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The effect of different materials and multi-unit angles in stress distribution on implant-supported fixed bridges: A finite element method study

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Abstract

Aim: Various abutment angulations can be used for implant-supported restorations. These angles are determined based on factors such as the structure of the jawbone, the position of the implants, and the design of the restoration. The aim of this study was to evaluate the effect of multi-unit abutment angles on stress patterns of the implant and the peri-implant tissue.

Methodology: In this finite element analysis study, three different three-dimensional models of maxillary three-unit fixed implant-supported prostheses were examined. A jawbone was created with jaw components in SolidWorks. Subsequently, implant models obtained from an implant company (Bilimplant®) were placed in the area of the maxillary premolar, and the other implants were placed in the area of the maxillary first molar. Multi-unit abutments were used at three different angles (0°, 15°, 30°). Two different restorative materials (Co-Cr feldspathic and zirconia feldspathic) were designed in EXOCAD software for the fixed implant-supported restoration. A force of 150 newtons was applied at an oblique angle of 30° to the implants. Subsequently, stress distribution was evaluated with finite element analysis performed using the ABAQUS software and analyzed with Von mises stress distribution.

Results: It has been observed that with an increase in the multi-unit angle in implant-supported prostheses, the stress values applied to the implant components and cortical bone increase, while the stress applied to the prosthesis decreases. The highest stress values on implant components and cortical bone were detected in the zirconia framework models.

Conclusion: This study evaluates the impact of multi-unit abutment angles on implant-supported restorations and examines the stress patterns of implants and peri-implant tissues. The study shows that increasing the multi-unit angle in implant-supported prosthesis increases stress values on implant components and cortical bone while decreasing stress applied to the prosthesis.

Keywords: Implant, abutment, finite element method, angle, Von Mises stress

Introduction

Recent technological advances in the field of dentistry have led to significant changes in dental treatments. Among these developments are dental implants and implant-supported prostheses. Implant-supported prostheses are widely used to replace missing teeth and help patients regain their chewing function, aesthetic appearance, and overall oral health.

One of the most significant advantages of implant-supported prostheses is that they integrate into the jawbone like a natural tooth root (1). This integration increases the stability of the prostheses, minimizing issues such as the movement or displacement of prostheses. Additionally, the support provided by implants to the jawbone prevents bone resorption, thereby helping to maintain the structure of the jawbone in the long term (2). Misch and Perel's study showed that implant-supported prostheses enhance long-term prosthetic success by preserving bone health (3). Other advantages offered by implant-supported prostheses include the distribution of chewing forces similar to those of natural teeth, improvement of speech function, and protection of adjacent teeth. In traditional tooth-supported bridges, adjacent teeth must be prepared; however, such interventions are not necessary with implant-supported prostheses (3). Additionally, the maintenance and cleaning of these prostheses are easier than for traditional removable dentures. Because implant-supported prostheses have a fixed structure, no special procedures are required during the daily oral hygiene routine (4).

In addition to these advantages, there are some points that need to be considered in dental implantology. One of these is that, ideally, the implants should be placed parallel to each other and perpendicular to the occlusal plane to distribute axial loads. However, due to insufficient bone volume and the location of anatomical structures such as the maxillary sinus and mandibular nerve, this is not always possible, and angled placement of implants may be necessary in some cases. Numerous studies have shown that as the angulation of implants increases, the occlusal loads on the implants can create more stress (5, 6). Papavasiliou et al. indicated that angled implants cause more stress accumulation than straight implants, posing a particular risk for implants placed in the posterior region (5). Similarly, Poletto-Neto et al. examined the stress distribution in implants placed at different angles and demonstrated that angled implants lead to higher stress accumulation and increased risk of peri-implant bone loss compared to straight implants (6). These findings indicate that the angulation of implants must be carefully evaluated during implant planning and placement. In such cases, angled abutments (15°–30°) can be used to compensate for implant angulation and ensure proper occlusion.

Various restorative materials used in implant-supported prostheses significantly affect stress distribution and the transfer of occlusal loads to the bone-implant interface (7). The behavior of different restorative materials under various loading conditions and their impact on stress distribution in the components of the implant-abutment-bone system were examined by Sannino et al., who concluded that material selection is an important factor (8). Sevimay et al. also studied the effect of different implant-supported restorative materials on stress distribution and found that they influence stress distribution on both the implant and peri-implant tissues (9).

Finite element analysis (FEA), or the finite element method, is based on the principle of dividing a structure into a series of small elements. FEA is a sophisticated engineering tool used to examine stresses and strains in complex mechanical systems. This method has a wide range of applications in the field of oral and dental health, providing a mathematical transformation and analysis of the mechanical properties of geometric objects. It is also useful for determining the mechanical properties of biomaterials and human tissues that cannot be measured in vital environments (10).

The aim of this study was to evaluate the effects of different multi-unit abutment angles and material types on the stress distribution in implant parts and surrounding tissues using FEA. The null hypothesis of this study is that neither the abutment angle nor the restoration material affects the stress distribution in different parts of the implant, restorative materials, and peri-implant tissues.

Materials and Methods

In this study, a maxillary jawbone model (mucosa, trabecular, and cortical structure) was designed using SolidWorks (SolidWorks Corp., Waltham, MA, USA) program to simulate the jaw of an edentulous patient. The obtained Standard for the Exchange of Product Model Data (STP) files, which included the properties of implant components for scientific research (Bilimplant ® R: 3.7 mm, L: 10 mm; Proimtech Medical Products Inc., Istanbul, Türkiye), were placed in the area of tooth number 14 (i4) and tooth number 16 (i6). During implant placement, perforation occurred in the 0° and 30° models, and graft material was applied to the resulting perforations. Three different angled (0°, 15°, 30°) multi-unit abutments were placed on the implants, and Standard Tessellation Language (STL) files were obtained. Prosthesis design was done using the Exocad (Dental Cad 3.1 Rijeka, Exocad, Darmstadt, Germany) program, and the designs were created as single-piece frameworks and superstructures. After the superstructure design was completed, the same design was scaled down to create the framework (Fig. 1).

The obtained STL files were transferred to the Geomagic Design X (Geomagic Design X 2020.0; Octon, NC, USA) program, where necessary adjustments, such as smoothing, were made to obtain STP files. The produced prostheses were then fitted onto the implants in the model (Fig. 1). The final version of the model was saved as an STP file and transferred to the ABAQUS (2020 Dassault Systems Simulation Corp., Johnston, RI, USA) program for the finite element analysis.

Table 1. Material properties assigned to the model

Material	Young's Modulus(E MPa)	Poisson's Ratio (ν)	Shear Modulus(G MPa)
Cortical Bone(12)	E_x 12,600 E_y 12,600 E_z 19,400	υ_{xy} 0.300 υ_{yz} 0.253 υ_{xz} 0.253 υ_{yx} 0.300 υ_{zy} 0.390 υ_{zx} 0.390	G_{xy} 4,850 G_{yz} 5,700 G_{xz} 5,700
Trabecular Bone(12)	E_x 1,148 E_y 210 E_z 1,148	υ_{xy} 0.055 υ_{yz} 0.010 υ_{xz} 0.322 υ_{yx} 0.010 υ_{zy} 0.055 υ_{zx} 0.322	G_{xy} 68 G_{yz} 68 G_{xz} 4,340
Bone Graft (13)	3,450	0.31	
Mucosa (14)	2.8	0.40	
Titanium (15)	110,000	0.33	
Feldspathic Porcelain (15)	82,800	0.28	
Zirconia (16)	210,000	0.30	
Co-Cr alloy (14)	218,000	0.33	
Composite Resin (17)	12,000	0.33	

In the ABAQUS program, material properties were individually assigned to each component, as specified in Table 1, and connections between components were defined in the "interaction" section. The framework-superstructure, bone-mucosa, and bone-implant connections were defined as "tie" to simulate osseointegration, whereas the connections between the screw parts were simulated with a torque feature.

Then, in the "load and boundary condition" section, a 30° oblique load of 150 N was applied to the occlusal table, inclined from the palatal to the buccal direction, and the maxillary jawbone was constrained in all directions (ENCASTRE). It was assumed that the implant was fully osseointegrated with the bone and that movement in the X, Y, and Z directions on the implant surface was completely restricted. The type of contact used to define the integration quality between the implant, abutment, and abutment screw interface was chosen as frictional with a friction coefficient of 0.3.

The equation used for the screw-tightening moment is as follows:

$$T = K \times D \times F \quad (1)$$

where T is the screw tightening moment (N·cm), D refers to the screw diameter (m), F is the screw preload (N), and K is the screw factor (or torque coefficient) valued at 0.2. (11) This equation allows for the calculation of the screw preload when a tightening moment is applied to the abutment screw. For example, with a tightening moment of 25 N.cm, the screw preload F is found to be 781 N.

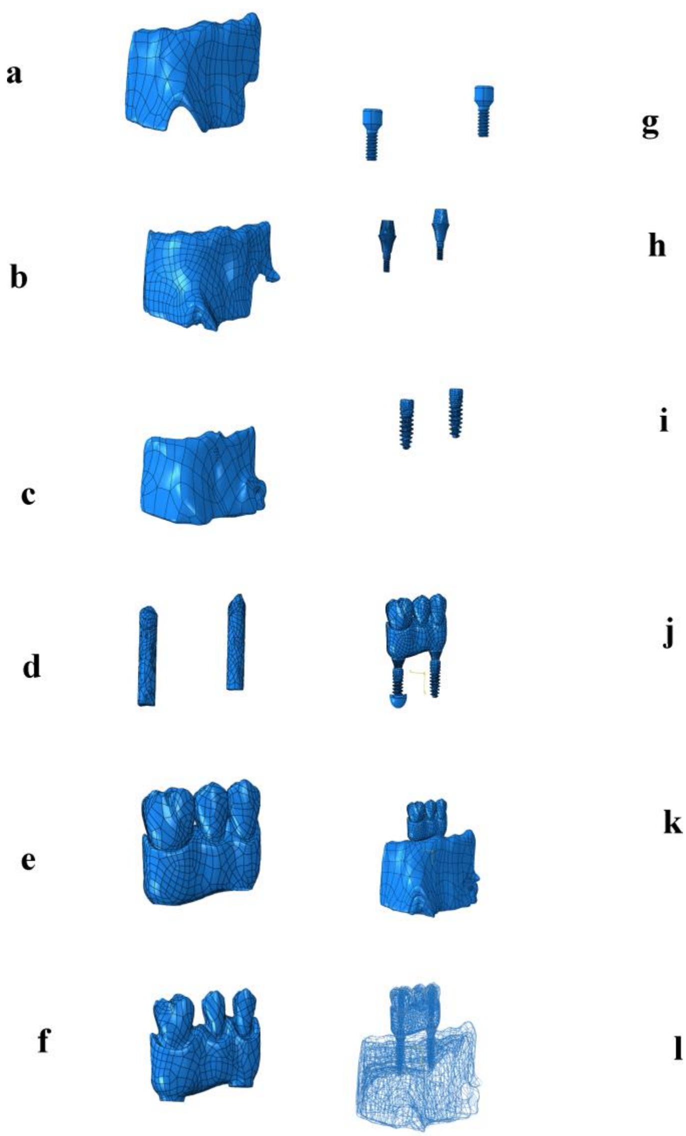

Figure 1. a) Mucosa, b) Cortical bone, c) Trabecular bone, d) Composite filling of screw, e) Superstructure, f) Framework, g) Occlusal screw, h) Abutment, i) Implant, j) Graft material, k) Complete model, l) Model in bone

Results

When the stress distribution on the implants was evaluated, the i6 group was found to exhibit higher von Mises stress (vMs) values compared to the i4 group across all models. Additionally, as the angle of the multi-unit abutment increased, the stress values also increased. A comparison of the two different restoration materials showed that the lowest vMs values on the implants were observed in models with Cr-Co frameworks, whereas the highest stress values were observed in models with zirconia frameworks. Furthermore, the highest vMs values were generally observed in the neck region of the implant (Fig. 2).

When evaluating the stress distribution on the abutments, the 6-numbered abutment exhibited higher vMs values than the 4-numbered abutment across all models. Additionally, as the angle of the multi-unit abutment (implant) increased, the stress values generally increased. Comparing the two different restoration materials, the lowest vMs values on the abutments were observed in models with Cr-Co frameworks, while the highest stress values were observed in models with zirconia frameworks. Furthermore, the highest vMs values were generally observed in the abutment-implant junction and margin region (Fig. 3).

An evaluation of stress distribution on the abutment screws showed that the 6-numbered abutment screw exhibited higher vMs values than the 4-numbered abutment screw across all models. Additionally, as the angle of the multi-unit abutment increased, the stress values also increased. In a comparison of two different restoration materials, the lowest vMs values on the abutment screws were observed in models with Cr-Co frameworks, while the highest stress values were observed in models with zirconia frameworks. Furthermore, the highest vMs values on the abutment screws were generally observed in the threaded section (Fig. 4).

During the assessment of stress distribution on the occlusal screws, the 6-numbered occlusal screw showed higher vMs values than the 4-numbered occlusal screw in all the models. Additionally, as the angle of the multi-unit abutment increased, the stress values tended to rise. When comparing two different restoration materials, the models with Cr-Co frameworks exhibited the lowest vMs values on the occlusal screws, while the models with zirconia frameworks showed the highest stress values. Furthermore, the greatest vMs values on the occlusal screws were generally found in the threaded section (Fig. 5).

As the angle of the multi-unit abutment increased, the stress values observed in the frameworks also increased. Unlike the implant components, the lowest vMs values in the frameworks were observed in zirconia, which has a lower elastic modulus. Additionally, the highest stress values in the frameworks were generally observed in the margin region (Fig. 6).

As the angle of the multi-unit abutment increases, the stress values observed in the cortical bone also increase. A comparison of the two different restoration materials showed that the lowest vMs values on the cortical bone were observed in models with Cr-Co frameworks, whereas the highest stress values were observed in models with zirconia frameworks (Fig. 7).

As the angle of the multi-unit abutment increased, the stress values observed in the trabecular bone also increased. A comparison of the two different restoration materials showed that the lowest vMs values on the trabecular bone were observed in models with Cr-Co frameworks, whereas the highest stress values were observed in models with zirconia frameworks (Fig. 8).

As the angle of the multi-unit abutment increases, the stress values observed in the graft material also increase. In the model with 0° angle, the highest stress value was observed in the Cr-Co framework model. Conversely, in the model with a 30° angle, the highest vMs value was observed in the zirconia framework model (Fig. 9).

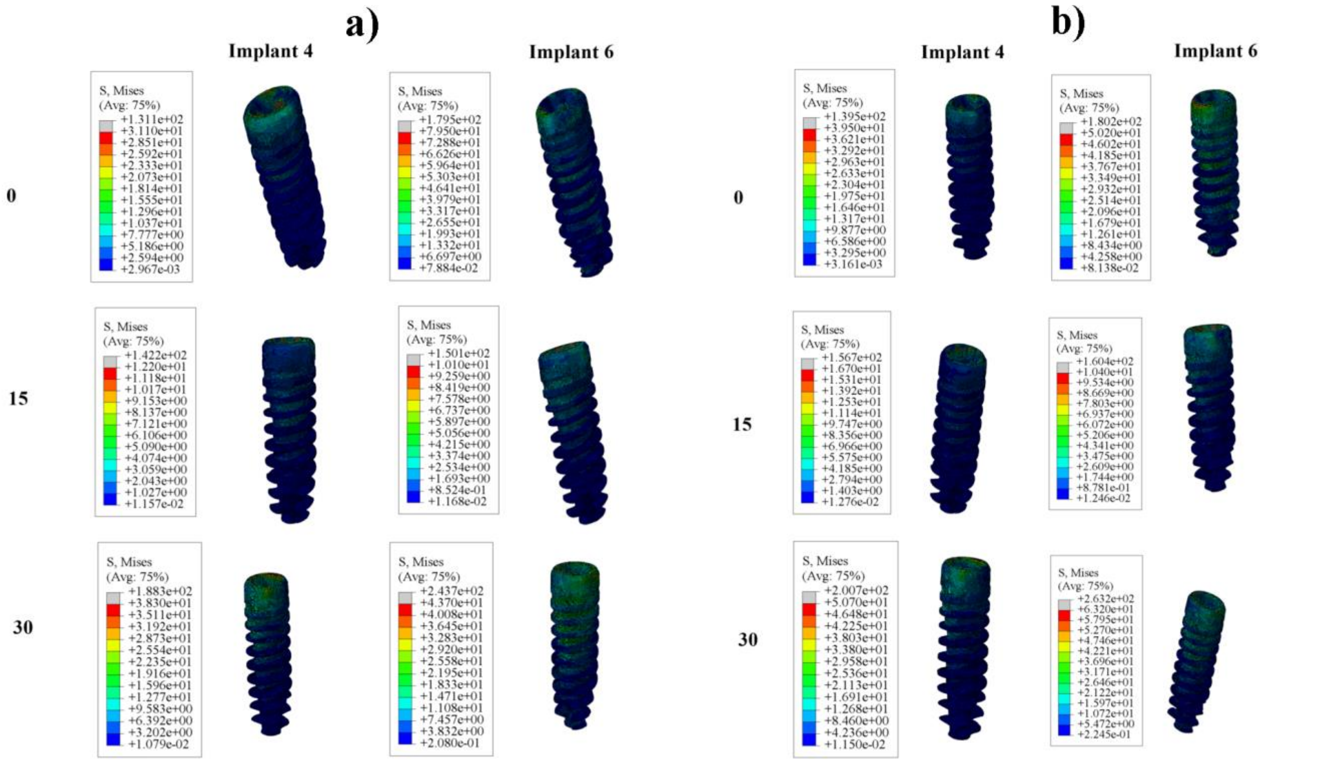

Figure 2. a) Stress distribution on implants with Cr-Co framework, b) Stress distribution on implants with Zr framework

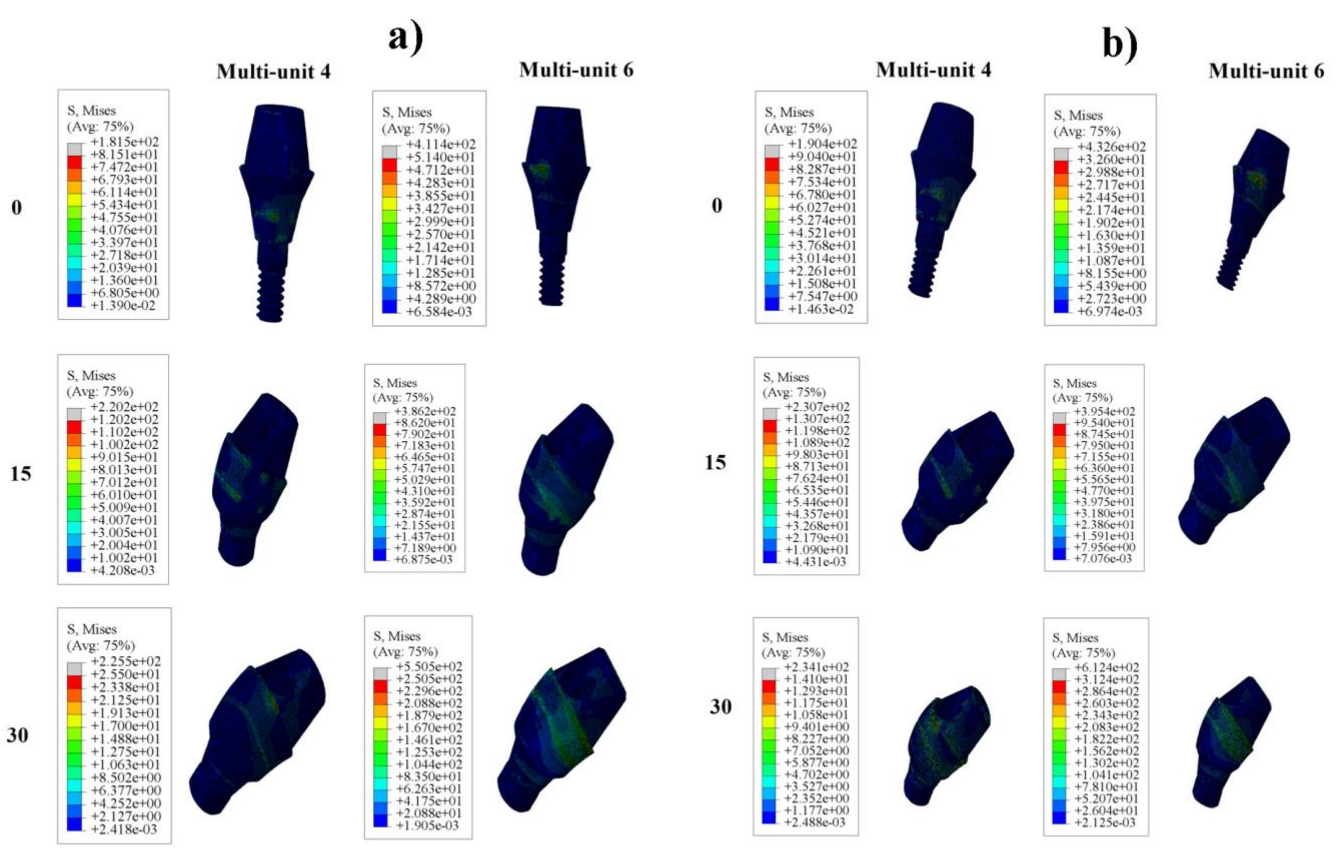

Figure 3. a) Stress distribution on multi-unit abutments with Cr-Co framework, b) Stress distribution on multi-unit abutments with Zr framework

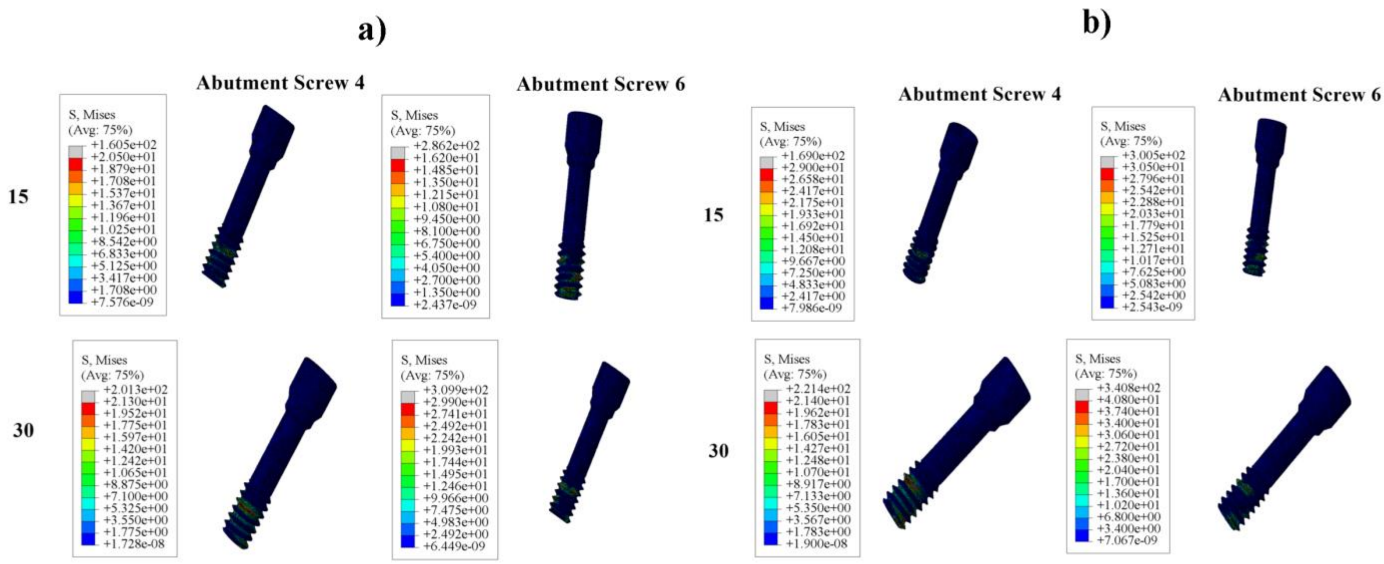

Figure 4. a) Stress distribution on abutment screws with Cr-Co Framework, **b)** Stress distribution on abutment screws with Zr framework

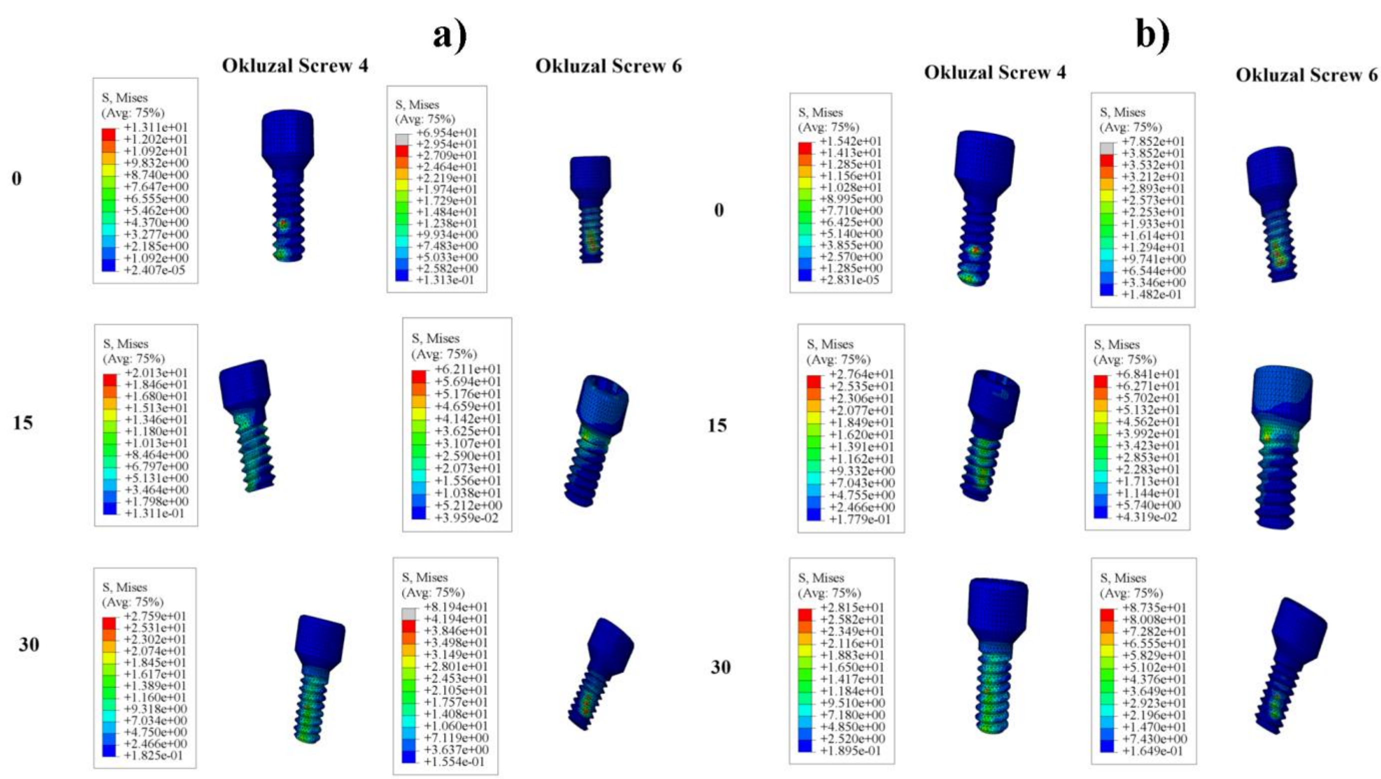

Figure 5. a) Stress distribution on occlusal screws with Cr-Co Framework, **b)** Stress distribution on occlusal screws with Zr framework

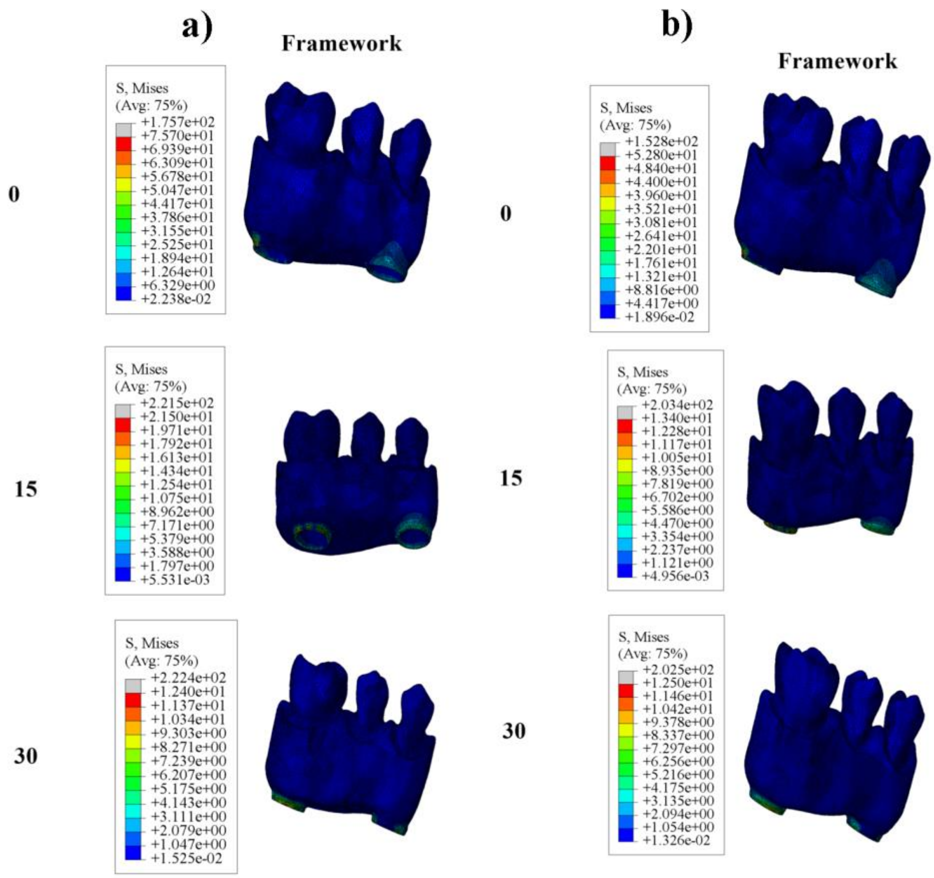

Figure 6. a) Stress distribution on Cr-Co framework, **b)** Stress distribution on Zr framework

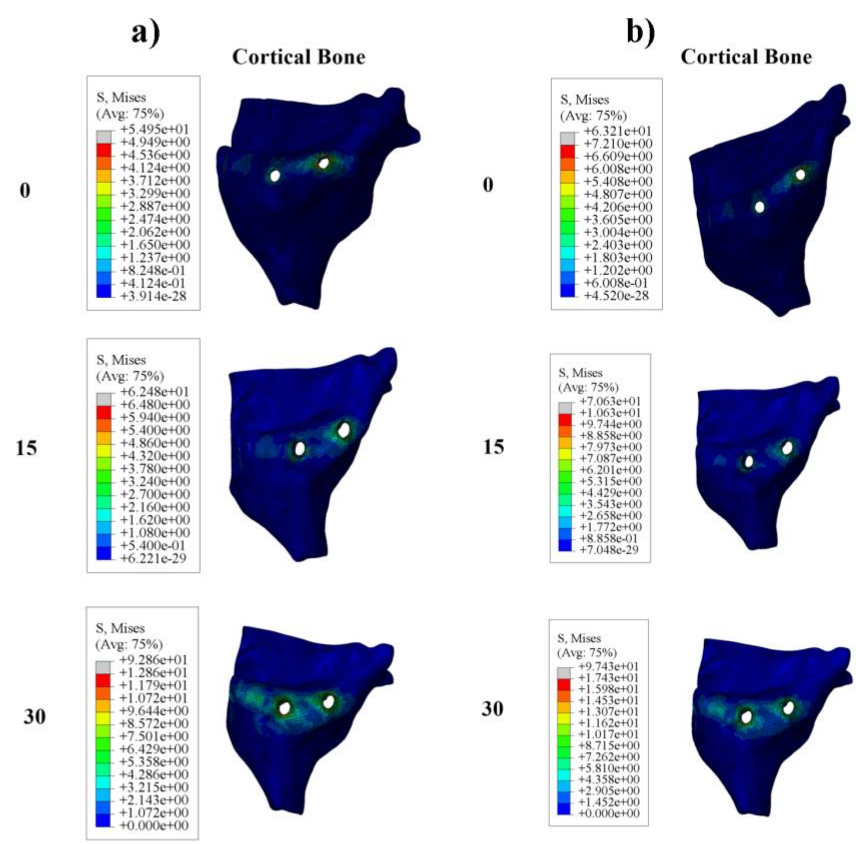

Figure 7. a) Stress distribution on cortical bone with Cr-Co framework, **b)** Stress distribution on cortical bone with Zr framework

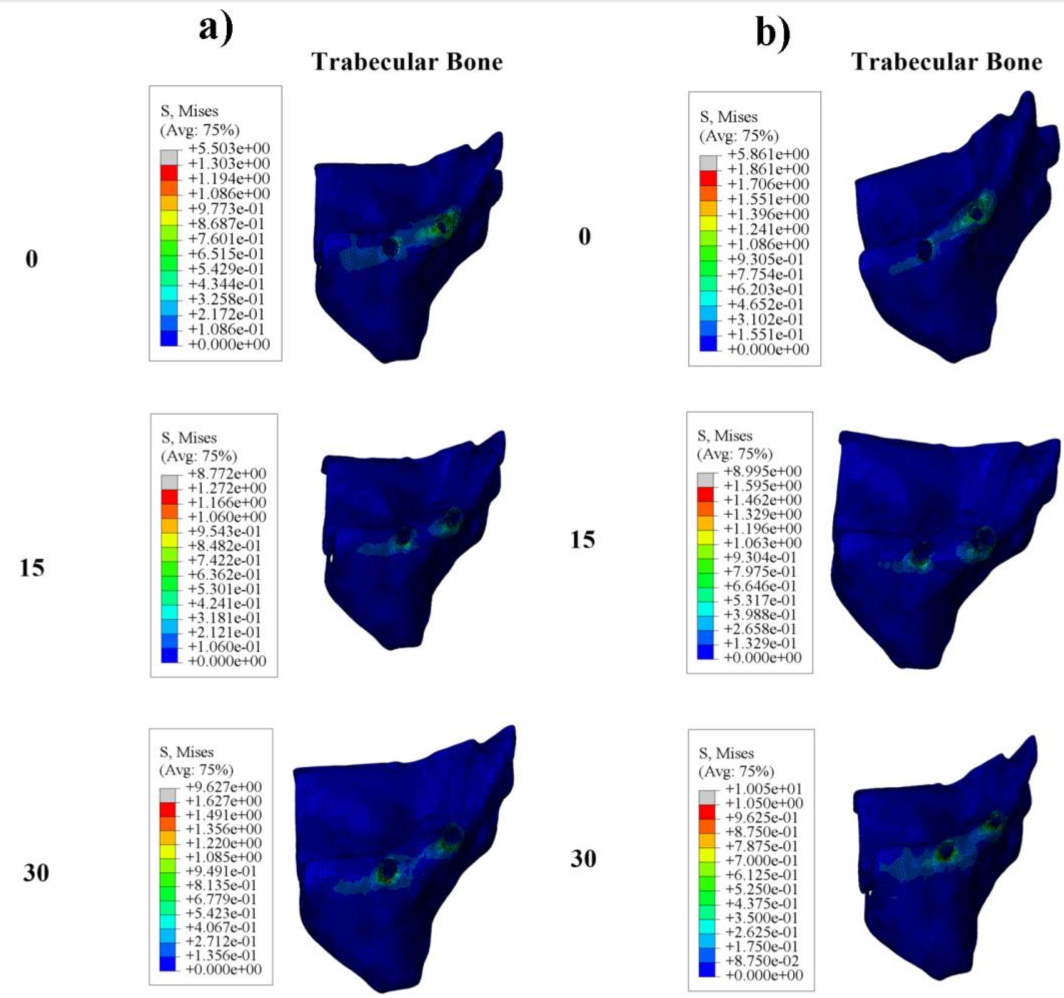

Figure 8. a) Stress distribution on trabecular bone with Cr-Co framework, **b)** Stress distrubition on trabecular bone with Zr framework

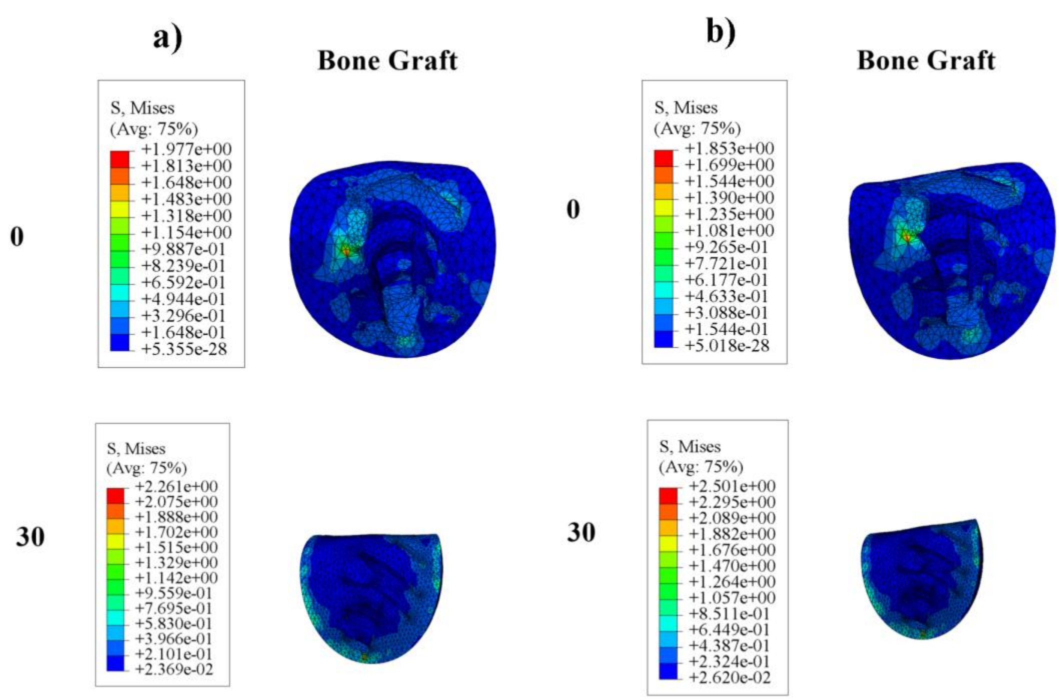

Figure 9. a) Stress distribution on graft material with Cr-Co framework, **b)** Stress distribution on graft material with Cr-Co framework

Discussion

In this study, the effects of different multi-unit abutment angles and material selections on the stress distributions in the implant parts and surrounding tissues were evaluated using finite element analysis. The finite element analysis results showed that all configurations influenced the stress values. Therefore, the null hypothesis was rejected.

In a study by Morita et al. they used three-dimensional finite element model (FEM) analysis to determine the ideal implant placement position and direction based on the horizontal and vertical distances between the residual bone and the opposing tooth in clinical cases. They concluded that the use of angled abutments would be beneficial in reducing occlusal stresses. In our study, it can be concluded that compensating the angles of implants placed at an angle by using angled multi-unit abutments provides acceptable results (18).

In another study, Chen et al. evaluated the effects of angled abutments at four different angles on the bone tissue under dynamic loading (19). For this purpose, they analyzed the equivalent stresses and deformations in the maxillary posterior region and bone tissue around the implant. They concluded that the stresses in the cortical bone were higher than those in the trabecular bone, and this result is similar to the findings in our study. Similarly, the conclusion that maximum stresses are concentrated at the implant neck also supports our study. Additionally, they concluded that the use of angled abutments is advantageous in compensating for the angles of implants placed at an angle, but the maximum angle should be 20°-25°, which is similar to our study's conclusion that stress accumulation increases with the increase in multi-unit abutment angles. It is possible to infer that angled implants and angled abutments affect stress distribution in peri-implant bone tissue, which directly impacts the osseointegration process and implant stability.

In a study conducted by Leblebicioğlu et al. conducted finite element analysis using different implant designs (Straumann BLT and BLX), four different bone types (D1-D4), and two abutment angles (0° and 17° angled) (20). They applied a 200 N force at a 30° angle to the implant abutments and calculated von Mises stress values as well as minimum and maximum principal stress values to analyze stress distribution using ANSYS software. Similar to our study, they concluded that stress was generally concentrated at the implant neck in all the models. Both studies observed that increasing the abutment angle resulted in increased stress on the neck, suggesting that this parameter should be considered in terms of postoperative mechanical implant complications. Additionally, both studies found that angled abutments caused more stress accumulation compared to straight abutments, which increased the load on the implant and surrounding bone. In conclusion, the abutment angle can be considered an effective factor in the changes that peri-implant tissues may exhibit.

Tamrakar et al. evaluated the stress distribution around carbon-fiber-reinforced polyetheretherketone (CFR-PEEK) and titanium (Ti) implants. (21) In their study, they used two different implant materials (PEEK and Ti) and five different restoration materials (PEEK, zirconia, PFM, metal, and acrylic resin) and concluded that the highest stress values were observed in the zirconia crown group. This result is similar to our study, and it can be interpreted that the reason behind this outcome is related to the elastic moduli of the materials. The resistance of the materials to distortion affects the transferred stress.

Owing to their high mechanical strength and low flexibility, rigid materials transmit applied stresses more than flexible materials (22). Tekin et al. compared PEEK and PFM crowns to evaluate the effects of different crown materials on stress distribution (23). They concluded that PEEK absorbs stresses and transmits them less due to differences in elastic modulus. A low elastic modulus causes the material to transmit applied forces more directly, leading to stress concentration not within the material itself but in other structures it directly contacts (e.g., bone). In this study, higher stress was observed in peri-implant tissues and implant parts, excluding the infrastructure, in the zirconia infrastructure group with a lower elastic modulus compared to the Cr-Co infrastructure group.

In this study, less stress was observed in implant models placed at a 15° angle, which can be attributed to the absence of perforation and graft material application during implantation, unlike in other models. Okumura et al. examined the effects of varying cortical, trabecular bone, and graft materials on stress values in their study and reported similar results to this study (24).

In this study, all models are considered to be homogeneous, isotropic, and linear elastic. It is acknowledged that no material is perfectly homogeneous or isotropic in nature. However, using mean values to represent these properties does not significantly impact the validity of the in vitro test results, which remain reasonably close to actual values (25). The study also assumed a 100% connection between implants and bone, despite the fact that such a perfect connection is never achieved in reality. These assumptions represent limitations of this study. Therefore, it is important to take these limitations into account when evaluating the results of the finite element stress analysis (26).

This study evaluated the impact of multi-unit abutment angles on implant-supported restorations and examined the stress patterns of the implants and surrounding tissues. Further studies should be conducted to improve the implant-supported prostheses.

Conclusion

This study evaluated the impact of multi-unit abutment angles on implant-supported restorations and examines the stress patterns of implants and peri-implant tissues. The study showed that increasing the multi-unit angle in an implant-supported prosthesis increases stress values on implant components and cortical bone, while decreasing the stress applied to the prosthesis.

Disclosures

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