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# Finite element analysis of the effect of framework materials at the bone–implant interface in the all-on-four implant system

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## ABSTRACT

**Background:** The "All-on-four" concept for treatment of edentulous arches incorporates four implants that are placed in between mental foramina in the mandible. The prosthetic framework is an important parameter in stress/strain concentration at the implants, prosthesis, and the underlying bone. Materials such as titanium, zirconia, and carbon fibers have been used for fabrication of framework in the past. The aim of this study was to analyze the effect of framework materials in the "All-on-four" implant system.

**Materials and Methods:** Finite element three-dimensional (3D) model of edentulous mandible was simulated using a computerized tomographic scan data of an edentulous patient. Threaded implants were replicated along with the abutments using 3D modeling software and the framework was designed and simulated using material properties of titanium, zirconia, and polyetheretherketone (PEEK). Axial and nonaxial load of 200 N was applied at the abutment region of right distal implants. The computer-generated numerical values were tabulated and analysed by ANSYS software.

**Results:** Principal strain, von Mises stress and micromotion were assessed in the peri-implant bone region to evaluate its stress condition. Zirconia framework showed the least stress/strain values at axial and oblique loading. Maximum strain values were seen at the PEEK framework material. Zirconia framework in all models showed the least micromotion/displacement.

**Conclusion:** The stress distribution pattern at implant–bone interface was influenced by the framework material used. The framework material, loading site, and direction of forces influenced the stresses and displacement at the bone–implant interface.

**Key Words:** Polyetheretherketone, titanium, zirconia

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## INTRODUCTION

In edentulous patients, implant-supported full-arch restoration is a common treatment option. An implant system called "All-on-four" used for treating such patients incorporates four implants that are placed between the mental foramina region of the mandible. In this system, two implants are placed axially in the anterior region, while two are placed in the posterior region at an angle. All the four implants are connected through a superstructure framework.[1]

Materials used for the prosthetic superstructure framework play a significant role in its biomechanical success. A rigid framework allows absorption

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and balanced distribution of stresses to prevent deformations.[2] Materials such as titanium, zirconia, and carbon fibers have been used for the fabrication of framework in the past. Metal frameworks used for the prosthesis design present good mechanical properties. Titanium has been a practical material for the fabrication of prosthesis superstructure on implants.[1] An esthetic alternative is a zirconia framework as it is biocompatible and has good mechanical properties and high flexural strength. However, conflicting results are seen in studies evaluating load transferred by this material.[3]

Recently, a new material called polyetheretherketone (PEEK) has been introduced which exhibits excellent mechanical properties and is used in the fabrication of removable dentures, fixed restorations, dental implants, and implant abutments.[4] The Young's modulus of this material is close to that of human bone making it as elastic as a bone.[5]

Studies have suggested that stiffer materials show higher stress values in the prosthetic framework as compared to less rigid materials.[2] Materials having higher elastic modulus will resist deformation, thus increasing the stress concentration. A framework material with a lower modulus of elasticity could decrease the occlusal forces and evenly distribute load.[3] However, it has also been noted that stiffer materials transfer lower stresses to other components of the system. These biomechanical complications can compromise the osseointegration of implants to induce bone resorption.[6] Furthermore, prior studies propose that the material properties, number of implants, its distribution as well as distal support aid in determining the stress levels and displacement in an implant-supported system.[2,3,7]

The three-dimensional (3D) finite element method (FEM) is a numerical procedure analyzing structures using computer models of a material. It uses a complex system of points (nodes) and elements which makes a grid called a mesh. The mesh is programmed to contain the material and structural properties (Young's modulus and Poisson's ratio), and the design is stressed and analyzed for specific results.[8]

The purpose of the present study was to analyze the effects of different materials used for framework fabrication on "All-on-four" implant system using FEM. The three framework materials used in the study varied in their material properties and were critical for the evaluation of stresses in peri-implant region. Evaluation of various stress distribution patterns for axial and nonaxial stresses and micromotion that occurs around these implants was also assessed.

## MATERIALS AND METHODS

### Designing a finite element model of "All-on-four implant" system

A 3D model of edentulous mandible was simulated using a computerized tomographic scan data of an edentulous patient. Threaded implants (11.5 mm, 13 mm length, and 4 mm diameter) were replicated along with the abutments using 3D modeling software. The bone segments were modeled as cortical bone representing the outer shell of 2-mm thickness and the inner volume of cancellous bone. The implants had 100% bone–implant contact. Following the "All-on-four" concept, two anterior implants were placed at the lower lateral incisor region, while the posterior implants were angled distally (30º) and placed anterior to the mental foramen [Figure 1].[1]

### Designing of a framework using material properties of titanium, zirconia, and polyetheretherketone

The framework was designed as a solid bar of height 5 mm and width 6 mm following the shape of the mandible. The cantilever extension was 11.5 mm. At the end of the bar, 2-mm diameter circle was created on the outer occlusal surface to standardize the load application. The framework was simulated using material properties of titanium, zirconia, and PEEK, obtained from previous studies. Young's modulus and Poisson's ratio were assigned to each of the components [Figure 2]. The materials were assumed to have isotropic linear elasticity and inhomogeneity

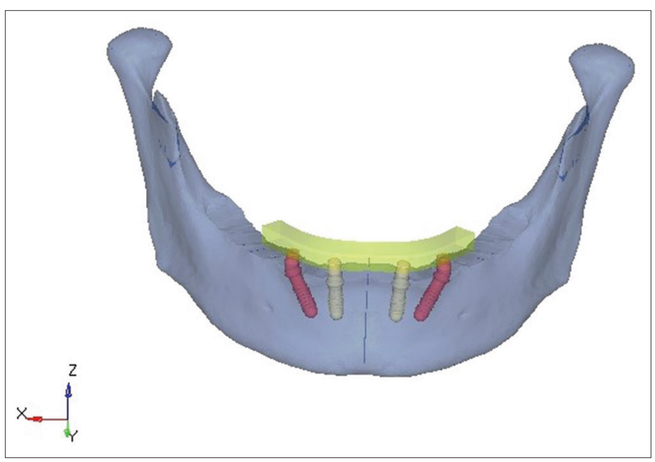


**Figure 1:** Mandible model with four implants according to "All-on-Four" concept.

for the bone. The properties of the materials used are shown in Table 1.

Solid elements were used to represent the geometry. All the 3D models of the implants and framework were built using Solid Edge software (Siemens PLM Software, USA). Bone was built by reverse engineering processor. Meshwork was prepared using HyperMesh software. The analysis was done by ANSYS software (USA).

### Application of load on the three frameworks

The axial load of 200 N was applied at the abutment region of right distal implants. Nonaxial load of 200 N was applied at an angle of 30º at the same site [Figure 3].

### Evaluation of the amount of stress distribution

The software gave quantitative values at different locations. Principal compressive and tensile strain along with von Mises stress was assessed in the peri-implant bone to evaluate the stress condition of the bone.

### Evaluation of micromotion

Micromotion was computed as the relative displacement between two nodes (a node of bone side and implant side) of elements on the interface.

## RESULTS

### Strain distribution

The compressive and tensile strains were observed at the posterior implant and cantilever extension on axial and oblique loading. Maximum strain values were observed with the PEEK framework material. On the axial loading of the posterior implant, the tensile strain of Peek framework was 0.004888 and the compressive strain was 0.008001 [Figure 4]; [Table 2]. At the posterior implant on oblique loading, the tensile and compressive strains of the Peek framework were 0.001781 and 0.002692, respectively [Table 3]. Least tensile strain values in cantilever loading were noted at zirconia framework of 0.002656. In oblique posterior implant loading, cantilever oblique loading, and cantilever axial loading, zirconia and titanium framework showed similar strain values, indicating that the framework material and the length of cantilever influence the strain values [Tables 4 and 5].

**Table 1: Material properties**

| Material | Young's modulus (GPa) | Poisson's ratio |
|---|---|---|
| Titanium | 110 | 0.35 |
| Zirconia | 200 | 0.31 |
| PEEK | 4 | 0.40 |
| Cortical bone | 13.7 | 0.30 |
| Cancellous bone | 1.37 | 0.30 |

PEEK: Polyetheretherketone

### von Mises stress distribution

von Mises stresses were higher on oblique loading of the titanium and PEEK framework materials in comparison to axial loading at cantilever length. The least amount of von Mises stresses was noted with the zirconia framework on axial and oblique loading of 21.0644 Mpa and 20.137Mpa, respectively [Figure 5]. PEEK framework had the highest von Mises stress values of 107.589 Mpa on axial loading and 97.4957 Mpa on oblique loading. Thus, the framework material and the site of load application influenced the von Mises stresses. Among the three materials, zirconia framework showed better stress distribution followed by a titanium framework.

### Micromotion/displacement

The maximum micromotion was observed in the PEEK framework on axial loading at the posterior

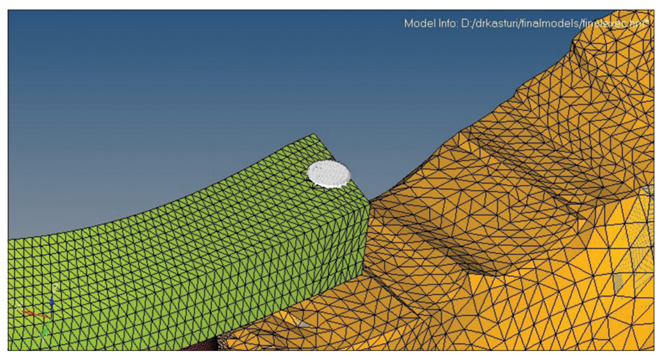

**Figure 2:** Standardized load application on the outer occlusal surface of framework.

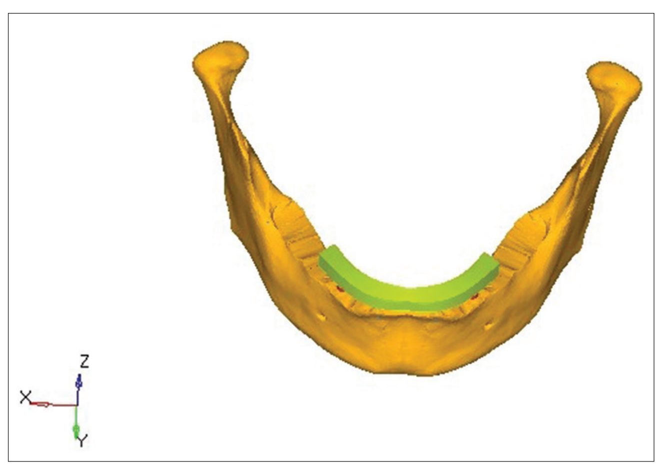


**Figure 3:** Framework design on the implants.

**Table 2: Stress concentration and displacement in the three framework materials on axial loading of distal implant**

| Material | Load | Displacement (mm) | Von mises stress (Mpa) | Tensile strain (maximum) | Compressive strain (maximum) |
|---|---|---|---|---|---|
| Zirconium | Posterior implant axial load | 0.226952 | 21.0644 | 0.001885 | 0.002143 |
| Titanium | | 0.372194 | 63.78 | 0.003894 | 0.004772 |
| PEEK | | 0.373588 | 107.589 | 0.004888 | 0.008001 |

PEEK: Polyetheretherketone

**Table 3: Stress concentration and displacement in the three framework materials on oblique loading of distal implant**

| Material | Load | Displacement (mm) | Von mises stress (Mpa) | Tensile strain (maximum) | Compressive strain (maximum) |
|---|---|---|---|---|---|
| Zirconium | Posterior implant oblique load | 0.198278 | 20.137 | 0.001154 | 0.001509 |
| Titanium | | 0.198302 | 21.64 | 0.001169 | 0.001622 |
| PEEK | | 0.198679 | 35.9464 | 0.001781 | 0.002692 |

PEEK: Polyetheretherketone

**Table 4: Stress concentration and displacement in the three framework materials on cantilever axial loading**

| Material | Load | Displacement (mm) | Von mises stress (Mpa) | Tensile strain (maximum) | Compressive strain (maximum) |
|---|---|---|---|---|---|
| Zirconium | Cantilever axial loading | 0.365205 | 56.0464 | 0.004146 | 0.00412 |
| Titanium | | 0.365478 | 55.91 | 0.004119 | 0.004182 |
| PEEK | | 0.367516 | 90.3858 | 0.003946 | 0.006738 |

PEEK: Polyetheretherketone

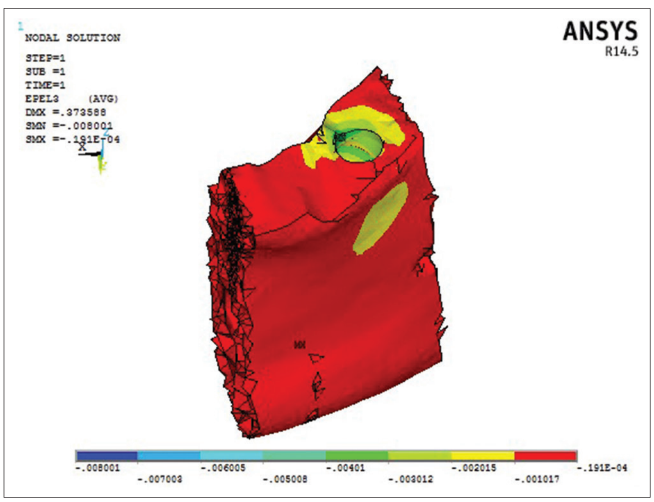


**Figure 4:** Compressive strain at polyetheretherketone framework on axial loading of posterior implant.

implant [Figure 6]. Zirconia framework in all the models showed the least micromotion compared to titanium and PEEK frameworks. The amount of micromotion seen was influenced by the loading site and the loading direction.

## DISCUSSION

In the present study, stress distribution and micromotion at bone–implant interface using different framework materials in "All-on-four" concept in the edentulous mandible were analyzed.

Studies have shown the occlusal masticatory forces in the posterior region of the tooth to be around 220N.[1] In the present study, a force of 200N was applied in an axial and oblique direction at the abutment region of the right distal implant and cantilever extension. The value was standardized in accordance with the previous studies.[2,9]

The "All-on-four concept" eliminates the need for augmentation procedure in many cases. The angulation of distal implants also opens a window for placement of longer implants, thus enhancing the load distribution.[9] In the present study, a distal implant was angulated at 30º. This was in accordance with the previous finite element studies.[10-12] The distal implant angulation is said to have a dominant effect in reducing stresses at the cortical and cancellous bone. A study conducted to analyze the effect of different implant inclinations in the maxillary arch concluded that stresses in the crestal bone declined with the increase in distal implant angulation.[11] These results were not in agreement with the study conducted by Malhotra *et al*. who compared the stresses developed at 30º and 40º and found no statistically significant difference.[12]

The knowledge of stress distribution around the implant–bone interface is crucial for its long-term

**Table 5: Stress concentration and displacement in the three framework materials on cantilever oblique loading**

| Material | Load | Displacement (mm) | Von mises stress (Mpa) | Tensile strain (maximum) | Compressive strain (maximum) |
|---|---|---|---|---|---|
| Zirconium | Cantilever oblique loading | 0.145041 | 51.8369 | 0.002656 | 0.003881 |
| Titanium | | 0.145247 | 56.8845 | 0.002891 | 0.004252 |
| PEEK | | 0.146557 | 97.4957 | 0.004425 | 0.007232 |

PEEK: Polyetheretherketone

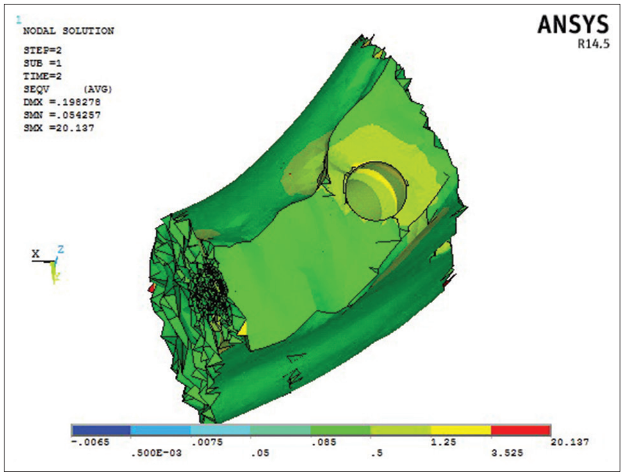


**Figure 5:** von Mises stress at zirconia framework on oblique loading of posterior implant.

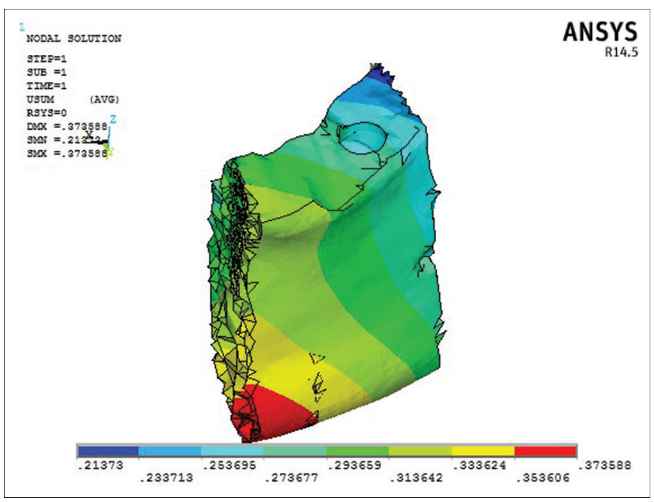


**Figure 6:** Micromotion at polyetheretherketone framework on axial loading of posterior implant.

stability. The stresses transferred onto the bone from different framework materials are divergent due to the variation in its Young's modulus of elasticity.[3] Since the bone has both ductile and brittle response, the use of primary stress/strain is appropriate for evaluating the yielding failure behavior.[1] Stiffer implant materials tend to absorb the stresses being transmitted to specific bodily area. This phenomenon is referred as stress shielding where the bodily tissues are shielded resulting in adjacent bone resorption.[13] Von mises stress is a combination of normal and shear stresses which predicts the yielding of materials under complex loading.[14] Micromotion is the minute displacement at the implant–bone interface affecting the adjacent tissues.[15]

In the present study, principal tensile and compressive strains were observed at the crestal cortical bone. The length of the cantilever influenced the strain values. A study conducted by Horita *et al*. compared cantilever and non-cantilever loading in immediate implant placement. They found 45.3%–52.5% reduction in peak compressive strains on non-cantilever loading.[1] The axial and oblique loading of the framework in the present study derived higher strain values as opposed to loading at the posterior implant abutment region. The least tensile strain was observed in the zirconia framework on oblique loading at the posterior implant. PEEK framework material exhibited maximum compressive strain values in all situations. This could be attributed to the higher deformity of PEEK framework due to its low modulus of elasticity.

In the present study, at distal implant axial loading, the highest von Mises stress of 107.589 Mpa was noted with PEEK framework. However, the stress values were lower on the distal implant oblique loading of the three framework materials. The least stress of 20.137 Mpa was noted at zirconia framework. Thus, the framework material exhibits the ability to absorb stresses and distribute the minimal load to the adjacent bone. Overloading of the cortical bone occurs beyond 170Mpa. The value observed here is below that considered pathologic to the bone. Resorption due to excessive loading of adjacent bone could be avoided by the use of zirconia framework. The use of rigid framework material clinically would thus prevent failure of the implant support system.

The increasing anteroposterior spread of implants shortens the length of cantilever extension. The cantilever length affects the stress distribution of the underlying bone and the bone–implant interface.[16]

A study reported a cantilever length of >15 mm had greater von Mises stress in buccal and lingual cortical plates.[17] The present study had a cantilever extension of 11.5 mm. Studies indicate that longer cantilever prosthesis shows higher stress concentration at the distal implant.[12,16] Similarly, in this study, higher stress values were noted at the cantilever loading of framework. On oblique loading of the cantilever, von Mises stress was maximum for PEEK framework followed by titanium framework. Titanium material showed similar values at both axial and oblique cantilever loading. Zirconia framework showed the least stress of 51.8369 Mpa among all parameters on cantilever loading. PEEK framework showed maximum compressive strain values at axial and oblique cantilever loading. Higher compressive strain values could be due to the material properties of PEEK, thus transmitting more stresses to other system components. The least tensile strain was seen in the oblique loading of the zirconia framework. Thus, in the present study, zirconia framework showed minimal stresses at the bone–implant interface. The values are below the pathologic loading of the underlying bone.

Excessive micromotion at the implant–bone interface can have deleterious effects on the implant system. In this study, during axial loading, the least amount of displacement was observed at the zirconia framework. The titanium and PEEK materials showed similar values on axial loading. On oblique loading of the distal implant site, all the framework materials showed similar values, and the displacement was less than axial loading. In cantilever loading, maximum micromotion was observed on axial load than oblique load. Thus, according to the present study, it can be inferred that the overall loading angle and the type of loading affected the micromotion of the implant. The values did not differ significantly for cantilever and noncantilever loading. These results however differ from the study where the smallest micromotion was seen at noncantilever loading (<1/3$^{rd}$) compared to cantilever loading.[18]

Prior studies suggest that lower Young's modulus of a framework material results in greater bending forces at distal implants and larger bending of the prosthesis under functional loading.[10,19] A study evaluated the effect of three framework materials, i.e. titanium, zirconia, and PEKK for implant-supported prosthesis in the maxilla. It was observed that the stress concentration on the framework increased with an increase in elastic modulus; however, the stress transmitted to the crown was reduced.[20] Study done by Sertgöz *et al*. summarized that materials with lower elastic modulus did not show substantial difference in stress patterns at bone surrounding the implants.[21] In the present study, zirconia frameworks showed low-stress values in all parameters on the distal implant and cantilever loading. This may be attributed to the high Young's modulus of the material. Thus, forces acting on the framework are absorbed by the material reducing the stresses at the distal implant and surrounding bone.

One of the limitations in this study includes the materials being assumed to have isotropic linear elasticity and inhomogeneity for bones. Although not seen in a clinical scenario, these are inherent in finite element studies due to limitations in biologic simulation. The study was also conducted under unilateral static loading. The framework materials may behave differently under cyclic loading such as those occurring during chewing movements. Further clinical studies are necessary for relevance and acceptance of the findings seen in the present study.

## CONCLUSION

Within the limitations of this study, it was concluded that:

1. The stress distribution pattern at implant–bone interface was influenced by the framework material used. Zirconia framework showed minimal stress distribution in all parameters
2. The site of load application and the direction of forces in axial and oblique patterns influence the compressive and tensile strain. PEEK framework material had the highest strain values
3. The length of cantilever increased the stress concentration in all three framework materials
4. The framework material, loading site, and direction of forces influenced the stresses and displacement at the bone–implant interface.

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## Conflicts of interest

The authors of this manuscript declare that they have no conflicts of interest, real or perceived, financial or nonfinancial in this article.

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