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Plates and Jaw Stress-Strain State in Case of a Lower Jaw Angular Fracture

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Abstract: One of the most pressing issues of maxillofacial surgery is the traumatism of the facial bones. At present, titanium plates with screw joints are the commonest for fixing jaw fragments in maxillofacial surgery. The cause of complications in osteosynthesis with titanium is the force generated by the masticatory muscles, transmitted through the plate and jaw fragments, and causing looseness of the screw joints. Moreover, plate fractures are caused by material fatigue due to plate bending occurring under surgery. The purpose of this paper is to compare the plate designs according to the maximum stresses arising under the action of masticatory loads and to check the fixation reliability with the subsequent plate development of a reduced bone-plate contact area. Ansys Workbench software package, namely the Transient Structural module, is used for calculations based on the finite element method to study the stress-strain state of the lower jaw after titanium osteosynthesis. Plates' designs for osteosynthesis metal are developed considering the strength of the masticatory muscles. The maximum stresses in the plates have been determined, which are 481 MPa for a straight plate, 487 MPa for a y-shaped plate, and 301 MPa for a square plate. Following the mentioned, these stresses do not exceed the yield strength of titanium grade BT1, the smallest of them occurring in a square-shaped plate. The maximum gap has been also determined, between fragments it is 0.75 mm for a straight plate, 0.15 mm for a y-shaped plate, and 0.13 mm for a square plate. Therefore, the square plate provides the most reliable fixation of jaw fragments.

Keywords: Angular fracture, mandible, masticatory muscle forces, stress-strain state, titanium plates, metal osteosynthesis, Ansys Workbench, Transient Structural module, finite element method, computational mesh.

1. Introduction

One of the most pressing issues of maxillofacial surgery is the traumatism of the facial bones. This is mostly the result of domestic injury, traffic, or street injuries.

Most fractures require rigid fixation, and for almost the past 40 years, surgeons have been using titanium plates and screw joints for this purpose. Although titanium is a biologically inert metal, its further prolonged presence in the human body can cause patients infectious complications at osteosynthesis sites, damage to nerve fibres, teeth damage, erosion of soft tissues, and a decrease in quality of life, which is associated with cold intolerance within the area where the plate is located and permanent sensation of the foreign body presence [1, 2].

Osteosynthesis is a bone segment repositioning, a routine procedure widely used

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to treat fractures of the facial bones in maxillofacial surgery. In 1886, Dr Carl Hansmann was the first to create and use a self-made plate system for osteosynthesis [3]. Today, with the help of such systems, surgeons can restore deformities and other defects. The present invention's meaning is to fix and contain cystic fragments, as well as immobilize the fracture site.

Now titanium plates and screw joints are commonly used in the practice of maxillofacial surgery, with their advantage, they are considered the golden standard. Titanium has become the biomaterial of choice, as it has many advantages: firstly, it makes rigid fixation possible, it is the closest in elasticity modulus to bone tissue, resistant to corrosion, and does not change in size [4]. Secondly, it exhibits the ability to osseointegrate and is biocompatible. Thirdly, titanium is not a ferromagnet; therefore, it has minimal scattering on computed tomography and is compatible with radiographic and magnetic resonance studies [5]. The main disadvantage of titanium plates is traumatization by screws during implantation and the need to remove the plates after bone fusion. It should be noted that there is still no consensus on the need for a second operation. It is believed that some asymptomatic plates may be left at the fracture site [6–8]. However, in some cases, titanium plates are to be removed. For example, in case of infection at the implant site, patient pain, hypersensitivity, reaction to a foreign body, problems with children's growth, plate fractures, if the plate is manifested by palpation or visually, a stress shielding effect is possible [3]. After all, titanium plates are considered more profitable, as they have a more affordable cost and better health outcomes [9].

Unfortunately, using plates for osteosynthesis, some complications arise, which are rather difficult to avoid. The most common complications include exposure, fracture of plates, plate loosening, or screw loosening. The complications' cause is the force generated by the masticatory muscles, which is transmitted through the opposing teeth site and leads screw looseness, as well as plate fractures caused by the presence of opposing teeth or material fatigue due to bending and rotation of the plate during surgical implantation [10].

Each of the fixation methods has its advantages and disadvantages, and given this problem's relevance, based on the incidence of mandibular fractures and complications that occur during treatment, it is obvious that the most optimal fixation method needs to be developed.

2. Experimental Section

The main purpose of this study is to compare plate designs in terms of maximum stresses arising under the action of masticatory loads, and verification of fixation reliability with the subsequent development of a plate with a reduced bone-plate contact area.

Ansys Workbench software package is used to study the stress-strain state of the lower jaw after titanium osteosynthesis, namely its Transient Structural module, the calculations based on the finite element method. The first step is the creation of a three-dimensional solid model, based on a performed computed tomography, after which, using the SolidWorks program, the fracture site is indicated and a plate with screw joints is built. The next step is to determine the mechanical properties of each element of the model, the following average properties are taken for the bone: Young's elastic modulus $E=16000MPa$, Poisson's ratio $\mu=0.3$, density $\rho=2.675g/cm^3$; for the plate material (titanium grade BT1): yield strength $\sigma_y=500MPa$; Young's elastic modulus $E=112000MPa$, Poisson's ratio $\mu=0.36$, density $\rho=4.505g/cm^3$ [11, 12]. Another important step is the computational finite element mesh construction, since the computational geometry has a complex shape, elements with mid-side nodes are used. Simulation grounds on a solid three-dimensional element. For better mesh production, Sweep Method has been used for the contact zone and the plate, which allows us to construct a structured mesh. In the settings, the number of elements chosen for the width of the plate is set to 5, and for the length of the screw body - 250. The elements of the jaw are proportionate. The lower jaw biomechanics is considered from the point of view of the function of the dentition, chewing is considered as the most loaded state. Consequently, the force as loads only from the action of those muscles that take part in this process is indicated. Figure 1 shows the location of the coordinate system relative to which the forces acting on the lower jaw under chewing and their vectors are set. Table 1 shows the values of these forces along the coordinate axes.

Table 1: Forces values of the muscles involved in chewing.

Muscle group name	*Muscle group force, N*
Temporalis media portion	(34; 35; 35)
Temporalis posterior potion	(34; 35; 35)
Masseter superficial	(22.7; 43.3; 45)
Masseter deep portion	(22.7; 43.3; 45)
Media pterygoid	(15; 53.7; 45)
Lateral pterygoid superior head	(28.9; 64; 30)
Lateral pterygoid inferior head	(28.3; 65; 17.5)

Table 2: Load features.

Force name	*Number of steps*	*Step time, s*	*step end time, s*
Temporalis media portion	5	0.024	0.24
Temporalis posterior portion	7	0.017	0.36
Masseter superficialas	10	0.012	0.48
Masseter deep portion	10	0.012	0.60
Media pterygoid	10	0.012	0.72
Lateral pterygoid superior head	10	0.012	0.84
Lateral pterygoid inferior head	5	0.024	0.96

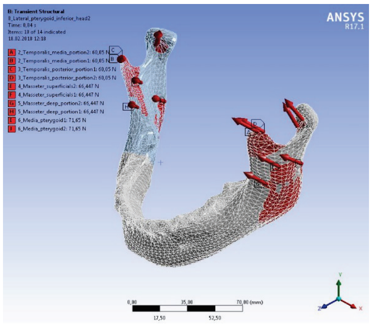

Figure 1: Forces vectors acting on the lower jaw under chewing.

To ensure the convergence of solution to the problem, the following approach of stepped loading in solid parts is used. The problem has been solved in 55 steps (the time of the end of the calculation is 0.84 s). Table 2 indicates how many load steps does it takes to each force and what is the size each time step. This division is made based on the stability of the problem solution convergence. Forces are applied according to a linear law.

Studying the stress-strain state. it is very important to correctly set the fixings as a set of boundary conditions. since it is the function of chewing that is considered. the jaw is to be constrained in three areas. For the side on which the food is ground relative to the coordinate system indicated in Figure 2a rotation restrictions around the Z axis and movement along Y. Z are set (all three other displacements: rotations around X. Y axes and movement along X are allowed); balancing side (the coordinate system is shown in Figure 2b) - are limited in rotation around the Z axis and movement along all axes. Since the chewing lump has a foam stiffness (2000N/mm^2). the type of Elastic Support contact is used (Figure 2c) [13].

(a) (b) (c)

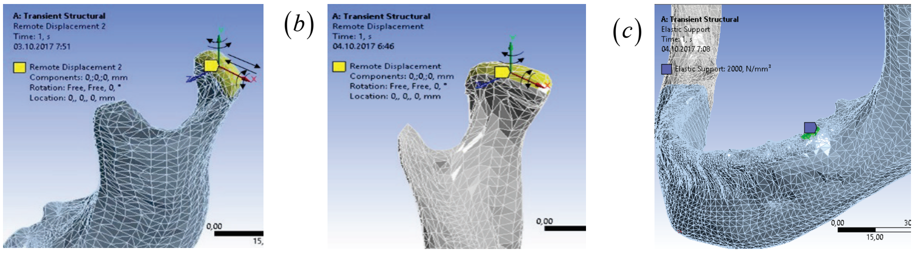

Figure 2: Displacement boundary conditions for simulation model: (a) The side of grinding food. (b) Balancing side. (c) The food hill area.

Of course. it is necessary to determine the nature of the contact interaction between the "jaw fragments - plate - screw joints" system elements to solve this problem. Ansys Workbench has great potential for contact modelling. Since there is friction between the elements of the system under study the type of contact “Frictional” is determined with friction coefficients of 0.5 for jaw fragments jaw and plates 0.3 and screws - plate 0.15 [14. 15]. The Interface Treatment parameter allows us to adjust the contact pair initial interaction, in this case, the target and contact surfaces of all bodies only touch, so Adjust to Touch setting is used to ignore any penetration and gap. For the same contact pairs the Augmented Lagrangian method is chosen as a calculation method. and the contact stiffness calculation is calculated at each iteration. A threaded connection between bone fragments and screws is simulated with the virtual screw method used to reduce the computational mesh size. The Multi-Point constraint contact calculation method and the calculation of contact stiffness depending on iterations are not carried out.

3. Results and Discussion

The study of the stress-strain state of the system "jaw fragments - plate - screws" has been carried out for the plate designs shown in Figure 3.

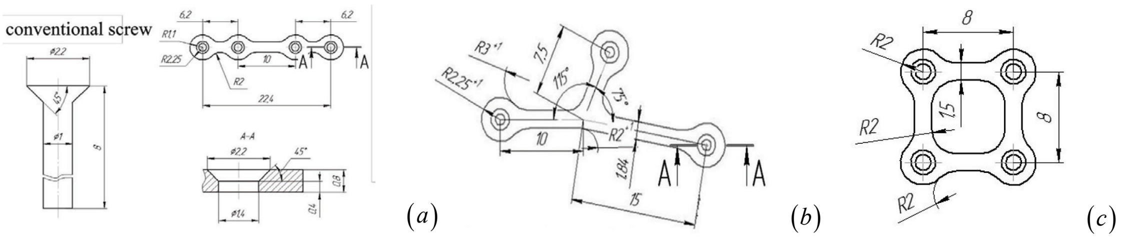

Figure 3: The design and dimensions of the plates: (a) Straight plate with a cross-section in the screw area. (b) Y-plate.

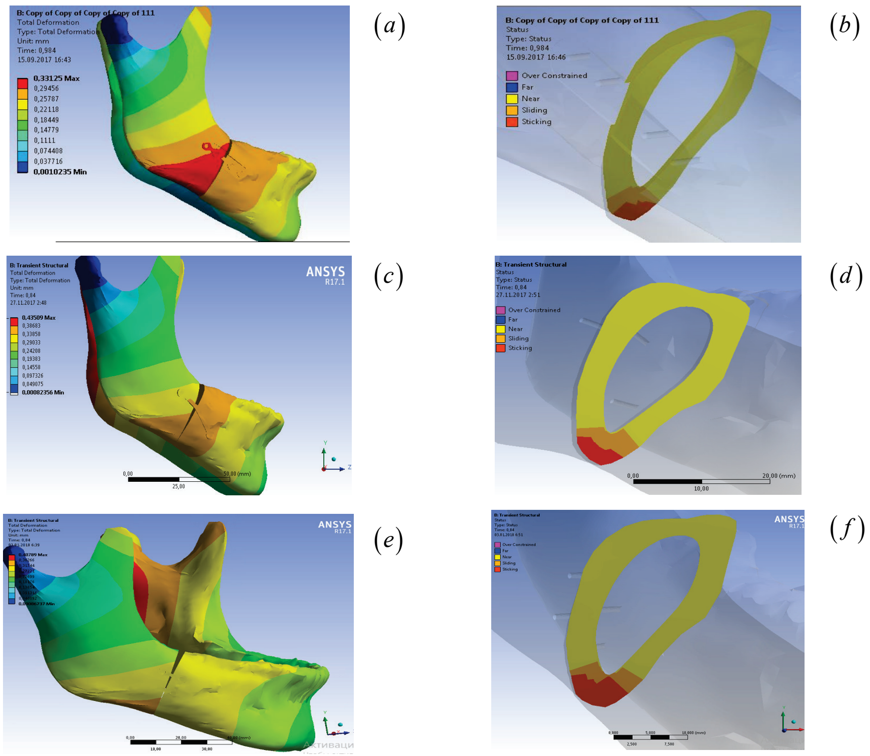

Figure 4: Displacement of the simulation model and contact areas: (a. b) straight plate, (c. d) Y-plate, (e. f) square plate

(c) Square plate.

Figure 4 shows the increased displacements of the simulation model with different plates and their contact areas. As can be seen from the calculation results. the jaw fragments in all cases are in contact in the lower part. but their contact area and the greatest distance between them are different in each case. For a plate having a straight shape (Figure 3a) this distance is 0.75mm . an y-plate (Figure 3b) - 0.15mm and a square plate (Figure 3c) - 0.13mm. The distance between jaw fragments is obtained from displacement solution to simulation as a distance between nodes simulating separated jaw parts. Consequently it can be concluded that the square plate provides the most reliable fixation of jaw fragments. It should be noted that all plates work under bending and torsion.

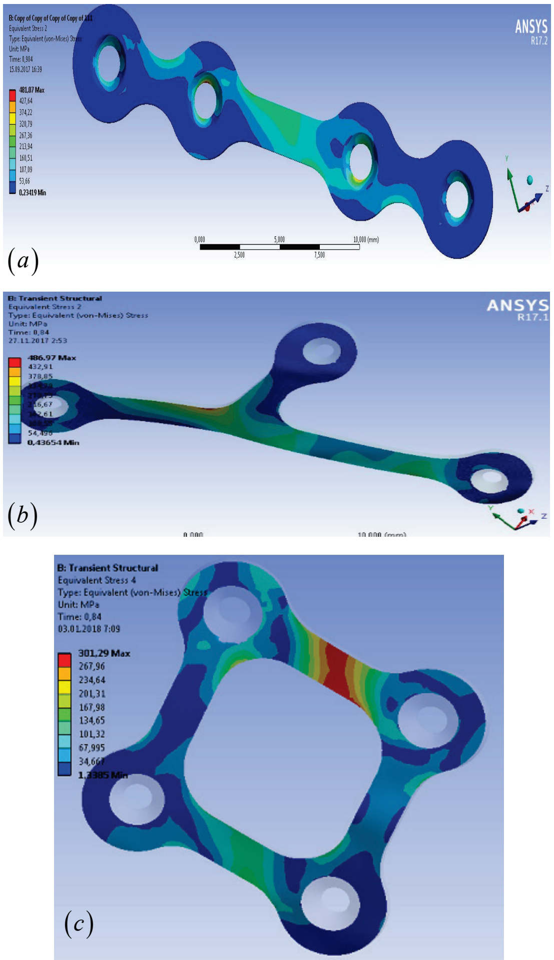

Figure 5: Equivalent von-Mises stresses of the simulation model: (a) Straight plate with a cross-section in the screw area. (b) Y-plate. (c) Square plate.

It is necessary that the stress used in the plates not only does not exceed the tensile ultimate material strength but also does not exceed the yield strength (after the load is removed they must return to their original undeformed shape). Figure 5 shows the equivalent von-Mises stresses of the investigated plates. As can be seen from the above results the maximum stress in a straight plate is the y-plate is the square plate is and the last stress is the smallest compared to others. Considering that one of the square plate parts practically does not perceive the load in the future it is necessary to investigate the change in its shape namely the absence of one side of the square.

4. Conclusions

Modelling methods for contact interaction of elastic bodies have been analyzed and a method for numerical simulation of the stress-strain state of the jaw fragmentation system - plate - screws has been developed. The maximum stresses in the plates have been determined which are for the straight plate for the y-plate. and for the square plate. As can be seen from these values these stresses do not exceed the yield point of titanium grade BT1 the smallest of them occur in a square-shaped plate. Analyzing its stress state. it can have been concluded that one of the square sides can be excluded; the following studies will be directed to the study of such a plate shape.

The maximum gap between fragments has also been determined which has been for a straight plate for a y-plate and for a square plate. Therefore the square plate provides the most reliable fixation of jaw fragments.

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