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VON MISES STRESS ANALYSIS IN 3D ALL-ON-6 MODEL WITH 1:1 C/I RATIO

АНАЛИЗА НА НАПРЕГАЊАТА ПО VON MISES КАЈ 3D МОДЕЛ ALL-ON-6 СО 1:1 СООДНОС C/I

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Abstract

Implant-prosthetic treatments provide better dental rehabilitation than other treatments. However, implant overload is considered a risk factor that may compromise the treatment. The aim of the study was to analyze the stress in the implants, cortical and spongiosus bone, at an equal ratio of suprastructure and implant (C / I 1/1) in All-on-6 implant concept in the mandible. Numerical tests were performed on a 3D model of the mandible, based on the finite elements method or finite elements analysis (FEA). Static simulated vertical forces of 100 N and oblique forces of 35 N at an angle of 45 degrees, were applied. The physical characteristics of biological tissues and component materials, as necessary data for model making, are taken from the literature. The study analyzed Von Mises stress in implants and peri-implant cortical and trabecular bone. The highest values of von Misess stress were observed in implants, then in cortical bone, and the lowest ones in trabecular bone. The stress has higher values and greater variations on the loading side. Oblique loads create greater stress. Von Misess stress does not exceed the limitation values of elasticity of the implants and peri-implant bone tissue. The results give a realistic vision of the stress, that can be used for implant-prosthetic treatments planning. **Key words:** crown/implant ratio, suprastructure, implant, von Misess stress, stress analysis, cortical bone, trabecular bone, implant treatment, vertical forces, oblique forces.

Апстракт

Имплантопротетските третмани овозможуваат подобра стоматолошка рехабилитација од другите третмани, но сепак преоптоварувањето на имплантите се смета за фактор на ризик, кој може да го компромитира третманот. Целта на истражувањето беше да се анализираат напрегањата во имплантите, кортикалната и спонгиозна коска, при еднаков сооднос на супраструктурата и имплантот (C/I 1/1) кај All-on-6 имплантолошки концепт во долна вилица. Нумеричките испитувања беа направени на 3D модел на долна вилица, базиран на методот на конечни елементи. Применети се статички симулирани вертикални сили со јачина од 100 N и коси сили под агол од 45^0 од 35 N. Физичките карактеристики на биолошките ткива и градивните материјали, како потребни податоци за изработка на моделот, се земени од литературата. Во истражувањето анализирани се напрегањата по Von Mises во имплантите и периимплантната кортикална и спонгиозна коска. Најголеми вредности на напрегањата по von Mises има кај имплантите, потоа во кортикалната коска, а најмали во спонгиозната коска. Напрегањата имаат повисоки вредности и поголеми варијации на страната на оптоварувањето. Косите оптоварувања прават поголеми напрегања. Напрегањата по von Misess не ги надминуваат граничните вредности на еластичност на имплантот и периимплантното коскено ткиво. Добиените резултати даваат реална слика на напрегањата кои можат да бидат употребени за планирање на имплантопротетските третмани. **Клучни зборови:** сооднос C/I, супраструктура, имплант, von Misess stress, стрес анализа, кортикална коска, спонгиозна коска, имплантолошки третман, вертикални сили, коси сили.

Introduction

Edentulous therapy in contemporary dentistry is a choice between complete dentures or implant therapy. Each option has its advantages and disadvantages.

The advantage of implant-prosthetic therapy is that the prosthetic suprastructures above the implants provide greater stability and 60-80% restoration of the lost function. This gives the patient greater reliability[1].

Findings about the quality effect of implant treatment, the quality of contemporary materials for making dental implants and solving the problem of osseointegration, the development of modern implantation methods, have contributed to its preference for edentulous treatment in clinical practice.

Implant-prosthetic therapy in edentulous patients, with fixed suprastructures, is one of the most significant achievements in clinical dentistry.

More and more authors agree that clinical implantology has advanced to the point that today's implant treatment is a predictable approach for replacing lost teeth [2,3,4 5,6].

Literature review

Although implant treatments provide better dental rehabilitation than other treatments, implant overload is still considered one of the risk factors for implant success.

The load applied to the dental implant is distributed to the bone peri-implant tissue, where certain stresses are caused. Biological tissues can tolerate these stresses or react by initiating remodeling activity or creating new bone tissue[7,8].

In fact, the load is transferred through the implants to the bone structures and causes stress, which acts as a stimulus for bone tissue maintenance through remodeling process or bone formation process[9].

Bone remodeling of cortical bone is 7.7% per year, and 17.7% of trabecular bone[10].

Other authors note that cortical bone has annual bone turnover increased by 3%, while trabecular bone by 24%[11].

If the load is excessive, i.e. exceeds the physiological limits that the bone tissues can withstand, great stresses occur at the level of the interface implant-bone, which impairs osseointegration, increasing the risk of implant failure[12,13].

Determining the stress in implants, bone tissue and suprastructure can provide timely information on potential overload locations and thus prevent side effects.

The biomechanical interaction between the implant and the bone plays a key role in implant treatment success[14].

Therefore, it is very important to have a good understanding of the behavior of the forces applied on the implants, the transmission of forces to the surrounding bones and the response of the orofacial tissues, as important elements for ensuring the effectiveness of dental implants[15].

Stress distribution on dental implants and peri-implant bone tissue is a widely debated topic in the literature[16,17,18,19].

The impact of the dental implant on the peri-implant bone tissue mainly depends on the direction and intensity of the loading force, the type and material of the suprastructure, the implant design, the bone density and the mechanical characteristics of the connection between implant and bone tissue[20].

In literature, there is a multitude of research data on the impact of all of the above factors.

Due to the numerous differences, research results cannot often be comparatively relevant.

The Finite Element Method (FEA) is the most commonly used method for analyzing the forces and stresses occurring in the structure of peri-implant bone tissue, but also for evaluating different clinical situations and prosthetic options[21].

The Finite Element Method (FEM) is an analytical technique that is one of the most complete digital tools in dentistry for stress distribution, deformation and structural displacement studies[22].

Masticatory forces are dynamic loads, but because these loads are difficult to number, most FEAs use static loads[23, 24, 25].

However, there are limitations to this type of studies. One of them is that literature data obtained by different methods are mostly often used for physical characteristics of biological tissues[14, 27].

Therefore, the obtained results should not be considered as absolute, but should be used as a comparison for possible developments in the bone structure and implant components.

Comparative results from 3D FEA studies have shown that 3D FEA results correspond to clinical results, when matched with in vivo stress measurements[27, 28].

It is inevitable to compare the results of 3D FEA with previously obtained experimental or clinical data. Published results in literature will be used as reference values for comparison in this paper as well.

Various reference values of bone tissue tolerance have been published in literature. This is understandable since bone tissue has many individual characteristics, as well as different research methods.

The average value of bite forces and their resultants in implant treated patients is said to be 50 N whereas their maximum value is 150 N[29].

Due to the way it is formed, a bone shows a higher compressive strength of about 170 MPa, a lower tensile strength of 104–121 MPa and a very low shear stress strength (51.6 MPa)[30, 31].

According to Bajraktar et al. the cortical strength on tensile yield strains is 104 MPa. On the other hand, the trabecular strength on tensile stress is 82 Mpa[32].

According to Shikha et al. physical characteristics of the bone are as follows: cortical tensile strength is 115 MPa, and trabecular 32.4 MPa, cortical bone compression strength is 133 MPa, and trabecular 37.5 MPa[22].

Baggi realized that the cortical bone could withstand compressive stress of less than 170–190 MPa and tension of 100–130 Mpa under normal loads[33].

During vertical loading, Macedo observed maximum values of von Mises stress from 73 to 118 MPa in cortical bone and values from 6 to 7Mpa in trabecular bone. At oblique load, the values of maximum von Mises stress were 15 to 21 MPa for trabecular bone, while values of 150 MPa were obtained for cortical bone[34].

Also, Vijapure et al. obtained higher values when subjected to oblique loading[35].

2.5 to 8 times higher Von Mises strains in cortical bone were received than those in trabecular bone by Pessoa et al. and Vijapure et al.[35, 36].

According to Hingsammer et al., stress is much more pronounced in cortical bone due to higher mechanical strength and larger elasticity modulus, and thus can accumulate larger amount of stress[37].

In studies where the load is unilateral, the stress in the peri-implant bone tissue is higher on the loading side compared to the contralateral side[38, 39, 40, 41, 42].

However, finite element analysis has its limitations because it simulates living tissue that is not constant in its natural state and cannot replicate its characteristics as accurately as in the oral cavity[43, 44].

Aim of the study

The aim of this study was to create a numerical three-dimensional (3D) model, with equal ratio of suprastructure and implant on All-on-6 implant concept, to examine the stress in implant and peri-implant tissue, as well as to compare the results with literature data, and to assess whether the created model can serve as a benchmark for future research.

Material and methods

Numerical tests were performed on a three-dimensional (3D) model based on the Finite Element Analysis. The finite elements network is generated by software package SOFiSTiK AG, a German software company.

A model of an edentolous mandible with implants was created, according to the All-on-6 implant concept, on which a circular (latefrontolateral) fixed prosthetic suprastructure is modeled, with a ratio of 1/1 to the placed implants.

The model is created based on 3D computer tomography of the mandible.

The incisions are made by computer scan, digitalized, the thickness of the cortical bone tissue is determined, and then the data are entered in the SOFiSTiK AG software package.

The analysis was performed using the Finite Elements Analysis (FEA).

The research uses static simulated vertical occlusal forces with strength of 100N and oblique forces of 35N that will act at an angle of 45 degrees, according to literature data on functional masticatory forces.

The loading point of the simulated force will be unilateral, on the occlusal surface of the suprastructure.

The physical characteristics of biological tissues and materials, as necessary data for model creation, are collected from literature.

There are certain numerical codes for monitoring the stress on implants and peri-implant bone tissue.

Results and discussion

Excessive strain on the implant and surrounding tissues, caused by loading forces, is one of the possible causes for implant failure. Since force is transmitted directly from the implant to the bone, a well-made plan of the number of implants and their position is crucial to ensure proper distribution of masticatory forces.

Von Mises stress is used to predict the yield of materials under complex load as seen from the results of one-way tensile tests.

1. The results of the research of the All-on-6 model with Crown/Implant ratio 1/1

The study analyzed von Mises stress in implants and peri-implant cortical and trabecular bone (Figure 1. a, b, c, d, e, f).

Table 1. Numerical codes of implants

Implant – loading site	Implant – non-loading site
5 implant (distal)	6 implant (distal)
15 implant (middle/angled)	16 implant (middle/angled)
25 implant (front, anterior)	26 implant (anterior)

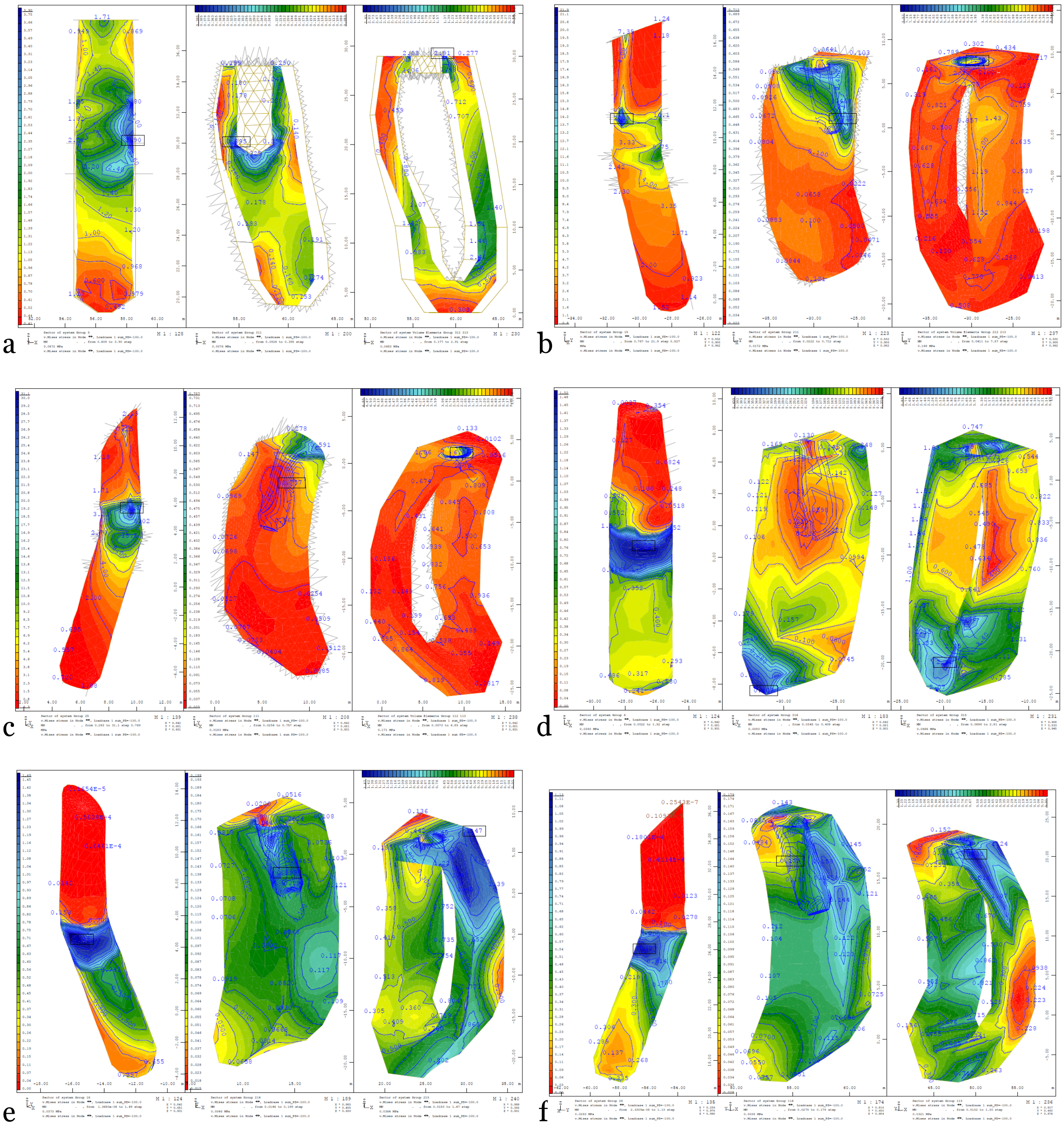
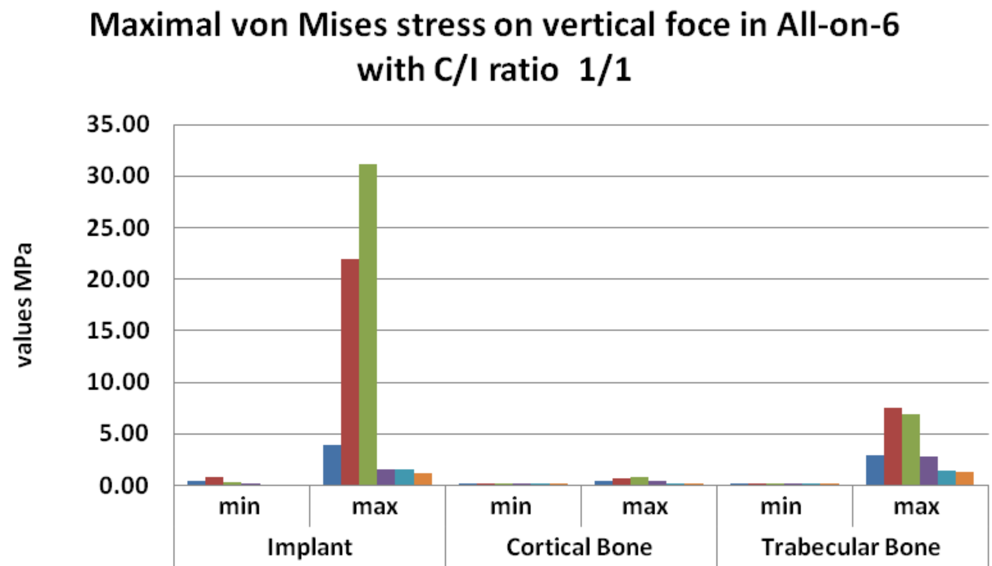


Figure 1. *Display of von Mises stress on vertical forces at All-on-6: a) distal implant 5, b) middle/angled implant 15, c) anterior implant 25, d) distal implant 6, e) middle/angled implant 16, f) anterior implant 25*

Figure 1 shows that the maximum v. Mises stress has different characteristics in each implant and peri-implant bone tissue. It is characteristic that maximum von Mises stress on distal implant 8 on the non-load side is located far from the implant zone in the basal part of the mandible (Figure 1.d.).

Figure 1 shows the values of the minimum and maximum von Mises stress in implant, cortical and trabecular bone.

The results in Figure 2 show that on vertical occlusal forces load, the higher values of maximum v. Mises stress are on the loading side. Stress values are higher on



	Implant min	Implant max	Cortical Bone min	Cortical Bone max	Trabecular Bone min	Trabecular Bone max
5 implant	0.41	3.90	0.09	0.40	0.18	2.91
15 implant	0.79	21.90	0.02	0.71	0.04	7.57
25 implant	0.28	31.10	0.03	0.76	0.01	6.85
6 implant	0.00	1.52	0.03	0.41	0.07	2.81
16 implant	0.00	1.49	0.01	0.20	0.02	1.47
26 implant	0.00	1.13	0.0275	0.179	0.0132	1.3

Figure 2. *Values of maximum Von Mises stress (MPa) on vertical forces at All-on-6 model with Crown/Implant ratio 1/1*

implants. Values of maximum v. Mises stress of peri-implant bone tissue are higher in the cortical bone.

On the non-loading side, the highest values of maximum v. Mises stress are higher on the distal implant 6 and its peri-implant bone tissue.

On implants – On the loading side, the highest values of maximum v. Mises stress are on the middle implant[15] with values of 21.9 MPa, and on the front implant[25] with values of 31.3 MPa. The distal implant[5] on the same side has much lower values, less than 3.90 MPa.

On the non-loading side, the obtained values for maximum v. Mises stress differ. On the distal implant[6], the maximum v. Mises stress is 1.52 MPa, on the middle (angled) implant[16] values are 1.49 MPa, and values on the front implant[26] are the lowest, 1.13 MPa.

In cortical bone - the values of maximum v. Mises stress are higher on the loading side. The highest value of 7.57 MPa is on the middle (angled) implant[15], and the anterior[25] has slightly lower values of 6.85 MPa. In the cortical bone around the distal implant 5, the values of maximum v. Mises stress are the lowest, 2.91 MPa.

On the opposite side, the non-loading side, the values for maximum v. Mises stress are close, 1.47 MPa on the middle (angled) implant 16 and 1.30 MPa on the anterior implant 26. The highest values for maximum v. Mises, approximately twice as high, are in the area of the distal implant 6, 2.81 MPa

In trabecular bone - on the loading side, the highest values for v. Mises stress are in the anterior implant[25] - 0.757 MPa and the middle (angled) implant[15] - 0.712 MPa. Around the distal implant[5] on the same side, the values of maximum v. Mises stress are approximately twice less, 0.395 MPa.

On the non-loading side, the highest values for maximum v. Mises stress of 0.408MPa are around the distal implant[6], and around the middle angled implant[16] and the anterior implant[26], there are approximate stress values of 0.199 and 0.2179 MPa.

Figure 3 shows that maximum von Mises stress on oblique forces is with higher intensity on the loading

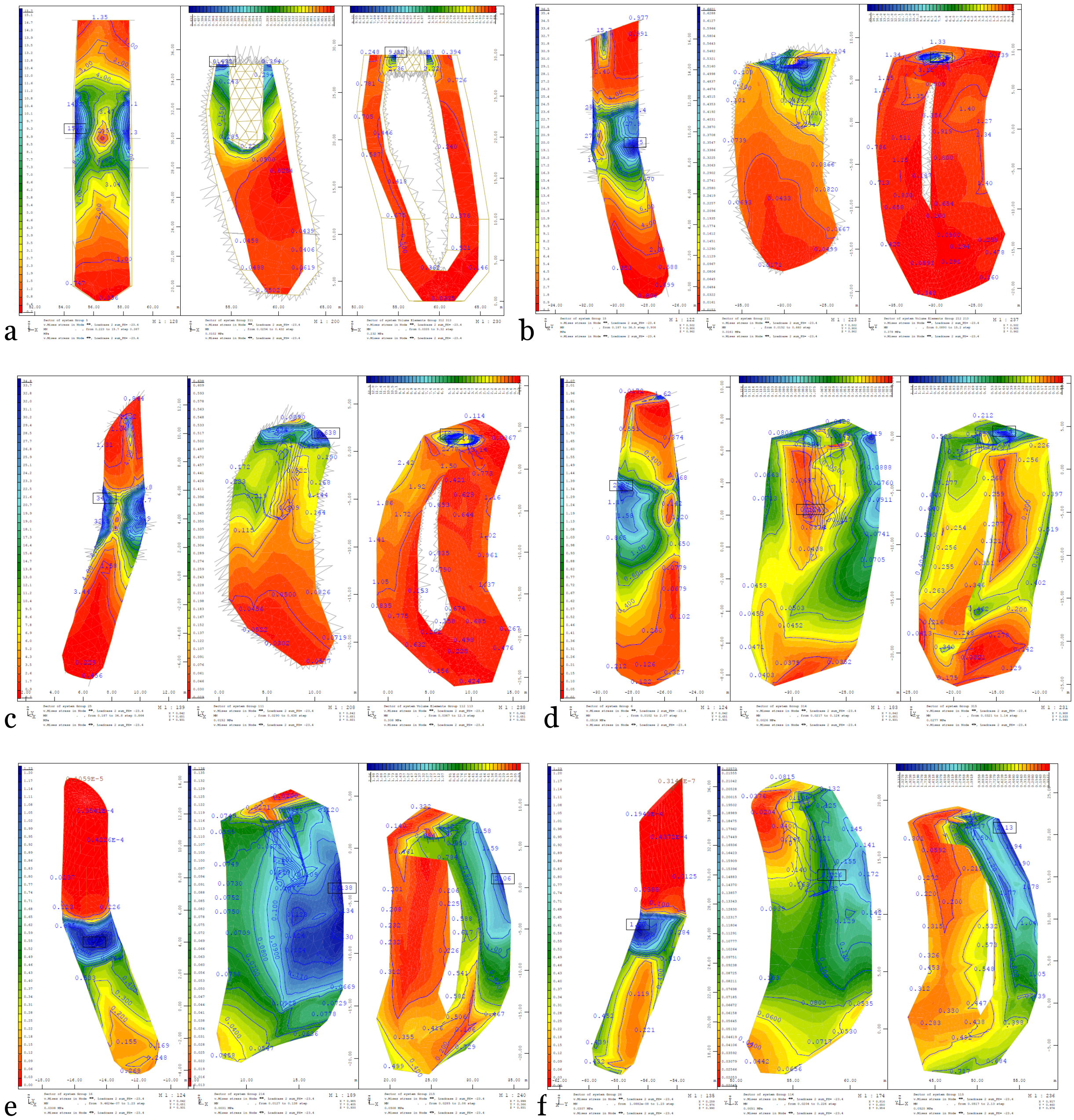
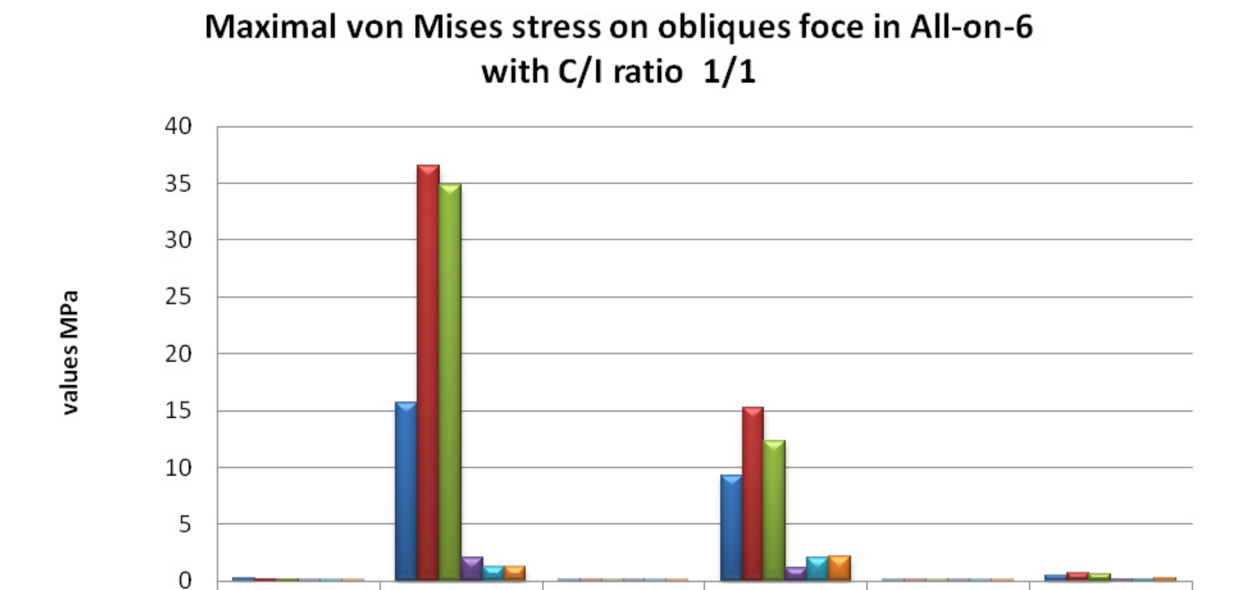


Figure 3. *Display of von Mises stress on oblique forces at All-on-6: a) distal implant 5, b) middle angled implant 15, c) anterior implant 25, d) distal implant 6, e) middle angled implant 16, f) anterior implant 25*

side. The maximum strains on the loading side are localized in the cervical part of the implants, in the cortical and the trabecular bone. On the opposite side stress has different localization in implants and peri-implant bone tissue. In implants, stress is always localized in the cervical part. In the trabecular bone, stress is always localized at the apical level of the implant, in the vestibular part, and in the cortical bone, in the distal[6], the anterior[26] and middle implant[16], stress is localized at the apical level of the implant, in the vestibular part.

The results show that, when loaded with oblique forces, higher values of maximum v. Mises stress are on the loading side. This is noted in implants, as well as in the trabecular and the cortical bone around them. The highest values have the strains in the middle implant zone[15].



	Implant		Cortical Bone		Trabecular Bone	
	min	max	min	max	min	max
5 implant	0.223	15.7	0.0335	9.32	0.0254	0.432
15 implant	0.187	36.5	0.089	15.2	0.0152	0.66
25 implant	0.187	34.8	0.0367	12.3	0.029	0.638
6 implant	0.0102	2.07	0.0321	1.14	0.0217	0.124
16 implant	0.0095	1.23	0.0285	2.06	0.0127	0.138
26 implant	0.0001	1.23	0.0517	2.13	0.0204	0.226

Figure 4. *Values of maximum Von Mises stress (MPa) on oblique forces at All-on-6 model with Crown/Implant ratio 1/1*

On the non-loading side, the highest values of maximum v. Mises stress are in the distal implant 6 and the values are approximately identical in the cortical bone in the area of the middle[16] and the anterior implant[26].

On implant - The highest values of maximum v. Mises stress are on the loading side, which are most pronounced in the middle (angled) implant[15] - 36.5 MPa and in the anterior implant[25] - 34.8 MPa. The distal implant[5] on the same side has values twice lower - 15.7 Mpa.

For implants on the opposite, the non-loading side, the obtained values of the maximum v. Mises stress are highest in the distal implant[6] of 2.07 Mpa. In the middle[16] and the anterior implant[26], the values for maximum v. Mises stress are identical, 1.23 Mpa.

In cortical bone - the values of maximum v. Mises stress are higher on the loading side. The highest value, of 15.2 MPa, is in the middle implant[15], then in the anterior[25], with a value of 12.3 MPa, and the lowest 9.32 MPa is in the distal implant[5].

On the non-loading side, the approximate values of maximum v. Mises stress are around the middle/angled implant[16] and the anterior implant[26], (2.06 and 2.13 MPa), and the values around the distal implant are almost twice as lower[6], 1.14 MPa.

In trabecular bone - Approximately close values of maximum v. Mises stress are present in the middle/angled implant[15] - 0.66 MPa and the anterior implant[25] - 0.638 MPa. While in the distal implant[5] the maximum v. Mises stress is one third lower, with value of 0.432 MPa.

On the non-loading side, the values for maximum v. Mises stress in the middle/angled1[6] and the distal implant[6] are approximately close, 0.14 and 0.12 MPa and are higher in the anterior implant[26], 0.23 MPa.

2. *Comparison of the results from the research on All-on-6 model with Corona/Implant ratio 1/1*

A comparison of the research results in Figure 1 - 4 shows that higher values of von Mises stress on the vertical and oblique loading forces of the implants, the trabecular and cortical bone, are on the loading side.

In implants - The highest values of maximum strains for vertical forces, measured by von Mises stress, are on the anterior implant[25], 31.1 MPa, and for oblique forces, the highest values are on middle/angled implant[15], 36.5 MPa.

The greatest differences are in the distal implant[5], approximately 1:3. The difference between the middle[15] and the anterior implant[25] is about 5 MPa.

On the non-loading side, the values of maximum von Mises stress for vertical and oblique forces are approximately equal, and are in the range from 1.13 to 2.81 MPa.

In cortical bone – Also, in cortical bone on the loading side, the values of maximum von Mises stress are greater for oblique forces in the zone of all implants. The differences are approximately 1/3 between distal implants 5 and 6, and approximately half between middle implants 15 and 16, and anterior implants 25 and 26.

On the non-loading side, the values of maximum von Mises stress in the distal implant 6 are 2.81 MPa for vertical forces, which are close to the values of middle implant 16 and anterior implant 26 (2.06 and 2.13 MPa) for oblique forces.

In trabecular bone - the maximum von Mises stress, for vertical and oblique forces are very close in middle and anterior implants, i.e. with values lower than one MPa (from 0.124 to 0.757MPa). The highest values of maximum stress are in distal implant 5 on the loading side (0.432 MPa), and the lowest are in distal implant 6 on the opposite side (0.124 MPa).

On the non-loading side in trabecular bone, the values of maximum strains in middle implants have close values (1.99 and 1.38 MPa). Distal implant 6 has the lowest value, 1.14 MPa, on oblique forces, with a ratio greater than 1:3 in relation to the vertical forces (0.124: 0.408 MPa).

The results obtained for the values of maximum strains, measured by von Mises stress, are close to a large number of published results from other studies.

The loading forces in the study are within the results for masticatory force, published by Hattori et al., according to which the average value of masticatory force in patients treated with implants is 50 N, and the maximum value is 150 N[29].

Higher values on the loading side are confirmed in findings of Hong et al (2012), Liu (2013), Bilhan (2013 and 2015), Ozan (2015)[38, 39, 40, 41, 42].

Higher values for von Mises stress in implant, cortical and trabecular bone, on oblique forces load, are equivalent to the findings of Macedo (2019) and Vijapure (2020)[34,35].

We have obtained higher values of maximum von Mises stress in the zone of all implants in the cortical bone than in the trabecular bone, on both, vertical and horizontal forces. These results are in accordance with the findings of Pessoa (2010), Macedo (2019), Pommer (2019) and Vijapure (2020)[30, 31, 32, 33, 34, 22].

The obtained results for the values of maximum von Mises stress are compared with the functional values of bone tissue tolerance, presented by Turner, (2001), Vincent (2013), Bayraktar (2004), Baggi (2008), Shikha (2019), and Macedo (2019). They are within the presented values and do not exceed the limits of implants, cortical and trabecular bone[30, 31, 32, 33, 34, 22].

However, in order not to overload the suprastructure or the implants with all the mechanical or biological consequences in the bone tissue, these results should be used with caution, as they are obtained only for vertical forces of 100N and only for oblique forces of 35N with an angle of 45 degrees. Literature data and findings indicate that von Mises stress strains, are increasing approximately linearly by increasing the loading force and this should be respected.

On the other hand, the load is not the only factor in implant stability. Other factors that affect the stability of implants must be considered in planning implant-prosthetic treatment.

Conclusion

The analysis of the results from the research, and their comparison with relevant researches by other authors, indicate that the model can be used as a benchmark for future research.

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