Original Article

A finite element analysis to study the stress distribution on distal implants in an all-on-four situation in atrophic maxilla as affected by the tilt of the implants and varying cantilever lengths

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Abstract

Aim: The aim of this work was to evaluate stress distribution on implants in All-on-Four situation with varying distal implant angulations (30°,40°,45°) and varying cantilever lengths (4 mm, 8 mm, 12 mm, 16 mm) in atrophic maxilla using finite element analysis.

Setting and Design: A *in vitro* study, finite element analysis.

Materials and Methodology: Three-dimensional finite element model of an edentulous maxilla restored with a prosthesis supported by four implants was reconstructed to carry out the analysis. Three different configurations, corresponding to 3 tilt degrees of the distal implants (30°, 40°, and 45°) were subjected to 4 loading simulations.

Statistical Analysis Used: The results of the simulations obtained were evaluated in terms of Von Mises equivalent stress levels at the bone-implant interface.

Result: From a stress-level viewpoint, the 45° model was revealed to be the most critical for peri-implant bone. In all the loading simulations, the maximum stress values were always found at the neck of the distal implants. With increasing distal implant tilt, cantilever length reduces depending on the quality of bone. At 30° angulation of distal implant a maximum cantilever length of 16 mm may be given if the quality of bone is D3 but only 8 mm cantilever may be recommended if bone quality is D4. At 40° angulation, 16 mm in D3 bone and 0 mm in D4 bone whereas at 45° angulation, it reduces to 12 mm in D3 bone and no cantilever is recommended with D4 bone.

Conclusion: The 45° tilt induced higher stress values at the bone-implant interface, especially in the distal aspect, than the other 2 tilts analyzed. Stress values increased with increased cantilever length which was further influenced by the distal implant tilt and the quality of the bone.

Keywords: All-on-four, atrophic maxilla, cantilever, full-arch prosthesis, tilted implants

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INTRODUCTION

A major problem in dentistry is edentulism and the incidence of complete edentulism has been estimated between 7% and 69%, globally. The rate of complete edentulism in India is 19%, in the USA is almost 26%, and in the UK is 46%.[1] As the age advances resorption of residual alveolar ridge occurs which makes it difficult to rehabilitate it with a prosthesis that meets the need of the dental patients.[2] So, for such patients removable dentures have been the treatment of choice as the dental treatment is still dictated by the cost economics especially in a country like India. However, literature shows that the oral health-related quality of life of patients wearing removable partial dentures was generally not optimal.[3] Consequently, removable dentures are now slowly becoming obsolete and are getting replaced with implant supported restorations.

Resorption of bone in posterior region restricts the use of dental implants due to the presence of vital structures like inferior alveolar nerve in mandible and maxillary sinus in maxilla. Implant supported prosthetic treatment in such cases of completely edentulous patients, becomes almost impossible without complex techniques such as nerve transposition, or grafting in posterior mandible. Rehabilitation of edentulous resorbed maxillary alveolar ridge is also very challenging with dental implants because of its complex three-dimensional (3D) resorption process which involves vertical and horizontal resorption with sinus pneumatization.[4] Stretched nasal cavities,[5] resorption of posterior region,[6] and low bone quality (D3/D4) and quantity[7,8] are often seen in maxilla. Sinus lift surgeries that are indicated in these cases have their own limitations such as multiple surgical procedures, patient's morbidity, high risk of complications, longer treatment time, high cost, and low patient acceptability.[9,10] Donor area morbidity, loss of bone graft, sinusitis, osteomyelitis and fistula may also occur as postsurgical complications of these treatments.[11]

All-on-Four concept was introduced by Malo *et al*. in 1990s in which two implants are placed in the anterior region vertically and two posteriorly at an angle of 30°–45° providing an advantage of eliminating additional advanced surgical procedures. It enables the rehabilitation of fully edentulous jaw with minimum bone volume. Short treatment duration, low cost, low patient morbidity and better quality of life[12-14] are other advantages of this procedure.

Little experimental clinical evidence is available regarding the effect of tilting distal implants on stresses generated in prosthetic components and bone implant interface. Similarly, not much data are available regarding the ideal cantilever lengths in cases of full arch fixed/splinted prosthesis in which four to six implants are placed in front of mental foramen and maxillary sinuses. According to Misch, under ideal conditions, the distal cantilever should not extend 2.5 times the A-P spread. Parafunction, crown height, masticatory dynamics, gender, age, and arch location will determine the magnitude and direction of force. While, number of implants, width, length, design, and bone density will determine the functional surface area. These are certain factors that have to be kept in mind while planning the treatment in an All on 4 or All on 6 splinted prosthesis. For instance, it is suggested that patients with severe bruxism should not be restored with any cantilevers.[15]

There are various ways to evaluate the stress experimentally in All-on-Four like strain gauge measurement, photoelastic strain measurement, computerized tomography (CT) scan, stereomicroscope, and finite element analysis (FEA). When investigating complex systems that are difficult to standardize during *in vitro* and *in vivo* investigations, FEA has been shown to be a useful tool.[16]

FEA is a 3D numeric simulation technique used in engineering analysis.[17] It is possible to verify level of stress, strain, and displacement in structures when subjected to external or internal loads, with this technique. Object to be studied is represented by a geometrically similar virtual model consisting of multiple discrete elements connected through nodes. It is a noninvasive computed numeric method.[18-24]

Resorption of edentulous ridges and its subsequent rehabilitation with complete dentures poses a major challenge to the clinician. Furthermore, in most of the cases, a hypersensitive gag reflex may further complicate the problem. Therefore, hybrid dentures screwed on osseointegrated implants may be the solution to such problems and may improve the oral health quality of life of the geriatric population. However, literature does not focus much on the all on 4 rehabilitations in maxilla; it mainly focuses on the rehabilitation in mandible. Therefore, the success of this treatment protocol in maxilla which is characterized by poor bone quality and quantity needs to be evaluated.

Using the 3D finite element method, this study aims to compare the stress distribution on distal implants in the "All-on-Four" situation with varying implant angulations of 30°, 40°, 45° and varying cantilever lengths of 4 mm, 8 mm, 12 mm, and 16 mm in atrophic maxilla.

MATERIALS AND METHODOLOGY

The study was approved by institutional review board (Ref no: SGTU/FDS/MDS/24/1/672). A 3D model of human maxilla, consisting of both cancellous and cortical bone was reconstructed from CT scans of edentulous patients in whom hybrid prosthesis was planned for the rehabilitation of edentulous maxilla. These planar CT scans were transformed into a solid model of maxilla using modeling software (solid Works release 2014, solid works Corporation, Waltham, Mass). Symmetry of the structure permitted the reconstruction of an edentulous maxilla. The arch had a radius of curvature of 23.5 mm and was 75 mm long, 20 ± 2.5 mm high, and 9.00 ± 1.1 mm wide. To simulate type 3 bone, a 1.8 ± 0.4 mm cortical bone layer was established, overlaying the entire maxilla, whereas cancellous bone was used in the entire internal structure. The final model represented a rehabilitated edentulous maxilla with a hybrid prosthesis supported by 4 implants (4.23 mm in diameter and 10 mm in length). In the lateral incisor regions, two mesial implants were modeled and positioned bilaterally and vertically. In the first premolar regions, two distal implants were placed and tilted distally at 45°. To carry out a comparative analysis, the apex of the distal implants was brought mesially to incline the implant to 30°, 40°, and 45°, to achieve 3 different configurations as suggested by the All-on-Four concept. Two cylindrical straight titanium abutments (4.20 mm high) were modeled and placed on the vertical implants and 2 multiunit abutments were placed on the tilted implants. A rigid type cobalt chromium prosthetic bar5 mm thick, 1 mm high and varying length of 80 mm, 72 mm, 64 mm and 56 mm was designed to serve as the framework and joined to the abutments, presenting a varying implant distal cantilever (4 mm, 8 mm, 12 mm, and 16 mm) and providing length for 12 masticatory units [Figure 1a and b]. This was done to compare 12 different configurations of a hybrid prosthesis with varying cantilever length, keeping the amount of masticatory load constant. These configurations were tested in the analysis for 4 cantilever lengths as mentioned earlier and 3 angulations of 30, 40, and 45 deg. For ensuring accurate results each component (such as implants, straight and multiunit abutments, framework) used in the fabrication of hybrid prosthesis were scanned separately and assembled together to convert into 3D solid model of maxilla using solid works modeling software.

The 3D geometry was exported to FEA preprocessing software (ANSYS Inc., Canonsburg, PA). A mesh of 68,406 elements and 122,791 nodes was generated for the FEA models [Table 1]. All materials were assumed to be isotropic, homogeneous, and linearly elastic. Young moduli and Poisson ratios of the materials used in the present study are shown in Table 2. Boundary constraints for the model were defined according to the union of the maxilla to the base of the skull, by which the movement of the maxilla was restrained, and were applied to the top of the bone. The movements of the nodes were completely constrained in this area.

The bone implant interface was considered completely fixed, in order to simulate an osseointegrated situation, and there were no craterlike defects around the implant neck, or gaps in the implant-abutment and abutment cylinder connections. Among the implants, bone and the prosthetic structure a perfect fit situation was assumed.

Four loading conditions were simulated in each of the 12 models, using load values similar to those of functional bite movements from patients with All-on-Four rehabilitation to evaluate and compare the distribution of stresses on the bone-implant interface [Figure 2]:

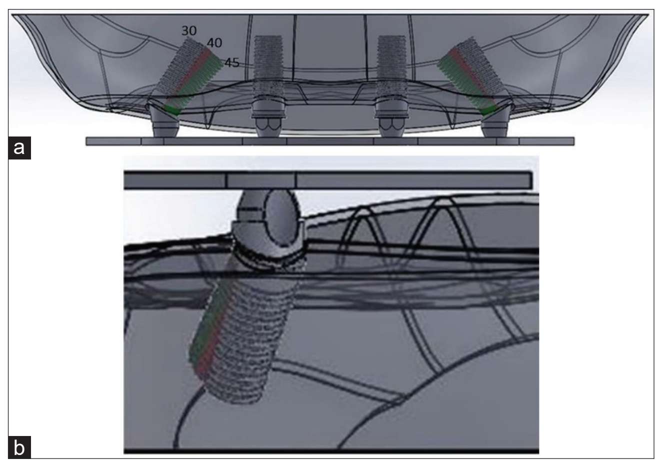

Figure 1: All-on-Four configurations three-dimensional model. (a) Front view. (b) Lateral view

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

Part	Number of nodes	Number of elements
Implant	9347	4840
Cortical bone	9250	4475
Cancellous bone	53,272	33,289
Abutment	1778	874
Bar 56 mm	1465	182
Bar 64 mm	1673	200
Bar 72 mm	1805	216
Bar 80 mm	2003	240

Table 2: Young moduli and poisson ratios of the materials used in the present study

Material	Young modulus (Gpa)	Poisson ratio
Cortical bone	13.7	0.3
Cancellous bone	1.37	0.3
Titanium	115	0.35
Cobalt chromium	200	0.3

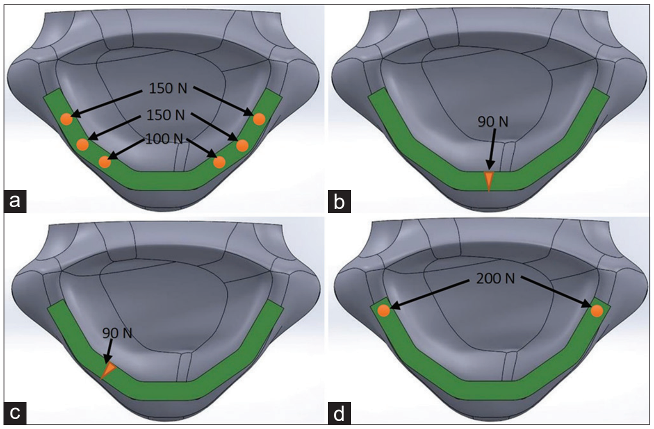

Figure 2: Occlusal view showing points of load application for each loading condition. (a) Loading 1. (b) Loading 2. (c) Loading 3. (d) Loading 4

- Loading 1 (full mouth biting): on the occlusal surfaces between the second premolars and the first molars, bilateral and simultaneous vertical static loads of 150 N, on the occlusal surfaces of the first premolars 150 N, and on the palatal surfaces on the canine 100 N were applied
- Loading 2 (anterior load): on the palatal region of the central incisors; a unilateral horizontal static load of 90 N was applied
- Loading 3 (lateral load): on the palatal region of the left canine; a unilateral horizontal static load of 90 N was applied
- Loading 4 (posterior load): on the first molars (cantilever); bilateral and simultaneous vertical static loads of 200 N were applied.

Mathematical solutions obtained in results were converted into visual results characterized by degrees of color, ranging between red and blue, with red presenting the highest stress values. The color gradient table was standardized; consequently the colors found during the evaluation of stress in the model represented the same quantities of stress. The results of the simulations obtained were evaluated in terms of Von Mises equivalent stress levels at the bone-implant interface.

RESULTS

Amounts of peak stress in the alveolar bone in all the four loading conditions in the 12 situations are described in Tables 3-5 whereas Table 6 describes the percentage difference in stress values at 30°, 40°, and 45°. Occlusal views were captured showing the stress distribution in the peri-implant region in the cortical bone of the maxillary bone model. When 12 configurations were analyzed in all the loading conditions, the highest stress values were located in the cervical region at the bone-implant interface of the tilted implants.

Table 3: Peak stress in alveolar bone in Mpa at 30° angulation of distal implant

Loading	4 mm cantilever	8 mm cantilever	12 mm cantilever	16 mm cantilever
1	21.258	22.741	24.327	26.024
2	5.7791	5.7791	5.7791	5.7791
3	11.142	11.142	11.142	11.142
4	24.546	27.216	36.695	49.476

Table 4: Peak stress in alveolar bone in Mpa at 40° angulations of distal implant

Loading	4 mm cantilever	8 mm cantilever	12 mm cantilever	16 mm cantilever
1	39.285	42.025	44.95	48.093
2	9.7169	9.7169	9.7169	9.7169
3	17.419	17.419	17.419	17.419
4	33.287	36.9	49.762	67.093

Table 5: Peak stress in alveolar bone in Mpa at 45° angulation of distal implant

Loading	4 mm cantilever	8 mm cantilever	12 mm cantilever	16 mm cantilever
1	55.785	59.676	63.829	68.292
2	16.338	16.338	16.338	16.338
3	27.232	27.232	27.232	27.232
4	45.141	50.030	67.482	90.983

In loading 1, the greatest stress values were found in the bone around the neck of the tilted implants. A significant increase in the stress was noticed when cantilever length was increased with implant angulations (30°, 40° and 45°) [Figure 3a-c].

In loading 2, stresses tended to be concentrated along the cervical region in the alveolar bone of the tilted implants. However, stress values at the bone-implant interface gradually increased as the degree of tilt increased in the distal implant [Figure 4a-c].

Loading 3, stress in the bone around the tilted implant increased as the tilt of the implant increased, but remained almost constant in the anterior bony region (i.e., around 5.62 Mpa). Change in the cantilever length did not seem to have any effect on the stress pattern around the bone in distal implant with stress within the same angulation remained similar with increased cantilever lengths but increased with increase in angulations [Figure 5a-c].

In loading 4, maximum stress values in the bone were found in the neck area on the posterior region of the tilted implants [Figure 6a-c]. The stress on the implants in the 45° model was nearly double that of the 30° models.

Table 6: Percentage difference

Loading	Between values from 30° to 40° (%)	Between values from 40° to 45° (%)	Between values from 30°to 45° (%)
1	+84.8	+42	+162.41
2	+68.14	+68.14	+182.70
3	+56.34	+56.34	+144.40
4	+35.61	+35.61	+83.90

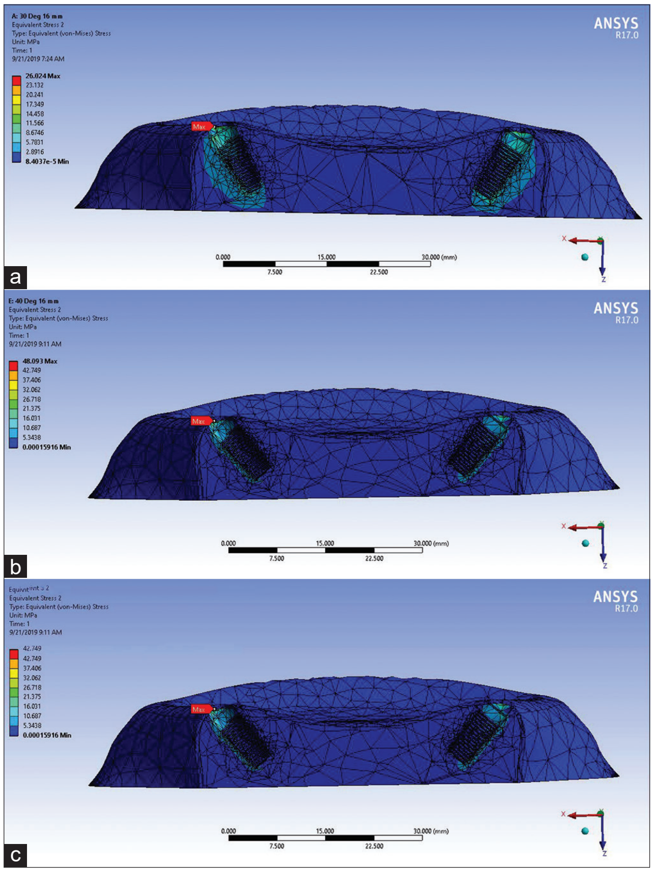

Figure 3: The Von Mises stresses for the loading 1 scenario. (a) 30° All-on-Four model, bone-implant interface of the distal implants. (b) 40° All-on-Four model, bone-implant interface of the distal implants. (c) 45° All-on-Four model, bone-implant interface of the distal implants

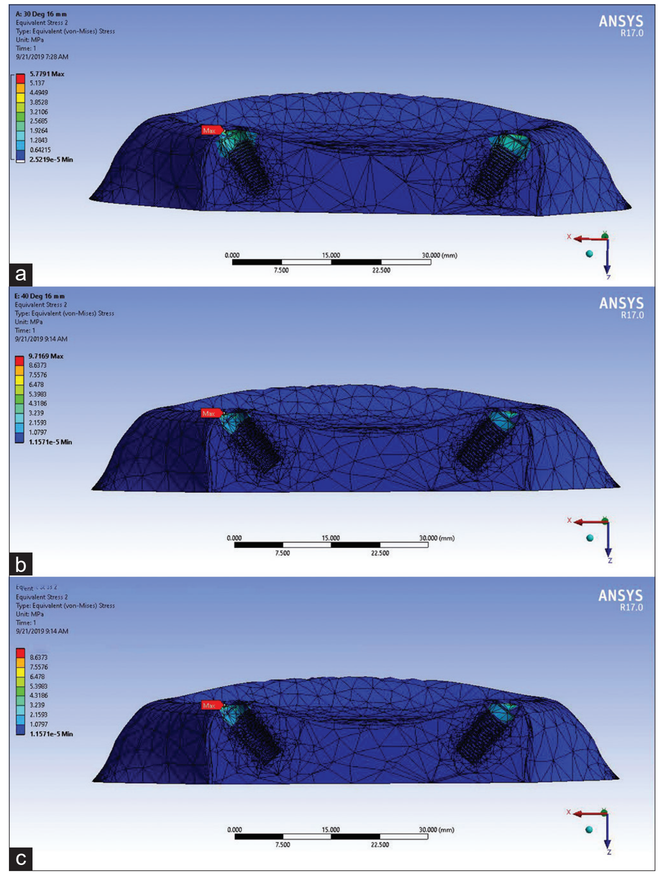

Figure 4: The Von Mises stresses for the loading 2 scenario. (a) 30° All-on-Four model, bone-implant interface of the distal implants. (b) 40° All-on-Four model, bone-implant interface of distal implants. (c) 45° All-on-Four model, bone-implant interface of the distal implants

Table 3 shows that as the cantilever is increased maximum stress value is increased in full mouth biting and posterior loading with the distal implant angulation of 30°.

Table 4 shows that maximum stress values are increased with increase in the cantilever length in full mouth biting and posterior loading conditions with distal implant angulation of 40°.

This 5 represents that maximum stress values are increased with increase in the cantilever length in full mouth biting and posterior loading conditions with distal implant angulation of 45°.

Table 6 represents that there is significant increase in the percentage difference of stress values from 30° to 45°.

DISCUSSION

Goal of modern dentistry is to restore the patient`s normal function, comfort, esthetics, speech and health, whether by removing caries from a decayed tooth or replacing several missing teeth. Implant dentistry is unique due to its ability to achieve this goal, regardless of the atrophy, disease or injury to stomatognathic system. However, more is the number of teeth missing, more challenging this task becomes. Implant supported prosthesis has various advantages over removable soft tissue supported prosthesis such as it maintains the alveolar bone, restores the occlusal vertical dimension, maintains facial esthetics, improve phonetics, masticatory performance and psychological health, reduce the size of prosthesis, increase survival time of prosthesis and more permanent replacement.[25]

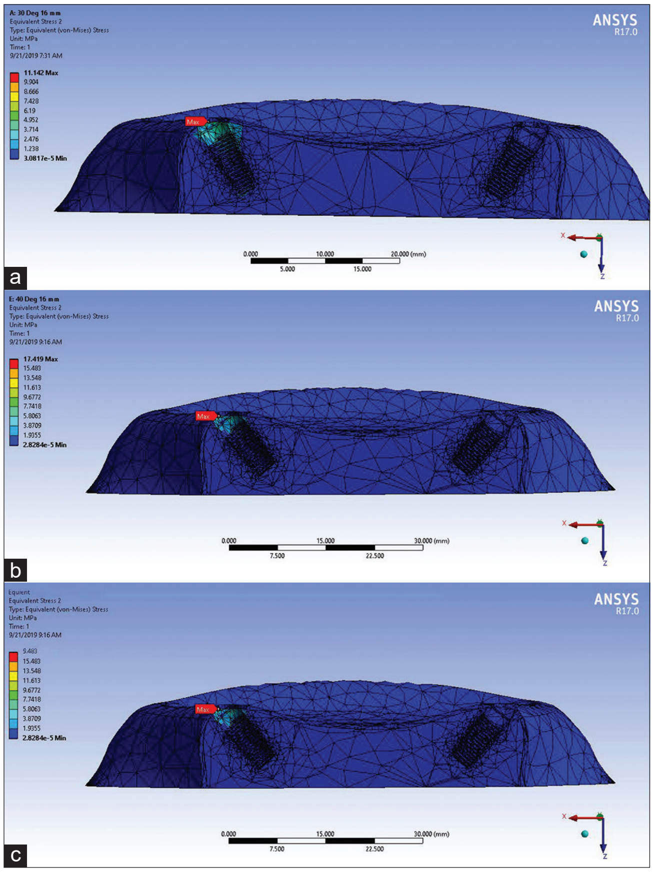

Figure 5: The Von Mises stresses for loading 3 scenario. (a) 30° All-on-Four model, bone-implant interface of distal implants. (b) 40° All-on-Four model, bone-implant interface of distal implants. (c) 45° All-on-Four model, bone-implant interface of distal implants

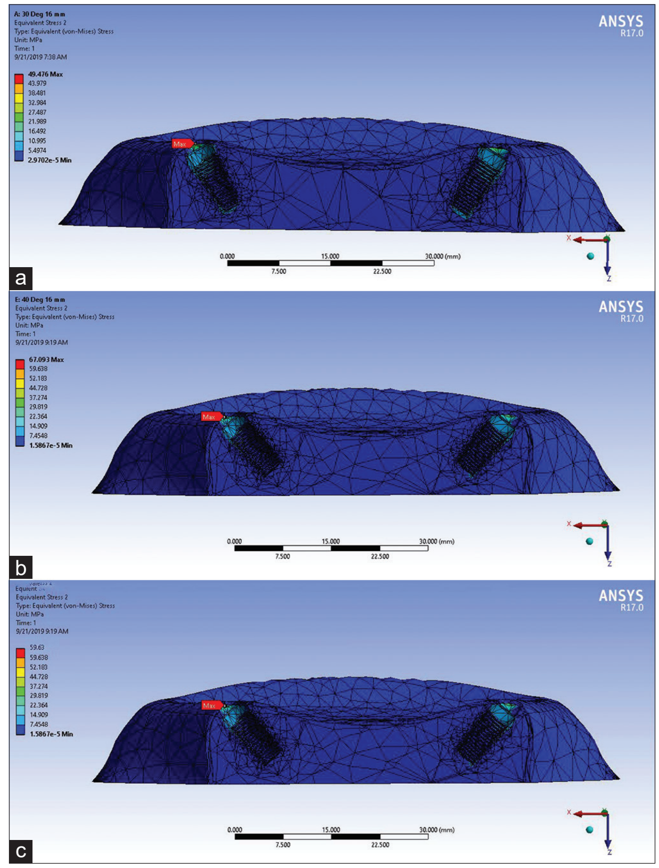

Figure 6: The Von Mises stresses for loading 4 scenario. (a) 30° All-on-Four model, bone-implant interface of distal implants. (b) 40° All-on-Four model, bone-implant interface of distal implants. (c) 45° All-on-Four model, bone-implant interface of distal implants

All-on-Four protocol is becoming increasingly popular especially in mandible as fewer implants are required therefore cost of treatment reduces however its success in maxilla is still not much documented.[26,27]

Masticatory forces used were based on averages found in the literature for the patients with implant-supported prostheses.[24] Four loading conditions were simulated, using load values similar to those of functional bite movements from patients with All-on-Four rehabilitation, these conditions are loading 1, 2, 3, and 4 as mentioned earlier.

In the present study, stress pattern were evaluated at different cantilever lengths of 4 mm, 8 mm, 12 mm, and 16 mm. It was observed that as the cantilever length increased stress exerted on distal implants also increased. This was in accordance to a study conducted by White in 1994 in which they concluded that the greatest stresses were located at the ridge crest on the distal surface of the distal implant for all cantilever lengths, and as cantilever lengths increased, the maximal stress on the implants increased.[28] Similarly, Silva *et al*. conducted a study on stress patterns on implants in prostheses supported by four or six implants, they suggested that cantilever presence greatly increases stress on the distal implant, regardless of whether or not the prosthesis is supported by four or six implants, so cantilever should be avoided or minimized.[29] Sertgöz *et al*. did a finite element analysis in which they investigated the effect of cantilever and implant length on stress distribution in an implant-supported fixed prosthesis in mandible and they concluded similar results that maximum stresses were concentrated at the most distal bone implant interface, increasing cantilever length resulted in increased stress values. Whereas implant length had no appreciable effect on stress distribution at the bone/implant interfaces.[18]

Canay *et al*.[30] did a study in which they compared the stress distribution around vertical and angled implants with finite element analysis and concluded that there were no measurable differences in stress values and contours when a horizontal load (50 N) was applied to the vertical and angled implants. However, with the vertical loading (100 N), the compressive stress values were five times higher around the cervical region of the angled implant than around the same area in the vertical implant. In the present study, in loading 2 (unilateral horizontal static load of 90 N) was applied on the palatal region of the central incisors simulating anterior load no significant stress was found in mesial and distal implants at 30° angulation but with other loadings more stresses were seen on distal implant around its neck and as the angulation and cantilever increased more stresses were observed on distal implants.

At 30° tilt of distal implants and varying cantilever lengths of 4 mm, 8 mm, 12 mm, and 16 mm, maximum stress was found at the neck of the distal implants. Peak stress was 21.25 Mpa at 4 mm cantilever, 22.74 Mpa at 8 mm cantilever, 24.32 Mpa at 12 mm cantilever, 26.02 Mpa at 16 mm in loading 1. During (loading 2), maximum stress was 5.77 Mpa on neck of the distal implants irrespective of cantilever length. Even when the load was applied near to anterior or mesial implant. In loading 3, maximum stress of 11.14 Mpa was found with 4 mm, 8 mm, 12 mm, and 16 mm cantilever near the neck of distal implant. In loading 4, maximum stress was 24.54 Mpa with 4 mm cantilever, 27.21 Mpa with 8 mm cantilever, 36.69 Mpa with 12 mm cantilever, and 49.47 Mpa with 16 mm cantilever. As maxillary posterior bone is characterized by a D3/D4 bone configuration as classified by MISCH which has an elastic modulus of 81 MPa and 35 MPa, respectively. These results show that at 30° angulation maximum stress value exceeded the elastic limit of D4 bone at cantilever lengths of 12 mm and 16 mm in loading 4 conditions whereas stresses are within the elastic limit of D3 bone. Therefore, at 30° angulation a maximum cantilever length of 16 mm in D3 whereas 8 mm of cantilever may be recommended in D4 quality of bone.

In loading 1, at 40° angulation maximum stress exceeded the elastic limit of D4 bone with all cantilevers [Table 4]. In loading 2, maximum stress was 9.71 Mpa with distal cantilever of 4 mm, 8 mm, 12 mm, and 16 mm. In loading 3, maximum stress was 17.41 Mpa with 4 mm, 8 mm, 12 mm, and 16 mm distal cantilever. In loading 4 i.e., posterior load maximum stress was 33.28 Mpa with 4 mm cantilever, 36.9 Mpa with 8 mm cantilever, 49.76 Mpa with 12 mm cantilever and 67.09 Mpa with 16 mm cantilever. Hence, at 40° angulation maximum stress exceeded the elastic limit of D4 bone at 4 mm, 8 mm, 12 mm, and 16 mm cantilever in loading 1 and at 8 mm, 12 mm, and 16 mm in loading 4 whereas elastic limit of D3 bone was not exceeded. Hence, it may be suggested that with distal implant angulation of 40°, 16 mm cantilever can be given if bone quality is D3 and no cantilever is recommended if bone quality is D4.

When stress was evaluated with 45° tilt of distal implants, maximum stress was 55.78 Mpa with 4 mm cantilever, 59.67 Mpa with 8 mm, 63.82 Mpa with 12 mm, and 68.29 Mpa with 16 mm cantilever in loading 1. In anterior loading, maximum stress was 16.33 Mpa with all cantilevers. In lateral loading, maximum stress was 27.23 Mpa with all cantilever lengths. In posterior loading, maximum stress was 45.14 Mpa with 4 mm cantilever, 50.03 Mpa with 8 mm, 67.48 Mpa with 12 mm and 90.98 Mpa with 16 mm cantilever. This shows that at 45° angulation maximum stress exceeded the elastic limit of D4 bone at 4 mm, 8 mm, 12 mm, and 16 mm in loading 1 and loading 4 whereas elastic limit of D3 bone was exceeded at 16 mm cantilever only in loading 4. So from above result, it can be concluded that, with distal implant angulation of 45° only 12 mm cantilever can be given with D3 bone and no cantilever is recommended with D4 bone.

Within the limitations of the models presented, numeric results reported in the present study must be taken as predictions, because FE models represent a simplification of the actual structure. A limitation of the FE models in the present study pertains to the mechanical behavior of bone that was assumed to be linearly elastic, homogeneous, and isotropic. Bone is a complex living structure without a defined pattern, its actual mechanical properties are not precisely established and its characteristics vary among individuals.[31,32] The FEA model used in this study assumed completely rigid equating to full osseointegration before loading. Moreover, ideal conditions, such as 100% contact between bone and implant and perfect fit of implants, abutments, and prosthetic bars were ensured. To avoid the appearance of internal tensions, the perfect passivity between the components was assumed.[16-22]

CONCLUSION

Under the limitations of the following *in vitro* study, the following conclusions can be drawn:

1. At 30° angulation of distal implant a maximum cantilever length of 16 mm may be given if the quality of bone is D3 but only 8 mm cantilever may be recommended if bone quality is D4
2. At 40°angulation of distal implant, 16 mm cantilever may be given if bone quality is D3 and no cantilever is recommended if bone quality is D4
3. At 45° angulation of distal implant only 12 mm cantilever may be given with D3 bone and no cantilever is recommended with D4 bone.

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Conflicts of interest

There are no conflicts of interest.

REFERENCES

1. Zarb G, Hobkirk J, Eckert S, Jacob R. Prosthodontic Treatment for Edentulous Patients Complete Dentures and Implant Supported Prosthesis. St Louis, United States: Elsevier; 2013. p. 13e.
2. Malhotra A, Padmanabhan T, Mohamed K, Natarajan S, Elavia U. Load transfer in tilted implants with varying cantilever lengths in an all on four situations. Aust Dent J 2012;57:440-5.
3. Shaghaghian S, Taghva M, Abduo J, Bagheri R. Oral health-related quality of life of removable partial denture wearers and related factors. J Oral Rehabil 2015;42:40-8.
4. Chiapasco M, Zaniboni M. Methods to treat the edentulous posterior maxilla: Implants with sinus grafting. J Oral Maxillofac Surg 2009;67:867-71.
5. Penarrocha D, Candel E, Ata J, Penarrocha M. Long term survival rates of implant supported overdenture. J Oral Implantol 2013;39:625-32.
6. Maló P, Nobre Md, Lopes A. The rehabilitation of completely edentulous maxillae with different degrees of resorption with four or more immediately loaded implants: A 5-year retrospective study and a new classification. Eur J Oral Implantol 2011;4:227-43.
7. Lekholm U, Zarb GA. Patient selection and preparation. In: Branemark PI, Zarb GA, Albrektsson T, editors. Tissue Integrated Prostheses: Osseointegration in Clinical Dentistry. Chicago: Quintessence Publishing Company; 1985. p. 199-209.
8. Guguloth H, Duggineni CR, Chitturi RK, Sujesh M, Ravvali T, Amiti RR. Correlation between abutment angulation and off-axial stresses on biomechanical behavior of titanium and zirconium implants in the anterior maxilla: A three-dimensional finite element analysis study. J Indian Prosthodont Soc 2019;19:353-61.
9. Schwartz-Arad D, Herzberg R, Dolev E. The prevalence of surgical complications of the sinus graft procedure and their impact on implant survival. J Periodontol 2004;75:511-6.
10. Cidade CP, Pimentel MJ, Amaral RC, Nobilo MA, Barbosa JR. Mechanical properties of resin glass fiber reinforced abutment in comparison to titanium abutment. J Indian Soc Periodontol 2015;19:273-8.
11. Misch CE. Contemporary Implant Dentistry. 3rd ed. St. Louis: Mosby; 2008. p. 404.
12. Patzelt SB, Bahat O, Reynolds MA, Strub JR. The all-on-four treatment concept: A systematic review. Clin Implant Dent Relat Res 2014;16:836-55.
13. Malo P, Rangert B, Nobre M. All on 4 immediate-function concept with Brånemark System implants for completely edentulous maxillae: A year retrospective clinical study. Clin Implant Dent Relat Res 2005;7:S88-94.
14. Malo P, de Araujo Nobre M, Lopes A. The use of computer-guided flapless implant surgery and four implants placed in immediate function to support a fixed denture: Preliminary results after a mean follow-up period of thirteen months. J Prosthet Dent 2007;97:S26-34.
15. Bellini CM, Romeo D, Galbusera F, Taschieri S, Raimondi MT, Zampelis A, *et al*. Comparison of tilted versus nontilted implant-supported prosthetic designs for the restoration of the edentuous mandible: A biomechanical study. Int J Oral Maxillofac Implants 2009;24:511-7.
16. Christel P, Meunier A, Heller M, Torre JP, Peille CN. Mechanical properties and short-term in-vivo evaluation of yttrium-oxide-partially-stabilized zirconia. J Biomed Mater Res 1989;23:45-61.
17. Reddy MS, Sundram R, Eid Abdemagyd HA. Application of finite element model in implant dentistry: A systematic review. J Pharm Bioallied Sci 2019;11:S85-91.
18. Sertgöz A, Güvener S. Finite element analysis of the effect of cantilever and implant length on stress distribution in an implant-supported fixed prosthesis. J Prosthet Dent 1996;76:165-9.
19. Bellini CM, Romeo D, Galbusera F, Agliardi E, Pietrabissa R, Zampelis A, *et al.* A finite element analysis of tilted versus nontilted implant configurations in the edentulous maxilla. Int J Prosthodont 2009;22:155-7.
20. Cağlar A, Aydin C, Ozen J, Yilmaz C, Korkmaz T. Effects of mesiodistal inclination of implants on stress distribution in implant-supported fixed prostheses. Int J Oral Maxillofac Implants 2006;21:36-44.
21. Zampelis A, Rangert B, Heijl L. Tilting of splinted implants for improved prosthodontic support: A two-dimensional finite element analysis. J Prosthet Dent 2007;97:S35-43.
22. Geng JP, Tan KB, Liu GR. Application of finite element analysis in implant dentistry: A review of the literature. J Prosthet Dent 2001;85:585-98.
23. Van Staden RC, Guan H, Loo YC. Application of the finite element method in dental implant research. Comput Methods Biomech Biomed Engin 2006;9:257-70.
24. Iplikçioğlu H, Akça K. Comparative evaluation of the effect of diameter, length and number of implants supporting three-unit fixed partial prostheses on stress distribution in the bone. J Dent 2002;30:41-6.
25. Sannino G. All-on-4 concept: A 3-dimensional finite element analysis. J Oral Implantol 2015;41:163-71.
26. Penaloza S, Alonso Z. The all-on-four treatment concept: Systematic review. J Clin Exp Dent 2017;9:474-88.
27. Poletto-Neto V, Tretto PHW, Zen BM, Bacchi A, Dos Santos MBF. Influence of implant inclination and prosthetic abutment type on the biomechanics of implant-supported fixed partial dentures. J Oral Implantol 2019;45:343-50.
28. Silva GC, Mendonça JA, Lopes LR, Landre J. Stress patterns on implants in prostheses supported by four or six implants a three-dimensional finite element analysis. Int J Oral Maxillofac implants 2010;25:239-46.
29. White SN. Effect of cantilever length on stress transfer by implant supported prosthesis. J Prosthet Dent 1994;7:493-499.
30. Canay S, Hersek N, Akpinar I, Aşik Z. Comparison of stress distribution around vertical and angled implants with finite-element analysis. Quintessence Int 1996;27:591-8.
31. Kanneganti KC, Vinnakota DN, Pottem SR, Pulagam M. Comparative effect of implant-abutment connections, abutment angulations, and screw lengths on preloaded abutment screw using three-dimensional finite element analysis: An *in vitro* study. J Indian Prosthodont Soc 2018;18:161-7.
32. Oswal MM, Amasi UN, Oswal MS, Bhagat AS. Influence of three different implant thread designs on stress distribution: A three-dimensional finite element analysis. J Indian Prosthodont Soc 2016;16:359-65.