A comparative evaluation of stress distribution between an All-on-Four implant-supported prosthesis and the Trefoil implant-supported prosthesis: A three-dimensional finite element analysis study

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Abstract:

Aim: The primary aim of this study is to analyse the stress distribution between an ALL ON FOUR implant supported prosthesis and the TREFOIL implant supported prosthesis with 3D finite element models.

Settings and Design: An *in vitro* perspective

Materials and Methods: Two mandibular three-dimensional Finite Element Models were constructed by the CREO version 5 software, in which Model A depicts a mandible with ALL ON FOUR implant supported prost hesis and Model B will depict TREFOIL implant supported prosthesis. Model A contains four implants, two anterior straight and posterior tilted implants (30˚), a bar and denture containing acrylic teeth. In Model B, it contains three straight implants and a prefabricated compensatory bar with standardised dimensions. To evaluate and compare the stress distribution between the bone and implant interface, one deleterious cantilever load of upto 300 N is applied on the second molar bilaterally and simultaneously. Another full bite biting load of 150 N is given bilaterally and simultaneously on the central groove of premolars and molars.

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

Results: The results of loading 1 showed that the maximum Von Mises stress was recorded in the anterior implant region of the Trefoil system (Model B) when compared to All on four concept. The results of loading 2 showed that the maximum Von Mises stress were recorded in the anterior implant region Trefoil system (Model B) when compared to All on four concept.

Conclusion: This invitro study concludes that All on Four implant supported prosthesis showed better stress distribution when compared to the Trefoil concept.

Keywords: All-on-Four, bone–implant interface, finite element analysis, Trefoil concept

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INTRODUCTION

Edentulism is a condition or a state where there is complete or partial loss of teeth in the oral cavity.[1] Elderly individuals are the most commonly affected with complete edentulism and are in need for adequate oral rehabilitation for their general healthy well-being and good quality of life.[2] A continuous debate in the literature is going on about the increasing and the decreasing rate of edentulism, and it has been stated that the total rate of edentulism is on a steady decrease in developed countries, while it is on a drastic increase in the developing countries. The enormous developments in dental care have declined the rate of edentulism.[1]

The most commonly followed treatment of choice for edentulism is the removable complete denture,[2] which is a cost-effective option that aids to regain the masticatory function and the lost esthetics. Maxillary complete denture has better retention and stability when compared to mandibular denture.[3,4] This compromised retention and stability of mandibular denture is due to its anatomical restrictions, such as the influence of tongue[3] and less denture bearing surface area compared to maxilla. Hence, the need for fixed solution in the treatment of edentulism, especially in the mandibular arch, is quite essential, which is aided by the emergence of dental implants.

The success of implant-supported prosthesis is influenced by various factors, and one of the key factors is the quality and quantity of available bone.[5,6] In long-term edentulism, there is reduced bone height and volume, which impairs precise placement of implants. In conventional implant rehabilitation with highly resorbed mandible, patients have to undergo highly technique-sensitive procedures such as extensive grafting[7] or nerve repositioning. To overcome these clinical limitations, the concept of tilted implant came into existence.[6]

Dr. Paulo Maulo's introduced the concept of All on Four in 1989, in which two anterior straight implants and two tilted posterior implants along with multiunit abutments for rehabilitation.[8] The tilting of the posterior implants was up to 45° and was very useful when there is reduced posterior bone height. This increased the bone-to-implant contact, thereby enhancing stress distribution, preventing injury to the underlying vital structures, increasing the anteroposterior (AP) implant spread, and minimizing the cantilever.

The major limitation in this technique is the surgical complications such as nerve injury and accumulation of stress in the tilted implants,[9,10] which can lead to a doubtful long-term prognosis. The improvisation and evolution of technology pertaining to implant design, surface texture, innovative techniques have reduced the number of implants required for rehabilitation and its subsequent limitations. The usage of minimal number of implants and graft-less procedures has reduced the postsurgical trauma and pain, cost, and instruments required and provides ease of operation.[6]

One such recently evolved concept in full arch mandibular rehabilitation is the Trefoil system which was introduced by Dr. Kenji W. Higuchi . This system consists of three straight implants , a prefabricated compensation bar and various components such as a round abutment , two framework discs , a screw disc and a clinical screw.[6,11] The prefabricated bar has adaptive joints which aid in the compensation of vertical, horizontal, and angular misfit.

Irrespective of different treatment concepts, one of the key factors for determining the decision on which concept to be opted is based on the amount of biomechanical stress[12] that is transferred to the bone–implant interface which plays a crucial role in long-term prognosis of the prosthesis. For the purpose of understanding the stress distribution, an *in vitro* engineering tool becomes handy which is known as the finite element analysis (FEA). FEA is three-dimensional (3D) tool used to simulate a physical phenomenon using numerical mathematic technique referred to as the finite element method (FEM). This method divides the complex mechanical model into smaller subunits and facilitates the researchers to predict and verify the stress distribution in the potential bone–implant interface.[12,13] With this objective in mind, this study was done to compare the stress distribution between All-on-Four implant concept and the Trefoil concept under two loading conditions using the FEA.

MATERIALS AND METHODS

The study was approved by the Institutional Review Board for ethics committee is MADC/IRB-XXVI/2018/411. Two mandibular 3D finite element models, Model A and Model B depicting the All-on-Four implant concept and Trefoil implant concept, respectively, were constructed using the CREO version 5 software, and the analysis was performed using the ANSYS R20 [Table 1].

The various steps involved in the FEA studies were preprocessing, processing (loading protocol),

Table 1: Models used in the study

Model A	Model B
Mandibular model with All-on-Four implant system	Mandibular model with the Trefoil implant system

and postprocessing (solution to linear equations). Preprocessing includes the geometric model construction which is aided by reverse engineering or computer aided design (CAD) software. This involves the conversion of geometric model into finite element model by providing data for defining the individual material properties and boundary conditions.

The model of the mandible was obtained from the digitally scanned computed tomographic (CT) images and then was converted into geometric models. The final mandibular dimensions of the bone were 20 mm in height, 10 mm in width, and 153 mm in length. The thickness of the cortical bone was 2 mm, and the cancellous bone was present internally. After construction, these models were converted into finite element model. The dimensions and the images of the implants, bar, and prosthetic components were used for the virtual modeling.

For Model A – All-on-Four implant concept

Materials required

1. Four Nobel Biocare implants of size – 4.3 mm × 13 mm
2. Customized titanium bar of size – 5.5 mm wide, 4 mm thick, and 90 mm long.

Site of implant placement

1. Two anterior, straight implants placed around the lateral incisor region
2. Two posterior, 30° tilted implants placed in the second premolar region.

Abutments

1. Two straight abutments for the anterior implants
2. Two multiunit abutments for the posterior implants.

The straight and the multiunit abutments were fixed to the anterior and distal implants, respectively. The customized bar is placed over the implants. The length of cantilever (18 mm) is kept 1.5 times the AP implant spread. Then, an acrylic denture containing acrylic teeth, from second molar to second molar, is screwed over the bar with a prosthetic screw [Figure 1].

For Model B – Trefoil implant concept

Materials required

1. Three Trefoil implants of size – 5 mm × 11.5 mm
2. Prefabricated titanium bar of size – 5.5 mm wide, 5.5 mm thick, and 86 mm long.

Site of implant placement

1. One straight implant placed along the midline
2. Other two straight implants placed anterior to the mental foramen.

Distance between the implant should be 7.3 mm and the interforamen distance is 22 mm. A round abutment in placed over the implant and one framework disc is placed above it. The prefabricated bar is placed over the framework disc which is then followed by the placement of framework disc, screw disc and an acrylic denture with acrylic teeth. This entire assembly is screwed using the clinical screw.

Table 2: Young's modulus and Poisson's ratio for the various components with reference[17,20,29,34]

Components	Modulus of elasticity (MPa)	Poisson' s ratio
Cortical bone	13.7-16	0.3-16
Cancellous bone	1.37-16	0.3-16
Titanium	115-16	0.35-16
Acrylic resin - denture base	1.96-34	0.3-34
Acrylic resin - artificial teeth	2.94-34	0.3-34

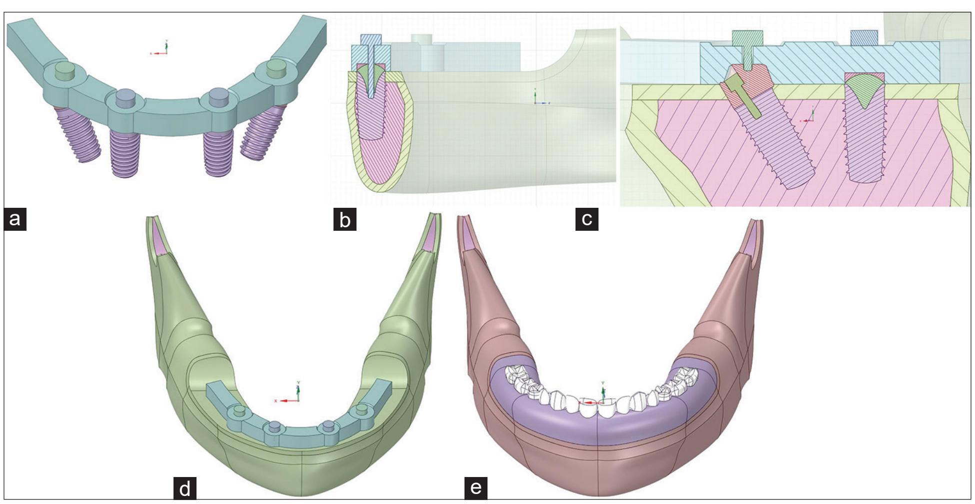

Figure 1: (a) Three-dimensional view of the implants and framework of the All-on-Four implant system; (b) Cross-sectional view of the anterior implant in All-on-Four implant system; (c) Cross-sectional view of the angulated distal implant in the All-on-Four implant system; (d) Three-dimensional view of the All-on-Four implant system with the framework; (e) Three-dimensional view of the completed All-on-Four implant system model - Model A

The AP spread in the trefoil system is fixed as the bar is prefabricated. The AP implant spread is 8.7 mm, and hence, the cantilevered bar is 14.5 mm [Figure 2].

The material properties that were used in the fabrication of the models include the Young's modulus and the Poisson's ratio [Table 2]. After the construction of geometric models, meshing is carried out for the purpose of detailed analysis and measuring the stress after the loading conditions [Figure 3]. All materials used in the models were considered to be isotropic. The boundary conditions were delineated after the meshing process and were defined particularly at the peripheral nodes of bone with no degree of movement in any of the directions [Tables 3 and 4]. In both models, implants were osseointegrated with the surrounding cancellous and cortical bone, and bone–implant interface was considered as a rigid junction.

The meshed images were analyzed in the ANSYS R20 software (Pennsylvania, United States). Von Mises stress was the principal stress that was obtained after the loading, and it is the most commonly used stress metric. The loading protocol includes a posterior cantilever load (loading 1)which is a bilateral and simultaneous vertical static load of 300 N which is applied on the cantilever portion exactly on the central groove of the second molar and a full mouth biting load (loading 2) which is a bilateral and simultaneous vertical static load of 150N applied on the central grooves of the occlusal surfaces of the first and second premolars. After loading, the maximum Von Mises stress values pertaining to the implant, bone, and the prosthetic screws were tabulated.

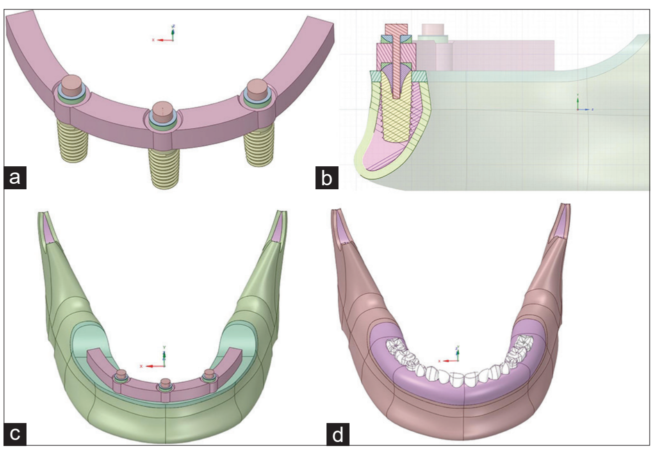

Figure 2: (a) Three-dimensional view of the implants and framework of the Trefoil concept; (b) Cross-sectional view of the implant in Trefoil concept; (c) Three-dimensional view of the Trefoil concept with the framework; (d) Three-dimensional view of the completed Trefoil Implant system - MODEL B

RESULTS

The various interpretations regarding the stress values can be visualized using the different color coding provided from blue (minimal stress) to red (maximum stress). The results showed the critical zones with their respective stress behaviors. The values of maximum Von Mises stress at the level of implant, bone, and framework level were obtained.

Loading 1 results (bilateral cantilever load)

A load of 300 N was applied bilaterally and simultaneously on the cantilever on both the models A and B [Figures 4 and 5]. The results showed that the maximum von Mises stress was recorded in the Trefoil system (Model B) when compared to All-on-Four concept. The maximum stress was recorded at the bone level of Model A and B being 43.4 and 48.36 MPa, respectively. The maximum stress found at the implants was around 73 and 165.9 MPa for Model A and B, respectively. In the framework also, the maximum stress was observed in the Trefoil system than the All-on-four [Tables 5-7].

Loading 2 results (full mouth biting load)

A full mouth biting load of 150 N was applied on the central grooves on the occlusal surfaces of the premolars and molars [Figures 6 and 7]. The results of this loading showed that the maximum von Mises stress were recorded in the Trefoil system (Model B) when compared to All-on-Four concept. The maximum stress was recorded at

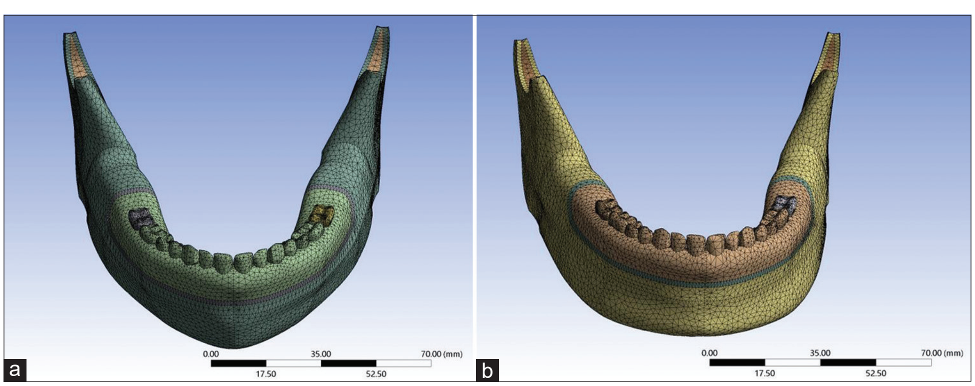

Figure 3: (a) MODEL A - meshing complete; (b) MODEL B - meshing complete

Table 3: Model A - All-on-Four - number of nodes and elements used

Total number of elements used	Total number of nodes used
189,062	350,877

Table 4: Model B - Trefoil concept - number of nodes and elements

Total number of elements used	Total number of nodes used
169,073	317,356

Table 5: Von Mises stress (MPa) at the bone, implant, and framework after loading 1 in Model A - All-on-Four

All-on-Four	Framework	Implant	Bone
Anterior	245	20.4	11.4
Posterior	255	73	43.4

Table 6: Von Mises stress (MPa) at the bone, implant, and framework after loading 1 in Model B - Trefoil concept

Trefoil	Framework	Implant	Bone
Anterior	1593	165.9	48.36
Posterior	834	29.45	26.5

Table 7: Comparing the maximum von Mises stress (Mpa) at the bone, implant, and framework after loading 1 in both the Model A and B

Type of model	Framework	Implant	Bone
All-on-Four	255	73	43.4
Trefoil	1593	165.9	48.36

Table 8: Von Mises stress (Mpa) at the bone, implant, and framework after loading 2 in Model A - All-on-Four

All-on-Four	Framework	Implant	Bone
Anterior	38.5	14.2	1.8
Posterior	121.9	65	21.8

Table 9: Von Mises stress (MPa) at the bone, implant, and framework after loading 2 in Model B - Trefoil

Trefoil	Framework	Implant	Bone
Anterior	432.8	71.3	11.2
Posterior	139.5	52.1	26.9

Table 10: Comparing von Mises stress at the bone, implant, and framework after loading 2 in Model A and B

Type of model	Bone	Implant	Framework
All-on-Four	21.8	65	121.9
Trefoil	26.9	71.3	432.8

the bone level of Model A and B being 21.8 and 26.9 MPa, respectively. The maximum stress found at the implants was around 65 and 71.3 MPa for Model A and B, respectively. In the framework also, the maximum stress was observed in the Trefoil system than the All-on-Four [Tables 8-10].

DISCUSSION

The rehabilitation of edentulous alveolar ridges was commonly done by removable complete denture prosthesis, which had certain disadvantages in terms of retention and stability, especially in case of mandibular denture.[3,4] To eliminate these problems and to provide a functional and a satisfactory treatment to the patient, fixed implant-supported prosthesis came into existence. Over the decades, many concepts and techniques for implant-supported full arch rehabilitation have been successfully introduced, and in the present-day scenario, rehabilitation procedures can be done with minimal implants in resorbed ridges also. This concept of rehabilitation with minimal implants has reduced the patient's postoperative pain and avoid injury to the underlying vital structures.[6]

Among the various concepts, All-on-Four implant system for the mandibular arches has been ruling for the past few decades.[9] The All-on-Four implant concept uses four implants where two implants are placed straight and anteriorly and the other two are placed posteriorly and are angulated. Recently, the concept of All-on-Three came into existence, the Trefoil concept which uses three straight implants and a prefabricated compensatory bar to rehabilitate the mandible. The prefabricated bar has a compensatory mechanism to match the vertical, horizontal, and angular misfit. This concept also allows immediate loading.

Upon literature search, there was not much evidence or correlation regarding the biomechanical stress or strain for these the All-on-Four and the Trefoil implant concepts. In terms of choice of treatment modality, it is necessary for the rehabilitating prosthodontist to have a wider knowledge in regard to the biomechanical behavior of each and every system apart from the patient-related factors.[6]

FEA was used as a tool for the analysis since various studies showed evidence of solving greater biomechanical domains and can accurately provide us with the inferences.[14,15] Geng *et al.* suggested that 3D FEA studies aided in understanding biomechanics of implant dentistry in a much better way and the bone–implant interface, implant prosthetic connection, and multiple implant prosthesis.[14] Trivedi stated that FEA has many advantages when compared to studies done with real models and also added that these studies are repeatable and there is no ethical considerations for study designs.[13] Pesqueira *et al.* suggested among the various methods for evaluating stress, FEA has the advantages of evaluating and analyzing new configurations of implants, prosthetic components, and their associated materials.[12]

The mandibular bone model was obtained by converting the scanned CT images into geometric

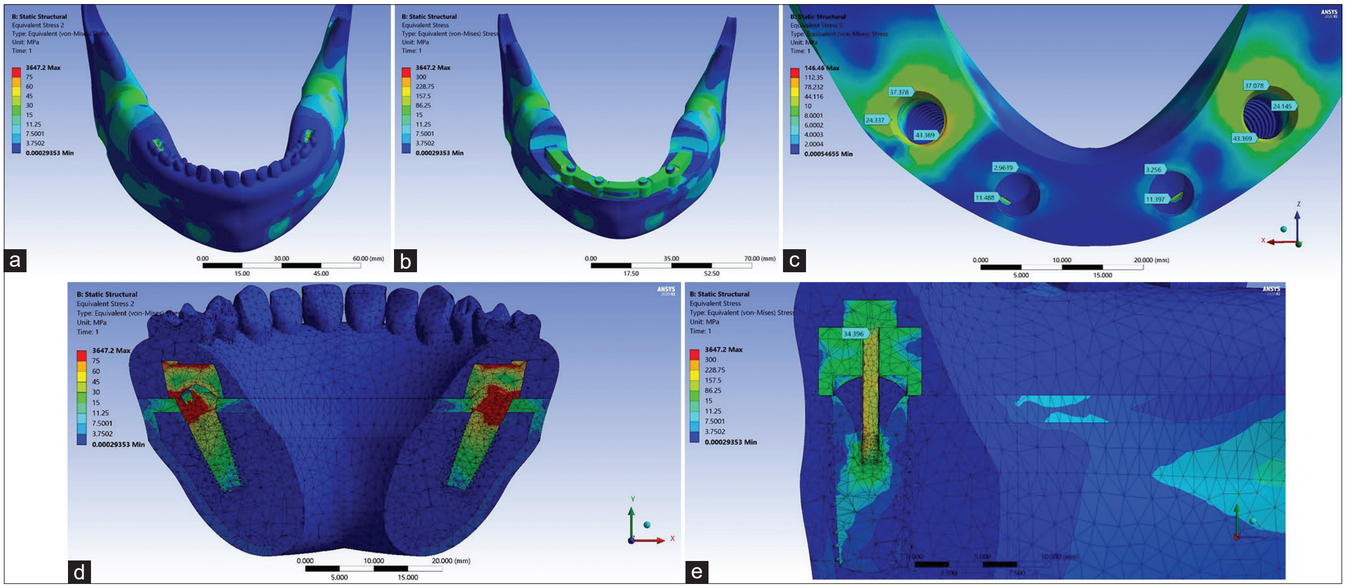

Figure 4: (a) Model A (All-on-Four) in response to load 1, stress distribution at the level of the denture; (b) Model A (All-on-Four) in response to load 1, stress distribution at the level of framework; (c) Model A (All-on-Four) in response to load 1, cross-sectional view distal to the posterior implant; (d) Model A (All-on-Four) in response to load 1, stress distribution at the bone level; (e) Model A (All-on-Four) in response to load 1, cross-sectional image along the center of the implant

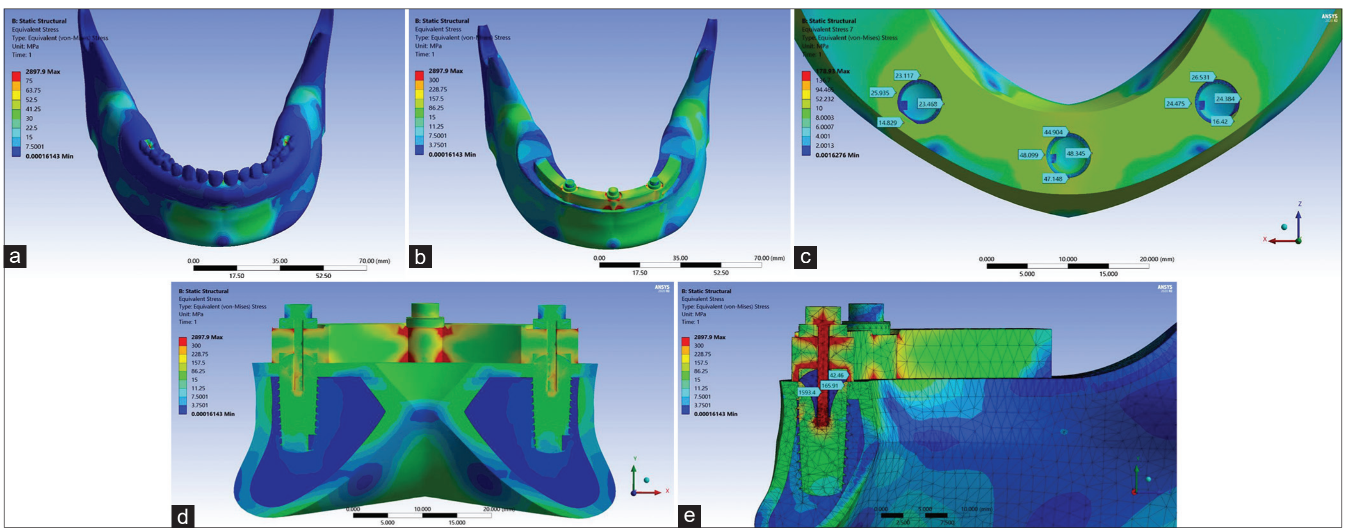

Figure 5: (a) Model B (Trefoil concept) in response to load 1, stress distribution at the level of the denture; (b) Model B (Trefoil concept) in response to load 1, stress distribution at the level of framework; (c) Model B (Trefoil concept) in response to load 1, cross-sectional view distal to the posterior implant; (d) Model B (Trefoil concept) in response to load 1, stress distribution at the bone level; (e) Model B (Trefoil concept) in response to load 1, cross-sectional image along the center of the implant

models and altered in way to make it parametric.[16] All-on-Four and Trefoil implant concepts were taken into consideration for the comparison as these are two concepts provide full arch rehabilitation with minimal number of implants and can avoid extensive surgical procedures such as nerve repositioning and grafting procedures.[6]

The dimensions of the implants and the bar used in All-on-Four and the Trefoil concept were decided based on the dimensions of the implants and prefabricated bar of the Trefoil concept as the dimensions were standardized in the Trefoil concept. The dimensions were kept nearly similar in both the models as the implant diameter and the bar thickness were important factors through which the stress distribution occurs.[17,18]

All-on-Four implant system contains two anterior straight and two posterior tilted implants. The angulations of the posterior implants were kept as 30°. According to Sannino, there was a negligible difference in the maximum von Mises stresses between the angulations of 15°–30°.[16,19,20]

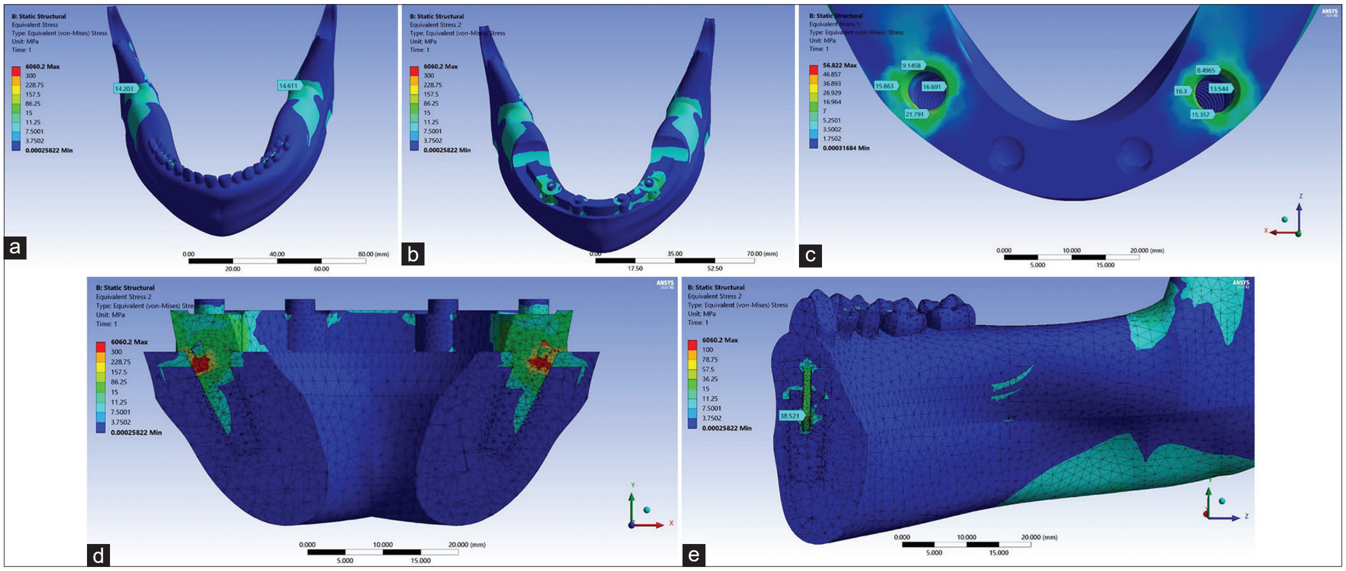

Figure 6: (a) Model B (All-on-Four) in response to load 2, stress distribution at the level of the denture; (b) Model B (All-on-Four) in response to load 2, stress distribution at the level of framework; (c) Model B (All-on-Four) in response to load 2, cross-sectional view distal to the posterior implant; (d) Model B (All-on-Four) in response to load 2, stress distribution at the bone level; (e) Model B (All-on-Four) in response to load 2, cross-sectional image along the center of the implant

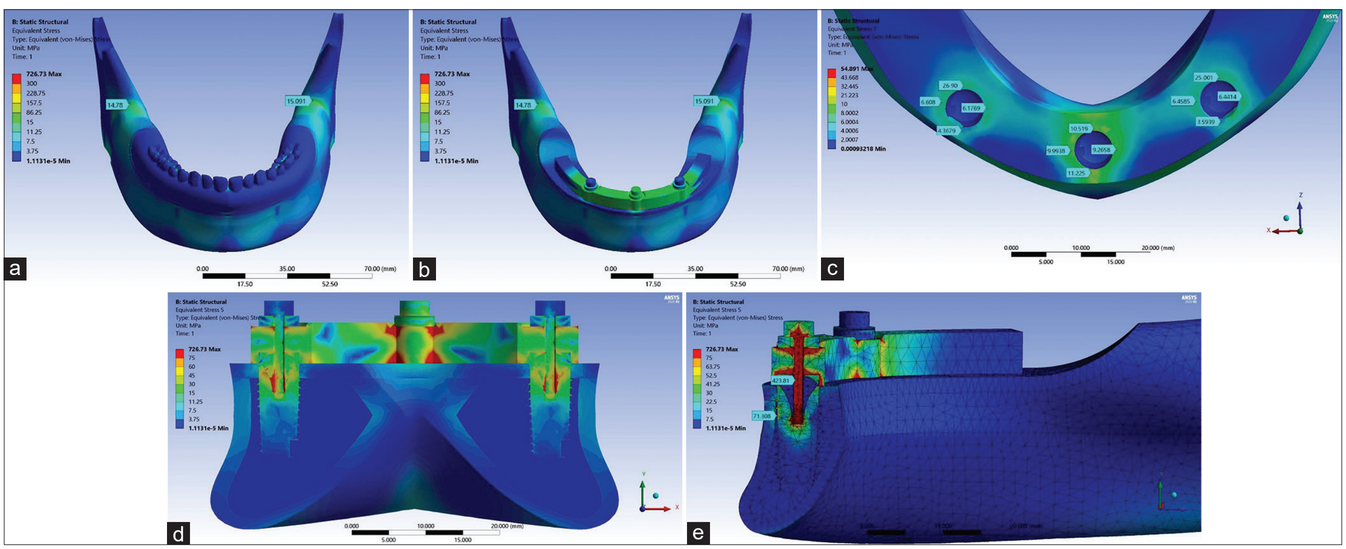

Figure 7: (a) Model B (Trefoil concept) in response to load 2, stress distribution at the level of the denture; (b) Model B (Trefoil concept) in response to load 2, stress distribution at the level of framework; (c) Model B (Trefoil concept) in response to load 2, cross-sectional view distal to the posterior implant; (d) Model B (Trefoil concept) in response to load 2, stress distribution at the bone level; (e) Model B (Trefoil concept) in response to load 2, cross-sectional image along the center of the implant

Studies done by Ozan *et al*., Liu *et al*., and Lofaj *et al*. also suggested that 30° tilted implant delivers less stress on the surrounding structure.[21-25]

In full arch mandibular rehabilitation with minimal implants with opposing natural teeth, one of the major factors that can induce greater biomechanical stress is the load in the cantilever region. Hence a cantilever load of 300N was chosen.[8,15] Following this, a full mouth simultaneous posterior biting load of 150 N was given to simulate the normal masticatory force.[16,26,27]

According to the results of both loading condition in Model A (All-on-Four), the maximum von Mises stress was recorded in the distal implant region. Liu *et al*.[21] in All-on-Four study suggested that the stress was maximum at the distal bone–implant interface due to the close proximity of load application. Lima *et al*.,[28] Saleh Saber *et al*.,[29] Sanino *et al*.,[16] Kumari *et al*.,[30] Horita *et al*.,[10] Deste and Durkan,[31] and Oh *et al*.[32] suggested that the maximum stress that occurred in the implant is also due to the fact that a vertical load is acting on an inclined implant.

According to the results obtained in Model B (Trefoil concept) after subjected to both loadings, maximum stress was recorded in the anterior implant region and amount of stresses was higher than the maximum Von Mises stress recorded in All-on-Four implant concept. The Trefoil concept has shown more stress concentration at the bone, implant, and framework interfaces with respect to the anterior implant.[33,34] The increased stress in the anterior implant region can be due to the fact that all three implants are placed straight because of which the cantilever or the inclined loads are not well tolerated by these implants. During the load application, when the load was given over the posterior cantilever, there was high stress in the anterior implant which could be due to a pivoting action in the anterior implant when load was given posteriorly. Another possible reason for anterior stress concentration is the lever action taking place with the posterior implant as the fulcrum and the anterior displacement load occurring due the cantilever loads.[35-37]

The Trefoil system also has a compensatory mechanism to compensate for the irregularities in implant position; however, since the study is a FEA study, the ideal implant positions are considered. The system accommodates for deviations of 4° angulation, horizontal deviation of 0.4 mm, and vertical deviation of 0.5 mm for passive fit.[38] In an *in vitro* study, prefabricated framework showed a passive fit comparable to prosthesis designed with CAD/computer-aided manufacturing even when implants were not exactly parallel.[39] In this study, the framework bar along with all its components was fixed to the implants which were parallelly positioned with no deviations. Passive fit was incorporated in the FEA model.[38-41]

Aouini *et al*. studied the prefabricated Trefoil framework and found that it matched a large proportion of patient mandibles studied for mandibular morphology.[38] The Trefoil system mandates that the implants are placed with the help of the system guide template so that the mandibular anatomy confirms to the prerequisites of the system in the implant placement sites.[39] Hence, the framework of Trefoil system matching the curvature of the patient mandible did not influence the study.[38-40]

On comparing the biomechanical behavior between the two treatment concepts, the Trefoil concept has shown more stress concentration at the bone, implant, and framework interfaces with respect to the anterior implant region. Since the number of implants is minimal, there is lesser surface area for bone anchorage in spite of its increased diameter, and hence, the bone anchorage is less, leading to improper force dissipation.[42] The lesser AP spread in the Trefoil concept also leads to deleterious effect on the bone and implant interface.[35]

The less stress distribution in All on Four concept was due to increased number of implants, tilted posterior implants and increased bone to implant contact which inturn increased the surface area and reduced the cantilever length due to the increased AP implant spread.[10,16,26-31] On the another hand, the occlusion given also greatly influences the biomechanical success of both All-on-Four and Trefoil concept. Implant-protected occlusion has to be given for the long-term success of the implant-supported full mouth rehabilitation.[43]

Clinical implication

The All-on-Four and the Trefoil concepts are viable treatment alternatives for patients with severely resorbed mandible. All-on-Four concept proves to be better than Trefoil concept in terms of biomechanical stress distribution.

Limitations of the study

1. In FEA, the oral conditions cannot be exactly simulated in the models
2. In FEA, the implants are considered to be 100% osseointegrated.

CONCLUSION

Within the limitations of the study, the following conclusions are made:

1. All-on-Four system has a better stress distribution than the Trefoil concept under both cantilever and full biting loading conditions
2. In the All-on-Four system, the stress concentration occurs in the tilted posterior implant and it is comparatively lesser than the stress in the Trefoil system
3. In the Trefoil concept, the stress concentration occurs in the anterior implant which is far greater than the stress in the All-on-Four system.

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Conflicts of interest

There are no conflicts of interest.

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