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A Study Case of Short Dental Implants Loading in the All-On-4® System on Fixed Dental Prostheses: A Finite Element Analysis

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1. Introduction

The quality of the jawbone is very important for achieving the initial stability of dental implant in the dental segment after implantation procedure. A planed direct immediate load of biting forces through a temporary or permanent prosthesis is important too [1, 2].

The most common complaints from patients, regarding the method of linear fixation on two dental implants, is rotation of denture during the functional load in the mesiodistal direction of incisor – molar teeth. [3, 4].

The implantation of four dental implants with immediate load on them is safe due to the structure of the D1–D2 bone in the interforaminal region of lower jaw [5-7]. However, the length of the cantilever is indicated in very abstract terms – in other words the length of cantilever or relation between the prosthetic teeth arch and the antagonists is unclear. The cantilever of ten teeth bridge is not used in the case of a temporary immediate prosthetic on the four implants [8].

The periodontal ligament around the tooth root absorbs and damps the bite strength, which can not be done by the prosthetic/implant support/dental implant and peri-implant bone joints, so occlusal loads directly affect peri-implant bone throughout the prosthesis. Due to the difference of this amortization characteristic, the complications of dentures with suspended parts on implants are statistically nearly twice higher than those with dangers fixed on the teeth group. According to research of Zurdo, Tan, Pjeturssoon they are 18.2% and 10.9% [9-11]. Complications are inevitable due to the cyclic loads of dental implants and inelastic connections between elements in prosthetics with cantilever. All of them are classified as biological or mechanical / technical complications.

Bonnet designed a toothless jaw with four dental implants (central implants – vertical, lateral – angled), a screw-retained bridge on implants without cantilever and loaded on an occlusive surface by using All-on-4® concept. It was found that the highest stresses appear in the cortical bone around implant, when the load is applied on the projection of the molar tooth and/or implants are tilted [12]. Silva found that the stresses formed during functional load concentrate on the posterior implants and by applying the load on the bridge with cantilever increases the stress by 100% comparing to the load on the bridge without the cantilever [13]. Takahashi research by using All-on-4® showed that tiltation of the posterior implants increase stress of the peri-implant bone, but by using them with shorter cantilever they are decreased in cortical bone [14].

In vitro studies with dental implants and bridges with suspended parts on them showed that the stress concentrates on the marginal boundaries of the bone-implant due to the occlusive load; especially, around implant which is closer to the suspended part. Researchers have hypothesized that the acting functional load causes overload in the peri-implant bone and increases the risk of jawbone resorption [15]. Aglietta and co-authors research showed that jawbone atrophy around implant is even 2.21 times higher comparing with other implants [16]. Also the research confirmed the hypothesis raised by Zampel and co-authors about the extent of the jawbone atrophy around implants.

The aim of the research is to determine the dependence of loading 8 mm length implants in the All-on-4® system on their position in the jaw, the tilting angle and the position of the occlusive load application to the prosthesis with the cantilever.

2. Methods

Loads during the chewing process cause the stresses in the jaw, the prosthesis and their supporting structures. Finite Element Method (FEM) is one of the theoretical stress analysis, which allows to analyse dental implant systems in vitro.

In this research, the physical model is system, which consists of jaw segment, peri-implant bone, dental implants, abutments, fixation screws, bridge prosthesis, and effect on it is simulated occlusal load.

The design of structure is modelled by considering several assumptions [17]:

1. The bone is isotropic and non-porous structure. This assumption is due to the fact that the bone porous and cavities greatly increase the degree of complexity of the structural element's geometry. In addition, it is not correct to refer to the geometry of one particular jaw and its internal structure. The chosen geometry determines the changes of the bone's mechanical properties (see Table 1).

2. The threads in dental implants, supports and fixing screws are not considered. This assumption is adopted for reducing the number of interactions between structural elements.

3. Bone with denser structure (peri-implant bone) formed around the implant. It is indicated [18] that around the implant is formed denser bone, which is close to its own characteristics in the cortical bone. However, there is no unanimity about the geometry of this bone's part. Therefore, the element of cylindrical structure design, the mechanical properties of which is the same as the jaw's cortical bone with its thickness of 1 mm, is chosen.

Based on the above stated assumptions, a symmetrical model (Fig. 1) is modelled of the following components of:

1) the lower jaw segment of the interstices *1*;
2) four peri-implant bone segments *2*;
3) four implants *3*;
4) four abutments *4*;
5) four fixation screws *5*;
6) 14 teeth prosthesis bridge *6*.

Table 1

Mechanical properties of components

Component	Material	Young's modulus	Poisson's ratio
Jaw	Bone	106 MPa	0.313
Peri-implant bone		125 MPa	0.313
Implant	Titanium alloy	110 GPa	0.30
Abutment			
Screw			
Bridge dentures	Chrom-cobalt	190 GPa	0.29

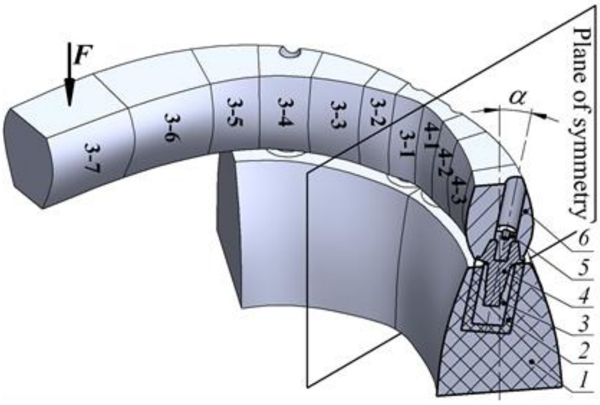


Fig. 1 The design of modelled structure

Obviously, with the adoption of the assumptions simplifying the FE model, the calculated stress does not correspond to the value of the stresses actually acting in the structure. Moreover, as mentioned before, the aim of the research is not calculations of exact stress values. A methodology was proposed for assessing the value of the average stresses occurring in the peri-implant near the boundary peri-implant/implant. The difference did not exceed 6% by comparing the exploratory results with the results obtained by the Skalak's method [20], which is widely used by implantologists. Therefore, it was concluded that these stresses indirectly show the value of load acting on bolt-abutment-implant-peri-implant system. It can be used to determine the loading dependence of All-on-4® system implants on the position of the implants in the jaw, the inclination angle of the implants and the position of applied occlusive load to the prosthesis with the cantilever.

The complete structure of the model structure performed on the lower surface of the jaw by limiting its movement during simulation of functional load. In all cases, the applied load was 300 N, which acts at 75° to the prosthetic occlusal surface of the tooth. The load value is based on the hazelnuts (Corylus avellana) crushing test.

In order to evaluate the possible relationship between the jaw bone spacing, the implants' positions modelled by changing the orientation to the occlusal plane (Fig. 1), where α (+10°, +5°, 0°, -5°, and -10°) is the angle between the tooth implant axis and the occlusive plane.

Depending on the structure, the number of finite elements varied from 60,000 to 200,000, and the nodes ranged from 90,000 to 271,000. Fine mesh of the elements was carried out at the concentrations of stresses and deformations. An adaptive mesh method was used.

3. Results and discussion

Two peculiarities were observed by analyzing the results of the research. Both values of the reactions variation and the stresses in the peri-implantbone average, which depend on the location of the loading, can be described by the exponential equation:

$$y = a + be^{x}, \tag{1}$$

where: x is the load position (from tooth 4-1 to tooth 4-7); a and b are constants, which depends from the geometry of the structure.

This equation, with a very high (even 99%) correlation, describes the changes of support reactions in the posterior implants. However, the changes of the support reactions in anterior implants are described just with a 93% correlation. The decrease in the correlation by 6 percentage points is affected by a decrease of the load on the anterior implants. When the load on the prosthesis bridge is applied to tooth 4-4, the load on the anterior implants is reduced by about 20-30% compared to the value, which could be received if the load variation was described by the Eq. (1).

The dependence of the support reactions value with 99% correlation from the load position for the anterior implants is obtained using this equation:

$$y = \frac{a + cx^2 + ex^4}{1 + bx^2 + dx^4 + fx^6}, \tag{2}$$

where: x is the load position (from tooth 4-1 to tooth 4-7); $a \div f$ are constants, which depend from the geometry of the structure.

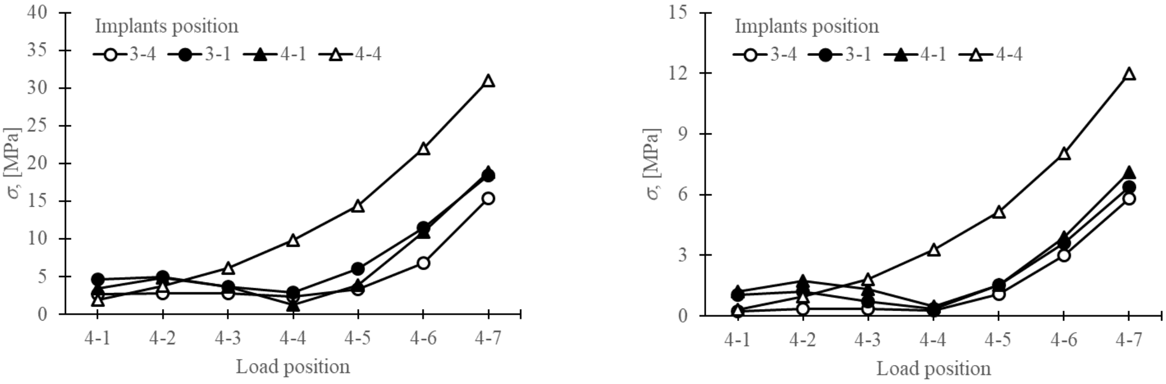
Thus, the authors of this research consider it would be appropriate to use different equations for describing the loading of the anterior and posterior implants, with the variation of the bridge prosthesis loading point.

As shown in Fig. 2, the peri-implant bone load is reduced about 2.5 times, when implants with a diameter of 4.5 mm were used instead of 3.5 mm. The research results showed that this difference for implants of 8 mm length does not depend on the position of the implants (Figs. 3 and 4), on their tilt in occlusal plane, or on the load position in the bridge prosthesis.

Applying loads on the cantilever at 4-5, 4-6, 4-7 tooth positions increases the loading of implants up to 2, 4 and 6 times, respectively.

As the anterior implants are positioned closer to the posterior implants, the load on them is increased by 16% (the diameter of the implants is 3.5 mm) and 23% at 4.5 mm diameter.

As shown in Fig. 5, the thinner implants are the more sensitive to the orientation angle of the implant is peri-implant bone. This is a logical peculiarity, since the angular orientation of the implant significantly increases the stress in the boundary of jaw/peri-implant-implant. This increases the value of the average stresses used in the assessment methodology. The medial or the lateral implant tilt at 5° angle has no influence on the implant load in comparison with a vertically oriented implants. The 10° angle was the least favourable because the implant caused the most significant load increase in investigate the load cases. The orientation of the medial direction (positive angle) significantly increases the load of the implants than the lateral orientation. This is especially noticeable in the 3-4-position implant when the load is applied on the opposite side (at the 4-4 position of the tooth). When the anterior and posterior implants are side by side, the sensitive to the orientation angle of the implants is the smallest. This allows us to conclude that two side by side implants function as one (multi root implant). On the other hand, the arrangement of the anterior and posterior implants next to each other forms an unstable system (due to two-point mounting of the prosthesis) and is not used in practice.



a b

Fig. 2 Dependence of stress on the position of occlusion load, when diameter of implants is 3.5 mm (a) and 4.5 mm (b) and implants position is at 34-31-41-44

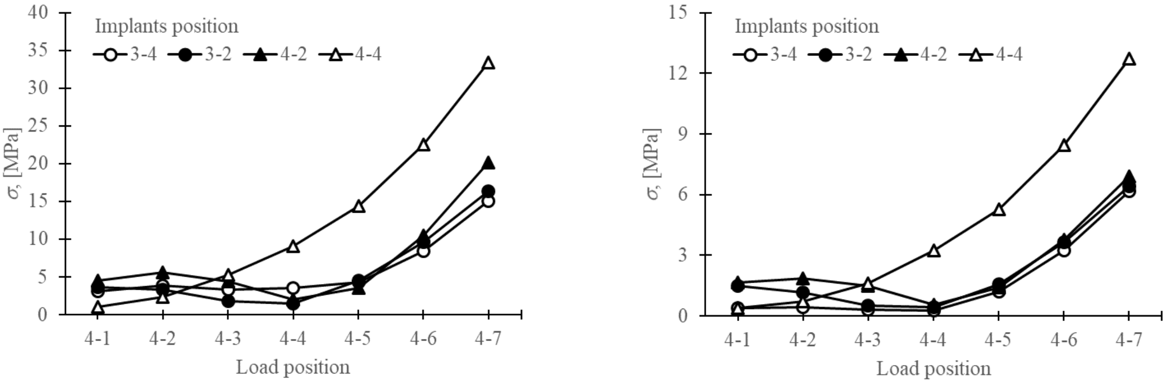


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Fig. 3 Dependence of stress on the position of occlusion load, when diameter of implants is 3.5 mm (a) and 4.5 mm (b) and implants position is at 34-32-42-44

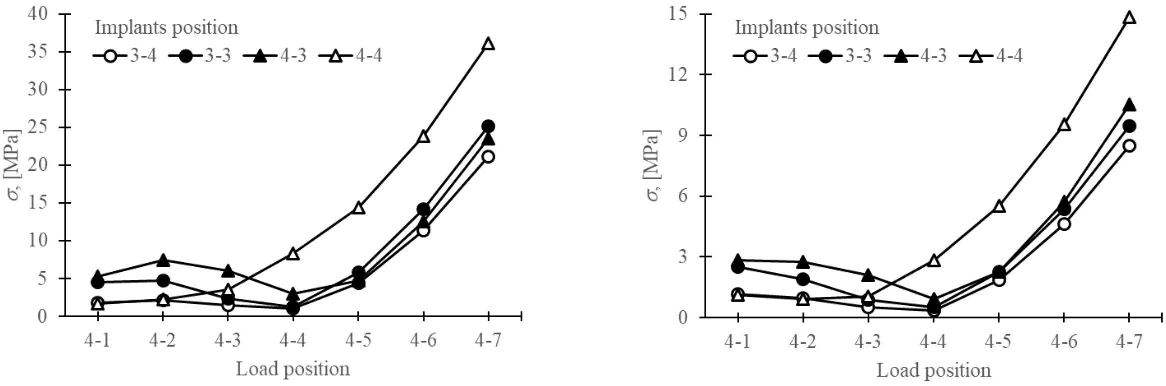

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Fig. 4 Dependence of stress on the position of occlusion load, when diameter of implants is 3.5 mm (a) and 4.5 mm (b) and implants position is at 34-33-43-44

Tilted implants affected by the additional load component in structures with a cantilever tooth load (load behind the 4th tooth or anterior implant). It tries to turn the entire system around the nearest support point. This build-up of the load component is not too big, but it increases the stresses in the peri-implant bone near the implant and changes the region of stress concentration. Due to this load component, the shear stresses are formed at the boundary between the peri-implant bone and implant, which are cause of fracture of the connection peri-implant bone-implant. These stresses can affect the implantation of the implant or even the disruption of its integration after some time.

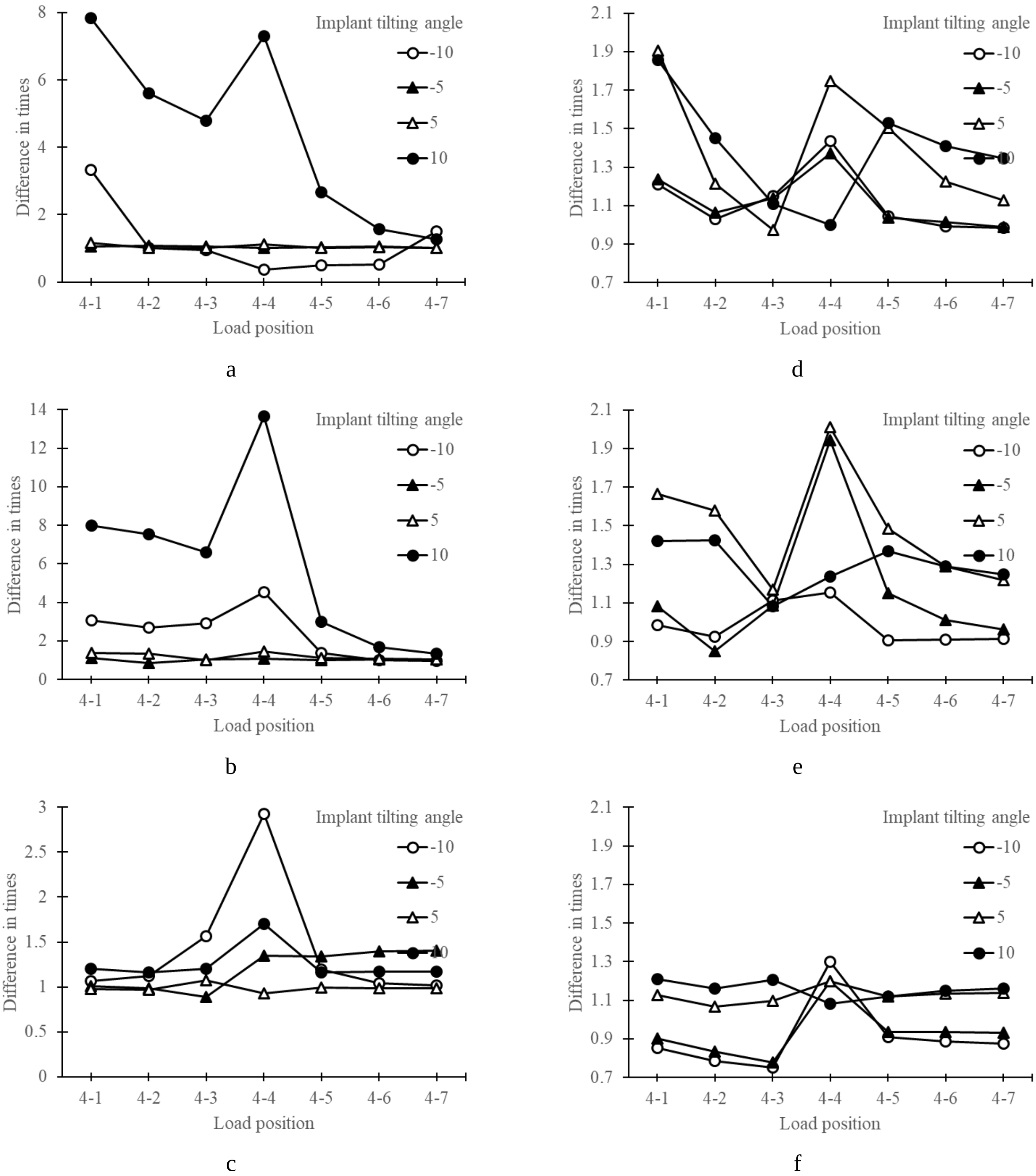

Fig. 5 The influence of implant tilting angle on implant load, comparing with vertical one at position 3-4. Position of implants are at: a) and d) 34-31-41-44, b) and e) 34-32-42-44, c) and f) 34-33-43-44. Diameter of implants is: a), b) and c) 3.5 mm, d), e) and f) 4.5 mm

For angular orientation of the posterior implants it is advisable to choose a larger diameter for them. On the other hand, this also corresponds to the nature of natural teeth – the periodontal area of root teeth is also bigger.

The tilt angle of the implant positioning has the greatest influence on the system 34-32-42-44.

According to the factors discussed above, it can be summarized:

1. The load on the pair of anterior implants with 3.5 mm diameter is redistributed so that the load of the implant side is exposed to by 1.13 to 2.74 times bigger force. Meanwhile, the load on the pair of the posterior implants is redistributed so that the implant on the side of the load is exposed even by the bigger force from 12.58 to 19.65 times;

2. The load on the pair of anterior implants with 4.5 mm diameter is redistributed so that the implant on the load side is exposed to the bigger force from 1.03 to 2.16 times. Meanwhile, the load on the posterior implants pair is redistributed so that the implant on the side of the load is exposed even to the bigger force from 8.84 to 15.54 times;

3. It can be concluded that, depending on the geometry of parallel positioned implants, the load on the pairs of anterior implants is redistributed so that the implant on

the load side is exposed to the force bigger from 1.02 to 2.74 times. Meanwhile, the load on the pairs of posterior implants is redistributed so that the implant on the side of the load is exposed to even bigger force at a value of 7.38 to 19.65 times.

After analysing the results of the research, the authors believe that some significant deviations of the average stress values from their even variation depend from the maxillary anterior / posterior curve of occlusion. The stress value, their variation may vary due to the bending and torque depending on the loading position because of different anterior / posterior curve.

4. Conclusions

Summarizing the received results can be concluded in two main points:

1. Placement and orientation of short, thin implants from mechanical view is the best, because the even values of the reaction force in all load cases are achieved. In this way, the load is distributed and a smaller load will be applied to next implant. Therefore, the structural elements are less deformed, which consequently reduces load redistribution, decreases the probability of element breaking. Of all the cases investigated, the most even distribution of the reactions is on implants‘ structures 3-4 3-1 4-1 4-4 by tilting them 100 degrees to the medial side. According to geometry and the resulting forces on the direction of the reaction can only be dealt with appears of significant forces‘ arms. Otherwise, it may be false information. Analysing geometry and forces‘ arms in structure of 3-4 3-1 4-1 4-4 , it can be said that a significant part of the effect consists of implant bending loads. This affects the formation of even greater reaction forces. However, the acting force concentrates on one side, causing stress concentration. The strength of the structural elements depends on the value of stress.

2. In view point of biomechanics, positioning and tilt of implants is the best when the bone near implant does not suffer from the implant's tension load. By nature, it's better that the bone is exposed to higher compression load, but not to small tension loads. With the four support systems, in which the cantilever is formed, it is not possible to avoid tension in implants (extraction of implants). Then it is necessary to choose a structure that ensures bone loading with a extraction force. From the examined systems, such criteria are most relevant in 3-4-3-1 4-1 4-4 system with vertical implants.

When discussing the acting load on peri-implant, research was relied on average values. However, it would be wrong to assume that the stresses across the entire implant and peri-implant contact surface are of equal values. As mentioned in the results due to the complexity of the geometric shape of structure, the implants are subjected to components of compression (in some load cases, extraction), bending, and rotational load. As a result of their effect, bearing and the shear appears in different zones of the contact surface. And it causes stress values variation and their increase (concentration). Stress concentrations are especially noticeable in structures with tilted implants. This stress concentration can effect bone resorption (atrophy), which unfortunately common in medical practice.

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A STUDY CASE OF SHORT DENTAL IMPLANTS LOADING IN THE ALL-ON-4® SYSTEM ON FIXED DENTAL PROSTHESES: A FINITE ELEMENT ANALYSIS

S u m m a r y

The biomechanical research about toothless mandible with four dental implants and a prosthetic system research, which shows the influence of the cantilever length of prosthesis on the weakest structural elements and the load changes in peri-implant bone by changing symmetrically position of the dental implants (in relation to each other), diameters and lengths, and orientation (in relation to chewing surfaces), is not discussed widely in the scientific literature. On the other hand, the use of short implants is more common in practice. Some of these implants are only 8 mm in length.

The odontologists, implantologists and dental technician can use results received by finite element method (FEM) in the daily clinical practice in order to reduce the potential for mechanical / technological and consequent biological complications already at the planning stage of the treatment, and thus determine best outcomes in the treatment of toothless patients.

With a unique interpretation of the results obtained by FEM, the paper discusses the results of implants (8 mm in length with 3.5 mm and 4.5 mm diameter) loading, when the cantilevered dental prostheses are loaded in different positions, as well as implant positions are changed.

The research determined the dependence of loading 8 mm length implants in the All-on-4® system on their position in the jaw, the tilting angle, and the position of the occlusive load application to the prosthesis with the cantilever.

Keywords: dental prosthesis with the cantilever, peri-implant, dental implants, implant loading.

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