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STRESS–STRAIN STATE OF BIOMECHANICAL SYSTEM IMPLANT–ELASTIC FOUNDATION

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Abstract. This paper describes the methods of experimental determination of the two main stiffness coefficients of the dental implants fixing, installed in the “the osseous tissue analogue” under the influence of the longitudinal force or a pair of forces. The results of numerical calculation for the corresponding stress-strain state of biomechanical systems are given. Also, the comparison is shown between the numerical results and experimental data obtained by the developed technique of laser testing. The advantages of simultaneous using of these two approaches when assessing the clinical situation and drawing up the reconstructive surgery plan are discussed.

Key words: implant, stiffness coefficients, displacements, stress fields, finite element method.

INTRODUCTION

Constructions used by dentists during reconstructive operations with dental implants are much like building ones when a pile grillage is the building foundation (pile field of reinforced concrete piles, interconnected by reinforced concrete slab on top.) The question is, whether is it possible to use the methods of structural mechanics to perform the necessary calculations of stress-strain state of the material in the vicinity of dental implants included in this design? There are some common approaches, of course, but also some specific differences. The point is not that the number of piles supporting the plate greatly exceeds the number of implants. Nor that the implant stiffness is incomparably larger than that for the osseous tissue, and there are many more possible ways of attachment to the prosthesis.

The main problem is that far less is known about the physical properties of the bone tissues compared to soil properties. Moreover, soil sampling and other methods to refine the physical properties for preparation of the future foundation in construction mechanics are much more informative than X-rays and ultrasound Doppler techniques. Therefore, even the problem of determining the stress-strain state of the bone tissue in the vicinity of a single implant is extremely difficult in the continuum mechanics framework. This difficulty is not due to complexity of reliable description of the medium geometry in the vicinity of the implant – it is due to the lack of reliable information regarding the physical properties of the material. Indeed, what do we know about the mechanical properties of bone tissue? There are some rather uncertain data about the density, Young’s modulus and Poisson ratio for the enamel and dentin, and these materials are also known to be anisotropic [8, 10, 11].

Of course, it is possible to do calculations by a hypothetical model, setting these properties approximately for an average patient. But what would be the practical value of such a study?

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Methodology for reconstructive operations using dental implants as an alternative to traditional methods, is gaining popularity in clinical practice [1, 11–13,]. However, complex clinical situations still remain its main field of activity, where a significant part of the bone prosthetic place is removed and implant prosthetics (to be installed in a number of cases in the zygomatic bone) is the only way to restore chewing efficiency, language function, and meet basic aesthetic requirements. It is necessary to make the right choice of the number and relative position of the implants for the success of such an operation. This choice will determine the chewing loads and stress-strain state in the vicinity of bone implants and, ultimately, the success of the rehabilitation program. The question arises: is it possible to make such a choice through appropriate calculations for the prosthesis attached to an arbitrary number of implants in the continuum mechanics framework? It does not seem possible, at present. It appears most preferable in this case to introduce stiffness coefficients (to be determined experimentally), to describe the relationship between the forces acting on the implants, and their displacements.

An implant fixed in an elastic base has six degrees of freedom (three translational and three rotational) and, therefore, its displacement under the action of external loads must be described using six stiffness coefficients.

When the implant displacements are small (which is the case), it is natural to assume linear superposition, i.e. decoupling between the actions corresponding to different degrees of freedom.

So, what are the stiffness coefficients necessary for?

First, they are required to assess the condition of the mechanical system implant – bone tissue. Once the implant is installed, dentists monitor the process of osseointegration (fusion of the implant with the bone) for a long time. Dynamics of the stiffness coefficients change is a key indicator of how successful this process is, and allows one to determine the time when the implant is ready to carry the load function.

Secondly, the introduction of the stiffness coefficients allows one to construct a theoretical model, based on the equilibrium condition for the prosthetic jaw attached to any number of implants and being under the influence of any chewing load, displacement compatibility conditions for the implants, and the force–displacement relationship (detailed model description and the results of calculations for various clinical situations are given in [14]).

Thus, with the knowledge of the stiffness coefficients and specified chewing loads, in the framework of the theoretical model [1, 12], we can determine the forces acting on the implants and their displacements, and thus ensure an optimal choice for the number and relative position of the implants.

Introduction of stiffness coefficients is not just a formal tool. The stiffness coefficients are physical constants that characterize the state of the implant – osseous tissue system. There is already an opportunity in clinical conditions to estimate the transversal rotational stiffness using the instrument Osstell Mentor, since the relation has been established between the stability coefficient of implants (measured by this instrument), and the transversal rotational stiffness [7].

The Institute of Mechanics at Moscow State University and Moscow State Medicostomatological University have developed a technique for measuring the stiffness coefficients in the clinical conditions [3]. Hopefully, in the coming years the prosthesis design calculations, performed with the loading capacity of the implants taken into account, will go into the preoperative practice. And yet, how to get information on the distribution of stresses and strains in the vicinity of the implants and to estimate the influence of their shape on the position and size of the regions where the stress becomes dangerous? Although, stiffness coefficients are very important, they are only integral characteristics.

This goal requires numerical calculations for the implant embedded in “osseous tissue analogues”, with well-known physical properties.

Without corresponding to any particular clinical case, these calculations give an idea about the features of stress and strain fields for the selected implant geometry, shape and size of the dangerous sections, i.e. exactly what must be considered when planning reconstructive operations.

This article describes methods for experimental determination of the two main stiffness coefficients for a dental implant fixing. A homogeneous and isotropic material (boxil), with well-known mechanical properties, is used as an "osseous tissue analogue". Experimental results on the determination of the stiffness coefficients are compared with the corresponding numerical calculations.

MEASUREMENT OF THE STIFFNESS COEFFICIENTS

The longitudinal stiffness coefficient K_b, corresponding to translational displacement along the axis of the implant symmetry, can be introduced as the ratio of the longitudinal force $\overline{F}$ to the corresponding displacement $K_b = F/\Delta$, where $\overline{F}$ is the force acting along the axis of the implant, Δ is its displacement. It is necessary to clarify the origin of the index "*b*" and others that appear below.

Two coordinate systems are introduced to describe the position of the implant [12, 13]: one of them is $Oxyz$, where xOy is horizontal plane (bite), yOz is jaw symmetry plane, the axis z points up. Other coordinate system $O\tau nb$ is associated with the implant, the axis $\overline{\tau}$ is tangential to the dentition, $\overline{n}$ is the normal inside the mouth, $\overline{b}$ is directed along the axis of the implant to its top.

We assume that the implants are absolutely rigid, and their displacements are only due to the elastic properties of osseous tissue. Fig. 1 shows a photo of the installation.

Scheme of the longitudinal stiffness coefficients measuring is shown in Fig. 2, where *1* is screw implant; *2* is "osseous tissue analogue". Pin *3*, rigidly connected with the implant and the lever *4*, rotating about an axis passing through the point *O*, is loaded by power $\overline{F}$. At the same time, the drop point of the laser ray *5* fixed to the lever *OA*, makes a displacement ξ on the screen *6*. Value of turning angle φ of the lever *OA* and vertical displacement of the implant Δ are given by formula:

$$\varphi = \xi/L, \; \Delta = \varphi OA,$$

where L is the distance from the centre of rotation of the lever O to the screen ($\xi \ll L$).

Fig. 1. Photo installation to determine the stiffness coefficients for the translational degrees of freedom

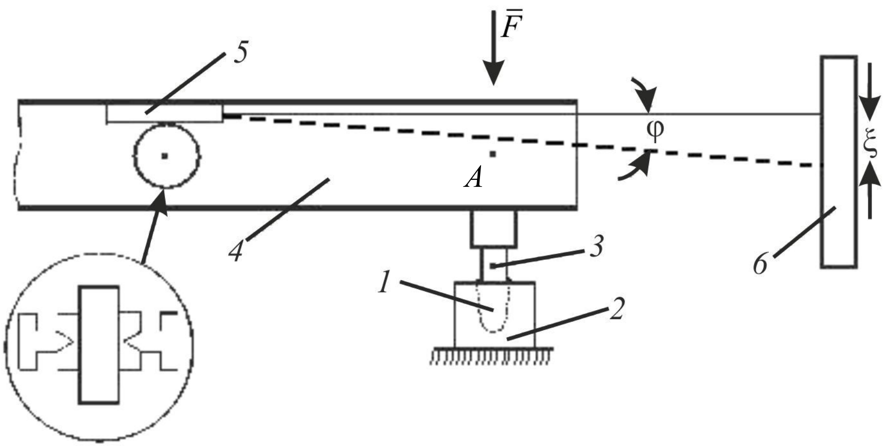


Fig. 2. Scheme to determine the stiffness coefficients corresponding to the translational degrees of freedom: *1* – implant; *2* – analogue bone; *3* – pin; *4* – lever-rocker; *5* – laser; *6* – screen

The loading by small weights was carried so that the line of action of the force passes along the axis of the implant (use a block under tensile loads). The distance to screen was chosen large enough for increase of apparatus sensitivity to the turning angles (in the latest version of the device $L = 46.55$ m).

We used the method of determination of small displacements [12] to measure the displacement of the laser ray on the screen. The measuring method is based on the detection of the centre of the light spot produced by a ray of laser transmitter attached to the lever of the loading device and based on the implant fixed in the "osseous tissue analogue". Measuring complex consists of a laser transmitter, screen, camera and computer. Video stream on a computer is divided into frames and this information is processed by a special program that is based on the use of computer vision library Open CV.

The processing cycle includes the following steps:

– frame reception;

– selection of the frame pixels, their color components fall within the specified range;

– calculation of the shape gravity centre formed by selected pixels;

– display and save in the file received coordinates of the light spot.

During the measurement, the Web-camera Philips SPC900NS and notebook HP with operation system Windows XP were used.

Fig. 3 shows a typical dependence of the longitudinal displacement Δ of screw implant (firm Conmet) on the value of acting compressive force F (N). Diameter of the implant is 4 mm and length is 19 mm [6], it is fixed in "osseous tissue analogue" of cylindrical shape ($D = 20$ mm, $H = 30$ mm) made of the boxil (see also Figs. 4 and 5). Here and below, the displacements and relative deformations are plotted on the horizontal, but forces and stresses are vertically.

Experiments have shown that this relationship is linear; with the load lines (circles) and unloading lines (crosses) are virtually identical.

Table 1 shows the experimental data for the longitudinal stiffness coefficients of implants $K_b = F/\Delta$ (firm Conmet) for different sizes, contained in the same cylinder made of boxil (d is diameter of the implant, l is the depth of the fixed part, S is the surface area of contact). They show that the longitudinal stiffness coefficient increases when the surface area increases, too.

Table 1

Experimental data for the longitudinal stiffness coefficients

Parameter	Variant		
	1	2	3
d, mm	3.3	4.0	4.0
l, mm	10	10	16
S, mm^2	112	138	213
K_b, N/m	$14.1\cdot10^3$	$15.6\cdot10^3$	$24\cdot10^3$

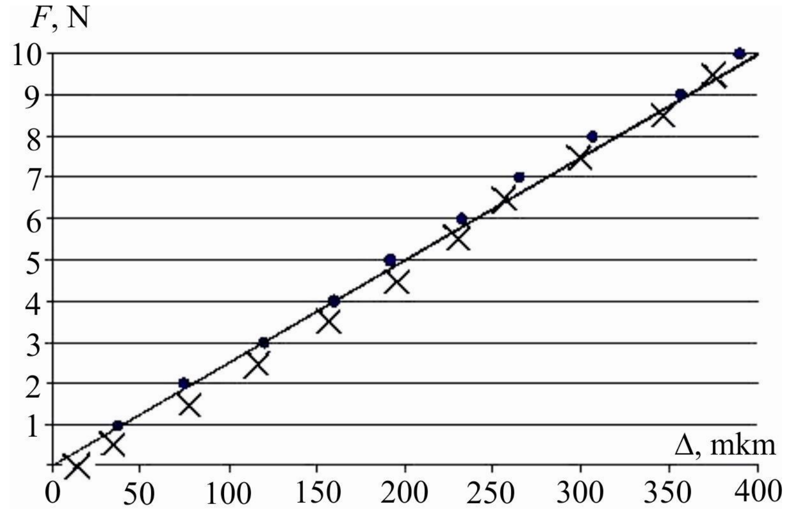


Fig. 3. Dependence of the longitudinal displacement of the implant Δ (mkm) on the value of the compressive force *F* (N)

Knowledge of the value of the stiffness coefficients is necessary in assessing the carrying capacity of implants, to establish the time they are ready for functional loads and the reconstructive operation quality. But, this is the integral characteristics and they do not provide information about the distribution of stresses and strains in the osseous tissue near the implant, the influence of its shape on the location and size of the regions where the stresses (or strains) are dangerous, do not allow recovering the full picture of the state of the mechanical system implant – osseous tissue and finding the ways of reconstructive operations improving.

Only a joint use of physical and mathematical modelling provides fairly complete and accurate information about the state of the implant – osseous tissue. Below, there is a numerical study of the stress-strain state of “osseous tissue analogue” in the vicinity of the implants, the values of the longitudinal stiffness coefficients, the values of which are compared with experimental data.

NUMERICAL STUDY OF STRESS AND DISPLACEMENT OF DENTAL IMPLANTS IN THE SAMPLE UNDER THE LONGITUDINAL LOAD

Some titanium implants of firm Conmet (Russia) were considered for the study and comparing the effect of the thickness of the implant and its length on the values of the displacements and stresses, which differ in length and diameter: variant No. 1 – implant length h = 13 mm and diameter d = 4 mm, with a particular screw-thread (height of the upper part of the implant surface of the sample is 3 mm in all models of implants) variant No. 2 – implant h = 13 mm and d = 3.3 mm, variant No. 3 – implant h = 19 mm and d = 4 mm.

Computer models of the implants are as close to real. To study the dependence of the implant displacements as well as the sample material on the vertical loads on the implant, and the fields of stress distribution, the identical samples of the material boxil in all variants were considered, representing a cylinder with a height 30 mm and diameter 20 mm. We studied the materials with the corresponding values of Young’s modulus E and Poisson ratio μ [4, 5, 7, 8] (see Table 2).

Table 2

Mechanical properties of materials

Material	Young’s modulus E, MPa	Poisson ratio μ
Boxil	1.9	0.47
Titanium	$1.1 \cdot 10^5$	0.30

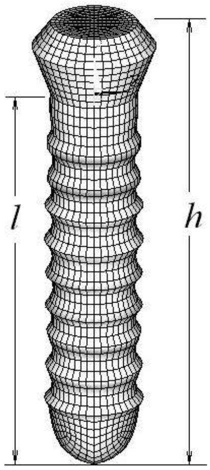


Fig. 4. Implant h = 19 mm, d = 4 mm. Variant 3

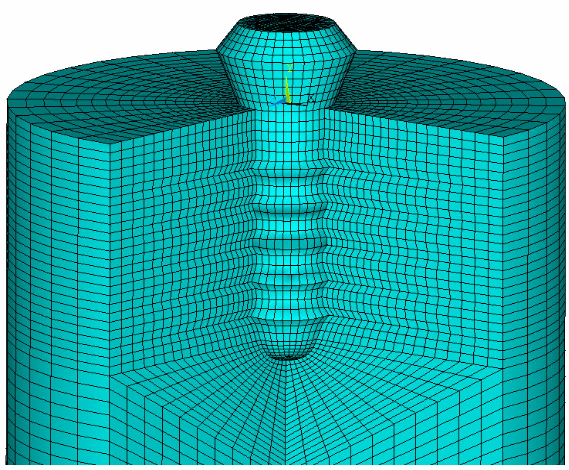


Fig. 5. Implant h = 13 mm screwed into a cylindrical sample of material boxil. Fourth part is cut specifically (ordered grid), the sample is D = 20 mm, H = 30 mm

Studied elastic model is related to the Cartesian coordinates X, Y, Z.

One of the most important stages in the finite element analysis is to construct a model of the finite element meshes, i.e. division of the whole model into finite elements connected to each other in knots. We can show in Figs. 4 and 5 the finite element models with an ordered grid of a single implant and a cylindrical sample with a screwed in it the implant, constructed in the software package ANSYS [2] (quarter volume was cut from the sample so that one can see the fragmentation of volume elements in the sample).

The problem was solved in three-dimensional statement in the software package ANSYS by finite element method [5, 6, 9, 15]. Volume element Solid 186 is used to model, this is element for 3D modelling of solids with 20 nodes and 3 degrees of freedom at each node (displacement at each node is in the directions x, y, z); there is, among the possible mechanical material properties of this element in particular, isotropic elasticity, characterized by Young's modulus and Poisson ratio. The same load F = 5 N is set on the upper surface of the implants in all variants.

Two variants of boundary conditions were considered (to evaluate the effect of boundary conditions on displacements and stresses distribution): in the numerical calculations (as well as in the physical experiment in which the bottom of samples was glued) the boundary conditions in the first version were given in the form of restrictions on the displacements of the lower surface of the sample only, i.e. option corresponding to a total prohibition of displacements in all x, y, z directions; displacement restrictions in the second version were set both on the lower surface of the sample (the prohibition of displacements in all x, y, z directions), and for restrictions on displacements on the lateral surface: prohibition of displacements in the directions of the radius of the cylindrical sample, i.e. the sample as if is enclosed in a hard glass.

The problem is solved for the 3D models of implants screwed into the sample for all variants and different boundary conditions (1/4 part of the volume of the cylindrical sample was cut for better visualization on the figures, and for clarity the deformed samples are shown everywhere especially in the exaggerated scale).

Different displacement distributions in the sample and the implants are shown in Figs. 6 and 7 for variant No. 1, with the same load on the upper surface F = 5 N (different boundary conditions): in the case when the bottom is fixed, the lateral surface of the sample was curved due to displacement of implant getting "tubby" image (this shape is possible only for boundary conditions No. 1, grid is a model before application of load).

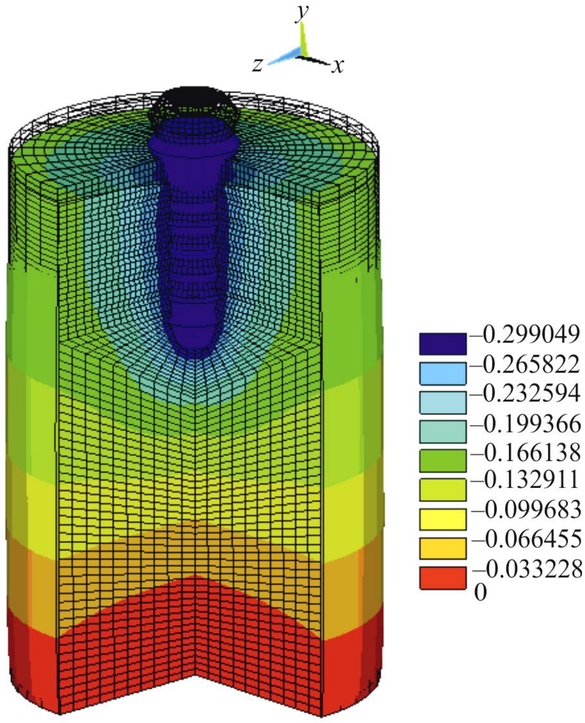


Fig. 6. Displacement along y-axis: implant h = 13 mm, d = 4 mm, the vertical force F = 5 N, the boundary condition: the bottom of sample is fixed, ΔY_{max} = 0.299 mm

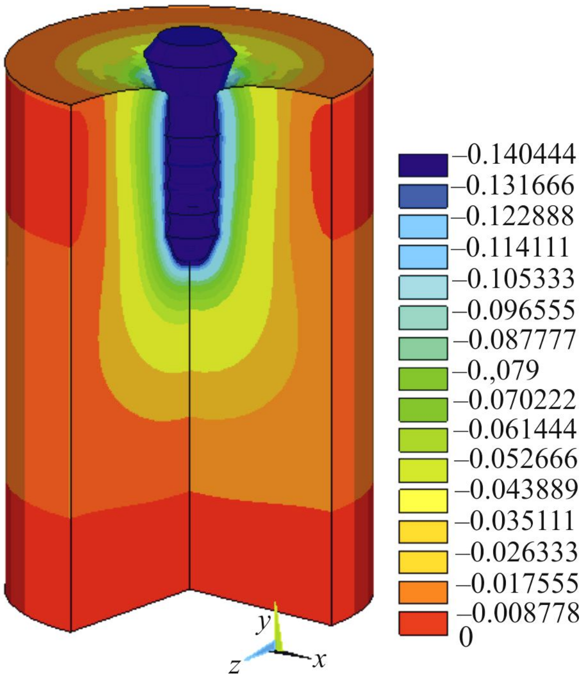


Fig. 7. Displacement along y axis: implant h = 13 mm, d = 4 mm, F=5 N, the bottom of the sample and its lateral surface are fixed, ΔY_{max} = 0.14 mm

Table 3

Stresses and displacements of implants under the vertical load for different variants

Parameter	Implants with a screw thread, mm			No thread, mm
	Variant 1 h = 13, d = 4	Variant 2 h = 13, d = 3.3	Variant 3 h = 19, d = 4	Variant 4 h = 13, d = 3.3
Boundary condition 1: sample bottom is fixed				
The maximum displacement of implant Δy, mm	0.2990	0.3237	0.2137	0.4394
K_b (calculation), N/m	$16.7 \cdot 10^3$	$15.4 \cdot 10^3$	$23.4 \cdot 10^3$	
S, mm^2	138	112	213	
The maximum von Mises stress at the base of the implant σ, MPa	0.101	0.143	0.083	0.172
Boundary condition 2: bottom of the sample and its lateral surface are fixed				
The maximum displacement of implant Δy, mm	0.1404	0.1632	0.0943	0.2062
The maximum von Mises stress at the base of the implant σ, MPa	0.091	0.117	0.057	0.135
Boundary condition 1: fixed sample bottom				
Physical experiment Δy, mm	0.3188	0.355	0.209	–
K_b (experiment), N/m	$15.7 \cdot 10^3$	$14.2 \cdot 10^3$	$22.9 \cdot 10^3$	–
The difference of values K_b in the numerical and physical experiments, in percent	6.0%	8.4%	2.1%	–

Here: d is diameter of the implant, h is implant length, S is area of contact, $K_b = F/\Delta$ is longitudinal stiffness coefficient, where F is acting force, Δ is displacement

As expected, the values of the maximum displacement are in the highest point of the implant (in its upper surface), the values for all variants along the *Y*-axis are shown in Table 3.

The von Mises stress (mean-root-square value of the tangential stress at a point) is selected as the equivalent stress used to assess a multiaxial state of stress for the study of stress distribution in the sample and implants. As an example, Fig. 8 shows the stress distribution in the sample for variant No. 1.

The maximum values of the stresses in the implants are on the edges of the screw thread, and correspond to the values from 0.89 to 2.326 MPa for all cases: these values are very small for implants (Fig. 8 shows the values of the stresses in kg/mm^2). As for the body of the sample, stress values σ in its volume significantly lower than in the implants. The values of the longitudinal (translational) stiffness coefficients obtained in the physical and numerical experiments are compared in Table 3, also the values of maximum stress in the sample material, mainly near the bottom of the implants are placed: maximum stress values are in the variant No. 2 (very thin and short with thread) and No. 4 (such as variant No. 2, but without thread) for both boundary conditions. The lowest values of displacement and stress were found in variant No. 3.

Comparison of the stress and displacement values of the implants detected that the best variant No. 3 (implant length h = 19 mm and diameter d = 4 mm) has the smallest values: implant displacement around 30–40% less than displacement of variant No. 2 (the most short and thin), and approximately 40–50% less than the stresses σ_{max} (boundary conditions are No. 1 and No. 2 respectively).

As might be expected, the lack of a screw thread led to a change: displacements in variant No. 4 are 26–36% more (boundary conditions are No. 2 and No. 1 respectively) than in the variant No. 2 (the same length and diameter, but with screw thread), as well as the maximum stresses near the base of the implants are increased from 15% to 20%.

Comparison of experimental measuring displacement of implants with appropriate numerical calculations showed quite satisfactory agreement: the value difference of implant maximum displacement Δy for variants 1, 2 and 3 is from 2 to 8% (the measurement error in the physical experiment is 5% [14]).

DETERMINATION OF THE TRANSVERSE ROTATIONAL STIFFNESS

Introduce it as the ratio of the torque acting on the implant to the turning angle: $K_n = m/\varphi$, where $m = F\,h$ is the value of the moment, φ is turning angle in radians. Diagram of the measurement of turning angles is showed in Fig. 9, where *1* is screw implant, *2* is bone analogue, *3* is pin connector, *4* is laser, and *5* is screen. The turning angle was determined by the formula: $\varphi = \xi/L$, where ξ is displacement of the laser ray on the screen, L is distance from the centre of implant rotation to the screen ($\xi \ll L$).

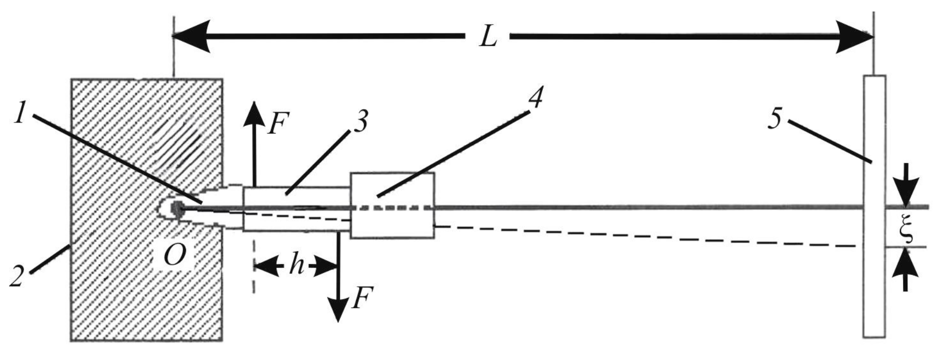


Fig. 9. Scheme for the implant turning angles measuring

Table 4

The transverse rotational stiffness coefficients

Parameter	Variant		
	1	2	3
S, mm^2	125.6	114.3	201
K_n, N·m/rad	0.330	0.298	0.518

The loading was carried out by two small weights at the points of the pin at a distance h from each other, one of which is suspended over a pulley. Centre of rotation O of the implant was not far from the bottom of the implant when loaded by a single force, but it was closer to the middle of its fixed part under the influence of a pair of forces [10]. Since the length of the implant is small compared to the distance to the screen (l<<L), the actual position of point O is not essential in determining the angle φ.

To determine the dependence of implant turning angle on the value of the torque we used the same implants (firm Conmet) fixed in the cylindrical samples of the boxil (D = 20 mm, H = 30 mm). Base of the cylinder was attached (glued) to the rigid vertical plate. Experiments have shown that this relationship is linear, and the lines of loading and unloading are virtually identical. The transverse rotational stiffness coefficients are given in Table 4.

STRESSES AND DISPLACEMENTS OF IMPLANT AND SAMPLE MATERIAL UNDER THE INFLUENCE OF A PAIR OF FORCES

The numerical results are presented in this section, the finite element method is applied to determine the displacement of the implant under the pair of forces, as well as the distribution of stresses in the sample material in the vicinity of the lateral surface of the implant. Calculations are made for four different variants, geometric dimensions of which are described above. Identical samples of material boxil are examined in all cases, representing a cylinder 30 mm in height and 20 mm in diameter. All samples have the same linear dimensions.

Here, just as in the previous section, two variants of the boundary conditions are considered: in the first variant – the prohibition of displacement only at the lower surface of the sample, in the second variant – the prohibition of displacement at the lower surface of the sample plus the displacement prohibition at the lateral surface in the direction of the radius.

The same load is set in all variants. As the load is set as a pair of forces in the physical experiment, then the load as a pair of forces is considered in the numerical solution F = 1.25 N applied at specific points of the upper part of the implant (Fig. 10), a shoulder of the pair of forces is 2 mm.

The problem is solved for the 3D models of implants screwed into the sample for all variants and two different boundary conditions. In order to be able to see the stress-strain state of the sample and the implant inside and especially in the vicinity of the implants, half part of the cylindrical sample is removed. The deformed samples are shown everywhere for a better visualization in the exaggerated scale specially (see Fig. 11).

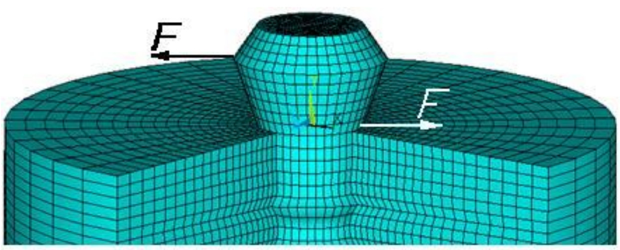
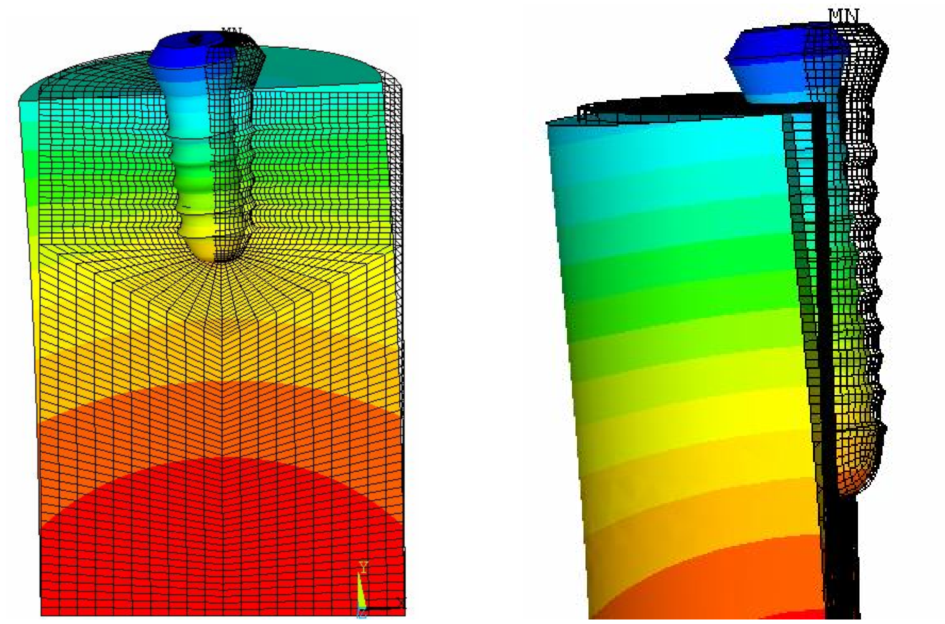


Fig. 10. A pair of forces applied to the top of the implant at different points. F = 1.25 N



a *b*

Fig. 11. Implants under influence of the pair of forces moved to the side, pulling the sample itself. Bottom is fixed (one can see how the lateral surface of the sample is curved; the transparent grid is the position of implant before the loading): a is longitudinal shear; *b* is lateral view of longitudinal shear

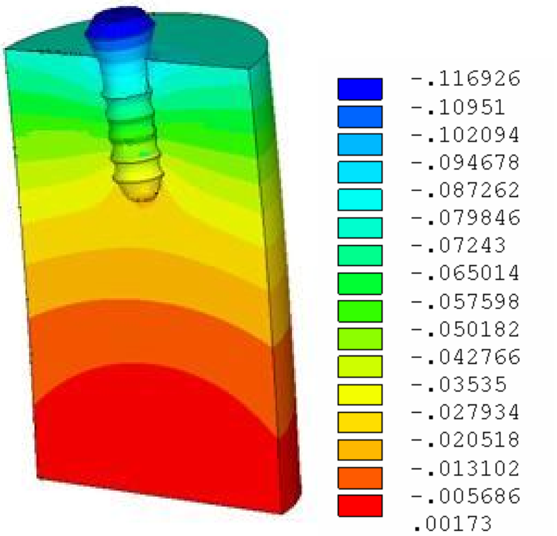


Fig. 12. Displacement along axis *X* (horizontal): implant *h* = 13 mm, *d* = 4 mm, fixed bottom of the sample. The maximum value of the implant displacement along X-axis is equal to 0.1169 mm

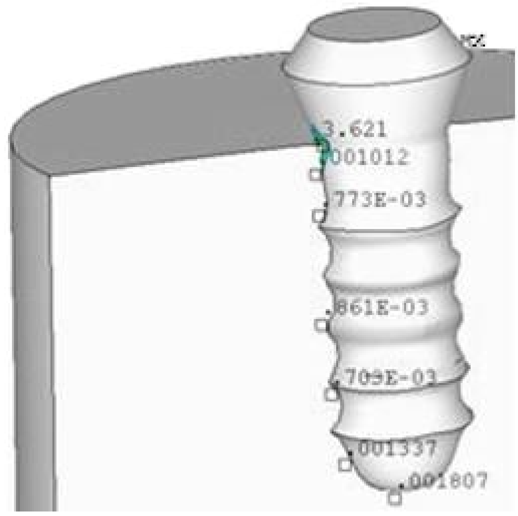


Fig. 13. The von Mises stress distribution: implant *h* = 13 mm, *d* = 4 mm, the bottom of the sample is fixed; σ_{max} = 0.01807 MPa = 0.001807 kg/mm^2 at the base of the implant

The values of implant displacements and the von Mises stress in the sample material obtained numerically for all variants – Table 5 (as an example, see Figs. 12 and 13). Measurements of implant turning angle under the influence of pair of forces are made in a physical experiment, the stiffness coefficient is defined as $\delta = M/\alpha$ (N·m/rad). Comparison of stiffness coefficients obtained in numerical and physical experiments are given in Table 5; the difference is between 2.5 and 4.2%.

Table 5

Stresses and displacements of implants under the influence of the pair of forces for different variants

Parameter	Implants with a screw thread, mm			No thread, mm
	Variant 1 h = 13, d = 4	Variant 2 h = 13, d = 3.3	Variant 3 h = 19, d = 4	Variant 4 h = 13, d = 4
Boundary condition 1: bottom of sample is fixed				
The maximum displacement of implant ΔX, mm	0.116926	0.125336	0.095014	0.11205
The maximum von Mises stress at the base of the implant σ, MPa	0.01807	0.02033	0.01306	0.0123
Boundary condition 2: bottom of the sample and its lateral surface are fixed				
The maximum displacement of implant ΔX, mm	0.032370	0.039648	0.013322	0.02758
The maximum von Mises stress at the base of the implant σ, MPa	0.01876	0.02582	0.01449	0.0150
Boundary condition 1: The stiffness coefficient = moment/turning angle, bottom of sample is fixed N·m/rad				
Physical experiment	0.330	0.298	0.518	–
Numerical experiment	0,322	0,286	0,532	–
The difference of values of stiffness coefficient in the numerical and physical experiments, in percent	2.5%	4.2%	2.6%	–

Numerical study allowed determining the stress-strain state dependence of the sample material both in the neighborhood of the implants and they themselves on parameters such as geometric dimensions (length and thickness), the magnitude of the applied load, the different boundary conditions of the sample fastening, the effect of the screw thread. Study found the best variant No. 3 (h = 19 mm, d = 4 mm), which has the lowest values of displacement and stress under the influence of a vertical load and a pair of forces.

Good agreement of the numerical calculations and the experimental data confirms the reliability of the experimental results as well as the adequacy of numerical calculation methods.

Conclusions

The effectiveness of reconstructive surgery and orthopedics depends on the results of a range of research, an important component of which is the mathematical modelling and physical experiments. Good agreement between numerical and experimental data presented above, confirms the feasibility of computer analysis of state of hard and soft tissues in pre-operative practice, the strength of their connection with implants, as well as the forces generated during chewing at the area where the prosthesis attached to the implants.

In difficult clinical situations during the reconstructive surgeries (especially in their final stages), it is necessary to monitor the change at least one of the stiffness coefficients to determine when the implant is ready to functional loads (or to control the change of the implant stability coefficients with a device Osstell Mentor [14]).

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