

Three-Dimensional Finite Element Analysis of von Mises Stress Distribution in All-on-4 Implants: Influence of Implant Dimensions and Loading Conditions in the Mandible: An *in vitro* Analysis

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Abstract

Background of study: The All-on-4 implant technique is a widely used method for full-arch rehabilitation, optimizing bone utilization while minimizing grafting. However, biomechanical complications such as implant failure and bone resorption remain concerns, particularly under varying implant dimensions and loading angles. Finite element analysis (FEA) is an effective tool for evaluating these biomechanical interactions, yet limited research has compared different implant dimensions under varying loading conditions in the All-on-4 system. This study aims to use 3D FEA to evaluate von Mises stress distribution in All-on-4 implants with different dimensions and loading angles, providing insights for optimizing implant design and improving clinical outcomes. **Materials and Methods:** Geometric models of mandibular structures with distinct implant systems were constructed using Mimics 8.11 and Rapid FORM2004 software. Finite element meshes were generated with Hypermesh 13.0, incorporating material properties and boundary conditions. Loading conditions of 300 N and 500 N were applied vertically and obliquely. Stress analysis, focusing on von Mises stress, was performed using ANSYS 12.1. **Results:** Group-2 is the group that exhibits higher von Mises stress, peaking at 73.60 MPa under 500N oblique loading in cortical bone, as assessed by the study. Cancellous bone also shows higher stress levels for Group-2, reaching 6.68 MPa under 500N oblique loading. **Conclusion:** This research confirms that all designs had peak stress points located on the crestal bone on the distal aspect of posterior implants. Longer and wider implants in both cortical and cancellous bone resulted in an increase in von Mises stress.

Keywords: All-on-4 treatment concept, Finite element analysis, Von mises stress.

INTRODUCTION

Immediate-function protocols involving the use of implant supported prostheses for the rehabilitation of completely edentulous mandibles are documented as having high success rates.^[1-5] In 1998, Dr. Paulo Malo successfully treated the first patient with the All-on-4 treatment concept.^[6] Patients can receive a fixed full-arch prosthesis on the day of surgery with the All-on-4 treatment concept, an efficient and graft-less solution that provides a cost-effective solution. However, biomechanical complications such as implant failure and bone resorption remain concerns, particularly under varying implant dimensions and loading angles.

A three-dimensional finite element analysis (FEA) is the tool employed here to evaluate the stress distribution

pattern. It produces highly valid results, and it is effective for investigating behavioral tendencies of the implant under loading conditions.^[7] The main objectives of the study were to evaluate the von Mises stress in implant system by varying implant diameters like 3.5 mm, and 3.75 mm and with varying lengths such as 10 mm and 11.5 mm and with a loading

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angulation in vertical and oblique direction with a magnitude of 300N and 500N and to identify the suitable modifications on the implant design based on stress distribution pattern obtained by FEA.

MATERIALS AND METHODS

The study was approved by the Institutional Ethics Committee (reference number: PCDC/IEC/K12/11/15). There are two groups. Each group consists of a single implant type which is four in number. After placing and simulating four implants in each group, a computer-aided visual geometric model is created. As it is a simulation study on a single mandible, an increase in sample size will not affect the result.

Grouping

- Group-1: 3.5×10 mm implant system
- Group-2: 3.75×11.5 mm implant system.

Software's used

1. Mimics 8.11:- Materialize's Interactive medical image control system (MIMICS) is a medical modeling software used for the visualization and segmentation of computed tomography/magnetic resonance imaging (CT/MRI) images.
2. Rapid FORM2004: Software used to convert cloud data points to surfaces, the converted surfaces are stored in IGES format.
3. Hypermesh 13.0: Software used for converting the geometric model into a finite element model.
4. ANSYS 12.1: Analysis System Software: This software is used for carrying out FEA of structures and Fluids.

Method of the study

The study was divided into the following steps:^[8]

Construction of a geometric model

To begin the process, we need to create a virtual geometric model (VGM) (Figure 1a) of the objects that we are going to examine. We are opting for a 3-D model because it allows for a complete evaluation of structure and loads from any direction.^[8-13] Materialize's Interactive MIMICS is a medical

modeling software used for the visualization and segmentation of CT/MRI images. The CT scan of a patient is procured, and then, they are converted into geometric models using reverse engineering techniques. "Rapidform" software is employed to perform geometric modeling, which exclusively utilizes surface data.

To ensure more reliable results, it is important for the VGM to have a close resemblance to the actual structures. To create the VGM, computerized tomographic scan of the mandible will be taken to generate a model of the bone.^[4-13] Implants and restoration (crown) are simulated similar to living structures. The computer-aided designed implant models of various sizes are embedded into the anterior and premolar zones of the mandible.^[14]

This study encompasses two scenarios. Two, 3-D working models are constructed for the analysis. Each model represented the mandible restored with four implants according to the All-on-4 concept. The simulated models of Adin implants (TauaregTM –OS) are used here for implant modeling. Dimensions of the implants were selected according to the standard dimensions available in the market. Abutments were designed over the implants.

Preparing the finite element mesh

Geometric models of the mandible including all the implants with metal framework and final restoration are then imported into the meshing software called "Hypermesh."^[13] In Hypermesh the individual parts such as soft bone, hard bone, teeth, and PDL are then discretized (meshing) and assembled. The meshed model is called as the finite element model and it consists of node and element data.

Application of the material properties

The important factors such as poison's ratio, Young's modulus, and density of each material are included in the mesh (Table 1). Young's modulus is a measure of the stiffness of elastic material. Poison's ratio is the ratio of the proportional decrease in a lateral measurement to the proportional increase in length in a sample of material that is elastically stretched. Each of these factors will provide the software with data on how a given material behaves when submitted to force application.

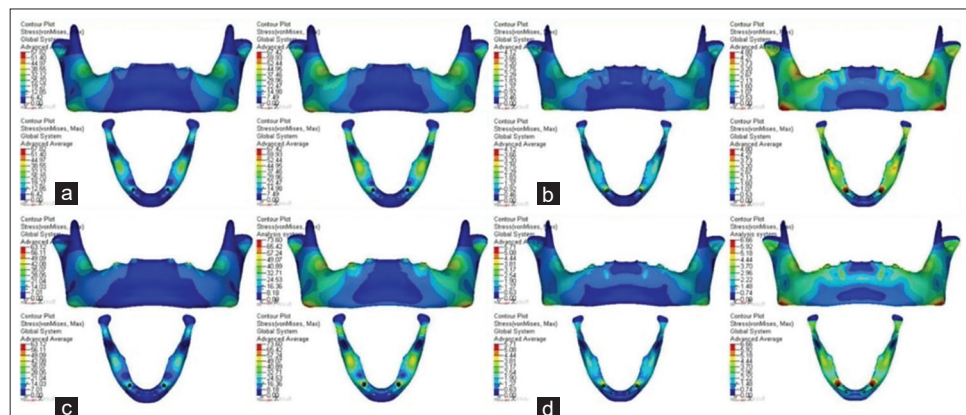


Figure 1: (a) Vertical loading 300N and 500N on cortical bone; (b) vertical loading 300N and 500N on cancellous bone; (c) oblique loading 300N and 500N on cortical bone; and (d) oblique loading 300N and 500N on cancellous bone

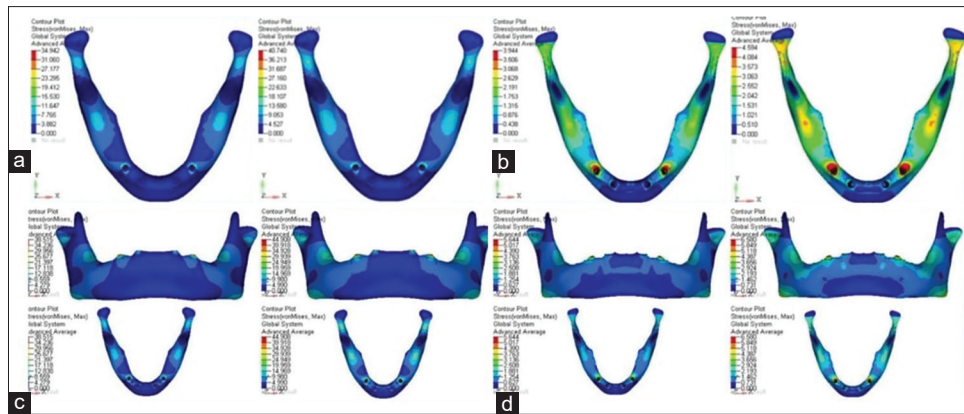


Figure 2: Stress patterns under vertical and oblique load for Group 2: 3.75×11.5 mm. (a) Vertical loading 300N and 500N on cortical bone; (b) vertical loading 300N and 500N on cancellous bone; (c) oblique loading 300N and 500N on cortical bone; and (d) oblique loading 300N and 500N on cancellous bone

Application of boundary conditions

It is the application of force and constraint which is applied to those areas where displacement and rotations are known. Such regions may be constrained to remain fixed (have zero displacement and rotation) during the simulation.^[13-23] Zero displacement constraints must be placed on some boundaries of the model to ensure an equilibrium solution.

Application of different loading conditions

To evaluate and compare the distribution of stresses of the implant system on the edentulous mandible, two loading situations were simulated in each model in vertical and oblique directions (Figures 1 and 2) (30°).^[23-30] The loading magnitudes selected are 300 and 500 Newtons (N), Table 2.^[14] Loading forces should be applied to the restoration first and then transmitted by the abutment to the implant and surrounding bone (Figure 1) stress patterns under vertical and oblique loading for Group 1: 3.5×10 mm.

Analysis of various stress patterns under different loading situations

The analysis is done using ANSYS 12.1: Analysis System Software. This software is generally used for carrying out FEA.^[14-30] FEA studies use von Mises stress (equivalent tensile stress) to evaluate the effect of loading forces on the peri implant region. The three principal stresses can be calculated at any point acting in the X, Y, and Z directions. The von Mises criteria refer to a formula for combining all these stresses into equivalent stress, which is compared to the yield stress of the material. Furthermore, the assumption is made that the materials (implants and crown) are homogenous and linearly isotropic.^[9-30]

RESULTS AND FINDINGS

The combined results of the numerical analysis of the models are shown in Table 2. Evaluation of the von Mises stress in implant system with varying implant diameters of 3.5, 3.75 and with varying lengths of 10, and 11.5 mms is calculated under different loading angulations in vertical and oblique

Table 1: Values of material properties incorporated in the mesh

Materials	Young's modulus N/m ²	Poisson's ratio
Cortical bone (D2)	55,000	0.3
Cancellous bone	7,930	0.3
Titanium implant and abutment, screws	110,000	0.35
Porcelain	82,000	0.35
Steel Frame	200,000	0.3

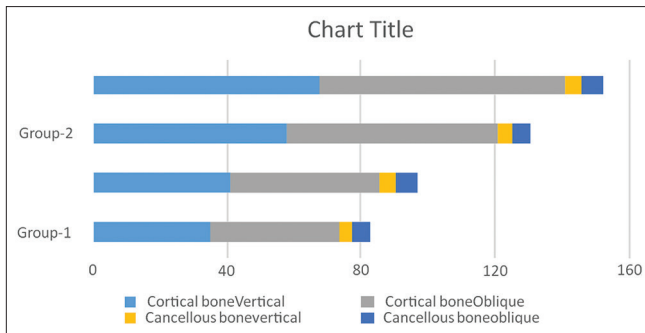
Table 2: The combined results of von mises stresses of models

Bone type	Direction of force	Group-1 (3.5*10 mm)		Group-2 (3.75*11.5 mm)	
		300N	500N	300N	500N
Cortical bone	Vertical	34.94	40.74	57.82	67.42
	Oblique	38.52	44.91	63.12	73.60
Cancellous bone	vertical	3.94	4.59	4.12	4.80
	oblique	5.64	6.66	5.71	6.68

(300) directions and magnitudes of 300N and 500N force in an edentulous mandible is obtained in the two groups (Graph 1).

In cortical bone

In cortical bone, the Group-2 implant system exhibits the highest von Mises stress of 57.82 MPa under a vertical loading of 300N, whereas the Group-1 implant system demonstrates the lowest von Mises stress at 34.94 MPa. When subjected to a vertical loading of 500N, the von Mises stress escalates to 67.42 MPa for the Group-2 system and 40.74 MPa for the Group-1 system. Under oblique loading of 300N, the von Mises stress peaks at 63.12 MPa for the Group-2 system and bottoms out at 38.52 MPa for the Group-1 system. With an oblique loading of 500N, the stress climbs to 73.60 MPa for the Group-2 system and 44.91 MPa for the Group-1 system. The highest recorded von Mises stress of 73.60 MPa is attributed to the Group-2 implant system under 500N oblique loading, whereas the lowest stress of 34.94 MPa occurs in the Group-1



Graph 1: Loading on cortical bone. X-axis-diameter in mm; Y axis-stress levels in MPa; Blue bar-length of 10 mm; Orange bar-length of 11.5 mm

system under 300N vertical loading. Analysis of the cortical bone loading graphs suggests that increasing the diameter and length of the implant system correlates with elevated von Mises stress on the cortical bone. (Graph 1) In addition, transitioning from a 300N to a 500N load results in a noteworthy increase in stress. Notably, oblique loading (bucco-lingual) induces greater stress compared to vertical loading

In cancellous bone

In cancellous bone, the Group-2 implant system exhibits the highest von Mises stress of 4.12 MPa under 300N vertical loading, whereas the Group-1 implant system displays the lowest von Mises stress among the groups at 3.94 MPa. With a vertical loading of 500N, the Group-2 system records the highest stress of 4.80 MPa, while the Group-1 system shows the lowest stress at 4.59 MPa. Under oblique loading of 300N, the Group-2 system demonstrates the highest stress at 5.71 MPa, with the Group-1 system registering the lowest stress at 5.64 MPa. For a 500N oblique loading, the Group-2 system again shows the highest stress at 6.68 MPa, while the Group-1 system exhibits a slightly lower stress of 6.66 MPa. The maximum von Mises stress is observed in the Group-2 implant system under 500N oblique loading, reaching 6.68 MPa, with the lowest stress recorded in the Group-1 system under 300N vertical loading at 3.94 MPa. (Graph 1) In the context of cancellous bone, the findings indicate that while increasing the diameter and length of the implant system tends to elevate von Mises stress, this increase is not as pronounced as observed in cortical bone. Unlike cortical bone, where a significant stress increase is noted, cancellous bone exhibits only a slight rise in stress with variations in implant dimensions. Similarly, transitioning from a 300N to a 500N load results in a minor increase in stress. Consistent with previous observations, maximum stress occurs during oblique loading (bucco-lingual), rather than vertical loading.

DISCUSSION

With each of these modeling schemes, the programmer can insert numerous algorithms (functions) which may make the system behave linearly or non-linearly. The non-linear systems do account for the plastic deformation and many are capable of testing the material to fracture. Previous FEM studies have

investigated the stresses in the surrounding bone around the implants which are placed according to the All-on-4 concept with different inclinations of distal implant.^[10-12]

In this study, a fixed prosthesis design was selected instead of a removable over denture design because a fixed prosthesis offers benefits from both a functional and esthetic point of view and may be regarded as quite similar to a patient's natural dentition. When compared to alternative treatment options such as complete dentures or implant overdentures, there is a significantly reduced bulk to a fixed prosthesis which is perceived to be more comfortable and since no mucosal support is needed, patients can chew with greater force and eat a wider range of foods. The All-on-4 concept is a newer technique which uses only four implants and that permits tilting of implants in atrophic edentulous ridges to avoid important anatomical structures such as maxillary sinus and mandibular nerve while also permitting cantilever reduction. The method of tilting the distal implants in the edentulous arches represents an alternative technique that leads to the placement of longer implants, improved prosthetic support with a shorter cantilever arm, improved inter implant distance, and improved anchorage in the bone.^[14-31] However, *in vitro* studies and theoretical calculations on single implants have shown that tilted implants may increase the stress on the bone.^[14,16-31]

Tilted single implants may also be subjected to bending during function, which may lead to increased stress in the marginal bone. However, if such implants are part of a multiple implant-supported prosthesis, the spread of the implants and rigidity of the prosthesis will reduce or change the nature of the bending forces.^[14,18-31] In this study, the highest stress concentration is seen on the crestal bone of tilted implants compared to the axial implants in the anterior region. It may be due to the cantilever action of the fixed prosthesis which extends to the first molar region. According to studies, the permissible cantilever length of the "All-on-4" fixed prosthesis should be 10–12 mm in the mandible.^[19] However, here the length of the cantilever arm is 15 mm which is more than the permissible level. Hence, a short dental arch concept in which the cantilever arm extends until 2nd premolar may be the best option for rehabilitating a full arch with the All-on-4 concept.^[14,20-31]

Loading on cortical bone shows that as the diameter and length of the implant system increases von Mises stress is increased. Also when the load increases from 300N to 500N, stress increases progressively. But when the direction of loading is considered, maximum stress is seen in oblique loading (bucco-lingual) rather than vertical loading. Narrow shorter implants induce less stress on cortical bone. The highest values of the compressive stresses were also evaluated in the crestal cortical bone layer in the study, like most of the other studies.^[14,21-31] The stress absorption capability of a material is directly proportional to the hardness of that material. It is believed that the high elastic modulus of the cortical bone, which surrounds the weakest part of the implant known as the neck, is the cause of these high stress values.^[14,23-31]

When loading cancellous bone, it is observed that increasing diameter and length leads to an increase in stress levels, but not significantly. Also when the load increases from 300N to 500N slight increase in stress is noted when compared to cortical bone. Same as the previous scenario maximum stress is seen in the oblique loading (bucco-lingual) rather than in vertical loading. Wider and longer implants induce slightly more stress than narrower and shorter implants in all loading conditions. As the forces were transferred to the bone by the threads of the implants, in this study model, the threads of the implants started from the trabecular bone due to the morphology of the mandible, and the forces are higher in this area. Although there have been short-term clinical studies about the applicability of the “All-on-4” concept, there are no sufficient *in vitro* studies about this subject.^[14,24-29,31]

CONCLUSION

- In all the designs, peak stress points were always located on the crestal bone on the distal aspect of posterior implants.
- Von Mises stress was higher in longer and wider implants in cortical as well as cancellous bone. The reason behind it may be the increased surface contact of the implants with the bone.
- The length of the cantilever of the prosthesis plays a major role in increasing the stress in the distal crestal bone of posterior implants. The cantilever length should be optimized below 12 mm in mandible. By following the short dental arch concept and by distally tilting the implant the cantilever length and the stress can be reduced.

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