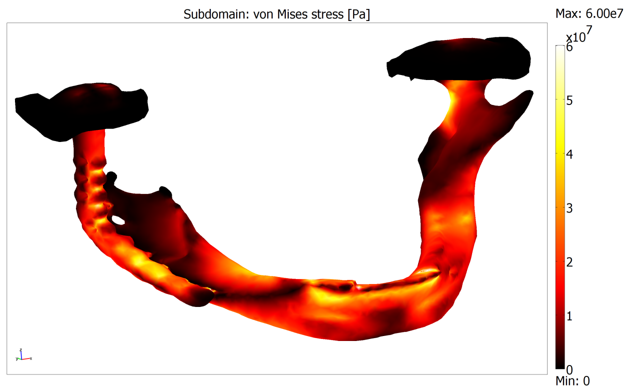

Fig. 7. The von Mises stress.

At Fig. 5 the vertical stress in Pa is presented and at Figs 6 a,b,c the shear stresses in Pa are presented. The von Mises (Fig. 7) and the principal stresses (Fig. 8) have a great expressive value for specialist in maxillofacial surgery. The von Mises stress is a mathematical combination of all components of both axial and shear stresses. The principal stresses inform us about stresses in directions of the principle axes. They can be usually used to describe the stresses in the studied mandible, and, therefore, they are reasonable indicators, where failures and fractures can later occur. The maximal von Mises stresses in the mandible are located in dorsal part of column mandilble, in the area of the artificial prosthesis and in alveolar processus of corpus mandible. We see that the more informed value have principal stresses. The principal stresses are characterized by pressures, denoted by $\rightarrowtail\!\!\times\!\!\leftarrowtail$ (red color), and by tensions, denoted by $\longleftrightarrow$ (blue color). The mandible in its frontal part is vaulted in the chin elevation that is then passing into the mandible body, where in its frontal part the pressures are observed. In the posterior part (i.e. from the interior = inner side) of the mandible the tensions are observed (Fig. 9a). The upper margin of the mandible body projects (jets) in the alveolar processus with the tooth beds where tensions are observed, while in the lower margin of the mandible, which is rounded off (plumbed), the pressures are indicated (Fig. 9b). The ramus of mandible is closed by the condylar and coronoid processus and that are separated by the mandible incisure. In this area in its anterior part in the healthy TMJ the pressures are observed, while in its posterior part tensions are observed, which is characterized by its bending. In the other side, where is the replacement, the distribution of stresses in the prosthesis is different in comparison with the healthy part of TMJ. The load from the joint is transported as the pressure in the anterior part of the prosthesis, while in its posterior part (side) small amplitude of tensions are indicated. From the distribution of stresses in the mandible, it is evident that the loading of the mandible body as well as TMJ is different, but the TMJ is functioned, although distribution of the acting muscles is different, the medial pterygoid medial muscle, masseter muscle and temporal muscle were cut out from their primary anatomical position and resutured to the prosthesis during the surgery and pterygoid lateral muscle have now minimal influence in distribution of stress.

We see that the maximal values of pressures are observed in the area of the condyles of TMJ, while tensions can be ob-

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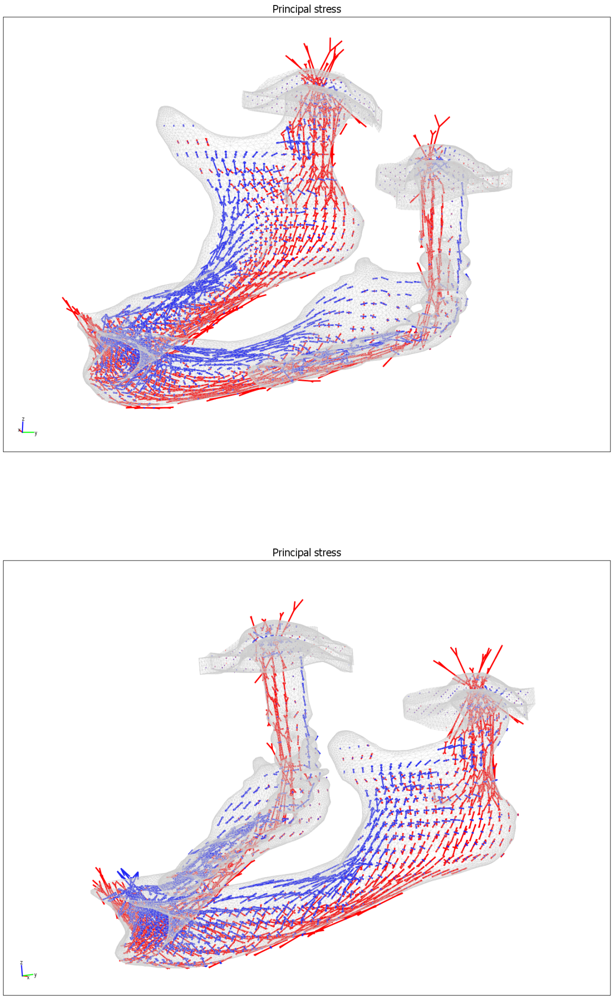
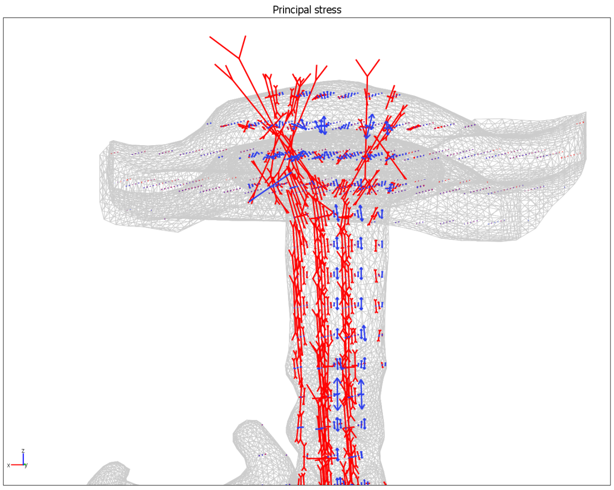


Fig. 8. The principal stresses.

(a)



(b)

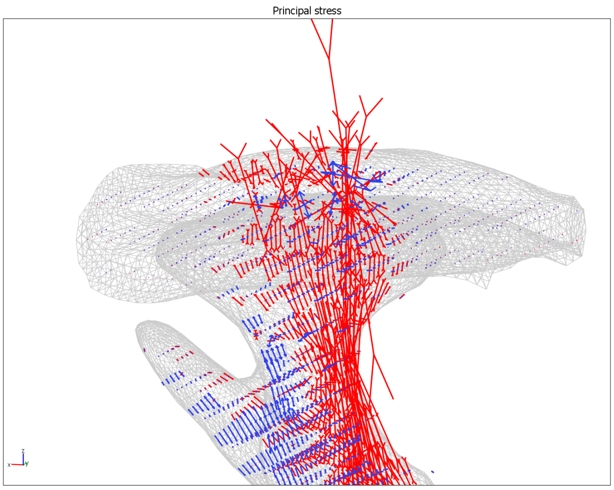


Fig. 9. The principal stresses - the details.

served in cranial part of corpus mandible. Numerical results show that the maximal pressure is approx. -1.05427×10^8 Pa and the maximal tension is approx. 2.02357×10^8 Pa. Interesting is the change of pressures and tensions in mandible ramus and ascendant part of the prosthesis. In the healthy left ramus are the pressures localized on posterior part and tensions on the anterior part on the right side is the opposite suitace (pressures localized anteriror and tensions posterior). It is because of changes of position of the muscle during the surgery. The studies of the detailed areas are at Figs 9a,b and 10a,b. At Figs 9a and 9b the principal stresses are presented while at Figs 10a and 10b the von Mises stresses are presented. The von Mises stresses shows that the loading of the glenoid fossa (acetabulum) is spread evently in the healthy TMJ, where the stresses have lower values then in the TMJP case and the stresses is situated into three greater areas, while in the TMJP case the stresses is accumulated into two areas with maximal stresses internal part of the head of TMJP. The principal stresses show how the loads are transferred into the mandible and which parts of the mandible are pressed and/or are strained by bending.

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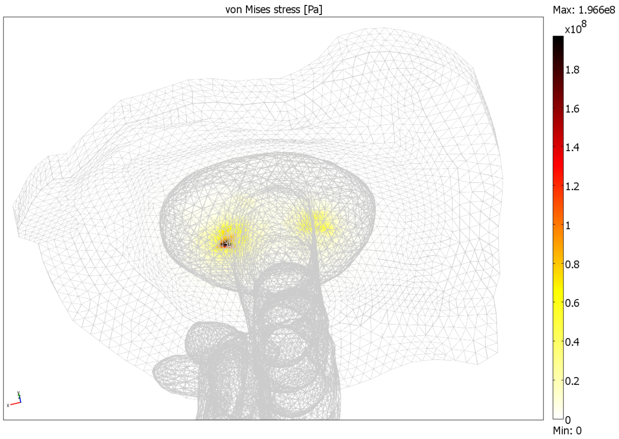
(a)



(b)

Fig. 10. The von Mises stress - the details.

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