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MODELING OF RESISTIBILITY OF THE JAW BONE TISSUES AT THE POWER LOAD OF ORTHODONTIC MINI IMPLANTS

Abstract

The objective of this study was to evaluate various types of stress in cortical and cancellous bone around miniscrew implants of different type using finite element analysis. Three types of constructions of the 8 mm long mini implants produced by different manufacturers ACR (Korea), POM (Russia) and OMG (own construction) were studied being inserted in the mathematical model of alveolar process at the 90^o, 60^o and 45^o angles and two types of cortical bone thickness – 1 mm and 2 mm. All the models of the biomedical systems "bone-mini implant" have demonstrated the best distribution of strains at the 2 mm cortical plate thickness as compared to the 1 mm thickness. At the power loading the biomechanical system "bone-mini implant", the area of strains concentration does not depend on the type of the mini implant construction and is located in the region of compression deformation of the cortical jawbone medium. The OMG mini implants demonstrated the largest maximal force degrees to be applied to the mini screw as compared to other mini implants used in this experiment.

Key words: mini implant, cortical and cancellous bone, stress distribution.

Introduction. Anchorage or orthodontic support is one of the most important factors of success in orthodontic treatment. Anchorage is defined as the resistance to undesirable displacement of teeth. A number of methods were suggested to solve the problem of orthodontic support, however, the most interesting of them are the systems of the skeletal anchorage onto the orthodontic mini implants. Many investigations have shown that the mini implant integrated into the alveolar bone is resistant to orthodontic force [8, 11, 12].

Within last years of particular interest is the use of the finite element method to study the orthodontic mini implants, namely, their biomechanical properties and distribution of strains in the surrounding bone. The finite element method was presented for the first time for studying biomechanics in dentistry in 1973 [6] and since that is being widely used to analyze the processes of compression and extension in the alveolar bone and periodontal ligament [7, 4]. This method of studies is also used to study biomechanical properties of dental materials and implants.

The finite element method was used to analyze viscoelastic processes in the bone tissue of the palatine suture region when applying titanium mini implants and have concluded that the above mini implants mounted in the palatine suture region can withstand applied loads with no risk of destroying the bone tissue even given the lack of osteointegration [10].

Another study utilized the finite element method to investigate strain distribution around the orthodontic mini implants inserted into the upper jaw to determine the dependence of biomechanical processes in the bone tissue on the mini implant length and degree of osteointegration in the "implant-bone" interface and have concluded that the 9 mm long mini screws are optimal for the use in the clinical practice, because they create the least strain in the alveolar bone and are more safe from the viewpoint of traumatic influence on the surrounding tissues. The authors summarized that the partial osteointegration is the most favorable, because it is sufficient for successful functioning of mini screw and does not create a danger of fracture in case of its removal [9].

The clinical data by other researches, demonstrated that the degree of success of the 8 mm long mini implant was 5.7 times larger than that of the same 10 mm long mini implant, which agreed with the previous studies [13].

Other scientists using the 3D-modeling determined the factors that may influence strain distribution in the bone tissue around the orthodontic mini implant. In accordance with the results of their studies, such parameters as the mini implant head diameter and length as well as the elasticity modulus of the cancellous bone influenced substantially the strain variations in the bone tissue around the implant, while the internal-bone length of implant, thread shape and pitch and the cortical bone thickness had no influence on it [5].

In another study the torque at insertion of mini implants at different angles was measured. According to it’s results, the most optimal insertion angle is 60^o–70^o, because in this case the larger torque was noticed ensuring primary stability. However, the authors did not study interaction of mini implant with the bone tissue at orthodontic load [14].

Despite any positive characteristics demonstrated by mini implants, their interaction with the bone tissue is not completely studied. The degree of failures described in literature reaches approximately 10 to 30% and remains quite large. Mini implant stability depends on many factors, including implant type, size, surface characteristics, insertion angle, drilling hole size, insertion torque, force magnitude, anatomic location, soft tissue characteristics etc. [3]. In our opinion, all the above factors need further analytical study.

Aim. The aim of this work was to carry out the comparative computational and theoretical investigation of regularities of strained and deformed state of biomechanical systems "bone-mini implant", to study the mechanism of transfer of static tension of orthodontic titanium mini implant on the bone tissue and to determine the boundary parameters of their biomechanical state at power loading the different-type mini implant constructions.

Materials and methods. The above problem is solved by using the methods of mathematical modeling to reconstruct the geometry of mini implants and heterogeneous structures of jaw bones that are visualized, the mechanics of solid state that is elastically deformed, the computational mathematics to solve the contact problems of elasticity theory and the information technologies for imitative modeling by means of the finite element method (FEM) in the CAD/CAE systems [2].

The object of present studies was the imitation computer model of biomechanical system "bone-mini implant" (fig. 1) with the normal density of human jawbone tissues formed of the three bulk structural elements, i.e. cortical bone, cancellous bone, titanium mini implant and their flat cross sections of specified thickness that could be elastically deformed and have isotropic characteristics of mechanical properties of materials (table 1).

Material	**E, MPa**	**ν**	**$\sigma_в$, MPa**
Cortical bone tissue	$2.46*10^4$	0.3	133
Cancellous bone tissue	$1.5*10^2$	0.3	8
Titanium (BT-6)	$1.20*10^5$	0.3	975
Titanium (Grade 4)	$1.15*10^5$	0.3	550

Table 1. Mechanical properties of materials of biomechanical system "bone-mini implant" (Malanchuk 2013), where *E* is the elastic modulus, *ν* is the Poisson ratio, $\sigma_в$ is the maximum strength.

It has been assumed that at power interaction between the contacting bone bodies and mini implant there is not complete osteointegration and sliding of biological tissues on the part of metal surface could occur.

Three types of constructions of the 8 mm long mini implants produced by different manufacturers ACR (Korea), POM (Russia) and OMG (own construction) were studied being inserted in the mathematical model of alveolar process at the 90°, 60° and 45° angles and two types of cortical bone thickness – 1 mm and 2 mm. Mini implant construction is determined by its functional purpose and involves the intraosseous part, neck that contacts with gingival tissue and supragingival technological part that serves to fix the power load. Small (1.2–1.8 mm) diameter of the endoosseous part of mini implants allows one to place them between the dental roots or in the area of missing tooth.

It has been found in accordance with the results of computational and theoretical studies [1] that the horizontal component of the implant power load vector defines the strength and reliability of biomechanical system. Therefore, to determine the resistibility of jaw tissue to deformation in the imitation model of biomechanical system the force vector directed in parallel to the external bone surface was applied to the mini implant head surface with different mini implant angular positions.

When determining the resistibility criteria of the biomechanical system "bone-mini implant" to the power load the indices of its boundary strained and deformed state (SDS) were set. Characteristics of the loss of resistibility of the bone medium at the strains preceding its destruction were determined as the criteria of full inapplicability for practical use of biomechanical system.

Results and discussion.

In order to determine the adequacy of obtained results and evaluate the numerical computations of resistibility to deformations of the biomechanical system "bone-mini implant" at the power load of mini implants the three-dimensional finite element model was developed with the ACR mini implant construction (fig. 1).

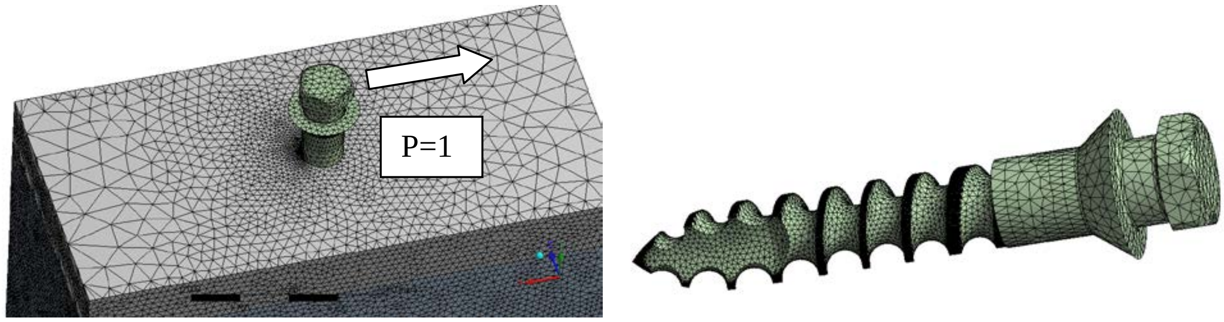


Fig. 1. The finite element model of the biomechanical system "bone-mini implant" and the ACR mini implant as well as the type of its power load. The number of finite elements joined by 590,241 nodes is 351,746.

In accordance with the results of the numerical experiment in the engineering analysis system ANSYS Multiphysics 12.1 when solving the three-dimensional contact problem of the elasticity theory, the dominating osteointegration surfaces of the jawbones and mini implants, the areas of concentration of stress and the intervals of variation of deformations and tensions of materials in the biomechanical system at given kind of its power load have been found (figs. 2–4).

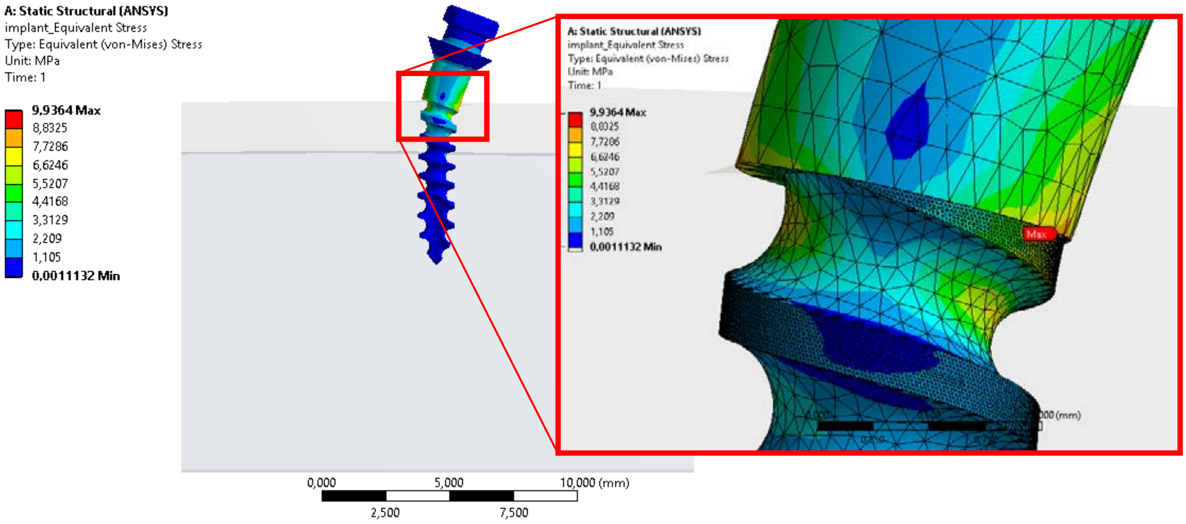


Fig. 2. The distribution of the von Misess equivalent stresses in the mini implant of the biomechanical system "bone-ACR mini implant".

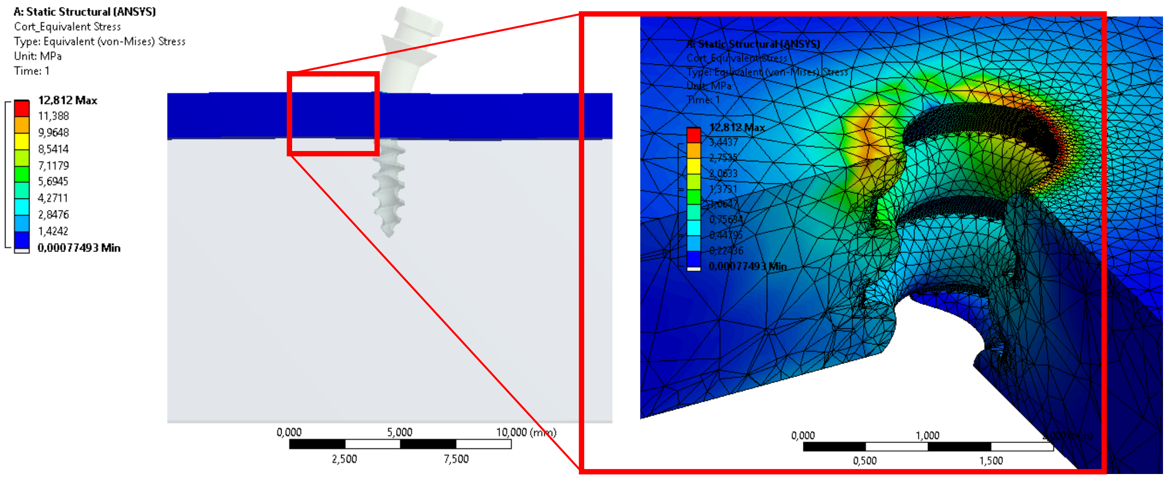


Fig. 3. The distribution of the von Misess equivalent stresses in the cortical jawbone of the biomechanical system "bone-ACR mini implant".

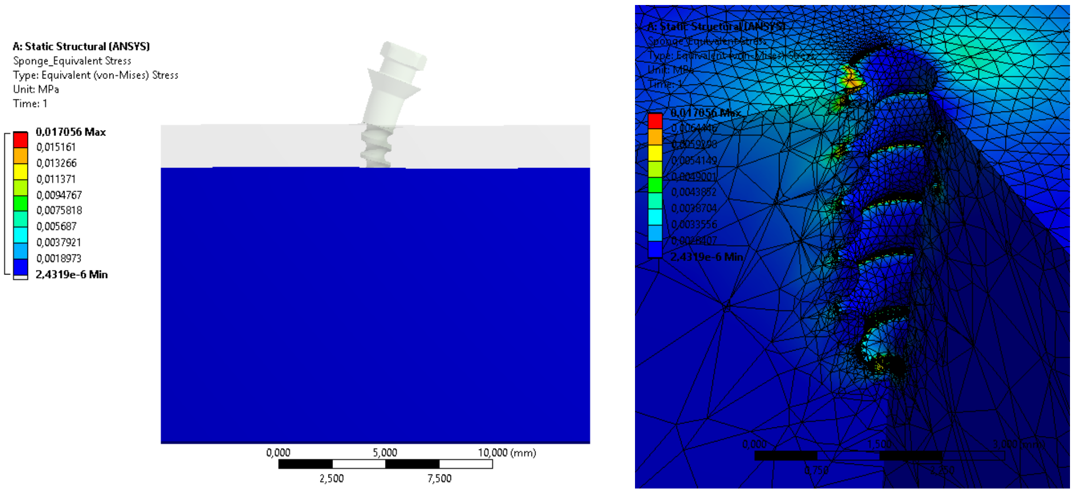


Fig. 4. The distribution of the von Misess equivalent stresses in the cancellous jawbone of the biomechanical system "bone-ACR mini implant".

The finite element method numerical solutions of three-dimensional contact problems of the elasticity theory are related to the necessity to use a significant number of finite elements in the areas of conjugation of the surfaces of different-type materials necessary to satisfy the conditions of non-penetration and sliding on the tribological surfaces.

Therefore, based on the data of computer testing on the three-dimensional models, a number of test two-dimensional flat imitation models of the strained and deformed state of biomechanical systems have been developed (fig. 5). The accuracy of the numerical solutions has been studied and the adequate finite element models of contacting elements with a posteriori preset conjugation surfaces have been developed in accordance with computational data on extension-compression deformation areas for materials in the 3D and 2D imitation models of the strained and deformed state of the biomechanical system "bone-mini implant" (fig. 5).

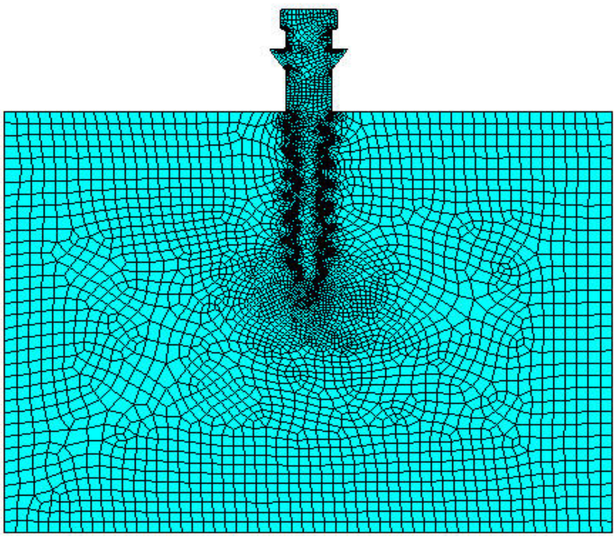


Fig. 5. Computational model of the flat cross section of rigidly joined heterogeneous elements of the biomechanical system "bone-ACR mini implant" and a view of its power load. The number of finite elements joined by 7,189 nodes is 7,378.

In accordance with the results of studying the accuracy of the numerical solutions of the 2D imitation models of the strained and deformed state of the biomechanical systems "bone-ACR mini implant", the convergence of the results on maximal computational values of the von Misess equivalent stresses up to 25.648 MPa was found for the area of the bone and mini implant contact at the approximation of the computational model by the flat square finite elements joined by 59,534 nodes.

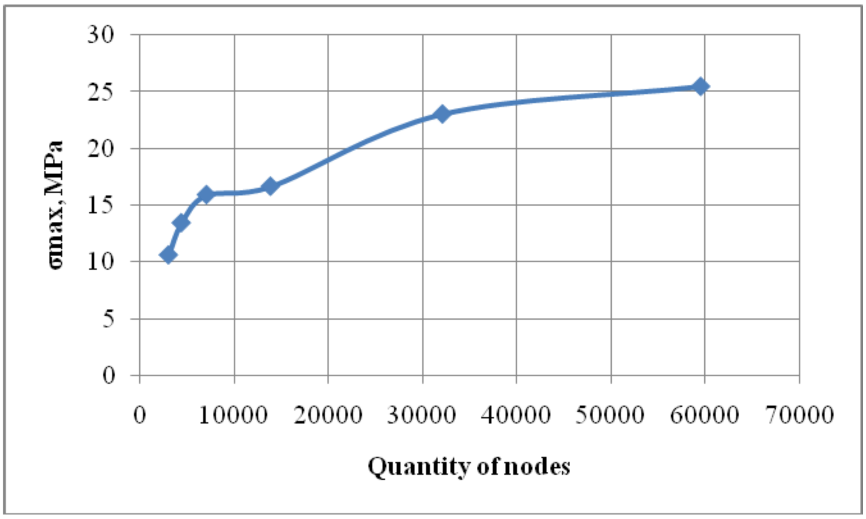
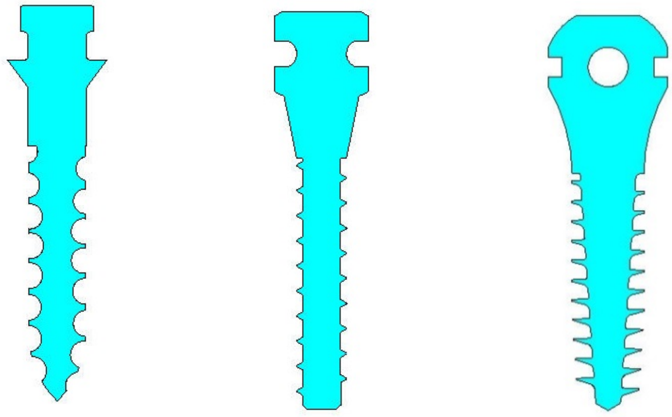


Fig. 6. Convergence of the results of computation of the von Misess equivalent stresses in the area of concentration of the strains in the biomechanical system "bone-ACR mini implant" at the power load dependent of the finite element approximation in the computational scheme.

Taking into account the obtained results of the numerical experiments, the computational schemes have been developed with specified number of finite element approximation of the areas of joining the contacting elements of the biomechanical systems "bone-mini implant" with various-type mini implant constructions (fig. 7).



a b c

Fig. 7. 2-D models of mini implants ACR, Korea (a), POM, Russia (b), OMG, own construction (c).

The results of the numerical computations of the experiments carried out have shown that in the case of applying the force normally to the mini implant, the main strains are concentrated in the region of the cortical plate of the bone. These data agree with those of the other study [9]. Thus, the resistibility of the cortical tissue to deformations is a principal factor when evaluating or comparing the biomechanical systems of the "mini implant-bone" and "implant-bone" types. The compact bone, as more rigid tissue, has maximal resistance to the external forces and this is reflected in the values of the peak strains and maximal forces for the given structure. The role of cancellous bone is the uniform distribution of forces in the bone bulk (figs. 8–10).

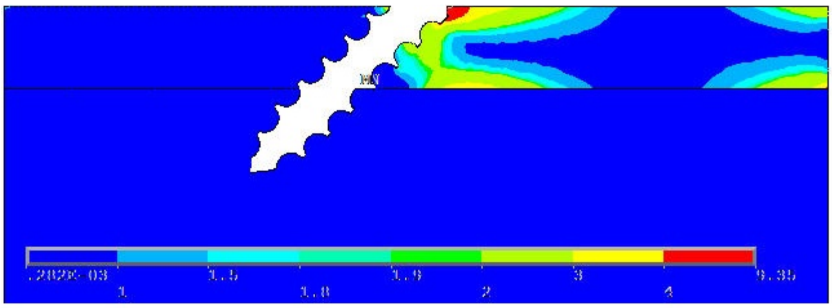


Fig. 8. The distribution of the von Misess equivalent stresses in the cortical jawbone with mini implant ACR (

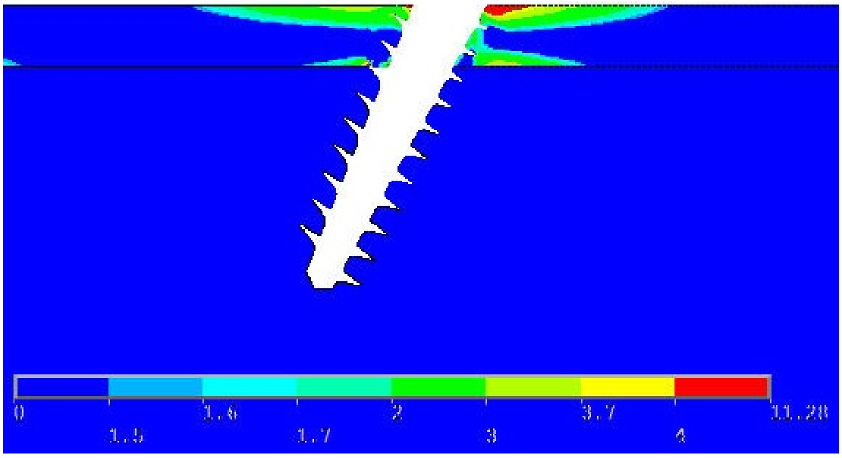


Fig. 10. The distribution of the von Misess equivalent stresses in the cortical jawbone with mini implant OMG (

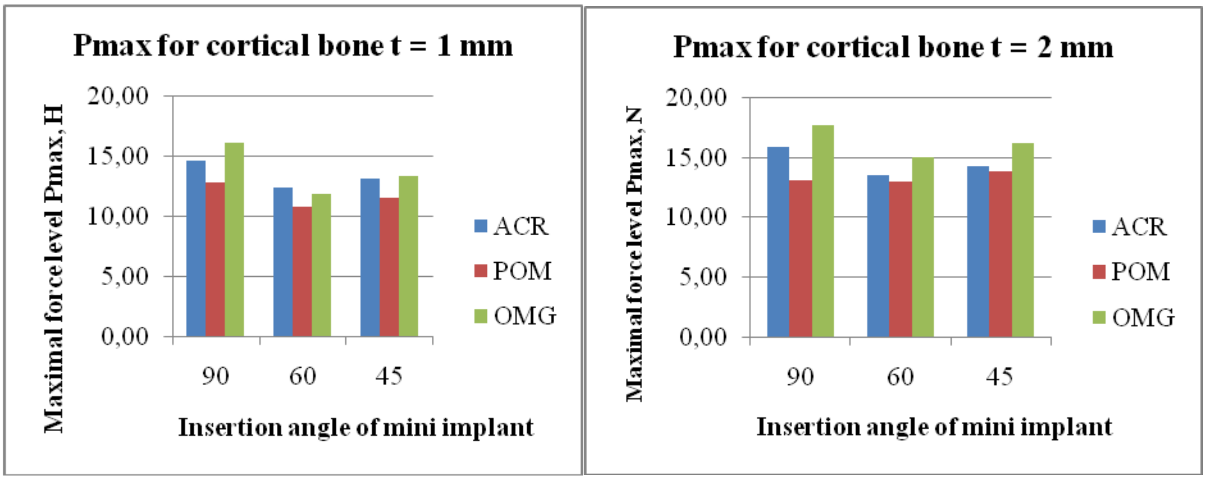


Fig. 11. Histograms of the maximal forces withstand by the human cortical jawbone of different thicknesses: t=1 mm (a); t=2 mm (b) of the biomechanical systems "bone-mini implant" with different-type mini implants.

σ, MPa							
Mini implant type	Cortical bone thickness, t mm	Insertion angle, degree					
		90		60		45	
		Titanium	Cortical bone	Titanium	Cortical bone	Titanium	Cortical bone
ACR	1	26,00	9,13	32,58	10,79	29,52	10,13
	2	25,47	8,41	29,64	9,84	27,83	9,35
POM	1	30,20	10,45	35,22	12,32	32,86	11,55
	2	29,43	10,18	31,58	10,30	30,22	9,62
OMG	1	25,60	8,27	31,35	11,28	25,87	9,99
	2	25,37	7,53	25,00	8,87	18,82	8,22

Table 4. Maximal strains in the biomechanical system "bone-mini implant" for different types of mini implants and different thicknesses of the cortical jawbone at the unit power load with the force vector of the unit amplitude applied to the mini implant head.

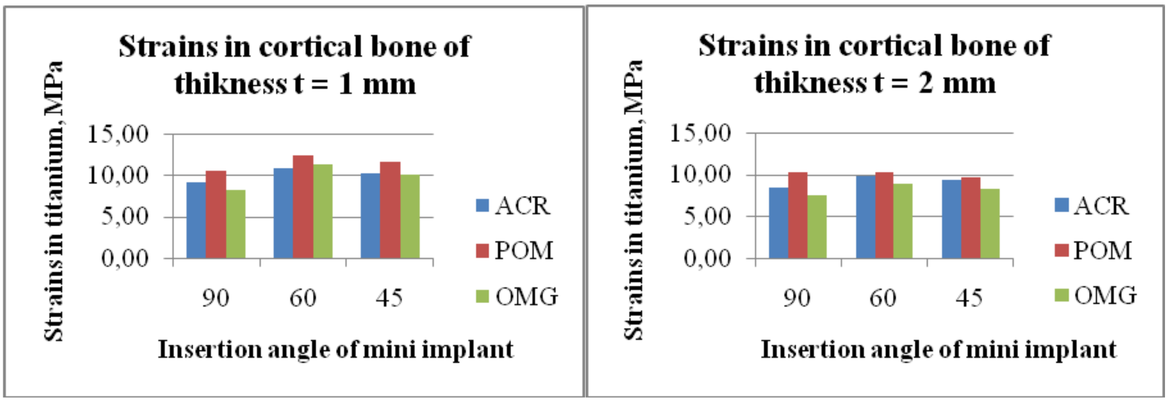


Fig. 12. Histograms of the extremal strains in the human cortical jawbone of different thicknesses: t=1 mm (a); t=2 mm (b) of the biomechanical systems "bone-mini implant" at the power load with the force vector of the unit amplitude applied to the mini implant head.

All the models of the biomedical systems "bone-mini implant" have demonstrated the best distribution of strains at the 2 mm cortical plate thickness as compared to the 1 mm thickness. At larger cortical bone thickness the system may withstand larger power loads and demonstrates less strain gradients at the unit load. These results have some contradictions with [5], who noted no essential dependence of strains in the system "bone-mini implant" on the compact plate thickness. In our opinion, this could be related to the fact that [5] carried out their studies with mini implants placed at the 90^{o} angle only, where the strain in fact varies slightly as a function of the cortical plate thickness. However, at the angular mini implant placement we noted significant variation of the strain indices at given parameters. In particular, the maximal allowable force to be applied to the mini implant head (own construction – OMG) placed at the 60^{o} angle at the 1 mm cortical plate thickness was 11.79 N, while that at the 2 mm cortical thickness – 14.99 N (see table 3). At the 45^{o} angle the relevant values were 13.32 N and 16.18 N, respectively. It should be noted that the OMG mini implants demonstrated the maximal values of force to be applied to the mini screw as compared to other mini implants used in this experiment.

The strains occurred in the system "bone-mini implant" in all the experiments did not approach the maximum strength of the implant material (i.e. titanium), thus, excluding its possible destruction at the orthodontic load application.

When analyzing the maximal forces that the system "bone-mini implant" can withstand at different mini screw inserion angles, the similar regularities were found for all the three mini implant types. The maximal force that the human cortical jawbone may withstand was observed at the 90^{o} mini implant insertion angle and reached 16.08 N for the 1 mm cortical plate thickness for the OMG mini implants, as well as for the ACR mini implants – 14.57 N and 12.73 N for the POM mini implants. The system withstands the least maximal force at the 60^{o} angle reaching 11.79 N for the OMG mini implants, 12.33 N and 10.79 N for the ACR and POM mini implants, respectively. The regularities found for insertion angles did not depend on the bone cortical plate thickness. Thus, in accordance with our studies, the priority in choosing the mini implant inserion angle must belong to the direction normal to the cortical plate one, i.e. the 90^o angle. However, since the inclined mini implant introduction is safer in the case of insufficient inter-tooth distance, the inclined introduction seems to be more effective, proving the efficiency of the 45^o inclination. Our data somehow differ from those quoted by [14], who stated that the mini implant introduction at the 60–70^o angles is more efficient. However, these authors have made their conclusions on the basis of measuring the torque at the mini implant insertion and its primary stability coefficient, while our studies are based on the biomechanical processes of the strain distribution in the system "bone-mini implant" just under its functional load.

Conclusions.

1. At the power loading the biomechanical system "bone-mini implant", the area of strains concentration does not depend on the type of the mini implant construction and is located in the region of compression deformation of the cortical jawbone medium.
2. According to the data of the numerical experiment, the extremal values of the power load vector $\mathbf{P_{max}}$ were determined for the different mini implant construction types.
3. The larger is the cortical bone layer thickness, the larger load should the system "bone-mini implant" withstand.
4. The power load $\mathbf{P_{max}}$ of the biomechanical system "bone-mini implant" with the maximal value of calculated force amplitude is observed for the mini implant inclination angle of 90^o and minimal value of $\mathbf{P_{max}}$ for the 60^o angle.
5. The OMG mini implants demonstrated the largest maximal force degrees to be applied to the mini screw as compared to other mini implants used in this experiment.

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