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Stress distribution of customized abutment material and angles in dental implant systems: A finite element study

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Abstract

Aim: This study aims to use finite element analysis to evaluate stress distribution in implant components, restoration materials, and biological tissues for implants placed at different angles using various customized abutment materials.

Methodology: 3D models of a three-member implant-supported fixed prosthesis were created using SolidWorks, with implants placed at positions 44 (4I) and 46 (6I). These models were imported into EXOCAD to design prosthetic restorations on custom abutments at three angles: straight (KD0), 10° (KD10), and 20° (KD20). Abutments were made from alumina (AL), titanium (TI), and zirconia (ZI). A 150 N load was applied to the occlusal table at a 30° angle in the buccolingual direction. Stress distribution was measured as von Mises Stress (vMS) values.

Results: For implants, the lowest vMS value was observed in the KD0-AL group (4I: 9.984 MPa, 6I: 22.91 MPa), while the highest vMS value was found in the KD20-TI group (4I: 25.30 MPa, 6I: 42.03 MPa). Custom abutment and custom abutment screws (in general) showed higher vMS values in the AL material and lower vMS values in the TI material. In contrast, for cortical bone and restoration material, higher vMS values were observed in the TI material and lower vMS values in the AL material.

Conclusion: Dental implants require effective stress distribution from occlusal loads to ensure long-term success. Excessive stress on the abutment and abutment screw can compromise the prosthetic outcome. Therefore, titanium (TI) abutments are preferred in the posterior region for their durability despite being less aesthetically pleasing. Additionally, a higher implant angle reduces strength, negatively impacting the implant's performance.

Keywords: Custom abutment, finite element analysis, implant-supported prostheses, stress distribution, Von Mises stress

Introduction

The material used for dental implant abutments significantly influences the fatigue performance of dental implants. The choice of material can impact factors such as abutment fit, stability, seal performance, and resistance to wear and fatigue. Commonly used materials for dental implant abutments include high-performance polymers such as polyetheretherketone (PEEK), titanium, and ceramics due to their biocompatibility, strength, corrosion resistance, and fatigue resistance (1,2). The mechanical and biological responses of different abutment materials are crucial for achieving harmonious crown integration in the dental arch (3).

Multiple studies have emphasized the importance of material selection for long-term success. Alumina abutments have been historically used in the anterior zone and for single-tooth replacements, showing high success rates (1). However, recent studies suggest that zirconia abutments may offer advantages over alumina abutments. Alumina abutments have been associated with a greater risk of abutment fracture at the implant-abutment connection during clinical use compared to zirconia abutments (4). Additionally, zirconia abutments have been reported to exhibit excellent long-term survival in clinical use for fixed restorations (5). Zirconia abutments provide sufficient stability to support implant-retained reconstructions, especially in regions with high aesthetic demand. They have been shown to maintain equivalent bone levels and soft tissue reactions compared to titanium, gold, and alumina abutments (6). Moreover, zirconia abutments have been found to reduce bacterial adhesion and plaque accumulation while promoting soft tissue integration due to their highly polished surface (7). On the other hand, zirconia abutments have emerged as a potential alternative to titanium abutments in dental implant applications. Studies have highlighted the advantages of zirconia abutments, such as superior aesthetic outcomes and color response of peri-implant mucosa compared to traditional titanium abutments (8). Zirconia has also been shown to inhibit bacterial adhesion better than titanium, making it more suitable for abutments (9). Research has compared the survival and technical outcomes of zirconia abutments with titanium abutments, with some studies indicating that zirconia abutments exhibit similar survival rates and clinical performance to titanium abutments (10). Zirconia abutments have been found to induce lesser stress in the implant and surrounding bone compared to titanium abutments, suggesting potential biomechanical advantages (11). Moreover, zirconia abutments have demonstrated better biocompatibility in terms of inflammatory responses in peri-implant soft tissues compared to titanium abutments (12). Studies have also shown that zirconia abutments can enhance aesthetic effects, especially in the anterior region, by avoiding the display of metal, which is common with titanium abutments (13). While zirconia abutments offer several advantages over titanium abutments, it is essential to consider factors such as fracture resistance and wear characteristics. Some studies have reported that titanium abutments exhibit higher fracture resistance than zirconia abutments in certain configurations (14). Additionally, zirconia abutments may be more prone to fracture and have less marginal accuracy than titanium abutments (15).

In this research, a 3D finite element analysis method is employed to evaluate the stress distribution in implants using different abutment materials, including titanium, alumina, and zirconia. The study focuses on understanding how stress is distributed in the implants based on the material properties of the abutments. By comparing the stress patterns generated by titanium, alumina, and zirconia abutments, the study aims to provide insights into the biomechanical behavior of these materials in dental implant applications. By utilizing finite element analysis, the study aims to simulate real-world loading scenarios to determine how titanium, alumina, and zirconia abutments respond to mechanical forces. The findings from this analysis will contribute to understanding the mechanical performance of these abutment materials and their implications for dental implant stability and longevity.

The aim of this 3D finite element analysis is to assess and compare the stress distribution generated by straight and angulated titanium, alumina, and zirconia abutments under oblique loading in the posterior maxilla. The study seeks to investigate whether the stress distribution in the posterior maxilla is affected by both angulation and material under axial loading. The null hypothesis is that these factors do not influence the stress distribution in the posterior maxilla.

Materials and Methods

In this study, a three-membered fixed prosthesis was planned on implants positioned at three different angles. The three-dimensional models were designed using the SolidWorks program (SolidWorks Corp, Waltham, MA, USA). In all models, implants were placed at tooth positions 44 (4I) and 46 (6I), and the obtained files were imported into the EXOCAD program in Standard Tessellation Language (STL) format (Image 1). Prosthetic restorations were designed on custom abutments placed at three different angles (straight [0], 10 [10] and 20 [20] degrees inclined), and the data were transferred back to SolidWorks. The cement gap was designed to be 30 µm, all parts were assembled appropriately, and the files obtained were converted to STP format and imported into the ABAQUS program (Figure 1). Material properties were defined for all components to be included in the study (Table 1). The properties were alumina (A), titanium (T), and zirconia (Z) for the abutment material; dual cure resin cement for the cement; and monolithic zirconia for the prosthetic restoration. The load was applied to the entire occlusal table with a force of 150 N and an angle of 30° in the palatobuccal direction (Figure 2).

The connections between the components were provided in the interaction area. The following connections were simulated as a tie to simulate the osseointegration property: substructure and superstructure, composite and prosthesis, bone and mucosa, and implant and bone. The connection between the screw parts was simulated by giving them torque properties.

A load of 150 N was applied to the occlusal table at a 30-degree angle from the palatal to the buccal direction. At this stage, the maxillary bone was fully constrained (encastre), meaning it was restricted from movement and rotation in all directions. The implants were assumed to have completely osseointegrated with the bone, and the implant components showed no movement on the implant surface. To define the quality of integration, a frictional contact type was applied between the abutment, fixture, abutment screw interface, and fixture, with a frictional coefficient set to 0.3.

The equation for the screw tightening moment is as follows:

$$T = K \times D \times F,$$

where T corresponds to the screw tightening moment (Ncm), D to the screw diameter (m), F to the screw preload (N), and K to the screw factor or torque coefficient (usually with a value of 0.2) (16). Using Equation (1), The screw preload value can be calculated when a tightening moment is applied to the abutment screw. In this study, using a tightening moment of 25 Ncm, the screw preload value was calculated to be 781 N. Following this, stress values were obtained and reported as vMS values.

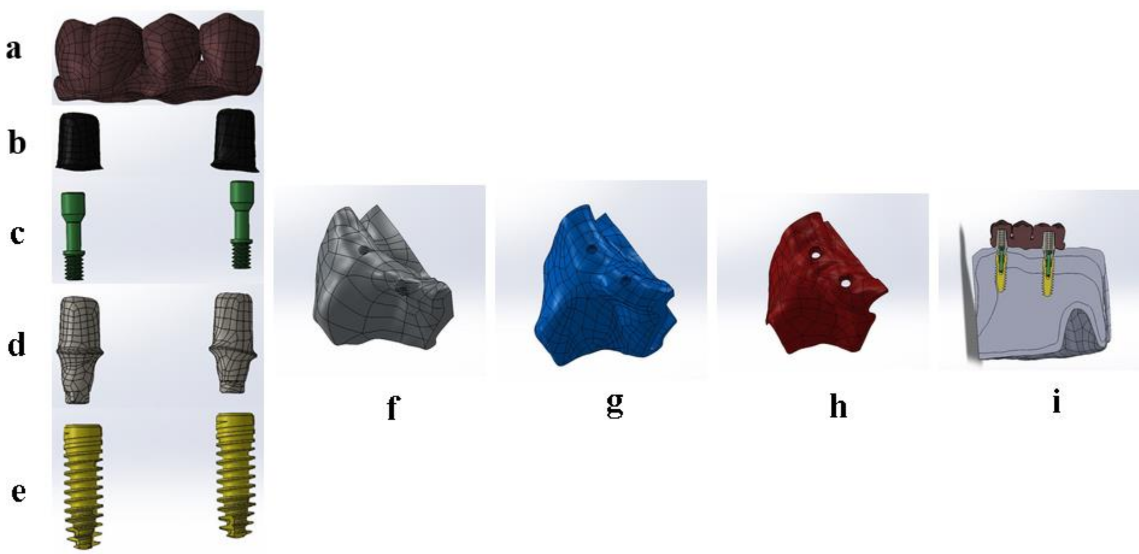

Figure 1. Finite elenemt models of implant components and bone block a) Restoration, b) Cement, c) Abutment screw, d) Abutment, e) Implant, f) Trabecular bone, g) Cortical bone, h) Mucosa, i) Geometric construction of model

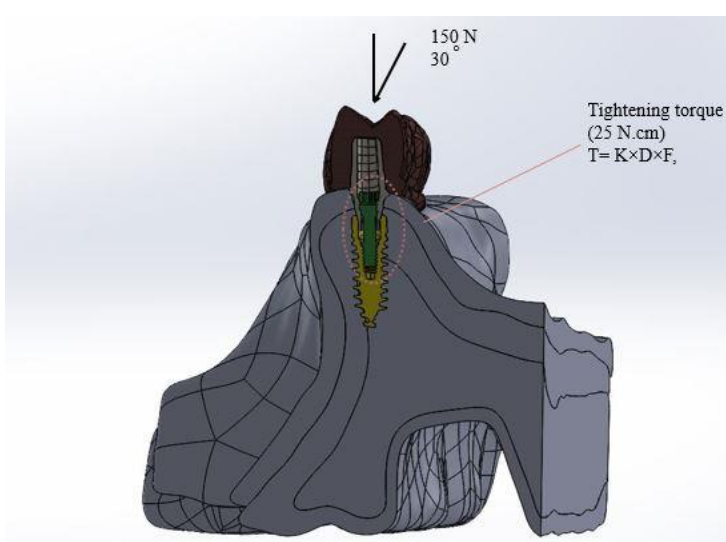

Figure 2. Screw preloading with the bone block fixed along all the axes

Table 1. Material properties assigned to the model

Material	Young's Modulus(E MPa)	Poisson's Ratio (ν)	Shear Modulus(G MPa)
Cortical Bone (17)	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 (17)	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} 434
Mucosa (18)	2.8	0.40	
Titanium (19)	110,000	0.33	
Zirconia Abutment (20)	210,000	0.34	
Alumina Abutment (20)	350,000	0,22	
Translucent Zirconia (21)	210,000	0.26	
Dual Cure Resin Cement (21)	18,600	0.28	

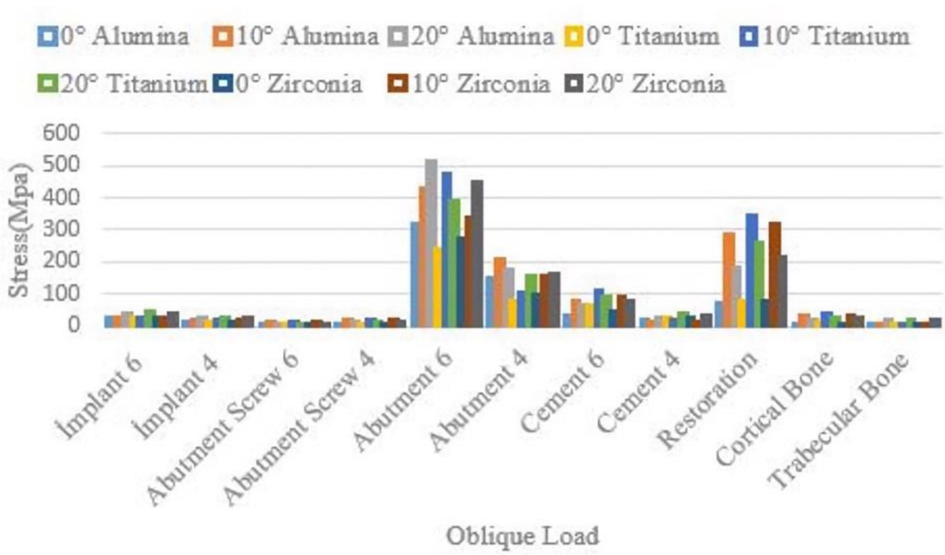

Figure 3. Von Mises stress distribution of the implant components, restoration, cement and bone components

Results

An examination of the results of the study showed that the highest vMS values occurred in the abutments, while the lowest values were observed in the abutment screws. Values observed in the implant and bone tissues were generally found to be low, whereas values in the restoration and cements were recorded as high (Fig. 3).

Regarding the stress values on implants, the highest vMS values were observed in the fulcrum area for each group. It was noted that, regardless of the region, the highest value was in the 20T group. The lowest values were seen in the molar region in the 0A group, while in the premolar region, they were found in the 0Z group. An evaluation based on regions revealed that stress values on implants placed in the molar region were recorded as higher than those in the premolar region. Additionally, as the angle of implantation increased, the stress values on the implant also increased. Considering the abutment materials, stress values were found to be very close to each other. Although the differences were not significant, the highest values were generally observed in aluminum (Figs. 4 and 5).

The highest stress values on the abutment were observed predominantly in the cervical region for each group. When evaluated based on region, the stress values on implants placed in region 6 were generally recorded higher than those placed in region 4. Additionally, as a general trend, vMS values tended to increase with increased abutment angulation. Regarding abutment materials, aluminum generally exhibited the highest values, while titanium abutments showed the lowest. The highest stress value was identified in the molar region within the 20A group, whereas in the premolar region, the highest value was observed in the 10A group. The lowest values were consistently found in the 0T group for both regions (Figs. 6 and 7).

The highest stress values observed on the abutment screws were located predominantly near the threads, close to the shaft, for each group. Additionally, the vMS values observed on the abutment screws generally exhibited a similar pattern to that of the abutments. The highest values were identified in the 10A group for both regions. The lowest stress values were observed in the 0A group in the molar region and the 0T group in the premolar region (Figs. 8 and 9).

The highest stress values observed in the restoration were primarily on the margins for each group, while in the cortical bone, they occurred in the cervical region. As the implant angle increased, there was generally an increase in stress values observed in both the restoration and cortical bone. Regarding abutment materials, the stress values observed in the restoration and cortical bone generally exhibited an opposite pattern to that of the abutments and abutment screws. The highest stress value on the cortical bone was observed in the 10T group, while in trabecular bone, the highest value was seen in the 20A group. The lowest values were observed in both bones in the 0A group. Furthermore, when examining the stress values on prostheses, the highest value was observed in the 10T group, while the lowest value was found in the 0A group (Figs. 10 and 11).

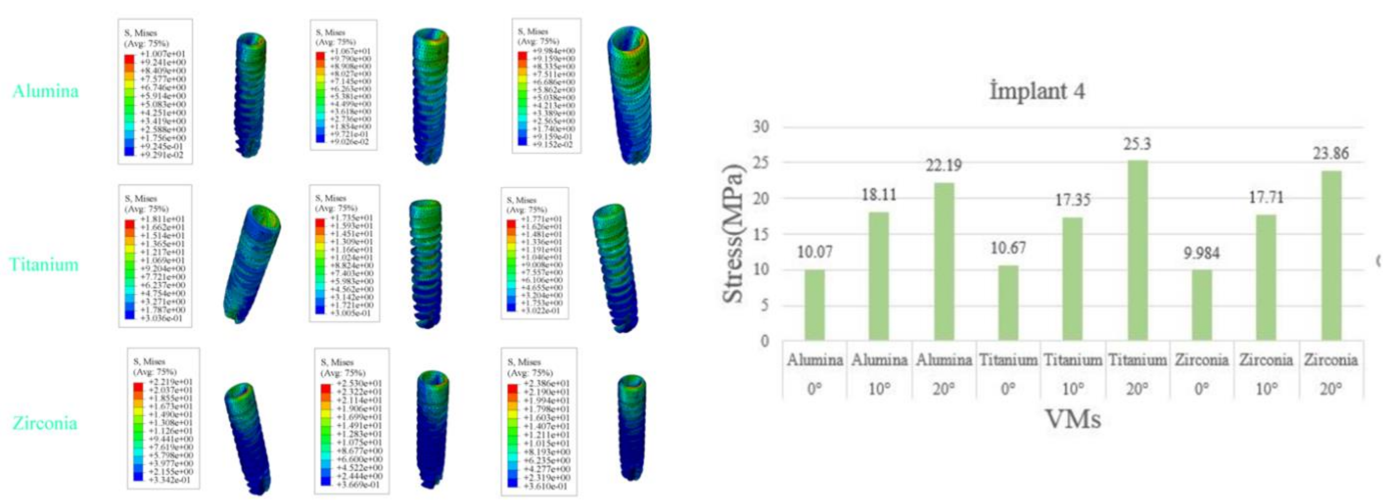

Figure 4. Von Mises stress distribution of the implant 4

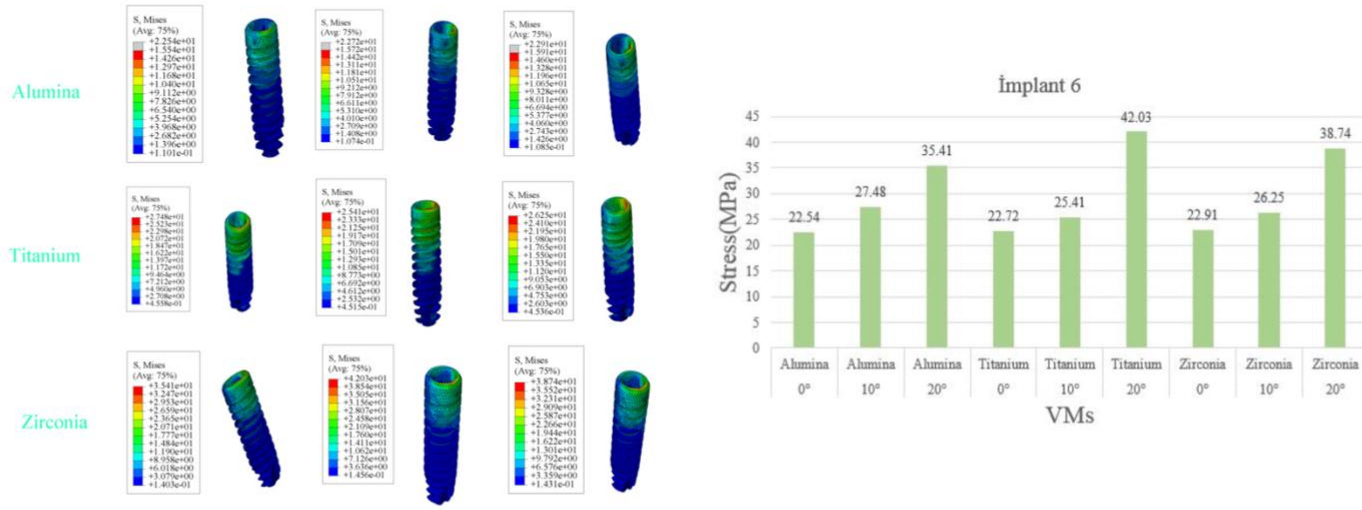

Figure 5. Von Mises stress distribution of the implant 6

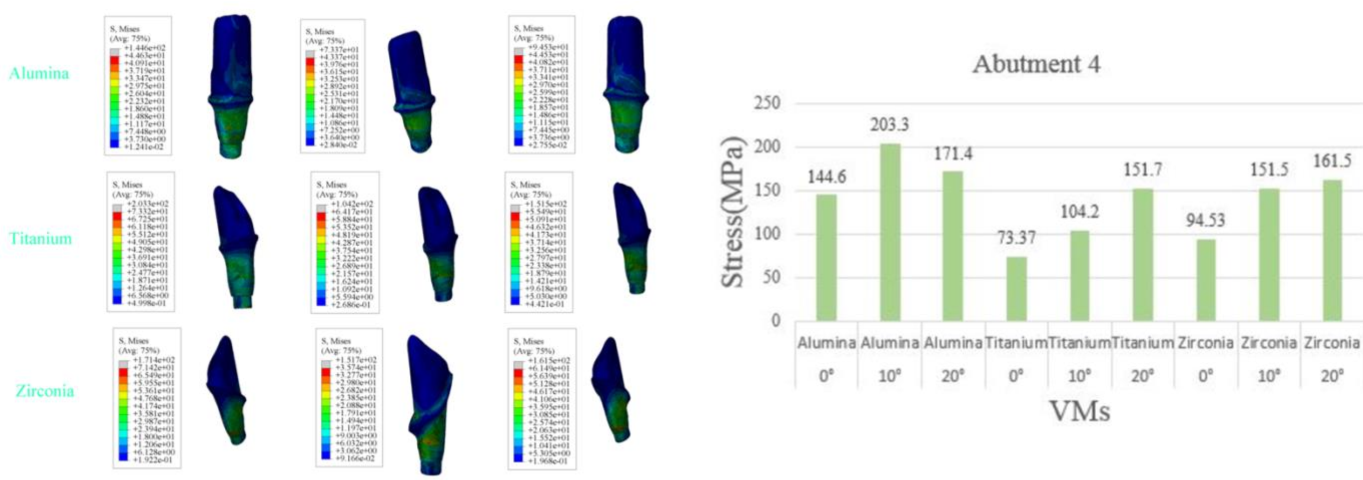

Figure 6. Von Mises stress distribution of the abutment 4

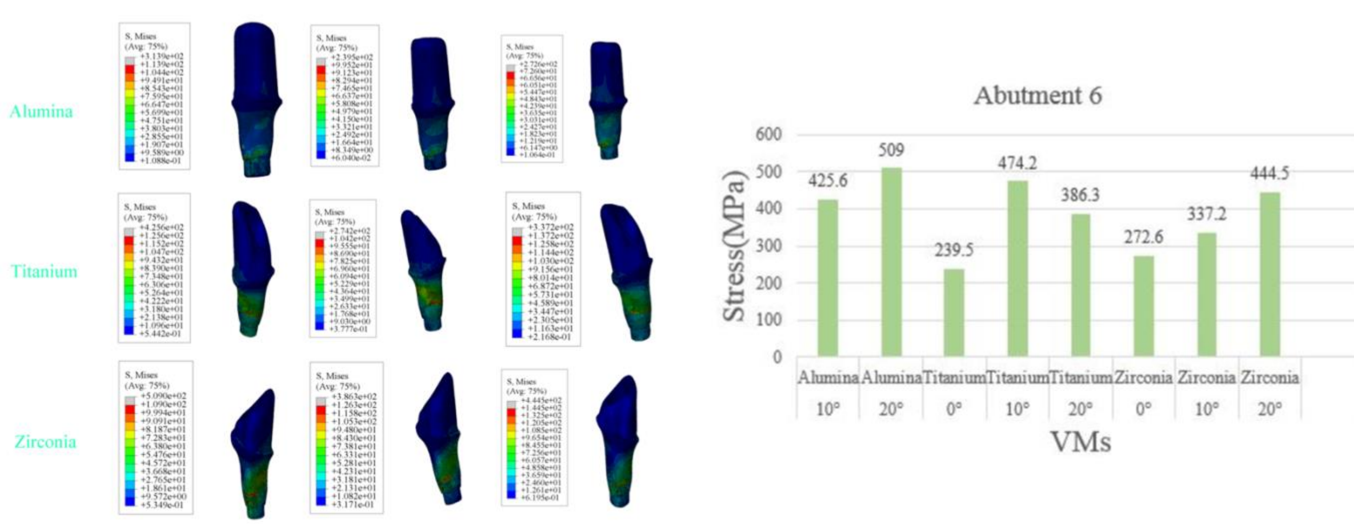

Figure 7. Von Mises stress distribution of the abutment 6

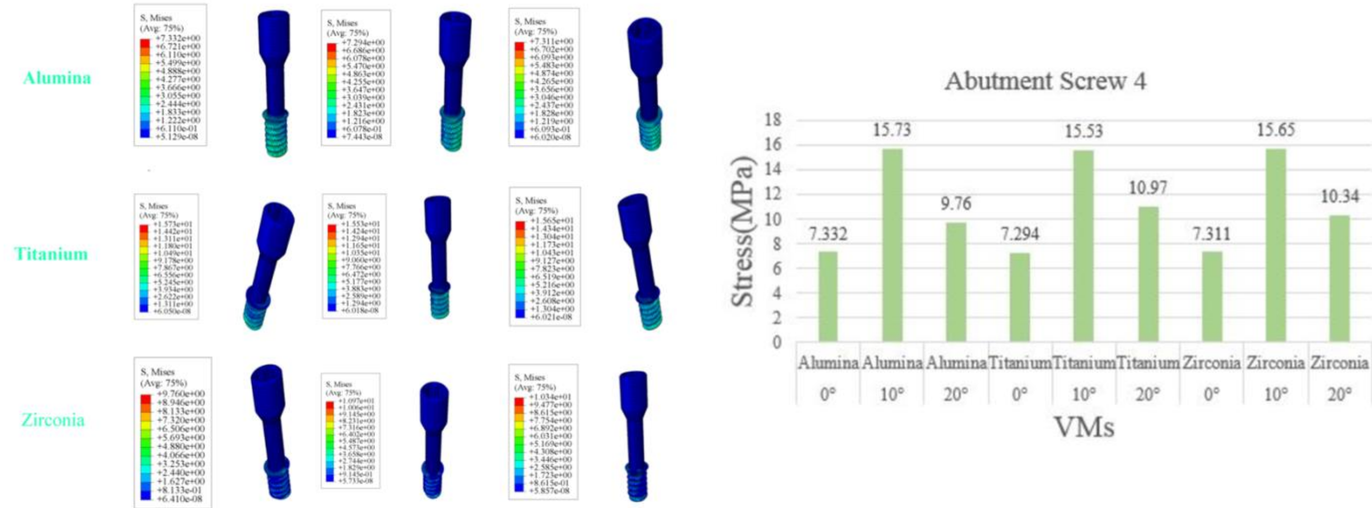

Figure 8. Von Mises stress distribution of the abutment screw 4

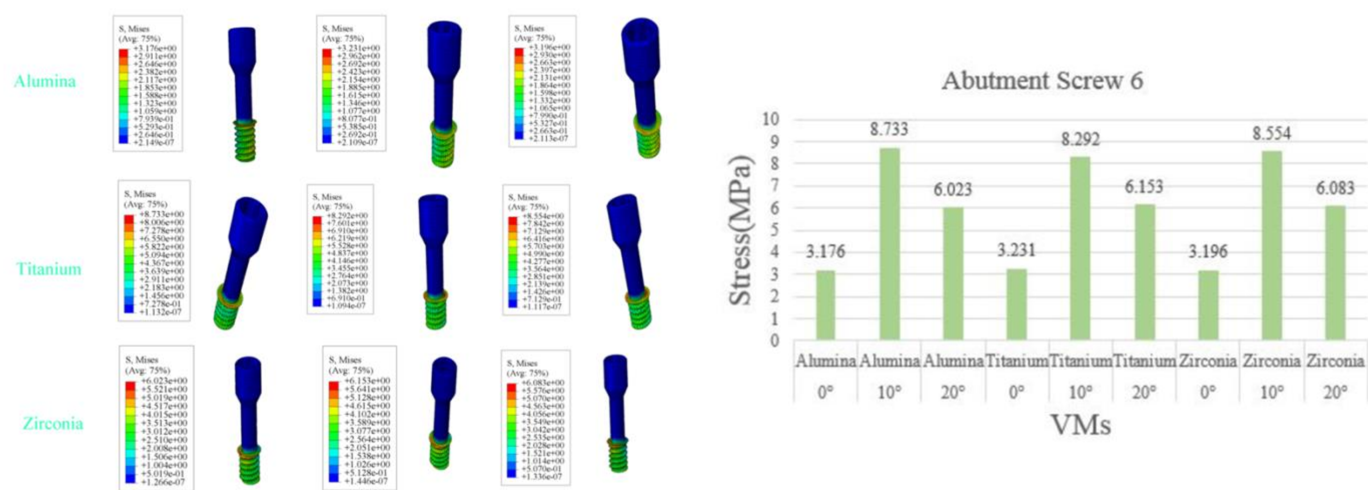

Figure 9. Von Mises stress distribution of the abutment screw 6

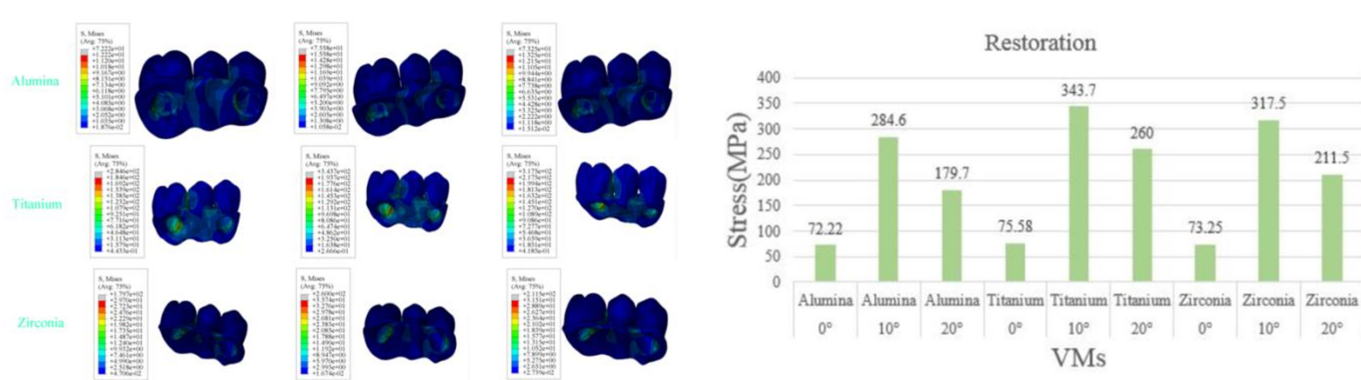

Figure 10. Von Mises stress distribution of the restoration

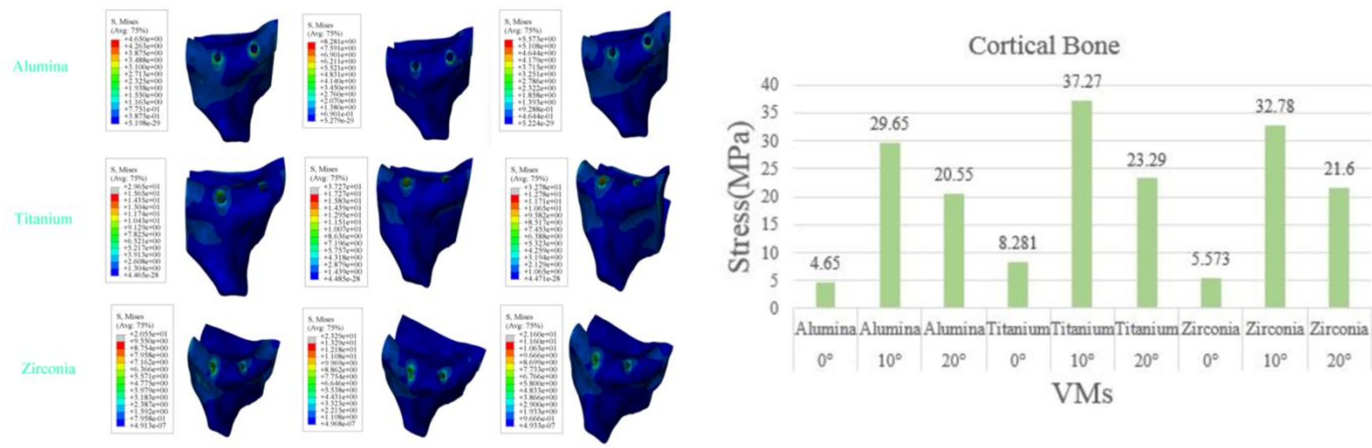

Figure 11. Von Mises stress distribution of the cortical bone

Discussion

This study evaluated the influence of the angle and material of the abutments on the stress distribution of dental implant components. The null hypothesis was rejected. The abutment material was found to influence the stress distribution of the abutment-implant complex. In addition, the implant angulation also influenced the stress distribution.

These findings are consistent with previous studies emphasizing the importance of abutment angulation in shaping stress patterns around dental implants (11, 22). Furthermore, the type of abutment material was found to be a critical factor in stress distribution, with titanium and zirconia abutments being commonly studied materials (23). Various finite element analysis studies have consistently shown that both the design and material of abutments significantly affect stress distribution in dental implants. The biomechanical behavior of dental implants is intricate and influenced by factors such as abutment angulation, material properties, and implant design. Understanding these factors is essential for optimizing the success and longevity of dental implant treatments. Through finite element analysis, researchers can simulate and analyze stress distributions to improve the clinical outcomes of dental implant procedures.

In this study, higher stress values were found in the molar region. The results are consistent with the literature. Several studies have investigated stress distribution in implant prostheses, particularly focusing on the differences between the molar and premolar regions. A study on stress distribution in dental and implant-supported zirconia restorations was conducted, and it was found that maximum principal stress was observed at both the premolar and molar regions for the implant-supported prosthetic model (24). Additionally, Serpa et al. qualitatively observed a higher prevalence of stresses on implants inserted in the molar region compared to the premolar region, attributed to the higher masticatory forces exerted on molars (25). Furthermore, a study found that stress distribution in complete-arch implant-supported prostheses varied between the premolar and molar regions, with reduced stress concentration observed in the premolar region (26). Lastly, highlighted that high stresses and strains induced by molar chewing movements could increase the risk of overload failure, including marginal bone loss and implant component fractures, emphasizing the impact of masticatory forces on stress distribution in implant-supported prostheses (27).

The result of this study, which is similar to the literature, also concluded that the increase in angle caused an increase in stress values. In all groups examined, the increase in stress values with the increase in implant angles can be thought to be due to the harmful effects of the lateral component caused by the incoming occlusal loads. Increased angulation in implants can lead to higher stress values due to several factors. Studies have shown that as the abutment angulation increases, there is a corresponding increase in stress concentration along the implant-abutment junction (28). This increase in stress values is particularly significant when comparing different bone densities and angulations, with the highest stress values observed in denser bone and greater angulations (28). Additionally, the stress peaks on the buccal aspect of the bone implant/tissue interface increase with greater implant angulation (29). Furthermore, the stress concentration can also be influenced by the length of the cantilever and the degree of implant angulation, with higher stress concentrations observed when the cantilever length is not reduced and the implant angulation is increased (30). Studies have indicated that the magnitude of stress within peri-implant bone can increase with an increase in abutment angulation, especially under axial loading conditions (31).

The choice of abutment materials led to different results on implant fragments and restoration materials. Alumina material, which has a lower modulus of elasticity, showed lower stress values in restorations compared to other abutment materials. In contrast, it produced higher stress values in implants and their components. This is a clinically undesirable situation. The reason for this is that restorations are the easiest part to compensate for clinical failure. Failure of the implant or its components will have more catastrophic consequences. In the literature, results similar to these findings are found. Alumina abutments are known to transmit more stress to implant components compared to titanium abutments due to several factors supported by research findings. One key reason is the material properties of alumina compared to titanium. Alumina abutments have been associated with higher stress concentrations throughout the prosthetic system, making them more prone to mechanical issues (32). In contrast, zirconia abutments, which are similar to alumina in terms of material properties, have also been found to concentrate more stress and exhibit higher susceptibility to mechanical problems than titanium abutments (32). This suggests that the inherent material characteristics of alumina and zirconia play a significant role in the transmission of stress to implant components. Zirconia abutments have been reported to exhibit higher stress levels than titanium abutments in implant models, indicating a potential for increased stress transmission with zirconia abutments (33). Furthermore, the mechanical behavior of different abutment materials under loading conditions has been investigated. Research has shown that zirconia abutments tend to show higher stress levels than titanium abutments, particularly in the implant and surrounding bone (11). This difference in stress distribution between zirconia and titanium abutments becomes more pronounced with increased stress levels applied to the implant (34).

The lowest stress values in the designed structure were found in the abutment screws. It can be seen as a very reasonable result that the stress values are low in this part, which only connects the parts at the very center of the whole system. However, a result that contradicts the actual clinical situation should also be taken into consideration. Although there are not enough studies on this subject in the literature, it can be explained by the fact that perfect passive compliance cannot always be achieved in clinical conditions. For this study, all the parts were assembled digitally under perfect conditions, and thus, maximum passive compliance could be achieved. However, in reality, these parts are produced and applied to the mouth through many stages. One of the most important results of this study is that in case of failures in any of these stages and the dentist's failure to meet the perfect conditions in this study, the passive fit cannot be achieved perfectly. FEA has been widely used in dentistry to assess various aspects of dental implants, stress distribution, and biomechanical behavior (35–37). FEA enables detailed simulations of stress distribution in dental structures under different loading conditions, aiding in the design and evaluation of dental implants and prostheses (35, 36). It has played a crucial role in examining the impacts of different materials, geometries, and loading scenarios on dental implants, offering valuable insights into their performance (32, 37). Nevertheless, despite the benefits of FEA in dental research, bedside applications in dentistry often yield more successful outcomes in specific contexts. Bedside applications, such as clinical trials and observational studies, provide direct insights into patient-specific factors influencing treatment outcomes, including individual anatomy, oral health conditions, and patient compliance (38, 39). These real-world scenarios allow for personalized treatment planning and adjustments based on patient responses, leading to more tailored and effective interventions (39). Furthermore, bedside applications in dentistry adopt a holistic approach that integrates patient preferences, expectations, and overall well-being, aspects that may not be fully captured in FEA simulations (38, 40). Patient-centered care in dentistry emphasizes factors like patient comfort, aesthetics, and long-term satisfaction, which are pivotal for successful treatment outcomes. Additionally, bedside applications enable clinicians to consider dynamic factors such as oral hygiene practices, dietary habits, and lifestyle choices that can influence treatment success (38, 40). Moreover, bedside applications offer opportunities for immediate feedback and adjustments during treatment, facilitating real-time optimization of interventions based on patient responses and clinical outcomes. This iterative process of assessment and modification can lead to more successful and patient-specific results compared to relying solely on FEA predictions.

In conclusion, while FEA is invaluable in advancing dental research and treatment planning, this study needs to be supplemented with bedside research, as bedside applications in dentistry provide unique advantages by taking into account individual patient factors, preferences, and real-time adjustments, which may ultimately lead to more successful outcomes in specific clinical scenarios. Furthermore, the fact that only stress values were analyzed in this study can be considered among the limitations of this study. Further studies examining fatigue performance are needed to determine how abutment materials and angle factor affect the actual success and longevity of the implant system.

Conclusion

This research endeavors to address a significant gap in the existing literature by offering a thorough examination of the rehabilitation process for implant-supported multi-unit restorations with angulation, aiming to furnish clinicians with essential insights for their practical application.

The outcomes of this study are as follows. The use of zirconia and alumina abutments, which are known to be more aesthetically successful, did not reveal significant differences in terms of forces transmitted to the implants. The difference in stress distribution between the abutments was significant. As a result of this study, titanium abutments showed the most durable results. Aesthetic abutment materials require further study.

As a result of the study, the lowest stress values in the system were observed in the abutment screw. It can be concluded that with full passive compliance at the patient's bedside, it may be possible to seriously eliminate failures occurring in the abutment screw.

An increase in stress distribution was observed in direct proportion to the increase in angle. Based on this result, it can be said that positioning implants as close to parallel as possible may affect the success of the treatment.

Disclosures

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Conflict of Interest: No conflict of interest was declared by the authors.

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