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Original Article

Evaluation of stress and deformation in bone with titanium, CFR-PEEK and zirconia ceramic implants by finite element analysis

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ABSTRACT

Background: As more recent implant biomaterials, Zirconia ceramic and glass or carbon fibre reinforced PEEK composites have been introduced. In this study, bone stress and deformation caused by titanium, carbon fiber-reinforced polyetheretherketone (CFRPEEK), and zirconia ceramic implants were compared.

Materials and Methods: In this *in vitro* finite element analysis study, a geometric model of mandibular molar replaced with implant supported crown was generated. The study used an implant that was 5 mm diameter and 11.5 length. Three implant assemblies made of CFR- polyetheretherketone (PEEK), zirconium, and titanium were created using finite element analysis (FEM). On the implant's long axis, 150 N loads were applied both vertically and obliquely. ANSYS Workbench 18.0 and finite element software were used to compare the Von Mises stresses and deformation produced with a significance level of $P < 0.05$.

Results: With no discernible differences, all three implant assemblies that is CFR-PEEK, titanium, and zirconia demonstrated similar stresses and deformation in bone.

Conclusion: It was determined that zirconia and PEEK and reinforced with carban fibres (CFR-PEEK) can be used as titanium-free implant biomaterial substitutes.

Key Words: Finite element analysis, CFR-PEEK, implant, stress distribution, titanium, zirconia

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INTRODUCTION

The most popular treatment option today is implant prosthesis for the restoration of missing jaws. Because of its superior mechanical qualities and successful osseointegration, titanium is regarded as the gold standard.

As a result of its high modulus of elasticity, metallic colour, allergic nature, and metal hypersensitivity reactions, titanium implants must be replaced.[1] Yellow nail syndrome can result from titanium toxicity. Inflammatory reactions caused by the presence of titanium alloy particles and ions in the surrounding tissues as a result of implant corrosion and wear can cause bone loss and osseointegration failure.[2,3] The main causes of titanium implant failure, according to the literature

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are, hypersensitivity, allergy, and toxicity to titanium.[1,2,4,5]

As more recent implant biomaterials, Zirconia ceramic and glass or carbon fibre reinforced PEEK composites have been introduced. Zirconia ceramic implants have gained popularity over metallic implants because they are thought to be inert in the body, have good mechanical properties, and have better aesthetics or tooth colour. Zirconia osseointegration resembles that of titanium.[6-9]

Poly-Ether-Ether-Ketone (PEEK) is a ketone- and ether-containing thermoplastic aromatic polymer. The polyaromatic ketone exhibits resistance to radiation damage and is stable at high temperatures without undergoing chemical changes.[10] PEEK has many benefits, including being extremely light, biologically inert, resistant to high temperatures and hydrolysis, having good mechanical and electrical properties, having a low elasticity modulus that is comparable to bone's, being anti-allergic by nature, tasting non-metallic, having excellent polishing properties, and having a low plaque affinity.[11,12]

Pure PEEK is reinforced with glass or carbon fibres to increase its modulus of elasticity for use as an implant due to its compatibility with reinforcing materials. Both cosmetic abutments and later implants were made of PEEK. Among its qualities are biocompatibility, MRI compatibility, adjustable mechanical performance, chemical resistance, and sterilisation ability.[10]

How stresses are transferred from implant assembly to the cortical and trabecular bone is a crucial aspect of implant dentistry. Systematic approaches can be used to examine how stress from implant assembly is transmitted to the cortical and trabecular bone.[13] The mechanical characteristics and functionality of dental implants can be evaluated effectively using finite element analysis (FEA). FEA is frequently used, according to the literature, in the design and study of the behavioural or functional characteristics of dental implants. When distributing forces from the implant assembly to the surrounding bone, the direction and duration of the load placed on the implant assembly are of utmost importance.[14] Jaw bones are directly influenced by cyclic masticatory forces. Therefore, fatigue testing is required to forecast long-term outcomes of clinical significance for dental implants.[15]

The functional interactions of the human anatomy and restorations with implant components are more accurately represented in 3D models because they mimic the actual situation and are more accurate. FEA studies are conducted in a methodical manner. These include applying material properties, creating boundary conditions around the implant assembly, and modelling the bone and implant in great detail in three dimensions.[16] This study compared and evaluated the stresses and deformation that titanium, zirconia, and carbon fiber-reinforced polyetheretherketone (CFRPEEK) implants caused in the bone.

MATERIALS AND METHODS

This *in vitro* experimental 3D finite element analysis study was carried out in the Department of Prosthodontics after receiving approval from the institutional ethics committee. The methodology involved geometric modelling, meshing the model after applying various loads, and analysing and contrasting Von Mises stresses.

Model meshing and geometric modeling

In Computer Aided Three-Dimensional Interactive Application (CATIA) software, Dassault Systèmes, France, a geometric model of replacing the mandibular molar with an implant-supported prosthesis was created. A bone section with cortical and trabecular bone measuring 5 mm in diameter, and 11.5 mm in length was taken into consideration. The posterior mandible's (D2) bone quality was produced. Table 1[17] provides implant dimensions, and the morphology and crown dimensions are consistent with those found in most textbooks.[18]

Using 1,50,350 nodes and 90,40,220 elements, a 3D mesh model of a section of the mandible with implant assembly was created using the processing software ANSYS version 18.0, Ansys, Inc, Canonsburg, Pennsylvania, United States. Figure 1 depicts a model of an implant with prosthetic elements and the cortical and cancellous bone surrounding the implant.

Evaluation

Zirconia, titanium, and CFR-PEEK finite element models were examined separately. With the exception of the materials properties, finite element models are

Table 1: Nobel active implant details

Dimension	In millimeter
Implant dimension	5 mm diameter 11.5 mm length

mm- millimeter

comparable. Material was viewed as homogeneous, isotropic, and linear elastic in the finite element models. Tensile stress and young's modulus of materials were used in FEM for FEA, as shown in Table 2.[19] On the model's occlusal surface, a load of 150N was applied both vertically (along the long axis of the implant) and obliquely (at 30 degrees to the long axis of the implant), simulating cuspal angulations of the crown. To compare Von-Mises stresses and bone deformation degree, FEA analysis was done.

The obtained data was tabulated and analysed statistically using IBM, SPSS software version 22.0, Chicago, USa with z-test and significance was kept as $P < 0.5$.

RESULTS

As mentioned in the Table 3, [Figures 2-4] amount of highest and lowest stresses pattern and deformation by CFR-PEEK, titanium and zirconia implant assemblies are similar without significant difference.

FEA results of CFR- PEEK implant

The highest stress measured during loading along the implant axis was 2.3652 Mega Pascals, and the lowest stress measured was 0.0090537 Mega Pascals. The deformation was 0.0038321 mm at its highest point and 0.0004183 mm at its lowest. Maximum stress under oblique load was 4.24258 MPa, and minimum stress was 0.0064642 MPa. The maximum and minimum deformations were measured to be 0.0069654 mm and 0.0069652 mm, respectively [Figure 2].

FEA results of zirconia

A stress of 2.3561 Mega Pascals and a least stress of 0.0091351 Mega Pascals were measured during loading along the implant axis. The bone showed maximum deformation of 0.0038723mm and minimum deformation of 0.0004375 mm. Maximum stress under oblique load was 4.6258 Mega Pascals,

Table 2: Young's Modulus and tensile stress of materials[19]

Materials	Tensile strength (Mpa)	Young's Modulus (Gpa)
PEEK	80	3-4
CFR-PEEK	120	18
GFR-PEEK	147–154	12
Titanium	954–976	102
Dentin	104	15–30
Enamel	47.5	40–83
Zirconia	77	210
Chrome-cobalt alloy	79	219

MPa- Megapascal, GPa- Giga pascal

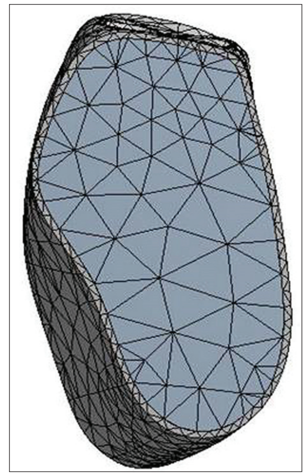

Figure 1: Mesh model.

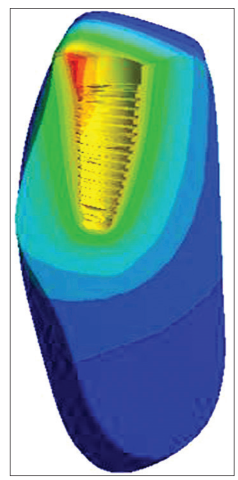

Figure 2: Stress with carbon fiber-reinforced polyetheretherketone (CFR PEEK).

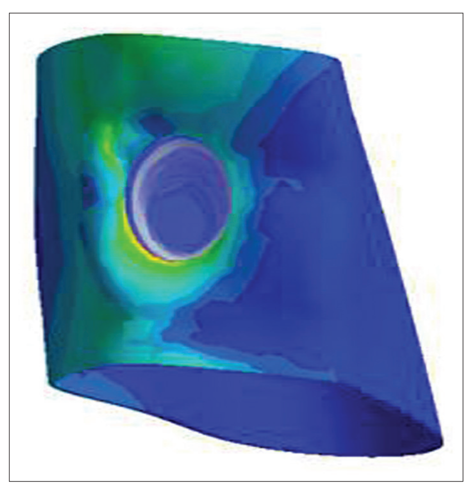

Figure 3: Stress with Zirconia Ceramic.

Table 3: Stresses and deformation with titanium, zirconia and cfr-peek implant under load

Different load	Highest von-Mises Stress in MPa			Lowest von-Mises Stress in MPa			*P*
	Titanium	Zirconia ceramic	CFR-PEEK	titanium	Zirconia ceramic	CFR-PEEK	
Stress under vertical load	2.3162	2.3561	2.3652	0.0091451	0.0091351	0.0090537	0.063NS
Deformation under vertical load	0.0037613	0.0038723	0.0038321	0.0004361	0.0004375	0.0004183	0.074NS
Stress under oblique load	4.2735	4.6258	4.24258	0.0063482	0.0065427	0.0064642	0.074NS
Deformation under oblique load	0.0068467	0.0069545	0.0069654	0.0068578	0.0069472	0.0069652	0.084NS

P<0.05, MPa- Megapascal, NS- Nonsignificant

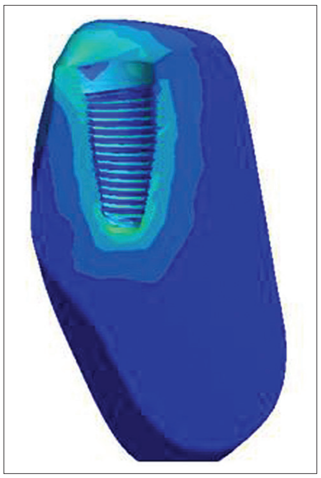

Figure 4: Stress with titanium.

and the lowest stress was 0.0065427 Mega Pascals. 0.0069545 mm and 0.0069472 mm, respectively, were the maximum and minimum deformation values recorded [Figure 3].

FEA results of titanium implant

The highest stress measured under load along the implant axis was 2.3162Mega Pascals, and the lowest stress measured was 0.0091451Mega Pascals. The largest bone deformation measured 0.0037613 mm, and the smallest was 0.0004361mm. Maximum stress under oblique load was 4.2735 Mega Pascals, and the lowest stress was 0.0063482 Mega Pascals. Bone showed a maximum deformation of 0.0068467 mm and a minimum deformation of 0.0068578 mm [Figure 4].

DISCUSSION

Because rehabilitation with implant-supported prostheses offers highest level of retention, stability, aesthetics, and comfort, both prosthodontists and patients are now choosing to replace missing teeth with implants. Zirconia ceramic and PEEK composites, which have superior mechanical qualities, aesthetic qualities, and biocompatibility, can replace titanium in patients who have a history of metal allergies as well as in those who demand aesthetics. According to published research, 0.6–1% of patients who receive restoration using titanium implants have a titanium allergy, which can result in implant failure. Zirconia ceramic and PEEK are biocompatible, have improved mechanical properties, and transmit stresses similarly to titanium, according to the literature.[10,18-25] PEEK is a thermoplastic polymer that is frequently used in the field of orthopaedics as an alternative biomaterial to metallic implants. Pure PEEK has a 4 Gpa modulus of elasticity, which exhibits greater deformation. In a FEA study by Sarot *et al*., PEEK implants with a 30% carbon fibre reinforcement and a modulus of elasticity of 17 GPa demonstrated higher stresses in the surrounding bone due to greater deformation than titanium.[26] To lessen deformation of PEEK implants, pure PEEK reinforced with stronger glass fibres and an elastic modulus of 115 GPa was considered in the study. It was proposed that a PEEK dental implant that had been further strengthened and reinforced with glass fibres might show less stress in the surrounding bone. A literature review suggests that tapered or screw-shaped implants are preferable to cylindrical implants.[18,27]

According to earlier studies, a load of 150 N was applied vertically along the implant's long axis and obliquely at 30 degrees to simulate the cuspal angulation of the crown. In earlier studies, an occlusal 150 N vertical and oblique load was applied to simulate real-world function.[28,29] It was noted that all three implant assemblies displayed a similar stress pattern under both vertical and oblique load. The best dental implants for withstanding lateral masticatory forces are tapered endosseous implants with high moduluss of elasticity because masticatory forces are cyclic in nature and acting in all directions during the process of mastication.[30,31] Zirconia ceramic with a high modulus of elasticity is recommended as an implant biomaterial for the same reason. In their study, Rieger *et al*. came to the conclusion that the low stresses distributed in the bone under lateral loading conditions are due to tapered zirconia implants with high modulus of elasticity.[27] Zirconia implants exhibited homogeneous stress distribution while titanium implants did not, according to studies.[27,30]

Under both loading conditions, all three implant assemblies produce a similar deformation pattern with little variation.

The CFR-PEEK and Zirconia implants, which have shown comparable von Mises stresses and deformation to titanium implants, have been shown to be important in this FEA study. As a result, titanium implants can be effectively replaced with CFR-PEEK and Zirconia, especially for those who exhibit titanium allergy and aesthetic concern.

PEEK has a few drawbacks in addition to its benefits, such as lower osteoconductivity than titanium.[32] Pure PEEK has a limited capacity for osseointegration, necessitating a number of surface modification procedures to enhance surface characteristics.[33,34] It is expensive, requires high-temperature processing, has a low surface energy that bonds poorly to resin cements, is weakly resistant to UV light, and can be attacked by halogens and sodium.[12]

The current study's limitation is that 3D finite element analysis will not accurately represent the actual conditions of oral cavity function. As masticatory forces act in all directions, there is a chance that the results will vary depending on the clinical circumstances. Additional research in this area is required to confirm the PEEK's quality for use in clinical settings.

CONCLUSION

We compare the stresses and deformation in bone caused by CFR-PEEK, zirconia ceramic, and titanium implants. With each of the three implant assemblies, stresses and deformation are comparable. Within the constraints of this study, it can be concluded that zirconia ceramic and CFR-PEEK are potential titanium implant biomaterial alternatives. The viability still requires more research.

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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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