IRBM ••• (••••) •••–•••

Contents lists available at ScienceDirect

IRBM

www.elsevier.com/locate/irbm

Elsevier Masson France
EM|consulte
www.em-consulte.com

Original Article

Fatigue Loading Effect in Custom-Made All-on-4 Implants System: A 3D Finite Elements Analysis

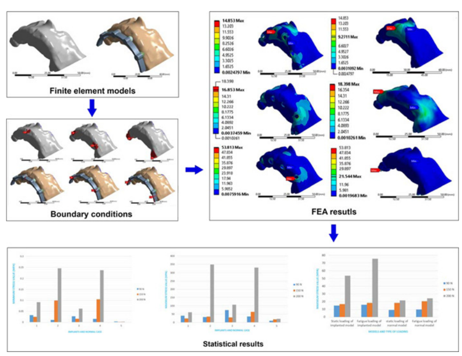
A. Darwich [a,b], A. Alammar [c], O. Heshmeh [c], S. Szabolcs [d], H. Nazha [d,*]

[a] *Faculty of Biomedical Engineering, Al-Andalus University for Medical Sciences, Tartous, Syria*
[b] *Faculty of Technical Engineering, University of Tartous, Syria*
[c] *Faculty of Dentistry, Damascus University, Damascus, Syria*
[d] *Faculty of Mechanical Engineering and Informatics, University of Miskolc, Miskolc, Hungary*

HIGHLIGHTS

- The biomedical response of dental implants during static and fatigue loading were assessed.
- Fatigue loading caused greater stresses in comparison with static loading.
- Cortical bone showed higher stress values than trabecular bone under either static or fatigue loading.
- Vertical implants showed more homogenous behavior in the system.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 24 March 2021
Received in revised form 3 May 2021
Accepted 14 June 2021
Available online xxxx

Keywords:
All-on-four concept
Fatigue loading
Dental implant
Finite element analysis

ABSTRACT

Objectives: This study aims to evaluate the fatigue stress around custom-made all-on-4 implants system to find out which type of implants have a better performance under different graded multidirectional occlusal forces.
Material and methods: 3D normal and implanted models simulating the "All-on-4" concept were created and analyzed under three different conditions of occlusal loadings. Two types of static and fatigue were applied. Stress distribution was analyzed based on von Mises and Goodman theories in ANSYS environment in addition to the safety factor. Statistical tests were performed to assess the significance of the results as well as the reproducibility of the results.
Results: The results showed stress increasing reaching a value of 48%, 29% in tilted implants compared to vertical implants and normal cases respectively. In contrast, tilted implants appeared to be less stable (safety factor may reach 0.7) and they may fail during the application of occlusal forces. The safety factor of cortical bone decreased by about 91% in the implanted model compared to the normal model, indicating a higher possibility of bone remodeling around the bone.
Conclusion: The orientation and position of occlusal forces had an important influence on stress distribution between the implant and the surrounding bone, and fatigue loading caused greater stresses in comparison with static loading. Lower amounts of stress were found in the vertical implants, ensuring a higher safety factor and a longer clinical service. In contrast, the critical safety factor values are observed in tilted implants, which may fail under the influence of applied occlusal forces.

* Corresponding author.
E-mail address: hasan.nazha@uni-miskolc.hu (H. Nazha).

https://doi.org/10.1016/j.irbm.2021.06.008
1959-0318/

1. Introduction

Alveolar ridge resorption after teeth extraction represents a clinical challenge in implant-supported restorations of completely edentulous patients [1,2]. The most popular surgical techniques for bone augmentation are sinus elevation, nerve repositioning, zygomatic implants, and bone grafting [3]. Although the high cost of these techniques, they are related to several post-surgical complications, including edema, infection, bleeding, pain, and discomfort [4].

Short implants, distal cantilever, all-on-four, and all-on-six concepts are also suggested to rehabilitate the edentulous jaw using tilted implants [1]. The all-on-four technique is based on two anterior upright implants and two tilted posterior implants placed in the second premolar region, with a distal inclination in parallel to the anterior wall of the maxillary sinus [6].

This surgical technique showed several advantages in terms of bone stress reduction and is also appeared to be less invasive compared to sinus elevation and bone grafting techniques [7–9]. Furthermore, this technique showed a success rate of 93% for tilted distal implants and 98% for axial implants [10,11].

The biomechanical behavior of natural teeth and implanted denture are different because of the presence of periodontal ligaments and other soft tissue structures, which play an important role in absorbing the occlusal forces [12]. The real chewing cycle is considered to be a complex biomechanical process, and it comprises different forces vectors, which necessitate the use of the multidirectional occlusal forces concept [13].

According to previous studies, the values of occlusal forces generated in dental implanted patients ranged between 25 and 1000 N. The maximum biting force values were 412 N as cited in previous studies [14]. In addition, it is reported that the forces on the anterior teeth are lower than those on the posterior teeth with maxima concentrated on the posterior teeth [14]. Where the value of the biting force was found in the range of 25-170 N on the anterior teeth, and within 50-400 N on the molar region [14]. Moreover, a biting force of 200 N was reported on the first premolar and first molars [14]. All of these important factors and values should be taken into account, due to their substantial effects on the stress distribution, compromising the stability of the implant [10–12].

Ozan and Yilmaz reported an inversely proportional relationship between stress values and implant angulation associated with the All-on-4 technique [14]. Four different finite element models were designed with different tilting angles (0, 17, 30, and 45 degrees) and a static load of 100 N was applied. Model components were considered homogenous, isotropic, and completely bonded [14]. Stress absorption was higher when the anterior implants were located in the canine region, and the distal posterior implants tilted by 30 degrees [15].

Sannino et al. studied the biomechanical behavior of an All-on-4 implant prosthesis based on FEA models comparing three different tilting angles (15, 30, and 45) of the distal implants under static loading. The bone-implant interface was considered completely fixed to simulate a fully osseointegrated condition, without any gaps or friction between the implant and the abutment, or the abutment and the prosthesis' bar [16]. 45 degrees-tilted posterior implant in the All-on-4 concept appeared to induce higher stress values at the bone-implant interface, leading to implants failure, specifically when stress values exceeded the yield strength of the implant's metal [17]. A proportional relationship was found between the angle of posterior implants and the stress values that appeared in both cancellous and cortical bone under unilateral 100 N static loading condition [13].

Most studies related to implants' biomechanical response considered static loading conditions only, which may underestimate the influence of loading on implant stability.

It is well-known nowadays that masticatory forces represent fatigue loading conditions, leading to a fatigue phenomenon of implant material which may change the stress behavior considerably. Geramizadeh et al. [18] showed that implants with micro threads caused lower stress on the surrounding bone by using finite element analysis. Liangjian et al. [12] studied the fatigue behavior of biomimetic titanium implant under static and dynamic loading conditions and decided the success of biomimetic style implant. The fatigue response of screws in dental implants under different occlusal loads was reported by Abasolo et al. [19]. They found that the acceptable vertical misfit of the screw was equal to or less than 40 μm.

Previous medical literature has investigated the effects of static loading on dental implants, but the effect of fatigue loading on the stress of implants and surrounding bone is not elucidated. To our knowledge, this the first investigation focusing on static and fatigue behaviors of dental implants during the inclination.

Therefore, this study aims to assess the biomedical response of dental implants during static and fatigue loadings in case of the inclination of the implant under different graded multidirectional occlusal forces by finite elements analysis (FEA) to gain a better understanding of the implants loading mechanism.

2. Materials and methods

2.1. Finite element model

A three-dimensional geometry of a fully edentulous maxilla consisting of both cancellous and cortical bone was created using cone-beam computed tomography (CBCT) images of a patient with edentulous maxilla for "All-on-4" treatment by Mimics 21.0 software. The 3D maxillary model consisted of a 1 mm-thickness layer of cortical bone at all points surrounding a core of trabecular bone. Solidworks software (v. 20, 3ds co.) was also used to produce 3D models of the implants: Straight type (megagen, Korea) with a diameter of 4 mm, length of 13 mm, the pitch of 0.8×2.0 mm, thread thickness of 0.8 mm and a thread height of 0.50 mm, and angulated type with 29 degree angulation and multi-unit abutments (height of 3.5 mm). A bar-shaped maxillary arch (width 3 mm, height 27 mm, and a bilateral end cantilever of 10 mm) was also constructed to connect the implants.

Fig. 1 shows the final 3D normal model and implanted model according to the "All-on-4" concept. We notice that two axially orientated implants are positioned in the lateral incisor region, and two tilted distal implants are placed in the second upper premolar position. An inclination of (30 degrees) was made according to the anterior wall of the maxillary sinus. A rigid metal prosthetic bar joined to the four implants as a framework consists of 12 masticatory units. Then, the final models were exported to ANSYS 20.0 R1 software. All models were discretized in linear tetrahedral elements, because of the complexity of the geometry. The numbers of nodes and elements of cortical, cancellous bone, and implant are listed in Table 1. It is worth to be mentioned that the mesh sensitivity, as shown in Fig. 2, represented after a convergence analysis, where the mesh was refined and accepted with relative errors of less than 1%.

The finite element analysis was performed using ANSYS 20.0 R1 software. Von Mises stress was used to evaluate the stress distribution and measure the maximum stress value on the peri-implant bone and implant-bone interface. A good technique and implant design should satisfy maximum or infinite fatigue life. By using ANSYS 20.0 R1 software and upon finite element stress analysis, a fatigue analysis was performed. Fatigue calculations are

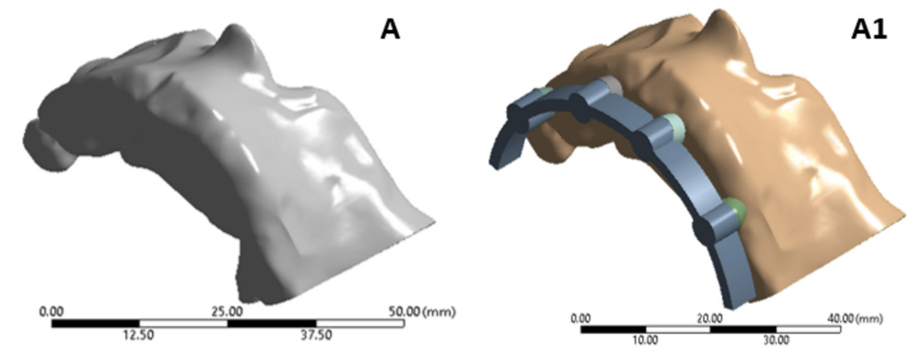


Fig. 1. A: Normal model, A1: Implanted model.

Table 1
Number of nodes and elements adopted for the models.

The component of the model	Number of nodes	Number of elements
Cortical bone	24742	12156
Trabecular bone	17412	10238
Bar	4038	1916
Right vertical implant	21504	11264
Left vertical implant	21492	11252
Right tilted implant	18996	9751
Left tilted implant	18762	9308

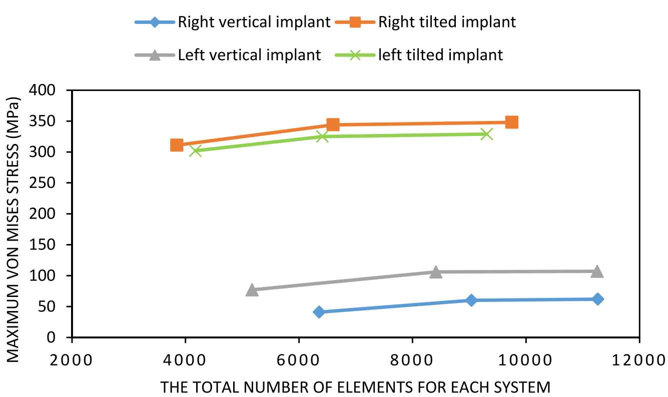


Fig. 2. Mesh sensitivity.

based on knowledge of fatigue properties of all components of the model (cortical and trabecular bone, Cr-Co alloy – titanium alloy) in terms of alternating stress versus a number of cycles known as S-N curves shown in Fig. 3. The fatigue life was calculated based on Goodman fatigue theory, which was illustrated in fatigue formulas as follows:

$$\sigma_m = \frac{\sigma_{\max} + \sigma_{\min}}{2} \tag{1}$$

$$\sigma_a = \frac{\sigma_{\max} - \sigma_{\min}}{2} \tag{2}$$

The relation between σm and σa according to the modified Goodman theory as:

$$\frac{\sigma_a}{S_e} + \frac{\sigma_m}{S_u} = \frac{1}{N_f} \tag{3}$$

The fatigue safety factor, N_f is given by:

$$N_f = \frac{1}{\frac{\sigma_a}{S_e} + \frac{\sigma_m}{S_u}} \tag{4}$$

Table 2
Mechanical properties for the components of the FE models.

Component	Young modulus (Gpa)	Poisson ratio υ	Density (g/cm^3)	Shear modulus (Mpa)
Cortical bone	13.7	0.3	1.85	3300
Trabecular bone	1.37	0.3	0.9	81923
Cr-Co alloy	218	0.33	10	58461
Titanium	110	0.35	4.5	24278

The annotations of the previous symbols as follows: N_f indicates the safety factor for fatigue life in a loading cycle, S_e is for endurance limit, S_u is for ultimate tensile strength of the material, σ_{m} present the mean stress, and σ_{a} is the alternating stress.

2.2. Material properties

Each component in the model (cortical and trabecular bone, Cr-Co alloy – titanium alloy) was considered to be isotropic, homogeneous, and linear elastic. Isotropic materials show the same mechanical properties regardless of loading direction [10,20]. All the reference values of mechanical properties of all the materials in this study were taken from the literature [3–5]. A summary of the mechanical properties used in this analysis is shown in Table 2.

2.3. Boundary conditions

The finite element model was fully constrained at the base of the skull. All the interfaces were considered bonded contact as indicated in Liu et al. (2019), Shash et al. (2019), Bhering et al. (2016), and Correa et al. (2014) [1–4]. Bone-implant interfaces were assumed to be fully bonded in order to simulate the ideal osseointegration [14]. We compared two 3D-FE finite elements models: A normal model representing a natural edentulous maxilla without implants, and an implanted model, representing the rehabilitation of natural edentulous maxilla based on the “All-on-4” concept as shown in Fig. 1.

Three static occlusal loadings were applied to normal and implanted models. As shown in Fig. 4, these conditions simulate masticatory forces related to functional bite movements from patients with “all-on-4” maxillary rehabilitation as follows: First loading condition: Unilateral horizontal static load of 90 N on the midline palatal surface of the bar (between central incisor positions). Second loading condition: Bilateral vertical static loads of 150 N on the occlusal surface of second premolar position on the bar. Third loading condition: Posterior bilateral vertical static loads of 200 N on the cantilever of the bar (first molar position).

All mentioned models and loading were used in order to assess the following conditions: Firstly, the impact of implant inclina-

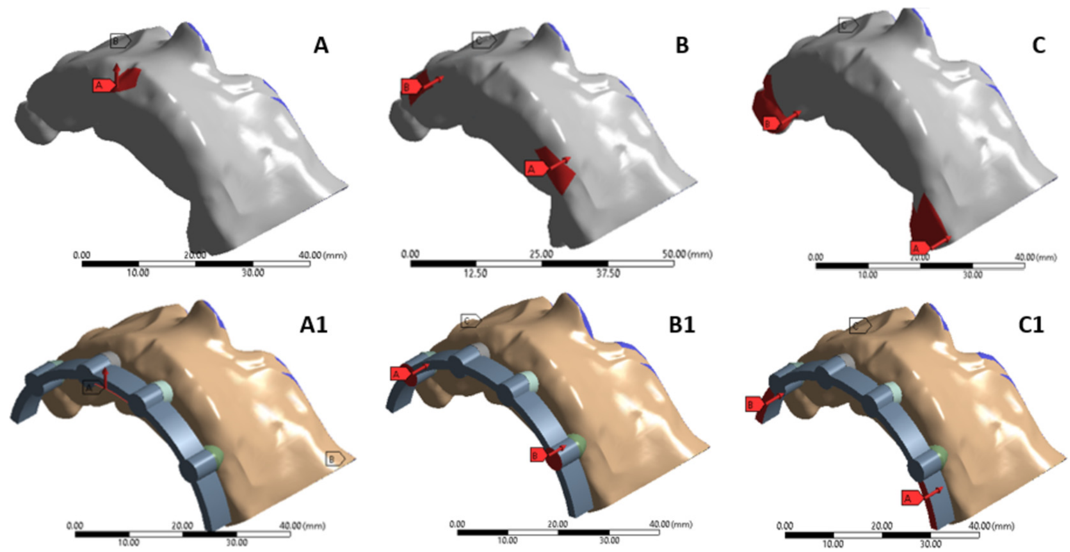


Fig. 3. The applied occlusal forces: A., B., and C. the positions of 90, 150, and 200 N forces in normal model respectively. A1., B1., and C1. the positions of 90, 150, and 200 N forces in implanted model.

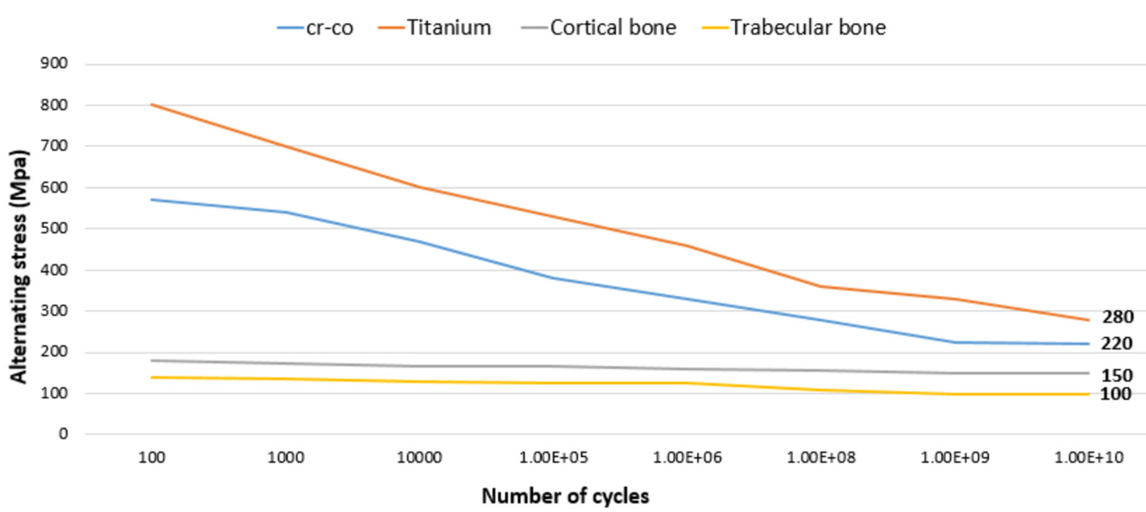


Fig. 4. S-N curves for cortical bone, trabecular bone, titanium, and cobalt-chromium alloy. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

tion on the stress distribution by comparing the 30° angulated implants with axial implants under the three different occlusal loading conditions. Secondly, the impact of varying the amplitude and direction of the applied occlusal forces on stress distribution by comparing between normal and implanted models. Finally, the impact of static and fatigue loadings on the stress distribution by comparing normal and implanted models.

2.4. Statistical analysis

Stress values and safety factors are determined for cortical bone, vertical, and tilted implants in both normal and implanted models under three different loading conditions. One-way ANOVA between safety factor and stress values related to the different components of normal and implanted models was performed. LSD and Bonferroni tests were also performed between stress and safety factor values in order to assess inter-set results. A limit ($P < 0.05$) was used to indicate the statistical significance of results by using SPSS software V26.

3. Results

3.1. Influence of implant angulation

Table 3 shows the analysis of variance statistical results of von Mises stress for vertical, tilted implants, and normal case. There were significant differences ($P < 0.05$) in the minimum stress values of implants. Higher implant minimal von Mises stress values were observed in the right vertical implant (0.03222 MPa), left tilted implant (0.10415 MPa), and right tilted implant (0.24546 MPa) under 90, 150, and 200 N occlusal forces respectively as shown in Fig. 5. The stress increased in tilted implants compared to vertical implants and normal cases. The highest stress on implants was observed in the neck area, and the stress decreases in the apical direction of the implants. There is a relationship close to the statistical significance ($P = 0.057$) of the maximum stress values of the implants. Higher values of implants' von Mises stress were observed in the left vertical implant (74.118 MPa), left tilted implant (63.044 MPa), and right tilted implant (347.93 MPa) under 90, 150, and 200 N occlusal forces respectively as shown in Fig. 6.

Table 3
ANOVA statistical results of von Mises stress for vertical, tilted implants, and normal case.

Dependent variable	Sum of squares	Dt	Mean square	F	P-value
Minimum stress values of implant	0.065	4	0.016	3.555	0.020

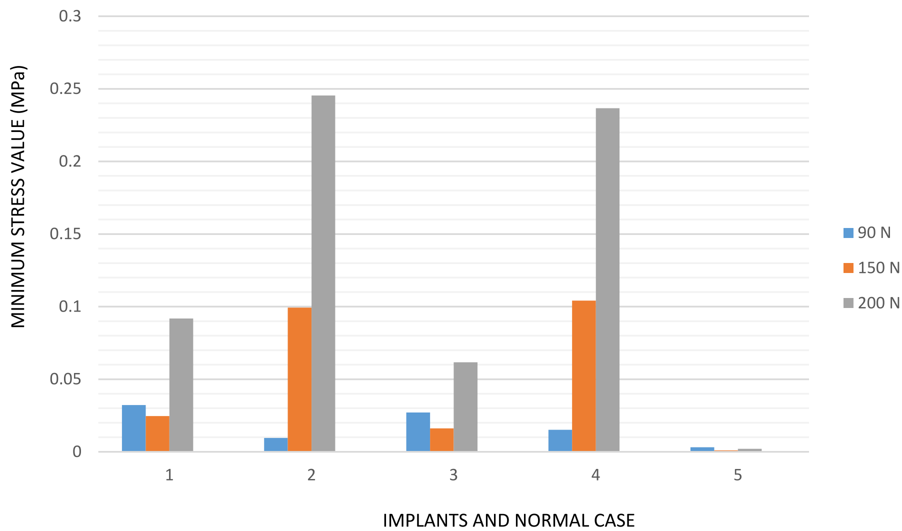


Fig. 5. Minimum stress values of implants and normal case (1: Right vertical implant, 2: Right tilted implant, 3: left vertical implant, 4: left tilted implant, 5: normal case).

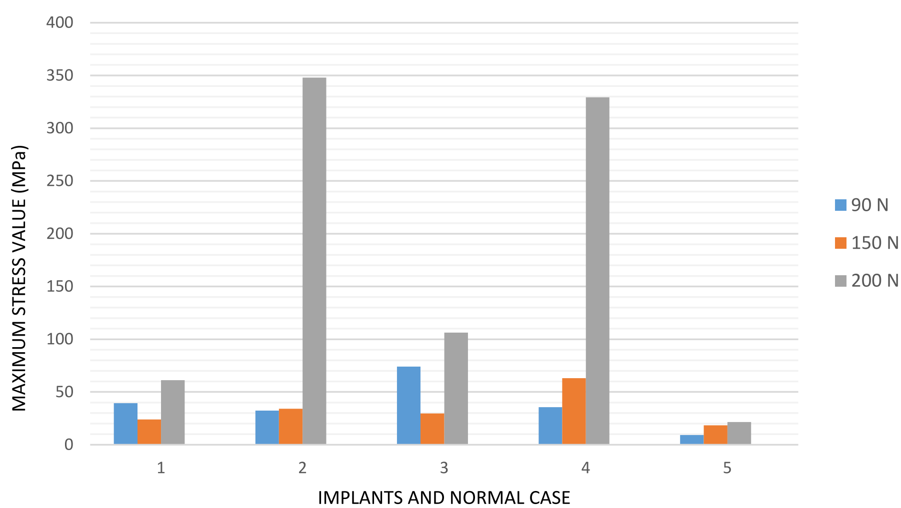


Fig. 6. Maximum stress values of implants and normal case (1: Right vertical implant, 2: Right tilted implant, 3: left vertical implant, 4: left tilted implant, 5: normal case).

The maximum von Mises concentrated on the tilted implants. All the maximum stress values generated in the tilted implants are lower than yielding stress of titanium material, which the implants are made from it.

3.2. Influence of forces amplitude

Statistical results of von Mises of bone and implants according to the difference in the amplitude and direction of the applied occlusal forces are shown in Table 4. There were significant differences ($P < 0.05$) in the maximum and minimum stress values of both bone and implants. The maximum and minimum stress values of bone and implants under different magnitude and direction of applied occlusal forces are shown in Figs. 5, 6, and 7. The stress values on the bone and implants increase by increasing the amplitude of the applied forces. According to the direction of the applied forces, the maximum stress value under horizontally applied force was observed in the left vertical implant and concentrated on the cortical bone surrounding the neck of the right anterior implant and the stress on the mesial bone of the anterior implant was greater than stress on distal, palatal, and buccal bones, whereas it was observed in the right tilted implant and concentrated on the cortical bone surrounding the neck of tilted implants. The stress on the buccal and distal bone of tilted implants was greater than that on the mesial and palatal bone under vertical applied force.

3.3. Influence of loading alternation

Cortical bone in both normal and implanted models under static and fatigue loadings showed higher stress values than trabecular bone. According to the One-Way ANOVA statistical test, there were statistically significant differences ($P < 0.05$) between maximum stress values and minimum safety factor of bone, and minimum safety factor of implants in both normal and implanted

Table 4
ANOVA statistical results of von Mises stress of bone and implants according to the force properties.

Dependent variable	Sum of squares	Dt	Mean square	F	P-value
Maximum stress values of bone	101201.936	2	50600.968	3.707	0.038
Minimum stress values of bone	.000	2	.000	21.329	.000
Maximum stress values of implant	206330.212	2	103165.106	7.452	.003
Minimum stress values of implant	.064	2	.032	7.561	.002

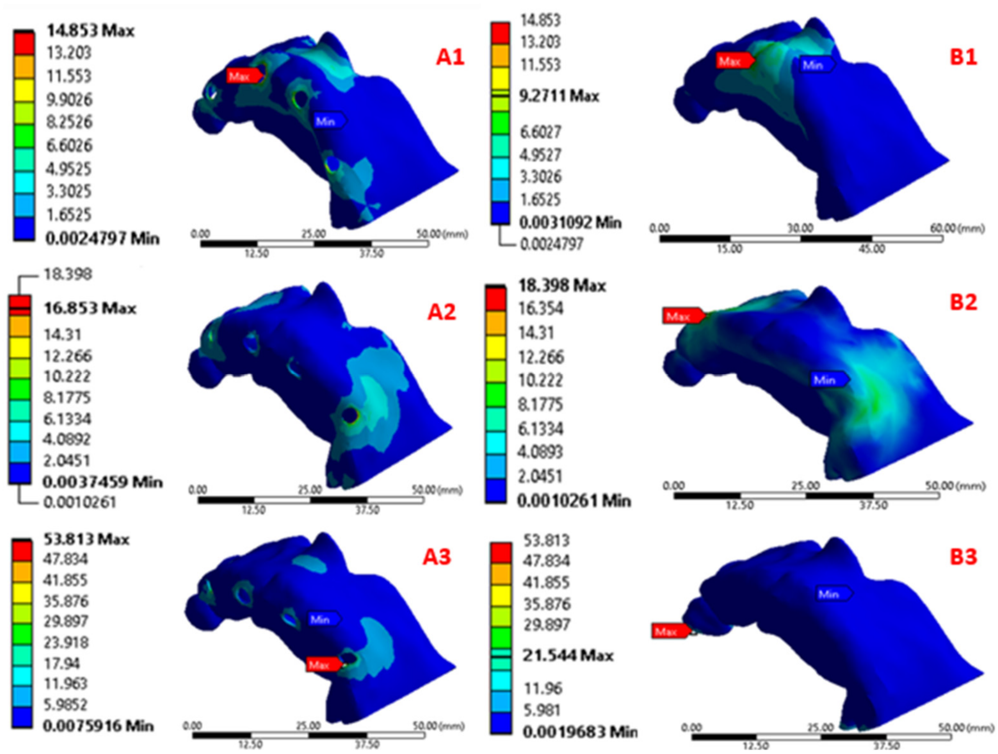


Fig. 7. Maximum and minimum stress values of cortical bone (A1., A2., and A3. in implanted model. B1., B2., and B3. in normal model under 90, 150, and 200 N loading forces respectively).

models. The finite element analysis of maximum stress generated on bone is used, and the results are shown in Fig. 8. In both normal and implanted models, the maximum stress values under fatigue loading are greater than those under static loading. All of the stress values obtained under static and fatigue loadings are lower than the conventional endurance limit of cortical bone. Safety factors for fatigue life have been calculated based on Goodman mean-stress fatigue theory according to infinite fatigue life criteria. Minimum safety factors for the bone and the implants based on infinite life criteria are given in Tables 5 and 6. It can be seen that the safety factor of cortical bone in both normal and implanted model were all above 1, but it decreased in the implanted model compared to the normal model. The safety factors for vertical implants are higher than those for tilted implants. The critical safety factor values are observed in tilted implants under 200 N applied occlusal forces. This indicates that vertical implants predicted to be safe against fatigue compared to tilted implants which may fail under different values of applied occlusal forces.

Table 5
Minimum safety factor of bone in both normal and implanted models under three different values of occlusal forces.

Loading	Minimum safety factor of cortical bone	
	Normal model	Implanted model
90 N	8.9413	5.6021
150 N	4.5058	4.9366
200 N	3.8479	1.5414

Table 6
Minimum safety factor of implants under three different values of occlusal forces.

	Loading value		
	90 N	150 N	200 N
Right vertical implant	6.2001	10.238	3.9975
Right tilted implant	7.5857	7.1854	0.70393
Left vertical implant	3.3045	8.2592	2.3034
Left tilted implant	6.8701	3.885	0.7438
Normal case	8.9413	4.5058	3.8479

4. Discussion

For a better understanding of implant inclination influence on implants system in all-on-4 technique, we compared between 30° angulated implants, axial implants, and the normal case under three different occlusal loading conditions. Numerical results showed stress increasing in tilted implants compared to the two other cases. This result concord with the results of Takahashi et al. comparing between different angulations of posterior implants (0°, 15°, 30°, and 45°) in all-on-4 concept under 50 N static load, and reported stress increasing of 30% in an inclined angle of posterior

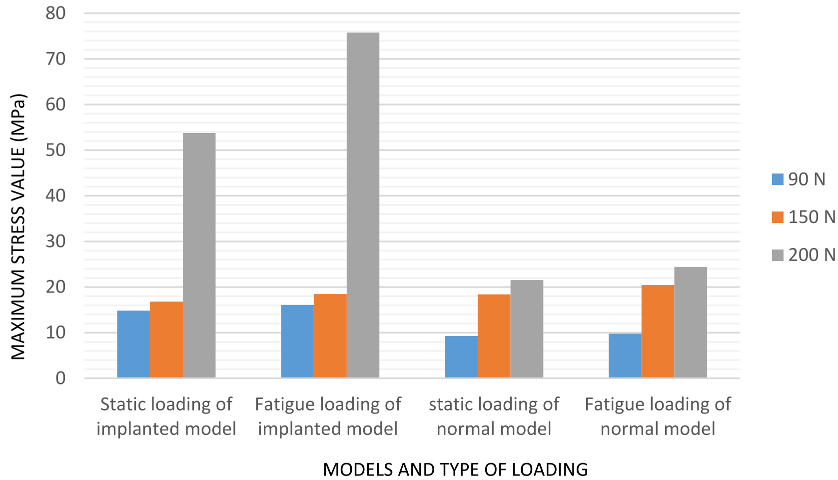


Fig. 8. Maximum stress values of cortical bone under static and fatigue loadings.

implants compared to the vertical anterior implants [13]. Similarly, the study of Türker et al. showed stress increasing of 46% in the 40° angulated posterior implants in respect to vertical implants under 200 N vertical static loading, and all the stresses were concentrated on the neck of both anterior and posterior implants [6]. The increased von Mises stress values in tilted implants may be explained by the possible elevation of shear forces related to the inclination compared to the vertical implants and the normal case. This issue was also mentioned in the study of Sannino et al. [16] who argued the elevation of tilted implants stress as they were positioned at the center of the chewing area. That means that the implant system should be more resistant to loads when used in the posterior area of the jaw according to the All-on-four concept.

The highest stress on implants was observed in the neck area. The stress decreased in the apical direction of the implants, and this most likely resulted from the closing of the implant neck to the loading area, these results are in agreement with Sannino et al. which found maximum stress values at the neck of distal implants with an increase towards the apical direction [16]. According to the previous studies, the ultimate strength of titanium is 950 MPa, so fracture possibility is assumed to be higher, especially in titled implants [17,18].

In order to achieve a more realistic study, we compared two models (normal and implanted models) under different occlusal loading properties. Both models underwent three conditions of occlusal forces to better simulate the oral clinical condition as follows: a unilateral horizontal static load of 90 N on the midline, bilateral vertical static loads of 150 N and 200 N on the occlusal surface of the second premolar position on the bar, and on the cantilever of the bar (first molar position) respectively. Significant differences ($P < 0.05$) were found in maximum and minimum stress values of both bone and implants. The stress values in the implanted model were greater than those of the normal model. This is quite normal as stress values are proportional to the amplitude of the applied forces. The maximum stress value resulted from the horizontal force was observed in the left vertical implant (74.118 MPa). Maximal values concentrated on the cortical bone surrounding the neck of the right anterior implant, and it is to be noted that stress on the mesial bone of the anterior implant was greater than stress on distal, palatal, and buccal bones. A quite high-stress value was observed in the right tilted implant (347.93 MPa), and it is positioned on the cortical bone surrounding the neck of tilted implants. These results are in agreement with Türker et al. [6] which reported higher stress in cortical bone in trabecular bone, and the stress values of the angulated implants placed in the posterior region were generally higher than those of the straight implants in the anterior region, and All of the stresses on the bone were observed around the neck of the implants. The maximum stress is most likely concentrated on the implant closest to the load application area. The direction of applied forces is important, as horizontal force could generate a larger moment on the neck of the implant, while vertical force would produce a smaller moment. We think that the connecting metallic bar is subjected to a bending moment under different directions, positions, and amplitudes of applied forces, leading to possible differences in stress distribution between right and left implants [20].

Fatigue loads were applied to represent more realistic loading conditions. All previous studies assessed stress distribution under static loading conditions without any mention of the possible effects of fatigue loading. Our numerical results showed significant differences ($P < 0.05$) in the maximum stress values of bone. In fact, cortical bone in both normal and implanted models showed higher stress values than trabecular bone similar to results of other studies, under either static or fatigue loading [7]. The maximum stress in the cortical bone can be explained by the biological structure of the cortical bone, which is harder and more compact, whereas the trabecular bone is porous and brittle. Moreover, the maximum stress value of cortical bone increased in the implanted model under both static and fatigue loadings. In both normal and implanted models, the maximum stress values under fatigue loading are greater than those under static loading, as shown in Fig. 8. Stress values in the normal model increased by 92%, 90.9%, 70.9% when alternating the application of the occlusal forces of 90, 150, and 200 N respectively, whereas stress values increased by 94.9%, 90%, and 88.3% in the implanted model respectively. The stress level under static loading increased in the implanted model compared to the normal model by 62.6%, 91.2%, and 40% under 90, 150, and 200 N applied occlusal forces respectively, and under fatigue loading by 60.6% 90.4%, and 32.1% respectively. According to physiological limits (ultimate bone strength), all of the stress values obtained under static and fatigue loadings are lower than the conventional endurance limit of cortical bone, because overloading in cortical bone occurs when the stress exceeds 185.3 MPa. Fracture possibility will increase as a result of the bone fatigue phenomenon, leading to stress elevation and non-recursive changes in bone.

The safety factor of cortical bone in both normal and implanted model were all above 1, but it decreased in the implanted model compared to the normal model as a result of the increased stress in the implanted model. Fatigue safety factors of implants play a significant role in the durability and survival of the implants under different loading conditions. The safety factors seemed to be higher in vertical implants compared to the values of tilted implants. The critical safety factor values (0.7) were observed in tilted implants under 200 N applied occlusal forces. This indicates that tilted implants may fail under different values of applied occlusal forces.

Although a significant effect of fatigue on bone stress values and implants stability was found, the presented numerical results remain predictive and dependent on the constraints of the analyses. In fact, the bone was considered as an isotropic tissue, while it is a complex living structure without a defined pattern, whose mechanical properties can vary among individuals, and this argument can slightly affect the results. Moreover, bone homogeneity is affected by the osseointegration defects causing a difference in functional distributed forces.

5. Conclusion

Within the limitation of this study, we noticed that the orientation and the position of occlusal forces had an important influence on stress distribution between the implant and the surrounding bone. The stress values increased proportionally to the amplitude of the applied forces. The results of the present study showed that fatigue loading caused greater stresses in comparison with static loading. The safety factor of cortical bone decreased by 40% in the implanted model compared to the normal model as a result of the increased stress of about 32% in the implanted model. Lower amounts of stress were reported in the vertical implants, ensuring a higher safety factor and a longer clinical service. In contrast, the critical safety factor values (0.7) are observed in tilted implants, which raise the ratio of failure under the application of the same occlusal forces.

Funding

This work did not receive any grant from funding agencies in the public, commercial, or not-for-profit sectors.

Author contributions

All authors attest that they meet the current International Committee of Medical Journal Editors (ICMJE) criteria for Authorship.

Declaration of competing interest

The authors declare that they have no known competing financial or personal relationships that could be viewed as influencing the work reported in this paper.

Acknowledgements

The authors are grateful for University of Miskolc (Institute of Machine and Product Design) for its unlimited support.

References

[1] Liu T, Mu Z, Yu T, Wang C, Huang Y. Biomechanical comparison of implant inclinations and load times with the all-on-4 treatment concept: a three-dimensional finite element analysis. Comput Methods Biomech Biomed Eng 2019;22:585–94. https://doi.org/10.1080/10255842.2019.1572120.

[2] Shash M, Nazha H, Abbas W. Influence of different abutment designs on the biomechanical behavior of one-piece zirconia dental implants and their surrounding bone: a 3D-FEA. IRBM 2019;40:313–9. https://doi.org/10.1016/j.irbm.2019.07.001.

[3] Bhering CLB, Mesquita MF, Kemmoku DT, Noritomi PY, Consani RLX, Barão VAR. Comparison between all-on-four and all-on-six treatment concepts and framework material on stress distribution in atrophic maxilla: a prototyping guided 3D-FEA study. Mater Sci Eng C 2016;69:715–25. https://doi.org/10.1016/j.msec.2016.07.059.

[4] Corrêa CB, Margonar R, Noritomi PY, Vaz LG. Mechanical behavior of dental implants in different positions in the rehabilitation of the anterior maxilla. J Prosthet Dent 2014;111:301–9. https://doi.org/10.1016/j.prosdent.2013.06.019.

[5] Borie E, Augusta I, Yoshito P, Takanori D. Three-dimensional finite element analysis of the biomechanical behaviors of implants with different connections, lengths, and diameters placed in the maxillary anterior region. Int J Oral Maxillofac Implants 2016;31:101–10. https://doi.org/10.11607/jomi.4120.

[6] Türker N, Büyükkaplan US, Sadowsky SJ, Özarslan MM. Finite element stress analysis of applied forces to implants and supporting tissues using the "all-on-four" concept with different occlusal schemes. J Prosthodont 2019;28:185–94. https://doi.org/10.1111/jopr.13004.

[7] Pellizzer EP, Falcón-Antenucci RM, de Carvalho PSP, Sánchez DMIK, Rinaldi GAT, de Aguirre CC. Influence of implant angulation with different crowns on stress distribution. J Craniofac Surg 2011;22:434–7. https://doi.org/10.1097/SCS.0b013e318207477c.

[8] Ferraz CC, Barros RM, Ferraz FC, Mundstock ÁA, Maior BS. Analysis of stress distribution in ceramic and titanium implants in alveolar sockets of the anterior region of the maxilla. J. Clinical Exp Dent 2019;11:850–7. https://doi.org/10.4317/jced.55945.

[9] Osman RB, Elkhadem AH, Ma S, Swain MV. Titanium versus zirconia implants supporting maxillary overdentures: three-dimensional finite element analysis. Int J Oral Maxillofac Implants 2013;28:198–208. https://doi.org/10.11607/jomi.3019.

[10] Cidade CP, Olate S, Pozzer L, Pimentel MJ, Nóbilo M, Albergaria BJR. Stress analysis in maxillary all-on-four model. Int J Odontostomatol 2015;9:205–11. https://doi.org/10.4067/S0718-381X2015000200005.

[11] Ghasemi S, Koodaryan R, Babaloo A, Abolfazli N. The comparison of stress distribution with different implant numbers and inclination angles in all-on-four and conventional methods in maxilla: a finite element analysis. J Dental Res Dental Clinics Dental Prosp 2015;9:246–53. https://doi.org/10.15171/joddd.2015.044.

[12] Chen L, Guo X, Yimin LI, Ting LI. Finite element analysis for interfacial stress and fatigue behaviors of biomimetic titanium implant under static and dynamic loading conditions. J Cent South Univ (Med Sci) 2010;35:662–72. https://doi.org/10.3969/j.issn.1672-7347.2010.07.004.

[13] Takahashi T, Shimamura I, Sakurai K. Influence of number and inclination angle of implants on stress distribution in mandibular cortical bone with all-on-4 concept. J Prosthodont Res 2010;54:179–84. https://doi.org/10.1016/j.jpor.2010.04.004.

[14] Ozan O, Kurtulmus-Yilmaz S. Biomechanical comparison of different implant inclinations and cantilever lengths in all-on-4 treatment concept by three-dimensional finite element analysis. Int J Oral Maxillofac Implants 2018;33:64–71. https://doi.org/10.11607/jomi.6201.

[15] Liu X, Pang F, Li Y, Jia H, Cui X, Yue Y, et al. Effects of different positions and angles of implants in maxillary edentulous jaw on surrounding bone stress under dynamic loading: a three-dimensional finite element analysis. Comput Math Methods Med 2019:1–9. https://doi.org/10.1155/2019/8074096.

[16] Sannino G. All-on-four concept: a three-dimensional finite element analysis. J Oral Implantol 2015;41:163–71. https://doi.org/10.1563/AAID-JOI-D-12-00312.

[17] Geramizadeh M, Katoozian H, Amid R, Kadkhodazadeh M. Static, dynamic, and fatigue finite element analysis of dental implants with different thread designs. J Long-Term Eff Med Implants 2016;26:347–55. https://doi.org/10.1615/JLongTermEffMedImplants.2017020008.

[18] Geramizadeh M, Katoozian H, Amid R, Kadkhodazadeh M. Finite element analysis of dental implants with and without microthreads under static and dynamic loading. J Long-Term Eff Med Implants 2017;27:25–35. https://doi.org/10.1615/JLongTermEffMedImplants.2017020007.

[19] Abasolo M, Aguirrebeitia J, Vallejo J, Albizuri J, Coria I. Influence of vertical misfit in screw fatigue behavior in dental implants: a three-dimensional finite element approach. Proc Inst Mech Eng, H J Eng Med 2018;232:1117–28. https://doi.org/10.1177/0954411918806325.

[20] Delgado-Ruiz RA, Calvo-Guirado JL, Romanos GE. Effects of occlusal forces on the peri-implant-bone interface stability. Periodontol 2019;81:179–93. https://doi.org/10.1111/prd.12291.