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DEPENDENCE OF PRIMARY STABILITY OF DENTAL IMPLANT ON THE DIRECTION OF THE OCCLUSAL LOAD

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Abstract. Dental implantology practice shows that oblique load on the implant is more dangerous than the vertical one. Of particular importance is the study of the implant-jaw system under oblique load studying the primary stability of dental implants, when osseointegration has not yet occurred and there is no adhesion at the bone-implant interface. The damaging effect of excessive loads in this case is associated with the danger of superfluous micromotions on the bone-implant interface (mutual displacements of corresponding points) arising under their action, which leads to disruption of the osseointegration process. On the simplest model of a dental implant with a square thread profile, the influence of the load tilt angle on the primary stability of the implant in the jaw is examined. Calculations are carried out by the finite element method in the *ANSYS* package. Graphs of changes in micromotion along the bone-implant interface are presented, tables of magnitudes and localizations of micromotion maximums and graphs of their dependence on the loading angle are given. It is shown that for non-integrated implants, transition from vertical to horizontal loading leads to a sharp decrease in implant stability, which at sufficiently high occlusal loads impairs osseointegration.

Key words: dental implants, biomechanics, primary stability, modeling, oblique loading, finite element method.

INTRODUCTION

In dental implantology it is well known that oblique load on the implant is more dangerous than the vertical one [10] (the same is true for native teeth [19]). There are a number of publications related to the calculation of the stress-strain state of the jaw or its fragments with implants under the action of an inclined load [4, 7, 12-15, 17, 20, 22]. Most of them deal with osseointegrated (fused with bone) implants. However, the study of the implant-jaw system under the action of oblique loading is of particular importance of studying the primary stability of dental implants, when osseointegration has not yet occurred and there is no adhesion at the bone-implant interface [3, 6-9, 18, 21, 23]. In this case, the damaging effect of excessive loads is due to the risk of excessive micromotions on the bone-implant interface (mutual displacements of corresponding points) arising under the action of those loads, which leads to disruption of the osseointegration process.

In [1, 2], on the minimal model of an implant in a jaw, the effect of thread characteristics on the primary stability of the implant and micromotion at the interface under vertical load was considered. Here, on the same model, we study the effect of the load angle on micromobility.

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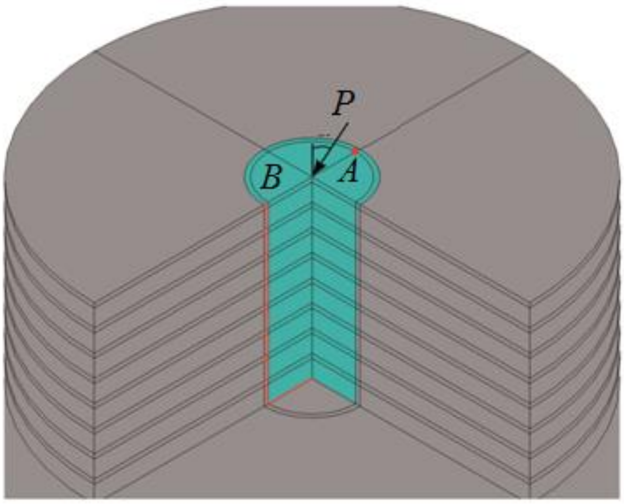
PROBLEM STATEMENT

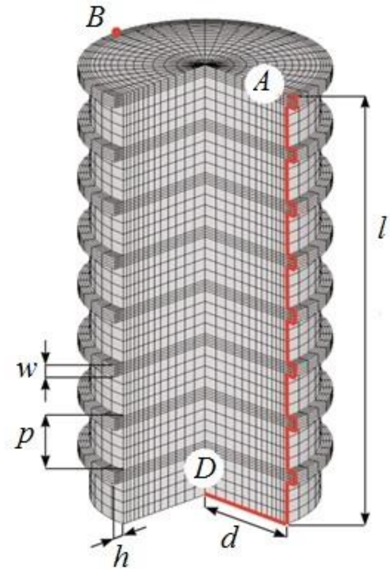
As the basic calculation scheme, the same one was taken as in [1, 2], but here the force P of the same absolute value forms an angle α with the vertical (α = 30°, 45°, and 90°). Therefore, in contrast to [1, 2], the problem under consideration is not axisymmetric (but still has one plane of symmetry). Bearing in mind the possible experimental verification, the boundary conditions were set similarly to [5]: the sample (a bone cylinder with an implant screwed) was inserted into a rigid smooth cup (holder), and the bottom of the sample was glued to the cup. The length and diameter of the cage were adopted, respectively, L = 30 mm, D = 20 mm [5]. A summary of all values used of the parameters of the basic calculation case is given in Table 1 (see also Fig. 1), where: E, ν are Young's modulus and Poisson's ratio respectively, l, d are implant dimensions (length and diameter), p, h, w are thread characteristics: thread pitch p, the depth (height) of the thread h and the width of the tooth base (thread turn) w. The thread profile was taken as a square one, since it was shown in [1, 2] that in the case of vertical loading, this was the profile that provided minimal micromotion on the interface. On the implant-bone interface, the sliding condition was specified.

Summary of calculation parameters values

E, ГПа		ν		*l*, mm	*d*, mm	*p*, mm	*h*, mm	*w*, mm	*L*, mm	*D*, mm	*P*, N	α, grad
titanium	bone	titanium	bone									
110	1	0.3	0.3	8	4	1	0.2	0.2	30	20	700	0, 90, 45, 30



a



b

Fig. 1. The load on the implant and the point of maximum micro-mobility *A* (*a*); an implant (general view with a quarter cut) with some notation (*b*)

Calculations were done using the finite element method in the *ANSYS* software package (version 15.0). When constructing the finite element mesh, we used bilinear 8-node finite elements in the form of a rectangular parallelepiped. Due to the presence of a plane of symmetry in the problem, only part (half) of the model bounded by this plane was subject to decomposition. The total number of elements used when partitioning was approximately 200,000. A penalty method was used to model the contact between the bone and the implant.

The stiffness (Young's modulus) of the implant is two orders of magnitude greater than the stiffness of the bone. Therefore, when a horizontal force is applied to the upper end of the implant, the latter bends and rotates almost like a rigid body around a certain point near its lower end, called the center of resistance [11]. With this, on one (front) side, the implant is pressed into the bone (and here the magnitude of micromotion is minimum - point *B*) (Fig. 1), and on the other (back one) - it lags behind the bone - and here micromotion is maximum (point *A*).

The places and magnitudes of maximum micromotions are of the greatest interest. Hence, the point *A* and corresponding vertical section and path *AD* were selected as the main objects of analysis (point *A* giving the maximum micromotions in that implant cross-section). Calculations were done for the normal and tangential components, as well as of the module of the full micromotion vector $|u^*|$ on the interface along the *AD* path and a similar *BD* path.

RESULTS OF CALCULATIONS. DISCUSSION

In Fig. 2, *a-d* graphs are presented of $|u^*|$ along *AD* for $\alpha = 0°, 90°, 45°, 30°$ respectively. For comparison in Fig. 2, *e* a graph of $|u^*|$ along *BD* for $\alpha = 90^0$ is given. Here in graphs, the 1st dashed column corresponds to the upper face of the tooth (thread turn), the 2nd column – to the lateral face, and the 3rd one – to the lower face.

First of all, comparison of Fig. 2, *b* and 2, *e* shows that micromotions at the point *B* are an order of magnitude smaller than those at the point *A*. Further, it is well known from practice that the biggest problems (up to bone resorption) arise mainly and most often at the top of the implant, in the “cervical” area. The calculated results can serve as a possible explanation of this phenomenon: graphs 3, *a-d* shows that with the vertical load maximum motions occur in the implant apical area, and with horizontal and oblique load - at the top of the implant, while micromotions with the horizontal load are an order of magnitude greater than with vertical loading. The fact that horizontal micromotions are greater than vertical ones expresses less rigidity of the structure under horizontal loading in comparison with the vertical one, which, in turn, is geometrically determined.

Further, it is known [3, 21] that only excessive micromotion is directly related to the violation of osseointegration and formation of fibrous encapsulation. According to [21], the allowable threshold of micromotion lies between 50 and 150 μm: at $|u^*| < 50$ μm osseointegration is guaranteed, at $|u^*| > 150$ μm fibrointegration always occurs, if 50 μm < $|u^*| < 150$ μm, the result depends on the other (additional) factors. In our calculations, with the load angle varying from 0^0 (vertical) to 90^0 (horizontal), the values of micromotions changed more than an order of magnitude (from 10-12 μm to 180 μm) and thus passed from the range of osseointegration through the intermediate zone to the region of fibrointegration. However, it should be noted that the accepted load values are close to extreme ones [10] and, therefore, they rarely occur normally. It is believed that typical load values are $P \sim 200$ N [10, 16], and at such forces, micromotion will be approximately 3.5 times smaller, i.e. about 50 μm, which, nevertheless, lies on the boundary of guaranteed osseointegration.

Oblique load is a combination of vertical and horizontal loads. Since displacements from vertical loads are an order of magnitude smaller than from horizontal ones, when the angle α is not too small, the first can be neglected and only displacements from horizontal forces that are equal to $P_{\rightarrow} = P \sin \alpha$ can be taken into account. When the force *P* changes, the contact areas will change, and thus the problem is non-linear in terms of *P*. If this nonlinearity is small, then the graph of $u (\sin \alpha)$ should be close to a straight line.

Table 2 gives the values of the maximum relative displacements (micromotion) on the interface depending on the load angle, and in Fig. 3 the same data are given graphically. It is seen that both functions $u (\alpha)$, $u (\sin \alpha)$ are essentially nonlinear, however, unlike the first, the second graph has no point of inflexion (keeps the sign of curvature).

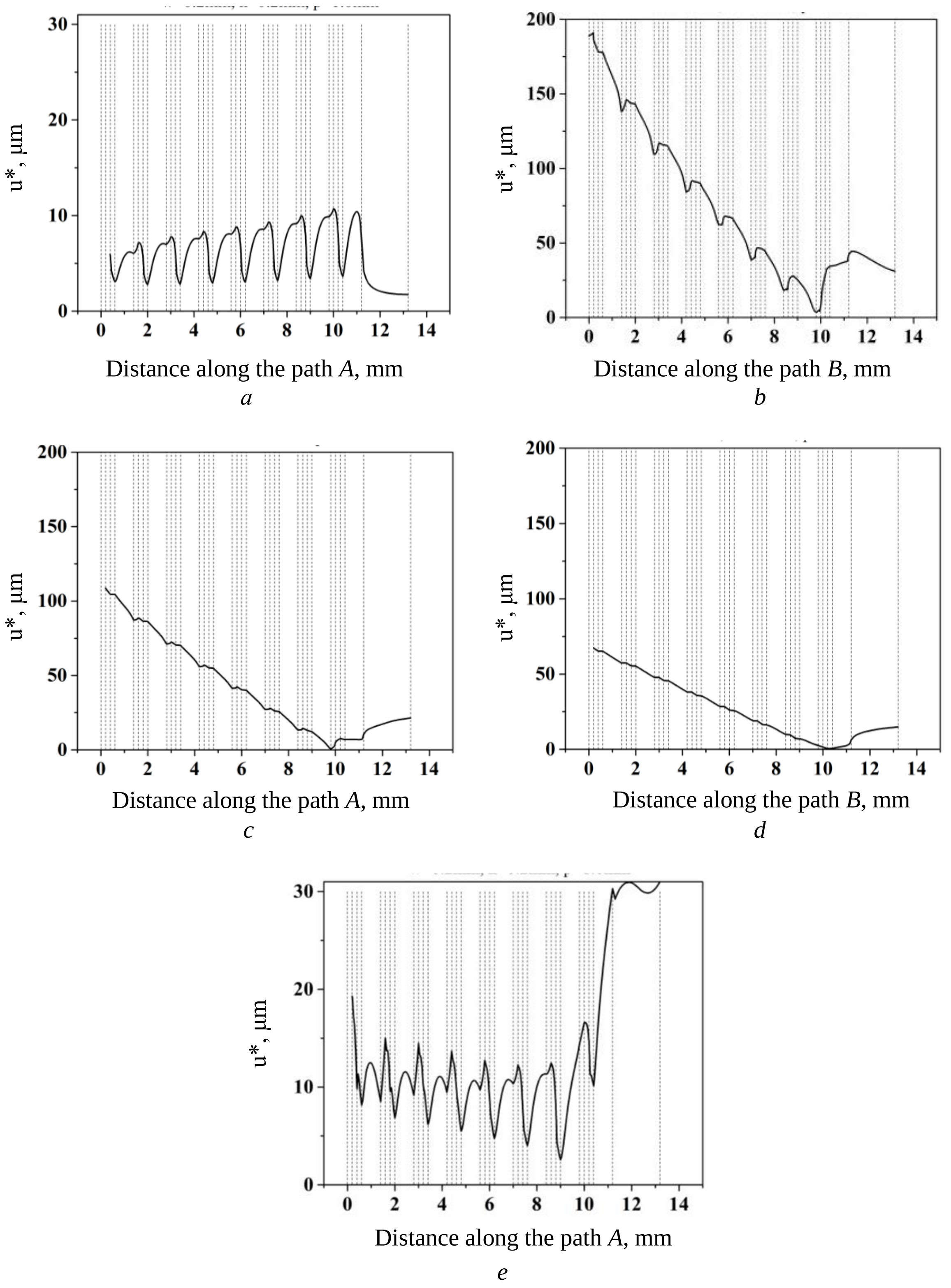


Fig. 2. Change in the absolute value of micromotions on the bone-implant interface along the path *AD* at α = 0 (*a*), 90° (*b*), 45° (*c*), 30° (*d*), the same for *BD*, α = 90° (*e*), *w* = 0,2 мм; *h* = 0,2 мм; *p* = 1,0 мм

Maximum micromotion on the bone-implant interface at different loading angles

Direction of load (angle α to vertical), grad	sin α	Maximum displacements, μm	The peak position (thread turn)
0	0	10.71	At the last
30	0.5	67.36	On the first (neck)
45	$\sqrt{2/2}$	108.65	On the first (neck)
90	1	184.34	On the first (neck)

In order to better understand the results obtained in layman's terms, let’s give an estimate for the implant displacements based on the simplest qualitative flat model (Fig. 4), in which we assume that the implant is a rigid smooth rod, and we describe the bone as a Winkler layer.

As already noted above, when the horizontal force is applied to the upper end of the implant, the latter almost like a rigid body bends and rotates around a certain point near its lower end, called the center of resistance. Such a rotation is described by the relation $u(y) = k\,(y - y_0)$, where y is the ordinate measured from the lower end of the implant, u is the horizontal displacement of the rod points (x axis), y_0 is the center of resistance, and k is the tangent of the rotation angle. Two unknown quantities y_0 and k are determined from two balance equations: of forces and of moments. For the distance between the implant and the rigid wall, we introduce the notation

$$\delta = \frac{D-d}{2}.$$

Then the equation of the force balance gives

$$P = \int_0^l N(y)dy = \int_0^l \sigma S dy = dE\int_0^l k\,\frac{y-y_0}{\delta}dy = kE\frac{d}{\delta}\int_0^l (y-y_0)\,dy =$$

$$= kE\frac{d}{\delta}\left(\frac{l^2}{2} - y_0 l\right) = kE\frac{dl^2}{2\delta}\left(1-\frac{2y_0}{l}\right),\ \bar{P} \equiv \frac{2P\delta}{kEdl^2} = 1-2\frac{y_0}{l} \equiv 1-2\bar{y}_0.$$

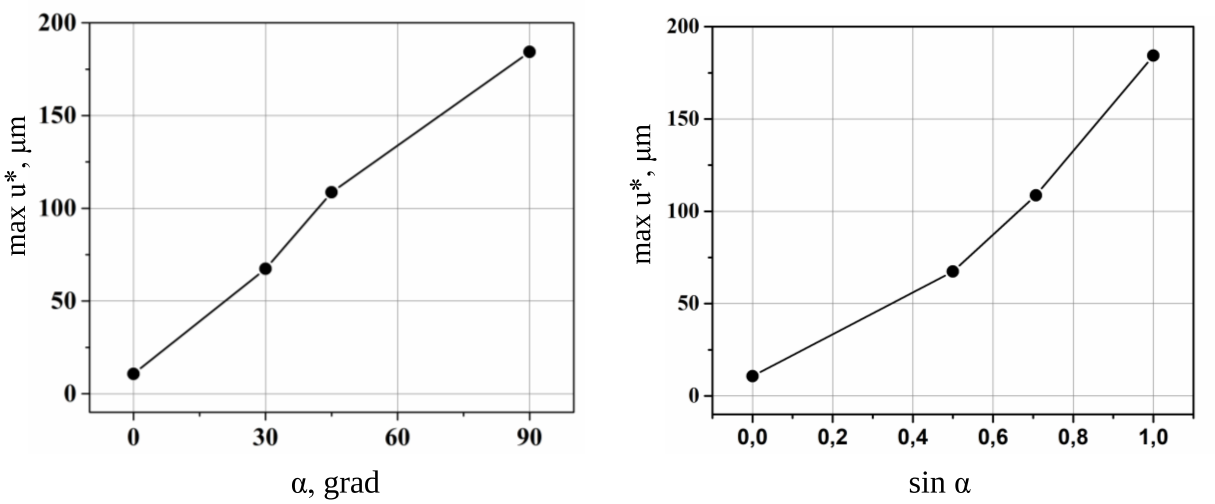


Fig. 3. The dependence of the micromotion maximum values at the bone-implant interface on the angle of loading

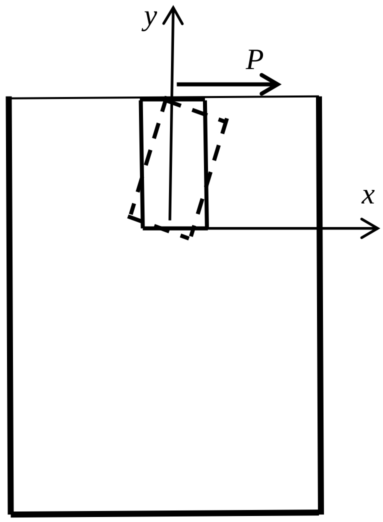


Fig. 4. Rotation of the implant under the action of the horizontal force *P* on its upper end

From the equation of the balance of moments

$$Pl = \int_0^l N(y)ydy = kE\frac{d}{\delta}\int_0^l (y-y_0)ydy = kE\frac{d}{\delta}\left(\frac{l^3}{3}-\frac{y_0 l^2}{2}\right),$$

$$P = kE\frac{dl^2}{2\delta}\left(\frac{2}{3}-\frac{y_0}{l}\right),\ \bar{P} \equiv \frac{2\mathrm{P}\delta}{kEdl^2} = \frac{2}{3}-\frac{y_0}{l} \equiv \frac{2}{3}-\bar{y}_0,$$

$$1-2\bar{y}_0 = \frac{2}{3}-\bar{y}_0,\ \bar{y}_0 = \frac{1}{3},\ \bar{P} = \frac{2}{3}-\frac{1}{3} = \frac{1}{3},\ k = \frac{2P\delta}{\bar{P}Edl^2} = \frac{6P\delta}{Edl^2},$$

$$u_{\max} = u(l) = k(y-y_0)\big|_l = k(l-y_0) = \frac{6P\delta}{Edl^2}\left(l-\frac{l}{3}\right) = \frac{4P\delta}{Edl}, \qquad (1)$$

$$u_{\max} = \frac{4P\delta}{Edl} = \frac{4\cdot 700\mathrm{N}\cdot 8\,\mathrm{mm}}{1\,\mathrm{GPa}\cdot 4\,\mathrm{mm}\cdot 8\,\mathrm{mm}} = 7\frac{10^2\ \mathrm{N}}{10^9\ {}^{\mathrm{N}}\!/\!_{\mathrm{m}^2}\cdot 10^{-3}\ \mathrm{m}} = 7\cdot 10^{-4}\,\mathrm{m} = 0,7\ \mathrm{mm} = 700\mu.$$

In the elementary model considered, the maximum micromotions (equal to the gap-lag of the implant from the bone at the point *A*) are exactly equal to the own absolute movements of the implant, thus the difference between accurate and estimated calculations for maximum micromotions being 4 times. This difference is due to the neglect in the elementary flat model of the resistance of the bone areas located below and on the sides of the implant, as well as the fact that in the exact model the gap will decrease due to extrusion of the bone into it, etc.

The derived formulas can be obtained up to a numerical factor without any calculations for dimensional and linear considerations. Parameters of the elementary model are

$$u \,\|\, P, E, l, d, \delta$$

(in the finite element method model there are also ν, and dimensions of the holder, and thread parameters).

Assuming linearity and from qualitative considerations

$$u \sim \frac{P}{E},\ u \sim \delta,\ u \sim \frac{1}{l}\ \rightarrow\ u \sim \frac{P}{E}\frac{\delta}{l}.$$

Further, in terms of dimension, *d* can enter uniquely into the denominator, and up to a numerical factor, we obtain, as in (1)

$$u \sim \frac{P}{E}\frac{\delta}{l}\frac{1}{d} = \frac{P\delta}{Eld}.$$

Of course, all these qualitative formulas are of little use for estimating the real values of the parameters of interest. Their significance is that they show approximately (in a tendency), but in the explicit form the pattern of the influence of some basic parameters on the quantities of interest. Here, estimates were done for displacements and micromotion, but the same can be done for stresses.

We note that the value for δ taken (δ = 8 mm) corresponds to stability (movements) in the buccal-lingual direction or to movements of a single implant in the medial-lateral direction in the absence of adjacent teeth; when carrying out such calculations and evaluations in practice, the parameter values should correspond to a specific situation.

Conclusions

Change in the direction of the force on the implant from vertical to horizontal in the absence of adhesion on the bone-implant interface (with immediate loading, with incomplete osseointegration) leads to a dramatic - more than an order of magnitude - increase in micromotions (mutual displacements of corresponding points) on the interface and drift of their maximum from the apex to the neck of the implant. In this case, occlusal loads being large enough, there is a risk of excessive micromotions at the interface, which can lead to disruption of osseointegration, especially in the cervical area of the implant.

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