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Original Article

Finite elements analysis of stresses formed in core and spongious bone tissue by restored implanted fixed prostheses with Polyetheretherketone (PEEK) and fiber-reinforced composite

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Abstract

Aim: This study uses the finite element analysis method to compare the effects of different abutments and prosthetic materials on stress distribution in the rehabilitation of maxillary anterior tooth deficiencies with fixed implanted prostheses.

Methodology: In our study, two titanium implant models with a diameter of 4.1 mm and a length of 10 mm were designed for the maxillary central and canine teeth regions. 3D models of the prosthetic restorations were created with PEEK and fiber-reinforced composite and two different abutment materials (titanium and zirconia). After meshing the materials used with cortical and cancellous bone, Poisson ratio and young module values were loaded into the program. Maxillary central and canine to the palatal surface of the tooth, 2 mm below the incisal edge; a 178 N force was applied in both the vertical and 45° oblique directions, and analysis was performed. The distributions of the highest compression and tensile stress values in peri-implant cortical and cancellous bone were examined, and the results were compared.

Results: Material with low elastic modulus caused higher stress accumulation in the cortical and cancellous bone tissue around the implant during oblique force application.

In all study groups, the maximum stress values observed in the cancellous and cortical bone during oblique force application were significantly higher than those observed during vertical force application. Thus, different prosthetic materials had different effects on stress distribution in peri-implant cortical and cancellous bone tissue, and the highest stress accumulations were in the peri-implant cortical bone.

Conclusion: Different prosthetic materials had different effects on stress distribution in peri-implant cortical and cancellous bone tissue.

Keywords: Polyetheretherketone, PEEK composite, fiber-reinforced composite, finite element stress analysis, dental implant

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Introduction

The use of dental implants in the prosthetic treatment of tooth deficiencies is a frequently preferred treatment method. The long-term success of implants is relatively high. However, ideal biomechanical conditions must be provided to achieve and maintain this success (1). The forces exerted on implants are transmitted directly to the bone because there is no periodontal ligament around the implant. Therefore, the factors affecting stress loads transmitted to the bone include implant material, implant design, prosthetic material, prosthesis design, direction and amount of load, bone type, mechanics of the bone-implant interface, and implant number. It is often preferred to examine stress values and distributions in trabecular and cortical bone, which cannot be determined by in vivo studies, using the finite element stress analysis method (2).

The flexibility and versatility of the finite element analysis method can be used to calculate cause-effect relationships in complex structures, field problems, continuum, and other problems. Real-like models of objects can be obtained easily thanks to the software used (3). Isotropic materials exhibit the same properties in all directions, and although no material is 100% homogeneous and isotropic in reality, the materials used in current studies in dentistry are considered to be sufficiently isotropic and homogeneous (1, 4).

Thanks to developments in adhesive technology, new, stronger composite materials and fibers have been made that can be directly bonded with the teeth adjacent to a lost tooth. In addition, they do not require any preparation of the abutment teeth, and more aesthetic restorations can be made (5, 6).

Advantages of fiber-reinforced composite resin bridges include ease of application, low cost, easy cleaning, no risk of metal allergy development, time-saving, and feeling of naturalness due to fewer appointments (7, 8).

Our study models of the maxillary bone, titanium implants, zirconia and titanium abutments, polyetheretherketone (PEEK), and fiber-reinforced composite (FRC) materials were created with implant-supported, three-member, cement-linked fixed partial prostheses.

The elastic modulus of PEEK material resembles that of bone. The PEEK material modulus is physically and chemically stable, resistant to aging, has good mechanical properties, and shows excellent biocompatibility. It is also radiolucent and compatible with imaging techniques such as computed tomography, magnetic resonance imaging, and x-ray. It is resistant to chemical and radiation damage, is compatible with many reinforcing agents (such as glass and carbon fiber), and has higher durability than many metal alloys (9-15).

This study aims to evaluate the effects of titanium (Ti) and zirconia (Zr) abutment materials and different framework materials on stress distribution over implant bridge prostheses in the anterior region using the 3D finite element stress analysis method.

Materials and Methods

In our study, two titanium implant models with a diameter of 4.1 mm and a length of 10 mm were designed for the maxillary central and canine teeth region. First, 3D modeling of prosthetic restorations made of PEEK and fiber-reinforced composite with two different abutment materials (titanium and zirconia) were performed. In the study, two titanium implants measuring 10 mm tall and 4.1 mm were used. After meshing the materials used with cortical and cancellous bone, the Poisson ratio and young modulus values were loaded into the program (Table 1).

Table 1. Physical properties of the materials used in the study (2, 4, 11, 15, 23)

	Young Modulus (Mpa)	Poisson's Ratio
Cortical Bone	13700	0.30
Cancellous Bone	1370	0.30
Titanium Alloy	100000	0.30
Titanium Framework	110000	0.28
Zirconium Framework	205000	0.22
PEEK	4000	0.36
Fiber Reinforced Composite	Longitudinal 46000 Transverse 7000	Longitudinal 0.39 Transverse 0.29
Hybrid Composite	22000	0.27

Maxillary central and canine to the palatal surface of the tooth, 2 mm below the incisal edge; A 178 N force was applied in both the vertical and 45° oblique directions, and analysis was performed. The distributions of the highest compression and tensile stress values in peri-implant cortical and cancellous bone were examined, and the results were compared. It is accepted that the connections of the implant parts (abutment screw, implant abutment) used in the analysis are also in continuous contact. Therefore, it has been assumed that osseointegration was 100%. The cement layer was neglected in our study.

As a final step, analysis was carried out by applying 178 N of force in the vertical and 45° oblique directions to the palatal surface of the 3D models we prepared from 2 mm below the crown incisal of the central incisor and canine teeth.

Results

In the finite element stress analysis method, statistical analysis is not used to evaluate the findings because the numerical values obtained by geometric mathematical models are constant, and there is no variance. In our study, the findings obtained as a result of stresses in cortical and cancellous bone after vertical and oblique force application were compared.

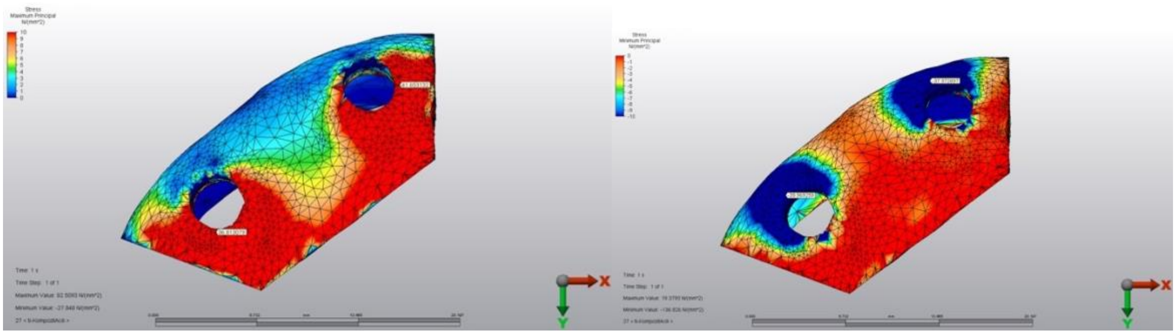

Figure 1. Oblique force application of the Ti-FGK group; Maximum and minimum principal stress distribution observed in cortical bone

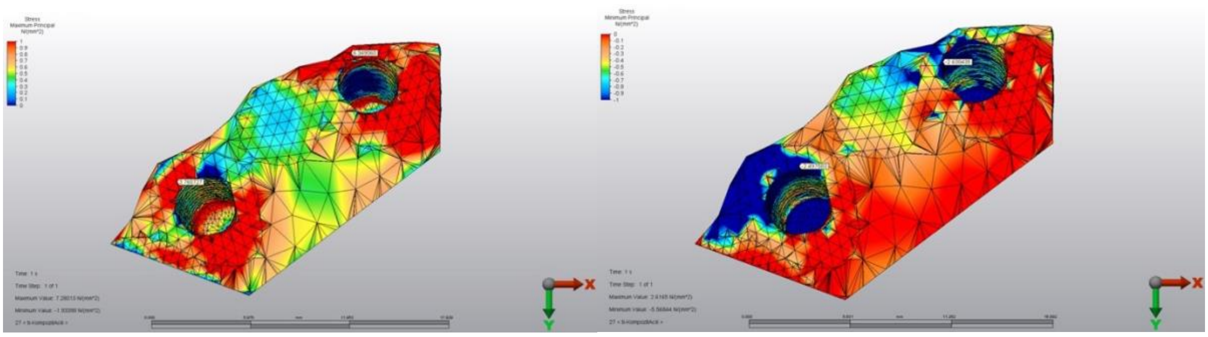

Figure 2. Oblique force application of the Ti-FGK group; Maximum and minimum principal stress distribution observed in cancellous bone

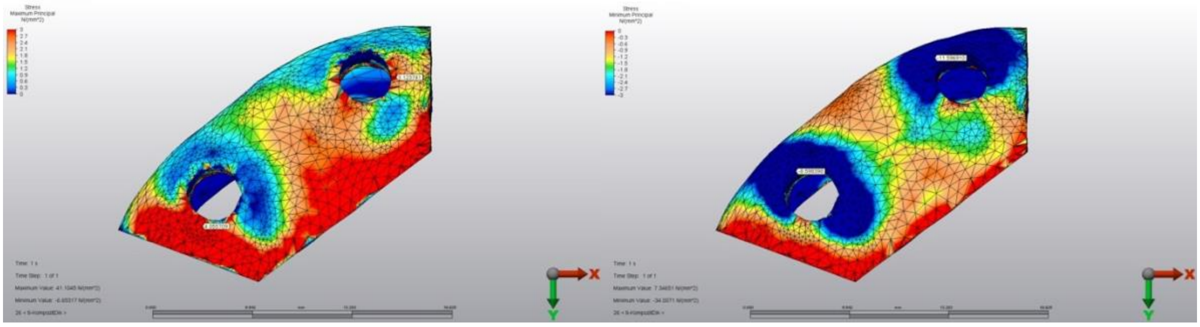

Figure 3. Vertical force application of the Ti-FGK group; Maximum and minimum principal stress distribution observed in cortical bone

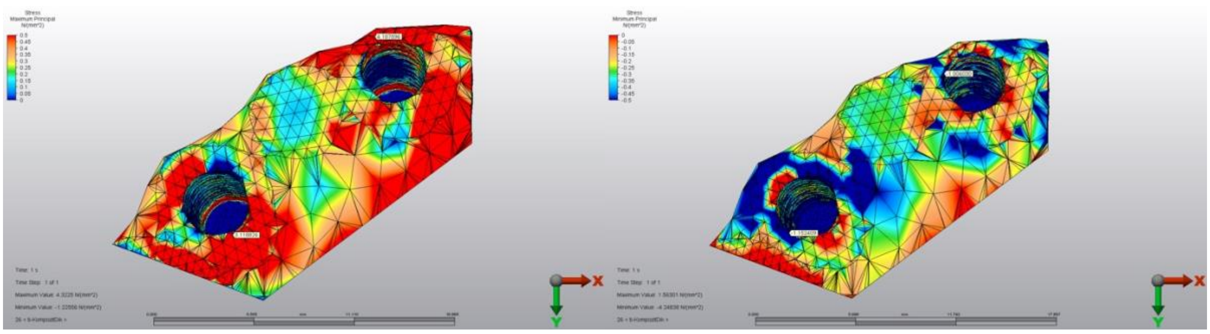

Figure 4. Vertical force application of the Ti-FGK group; Maximum and minimum principal stress distribution observed in cancellous bone

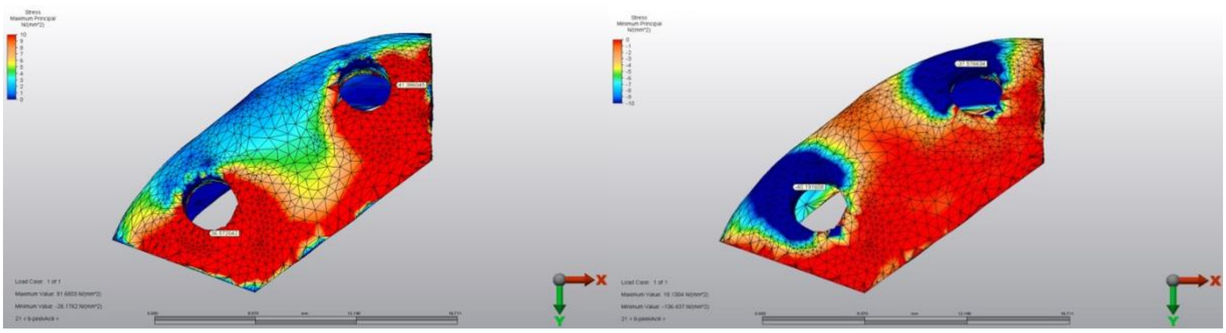

Figure 5. Oblique force application of the Ti-PEEK group; Maximum and minimum principal stress distribution observed in cortical bone

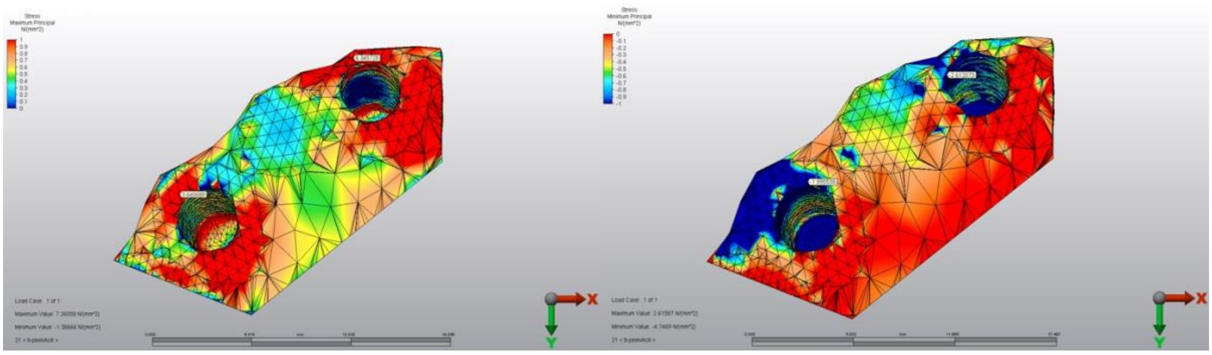

Figure 6. Oblique force application of the Ti-PEEK group; maximum and minimum principal stress distribution observed in cancellous bone

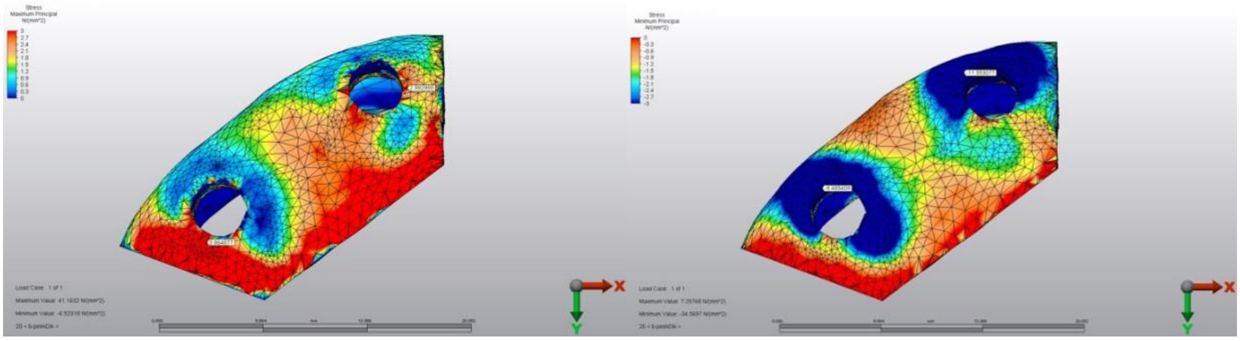

Figure 7. Vertical force application of the Ti-PEEK group; Maximum and minimum principal stress distribution observed in cortical bone

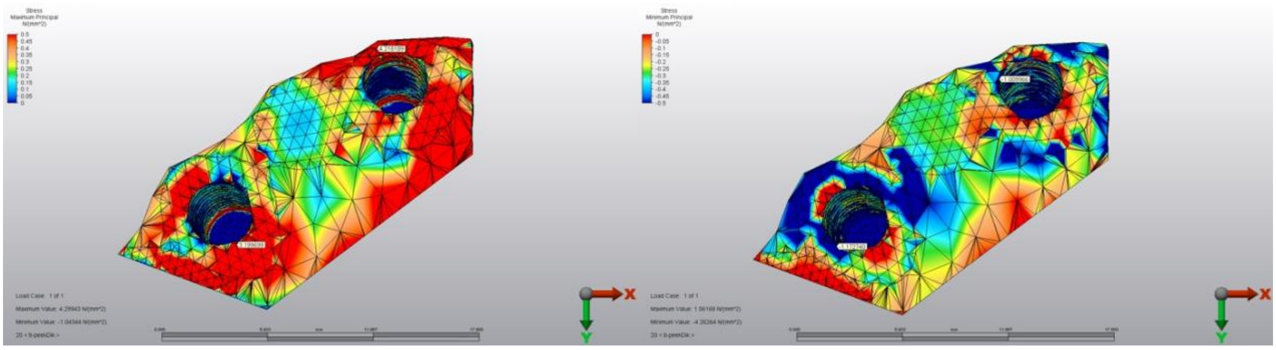

Figure 8. Vertical force application of the Ti-PEEK group; Maximum and minimum principal stress distribution observed in cancellous bone

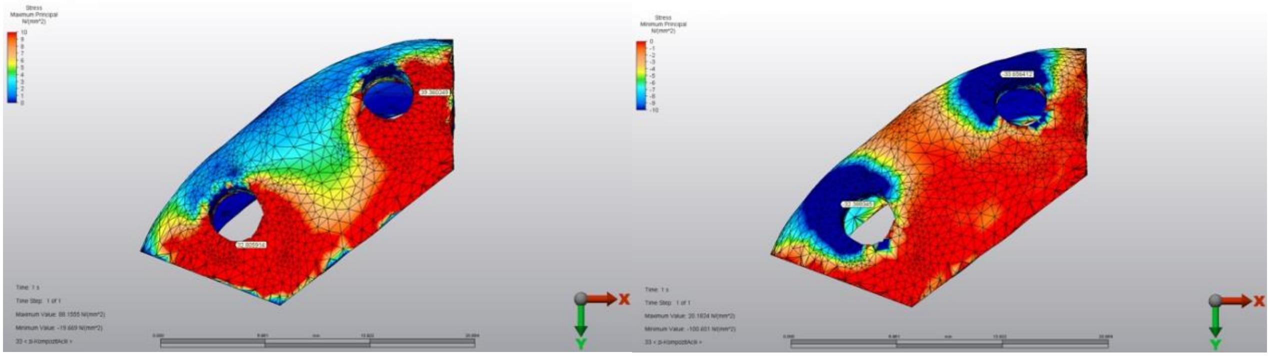

Figure 9. Oblique force application of the Zr-FRC group; Maximum and minimum principal stress distribution observ in cortical bone

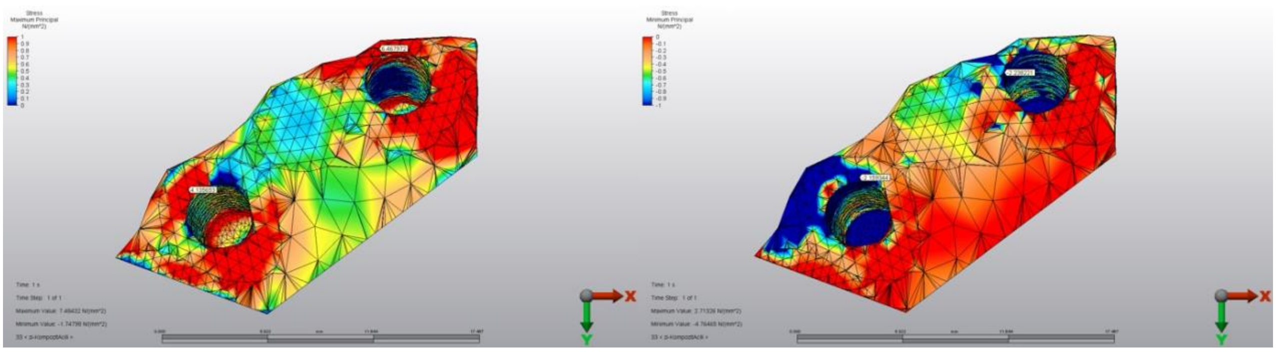

Figure 10. Oblique force application of the Zr-FRC group; Maximum and minimum principal stress distribution observed in cancellous bone

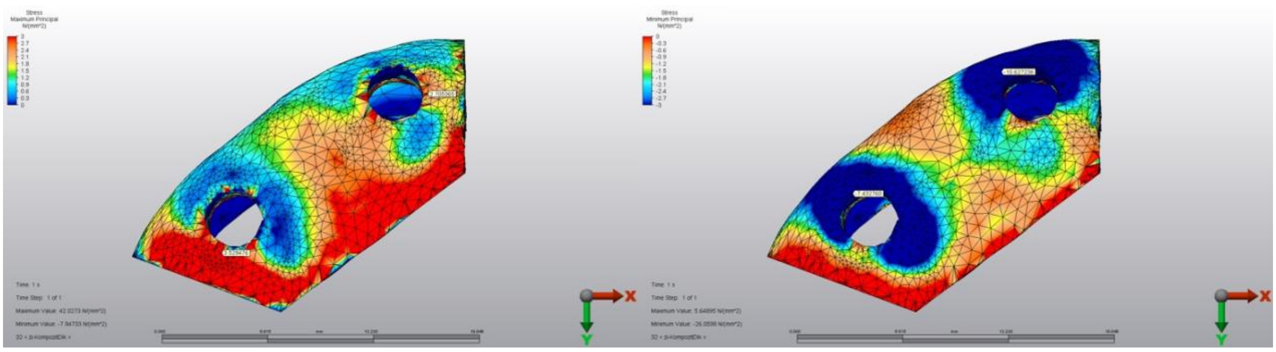

Figure 11. Vertical force application of the Zr-FRC group; Maximum and minimum principal stress distribution observed in cortical bone

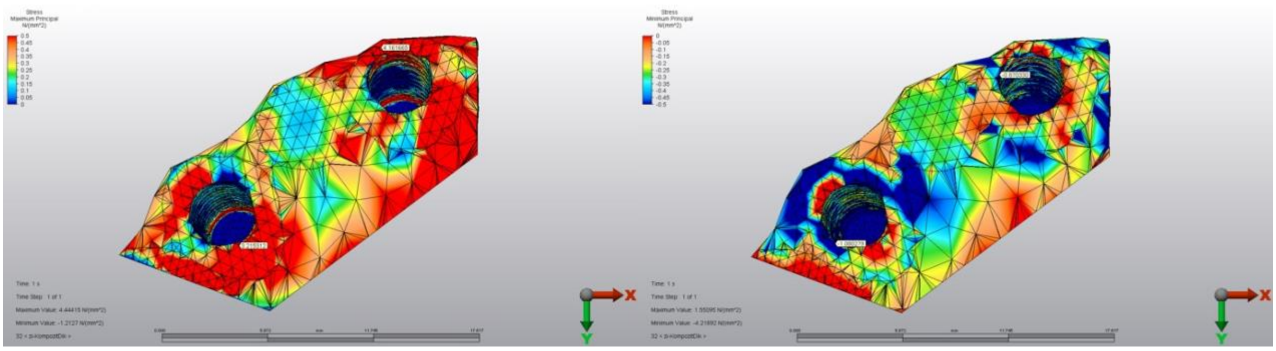

Figure 12. Vertical force application of the Zr-FRC group; Maximum and minimum principal stress distribution observed in cancellous bone

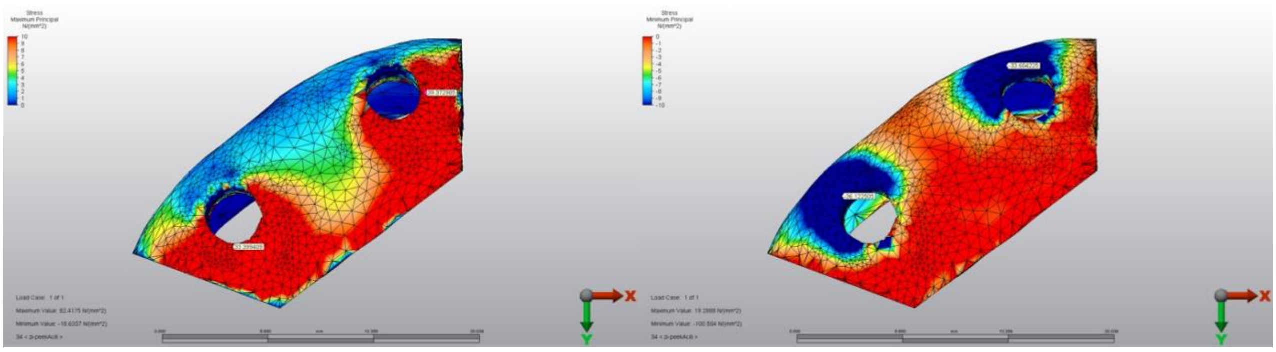

Figure 13. Oblique force application of the Zr-PEEK group; Maximum and minimum principal stress distribution observed in cortical bone

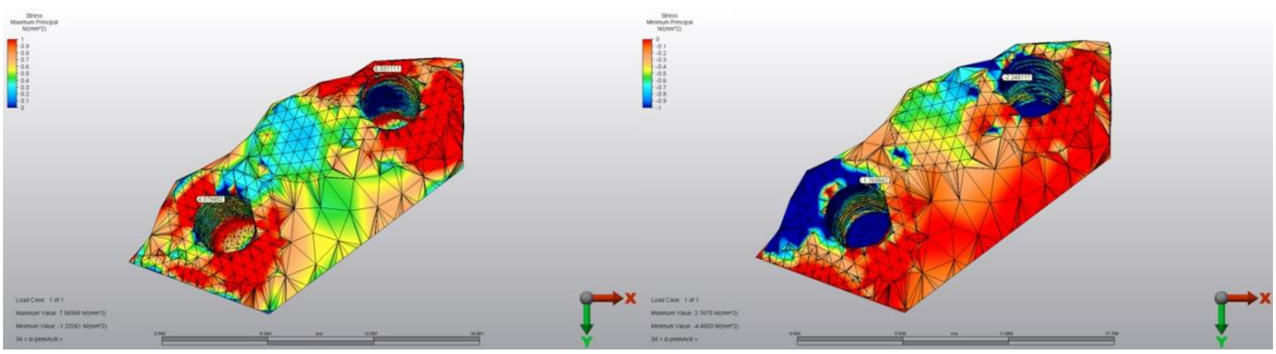

Figure 14. Oblique force application of the Zr-PEEK group; Maximum and minimum principal stress distribution observed in cancellous bone

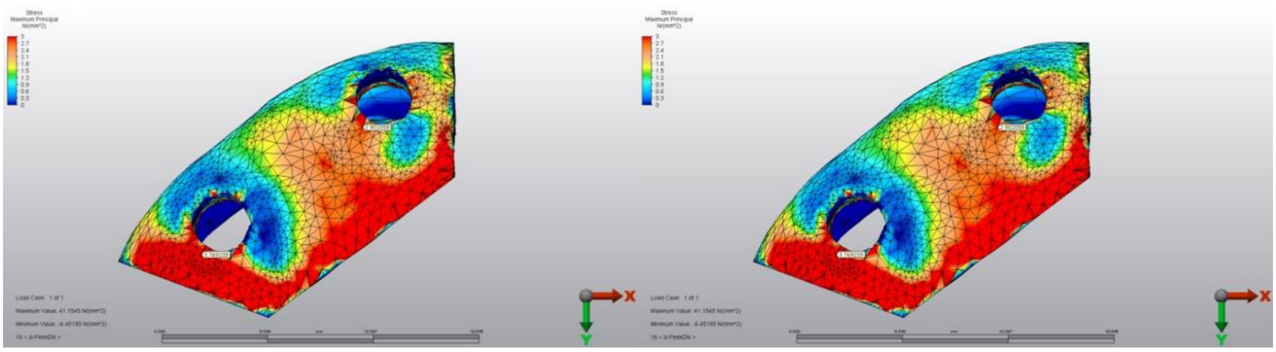

Figure 15. Oblique force application of the Zr-PEEK group; Maximum and minimum principal stress distribution observed in cortical bone

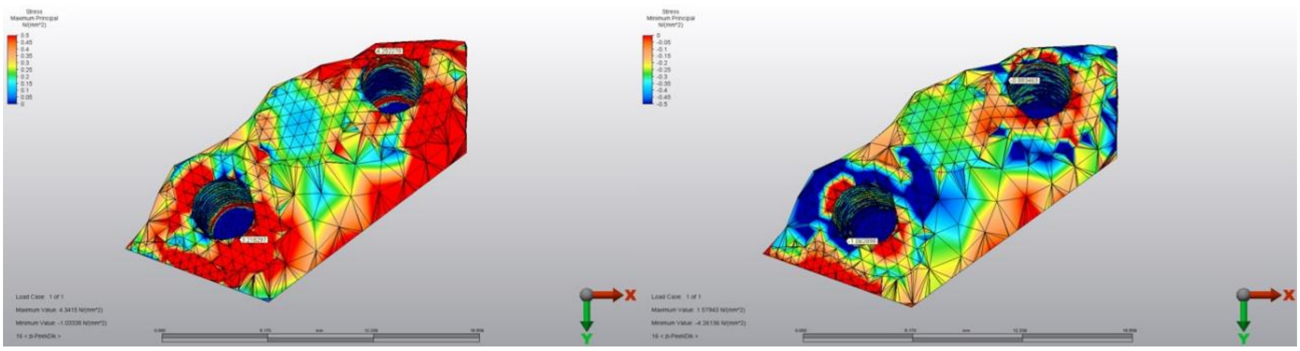

Figure 16. Oblique force application of the Zr-PEEK group; Maximum and minimum principal stress distribution observed in cancellous bone

Table 2. The minimum and maximum principal stress values observed in the groups as a result of vertical force application (Mpa)

Vertical	Cortical Bone	Spongious Bone
	(Minimum)- (Maximum)	(Minimum) – (Maximum)
Group Ti-PEEK	(-34.56)- (41.163)	(-4.262)- (4.322)
Group Ti-FRC	(-34.007)- (41.104)	(-4.248)- (4.360)
Group Zr-PEEK	(-26.651)- (41.154)	(-4.261)- (4.341)
Group Zr-FRC	(-26.059)- (42.027)	(-4.218)- (4.444)

Table 3. The minimum and maximum principal stress values observed in the groups as a result of oblique force application (Mpa)

Oblique	Cortical Bone	Spongious Bone
	(Minimum)- (Maximum)	(Minimum- Maximum)
Group Ti-PEEK	(-135.374)- (81.680)	(-4.678)- (7.260)
Group Ti-FRC	(-136.764)- (82.509)	(-4.751)- (7.280)
Group Zr-PEEK	(-100.223)- (82.417)	(-4.406)- (7.569)
Group Zr-FRC	(-100.775)- (88.155)	(-4.567)- (7.484)

Discussion

Three types of stresses in the FEA method, von mises, minimum principal stress, and maximum principal stress values are examined (16). It makes more sense to use principal stresses when evaluating fragile materials such as bone (17).

Maximum principal stress values determine the highest tensile stresses, and they are positive values. It is also defined as maximum principal stresses or tensile, tensile stresses. Minimum principal stress values determine the highest compression type stresses, and these are negative values. Also called minimum principal stresses or compression, compression forces (17). It has been observed that the loading condition, which mainly determines the results of the finite element stress analysis studies, is the oblique loading condition (18). The reason for this idea is that the actual destructive stress accumulations are not so pronounced in vertical force applications but more prominently under oblique loading conditions. These oblique forces are the type of force that best mimics bite forces.

Çelik reported in his study that more stress occurred in implants and bone as a result of oblique loading (19). Behr et al. conducted a study in which two implant-supported, four-member fixed partial prostheses on the implant were restored using unidirectional composite reinforced with glass fibers in the posterior region (20). In their study, where they followed the restorations for five years with mechanical tests and thermal cycle applications, they stated that the fracture resistance of composites reinforced with glass fibers could be an alternative to metal-supported prostheses in implant-supported fixed partial dentures.

In a study on fiber-reinforced composite materials (21), the load-bearing capacity of crowns made of fiber-reinforced composite and lithium disilicate was compared. Fiber-reinforced composites exhibited more successful loading capacity than lithium disilicate crowns. This has shown that fiber-reinforced composites can be safely preferred in clinical use.

Our study observed that the forces applied to the prosthesis in the application of vertical force in FGK groups spread more evenly in the surrounding bone tissue; In oblique force application, these forces were found to be more concentrated in the surrounding bone tissue the palatal region.

Lee et al. compared the stresses created by different framework materials on prosthetic components in implant-supported prostheses in a study they conducted with the FEA method (22). According to the results of the study, PEEK material was compared with titanium and zirconia, and they found that the framework material with high elastic modulus reduced the stress in the components of the prosthesis, and the stress absorption ability of the lower elastic modulus material was low in certain areas. Similar to this study, in our study, the highest stress values in the bone tissue around the implant were observed in the fiber-reinforced composite group in both vertical and oblique force applications.

Akdeniz et al. compared the stresses caused by carbon fiber reinforced PEEK implants applied to the maxilla anterior region and traditional titanium implants in the surrounding bone tissue with the FEA method (23). According to the study results, the titanium implant transmitted the incoming forces to the bone more homogeneously with a lower stress value than the carbon fiber reinforced PEEK material. Carbon fiber reinforced PEEK dental implants have not found a biomechanical advantage over titanium implants. Similarly, Schwitalla et al. evaluated the stress accumulation at the bone-implant interface of carbon fiber reinforced PEEK and titanium dental implants under oblique load, and it was stated that dental implants made of PEEK material underwent more deformation and showed higher stress accumulation than those made of titanium (24). In both studies, parallel to our study, it was stated that materials with low elastic modulus transmit more stress.

When the stresses occurring in cortical and cancellous bone are evaluated; In the group with composite prosthetic framework reinforced with titanium abutment-fiber, the highest compression stresses occurring in cortical and cancellous bone in oblique force application; The highest tensile stresses were found in the zirconia abutment-fiber reinforced composite prosthetic substructure group. When the maximum tensile forces in vertical force application are examined, the highest values occurring in cortical bone are in the group with composite prosthetic framework reinforced with titanium abutment-fiber; In cancellous bone, zirconia was found in the group with an abutment-fiber reinforced composite prosthetic framework.When the minimum compression forces are examined, the highest values in cancellous bone are in the titanium abutment-PEEK group; The highest values in cortical bone were found in the titanium abutment-fiber reinforced composite prosthetic substructure group.

Conclusions

When the study results are examined, the material with low elastic modulus causes higher stress accumulation in the cortical and cancellous bone tissue around the implant in oblique force application. In all study groups, the maximum stress values observed in spongiosis and cortical bone as a result of oblique force application were found to be significantly higher compared to vertical force application. It has been observed that different prosthetic materials affect the stress distribution in peri-implant cortical and cancellous bone tissue, and the highest stress accumulation is in the cortical bone around the implant.

FEA is an in vitro study in which standard bone density is based on mathematical groups, clinical conditions are tried to be simulated, and results are interpreted comparatively. When evaluating the study results, the limitations of the FEA method should be considered. Therefore, more in vitro and in vivo studies examining stress distributions are needed.

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