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Investigation of the effects of various restorative materials on stress distribution in a zirconia abutment in the anterior region: A finite element analysis

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Abstract

Aim: The aim of this study was to investigate the effect of using aesthetic restorations and abutments in cases where implants will be applied in the anterior region on the stress distribution on implant components and surrounding biological tissues.

Methodology: The data was created in the SolidWorks program, with cortical bone approximately 2 mm thick and trabecular bone approximately 15 mm thick. An implant obtained from a dental implant company, with a length of 12 mm and a diameter of 3.7 mm, was placed into the created data. The obtained data was exported as the Standard Tessellation Language (STL) file and imported into the EXOCAD program. A custom abutment and a prosthetic restoration with central incisor morphology were designed within the data, and all data were exported in STL format and re-imported into SolidWorks. Cement data with a thickness of 30 μm was created, and then all parts were assembled appropriately. The assembled data was converted to Standard for the Exchange of Product Model Data (STP) format and transferred to the ABAQUS program. In ABAQUS, zirconia was assigned to the custom abutments, dual-cure resin cement to the cement, and three different all-ceramic materials, MZ, zirconia-reinforced lithium silicate (ZLS), and lithium disilicate glass ceramics (LS), to the restoration material. A load of 150 N was applied obliquely at a 30° angle to the palatoincisal corner, and the resulting values were recorded as von Mises stress (VMS) values.

Results: In each of the three restorations, the highest von Mises stress value occurred around the abutment, while the lowest stress value was observed in the trabecular bone. The stress value around the restoration was highest in monolithic zirconia. The highest stress value around the abutment was observed in lithium disilicate.

Conclusion: In cortical and trabecular bone, similar values were found across all three restorations. The highest stress concentration, excluding the area around the restoration, was observed in lithium disilicate.

Keywords: Finite element analysis, monolithic zirconia, lithium disilicate, Von Mises stress analysis, zirconia-reinforced lithium disilicate, stress distribution

Introduction

In dentistry, tooth deficiencies have caused various problems in patients, leading to the development of numerous treatment methods to address tooth loss. This treatment, which is a more conservative approach, as it does not involve altering any existing teeth, has recently become the focus of many research studies. Restoring function, phonation, and oral health in patients using predictable methods has become the primary goal of modern dentistry. Therefore, implant treatment is a clinically and scientifically proven option. (1, 2)

Implant treatments offer many advantages, including biological, physical, and aesthetic benefits; however, they also have some disadvantages. The biomechanical behavior of dental implants due to the absence of the periodontal ligament means that stresses from occlusal forces are directly transmitted to the implant and the surrounding biological tissues. This transmitted stress can lead to various failures in the periodontal tissues, and implant and associated parts (3, 4).

The direction and orientation of the load on the implant affect the stress distribution on the implant and restorative materials. (5, 6). These materials must be carefully selected to achieve more favorable biomechanical outcomes. Due to the complex behavior of dental implants, the evaluation of their long-term survival has not yet yielded definitive results (7). The success and survival rate of dental implants primarily depend on bone quality, the structure of the bone-implant interface, and the stress distribution at this interface (8).

Rehabilitation with implants is particularly important in cases of single-tooth loss in the anterior region, where aesthetic expectations are high (9-11). Titanium, which has been preferred by clinicians for many years as an abutment material, is considered the gold standard due to its good mechanical properties and high biocompatibility (12). However, challenges in this region, such as gingival recession, marginal bone loss, thin gingival biotype, and visible metal color, have made it more difficult to meet aesthetic expectations with implant applications (13).

One of the major disadvantages of titanium material in the anterior region is the undesirable blue appearance of the peri-implant tissues in aesthetic situations, which negatively affects the aesthetic outcomes of the restoration (14). To prevent such complications, the routinely and widely used titanium abutments have led to the adoption of other alternatives.

Therefore, the use of materials such as zirconia abutments, which have ideal biocompatibility, high fracture resistance, and suitable optical properties, is becoming increasingly prevalent (15).

In 1994, Wohlwend introduced a fully ceramic abutment made from yttria-stabilized tetragonal zirconia polycrystal (Y-TZP, zirconium dioxide) material. These zirconia abutments offer advantages in terms of the aesthetic appearance of peri-implant soft tissues and restorations (16, 17). In the initial phase of their clinical use, the application was primarily limited to the anterior region. It has been proven that these abutments have good technical and suitable biological outcomes, but due to the nature of the material, they carry certain risks, such as fracture (18, 19).

In this study, ceramic restorative materials with excellent mechanical and optical properties, such as lithium disilicate (LS), monolithic zirconia (MZ), and zirconia-reinforced lithium disilicate (ZLS), were used. MZ has gained popularity owing to their superior mechanical characteristics. In contrast to the more prone-to-fracture structure of veneer ceramic porcelain layers, full-contour zirconia restorations can be successfully applied. Currently, MZ can be milled with reduced thickness owing to its high flexural strength, thus providing sufficient durability for posterior fixed restorations (20).

The second-generation LS ceramics, also known as "IPS e.max" (Ivoclar Vivadent, Ellwangen, Germany), are characterized by high durability and were introduced in 2005. It demonstrated excellent clinical performance for single crowns on natural teeth and short-span fixed dental prostheses. LS is a ceramic containing both lithium oxide and a glassy phase, which differs from polycrystalline ceramics, such as monolithic zirconia, which consist of sintered crystals without a glassy matrix. However, manufacturers have recently introduced lithium disilicate reinforced with 10% zirconia by weight in their glassy matrices to enhance mechanical performance (Celtra Duo, Dentsply Sirona, York, PA, USA; VITA Suprinity, VITA Zahnfabrik, Bad Säckingen, Germany) (21). ZLS has gained popularity in CAD/CAM glass-ceramics used in prosthetic treatments, and is produced from partially or fully sintered millable blocks. This enables one-step milling, which allows restorations to be delivered at the same appointment. The indications include inlays, onlays, and monolithic anterior and posterior crowns. The excellent optical and mechanical properties of ZLS are defined by a flawless microstructure comprising sparsely embedded nanocrystals of Li_2SiO_3 (lithium metasilicate), $Li_2Si_2O_5$ (lithium disilicate), and Li_3PO_4 (lithium orthophosphate) (22).

In addition, this material showed similar or better results than LS in terms of mechanical performance.

Finite element analysis was used to obtain accurate numerical solutions by measuring the response of physical systems to external stresses. Using this method, any problem can be divided into a series of smaller problems. To solve the problem associated with an error function, it utilizes the subdivision of the entire problem domain into simpler components called finite elements, and employs variational methods based on the principle of virtual work. This is done considering that a complex geometric shape is composed of a series of simpler shapes, with each simple shape known as an "element," and the collection of all elements is known as a "mesh." In finite element studies, the types of stresses, such as shear, tensile, and compressive stresses, or the effective absolute magnitude of principal stresses (Von Mises equivalent stress), are defined (23).

In FEA, the stress distribution analysis can be recorded using von Mises criteria or maximum principal stress. Despite its complex geometric shape, a body can be safely analyzed using the FEA method, allowing for the measurement of stresses created by applied forces at any point on the object. In addition, a body made from a combination of different materials or possessing time-dependent variable properties can be easily evaluated. Being a noninvasive method, its ease of application, and repeatability of the analysis are among the main advantages of FEA.

The aim of this study was to investigate the effect of using different aesthetic restorative materials and abutments on the stress distribution on implant components and surrounding biological tissues in cases of implant treatment in the anterior region of the maxilla with single tooth loss, using finite element analysis.

The null hypothesis is that different restorative materials supported by a zirconia abutment applied to a single implant in the maxillary anterior region will not affect the stress distribution on the implant, implant components, and surrounding tissues.

Materials and Methods

For this study, a maxillary jawbone (including mucosa, trabecular bone, and cortical bone) simulating an edentulous patient's jaw was designed using SolidWorks (Solidworks Corp., Waltham, MA, USA). After obtaining The Standard for the Exchange of Product Model Data (STP) files, implant files (Bilimplant, Proimtech Sağlık Ürünleri AŞ, İstanbul,Türkiye) (Φ: 3.7 mm, h: 12 mm) were positioned as tooth number 11. After obtaining standard tesselation language (STL) files, the prosthetic design was created using EXOCAD software (Dental Cad3.1 Rijeka, EXOCAD, Darmstadt, Germany). The generated STL files were imported into Geomagic Design X (Geomagic Design X 2020.0; Octon Inc, Los Angeles, LA, USA) for necessary adjustments such as smoothing, and then STP files were obtained. The produced prosthetic restoration was subsequently placed on the implant, and the internal gap (30 μm) was filled with cement. The final model was saved as an STP file and imported into the ABAQUS software (2020 Dassault Systems Simulation Corp., Johnston, RT, USA) for finite element analysis.

In the ABAQUS program, the material properties were assigned to the components listed in Table 1, and the connections between the components were defined in the interaction (contact) section. The connections between the restoration and abutment, bones and mucosa, and implant and bone were defined as tie constraints to simulate osseointegration, while the connections between the threaded parts were simulated with torque properties. In the load and boundary condition sections, a force of 150 N was applied at an angle of 30° to the palatoincisal edge, and the maxillary jawbone was constrained using the encastre condition (restriction of movement and rotation in all directions). The implant was assumed to be fully osseointegrated with the bone, and the movement of the implant components in the X-, Y-, and Z-directions on the implant surface was completely restricted. The contact type used to define the integration quality between the abutment, implant, and abutment screw was selected as frictional with a friction coefficient of 0.3. The equation for the screw-tightening torque is as follows:

$$T = K \ x \ D \ x \ F \qquad (24)$$

which is, T represents the tightening torque (N·cm), D is the screw diameter (m), F is the screw preload (N), and K is the screw factor (or torque coefficient), typically having a value of 0.2 By using the equation the preload value F can be calculated when a tightening torque is applied to the abutment screw. For instance, when the tightening torque T was 25 N·cm, screw preload F was 781 N.

Results

The results obtained from the von Mises stress values are presented in Fig. 1 and Table 2.

According to the results of this analysis, the highest stress value for all groups in the study was observed on the abutment, with the group restored with LS showing a value of 94.35 MPa (Fig. 2). Conversely, the lowest stress value among the three groups in the study was observed in the trabecular bone, with the group restored with MZ showing a value of 0.3034 MPa.

There were no remarkable differences in the trabecular bone and cement among the three groups (Fig. 3). When examining the stress values observed on the implant for each group, the values in the ZLS group were approximately the same as those in the LS group but were observed to be twice as high as those in the MZ group. The highest stress values were observed in the group restored with MZ, while the lowest values were observed in the group restored with LS (Fig. 4).

Regarding the stress values on the cement examination, the lowest stress values were observed in the group restored with LS, whereas the highest stress values were observed in the group restored with MZ.

The lowest von Mises stress values measured on the implant components and surrounding biological tissues were observed in the group restored with MZ, independent of prosthetic restoration and cement. Conversely, the highest von Mises stress values were observed in the group restored with LS, independent of the prosthetic restoration and cement (Fig. 5).

When examining the stresses on the abutment screws in all three groups, notable changes were observed. The results in the group restored with LS were found to be approximately three times higher than those in the group restored with MZ (Fig. 6).

Table 1. Material properties assigned to the model

Material	Young's Modulus(E MPa)	Poisson's Ratio (ν)	Shear Modulus(G MPa)
Cortical Bone (25)	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 (25)	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
Mucosa (26)	2.8	0.40	
Titanium (27)	110,000	0.33	
Monolithic Zirconia (28)	210,000	0.30	
Resin Cement (29)	5,100	0.27	
Zirconia Abutment (30)	210,000	0.30	
Lityum disilicate (31)	98,000	0.23	
Vita Suprinity (32)	104,900	0.21	

Table 2. Von Mises stress values on component (MPa)

	MZ	LS	ZLS
Implant	23.97	54.82	46.98
Trabecular Bone	0.3034	0.4008	0.3764
Abutment	50.48	94.35	79.64
Prosthetic Restoration	46.78	25.64	31.79
Cortical Bone	2.009	5.001	3.243
Cement	8.989	7.1185	7.565
Abutment Screw	5.765	17.67	10.75

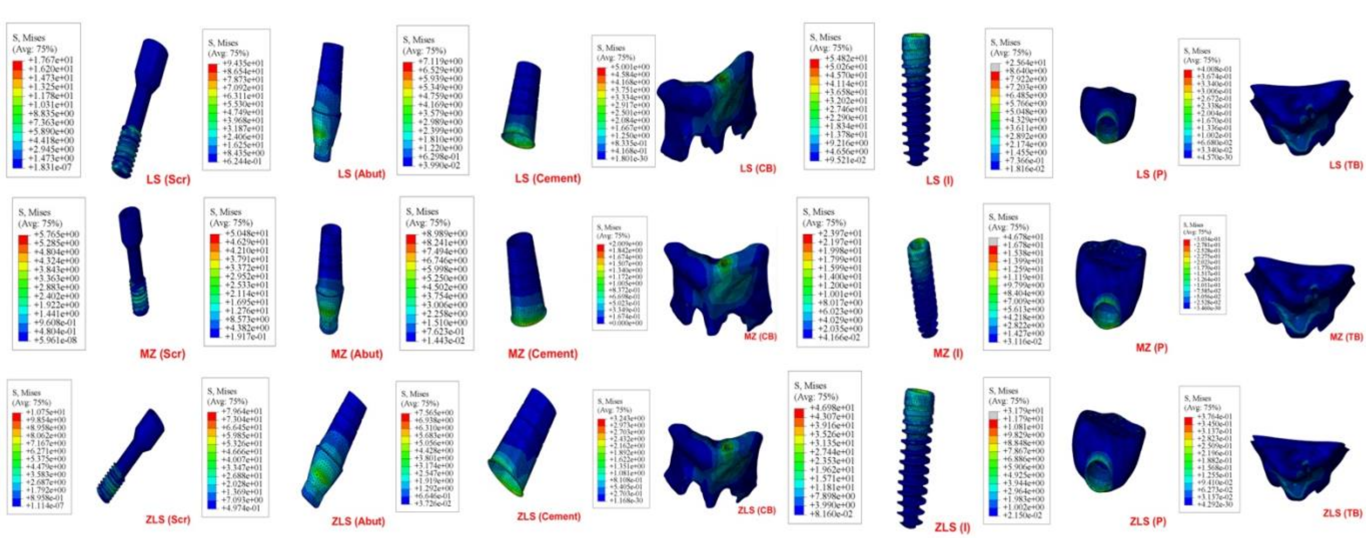

Figure 1. Von Mises stress values on component

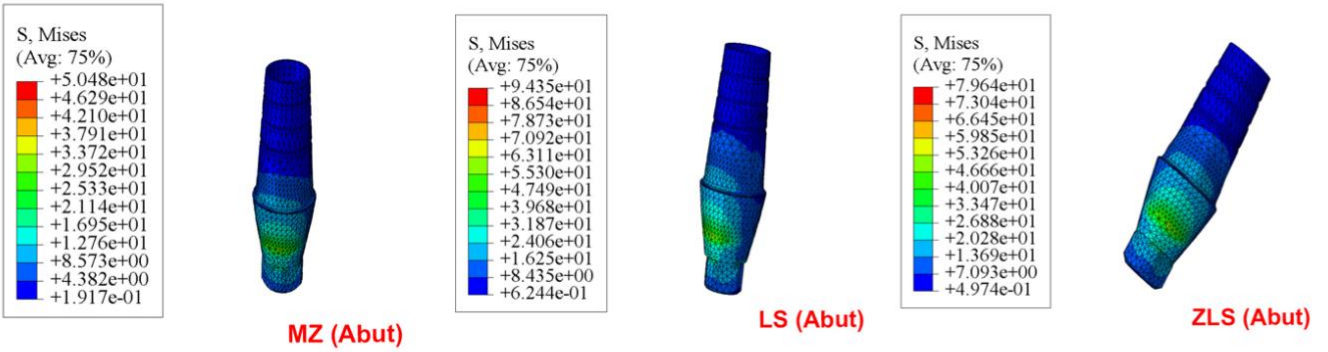

Figure 2. Von Mises stress values on abutment

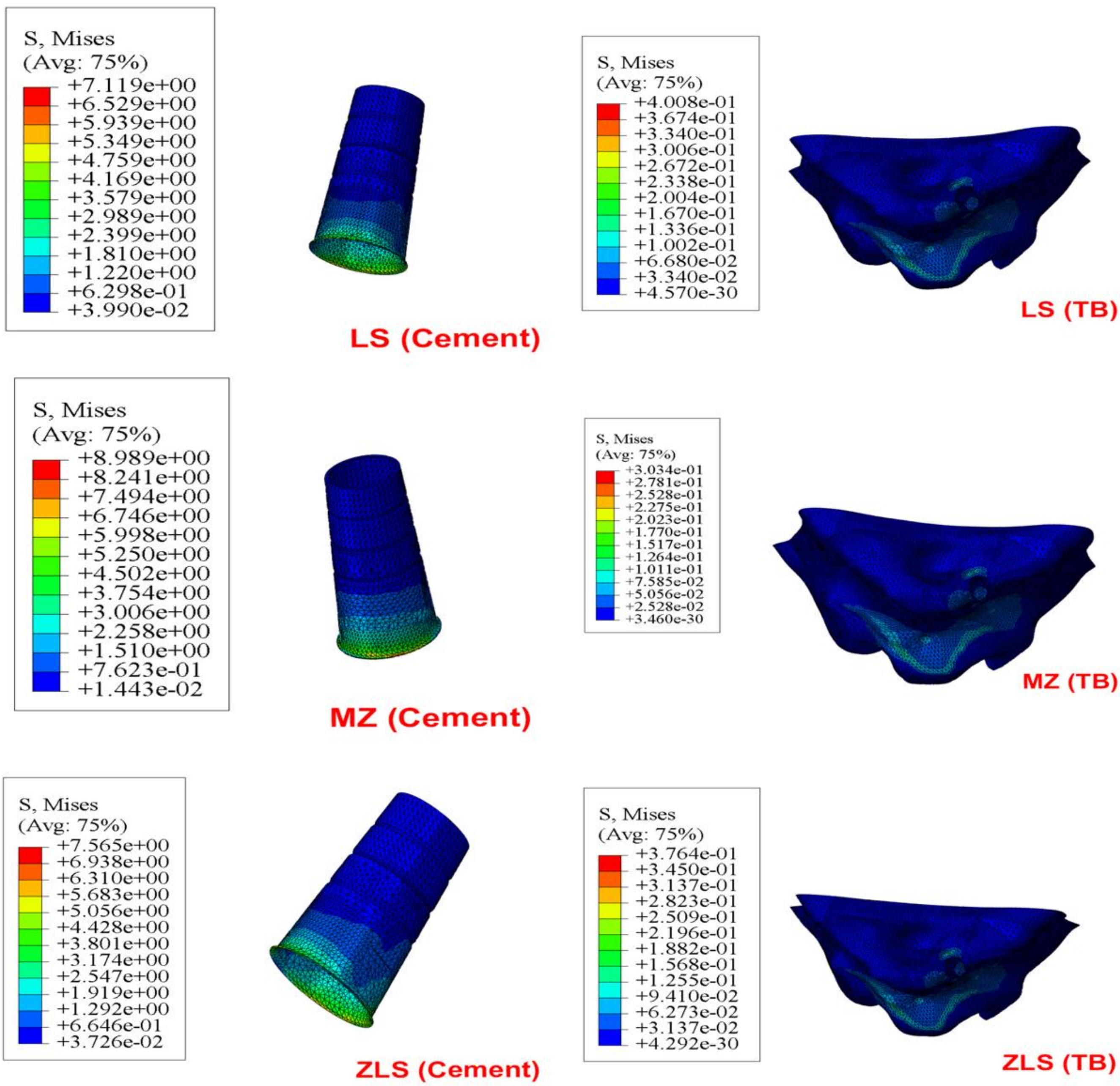

Figure 3. Von Mises stress values on cement and trabecular bone

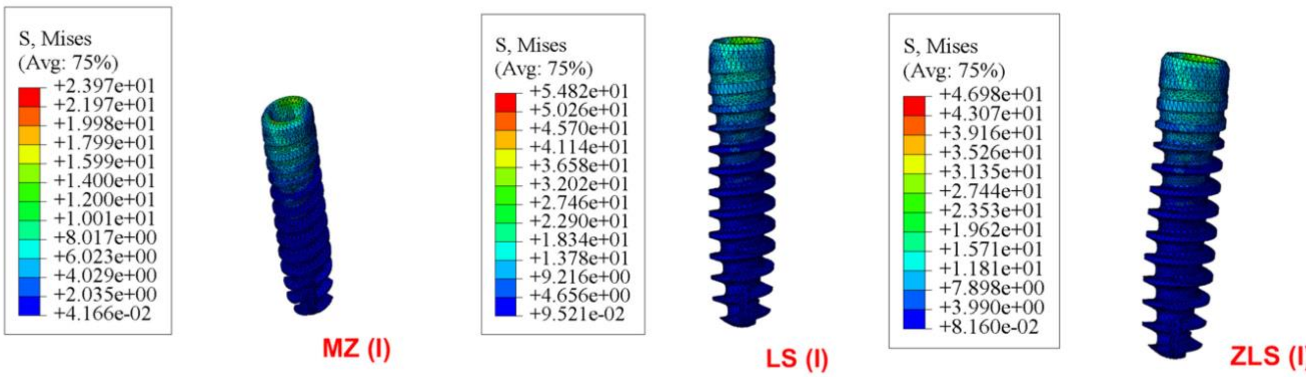

Figure 4. Von Mises stress values on implant

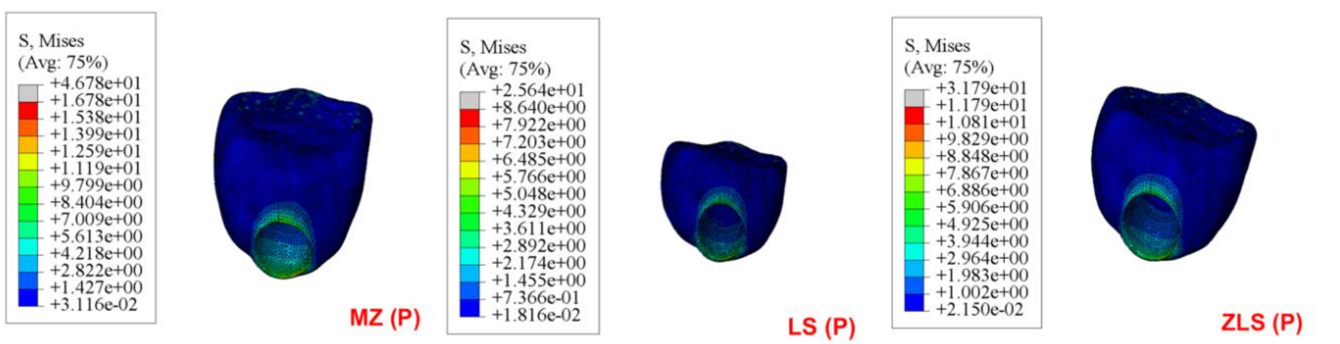

Figure 5. Von Mises stress values on prothetic restoration

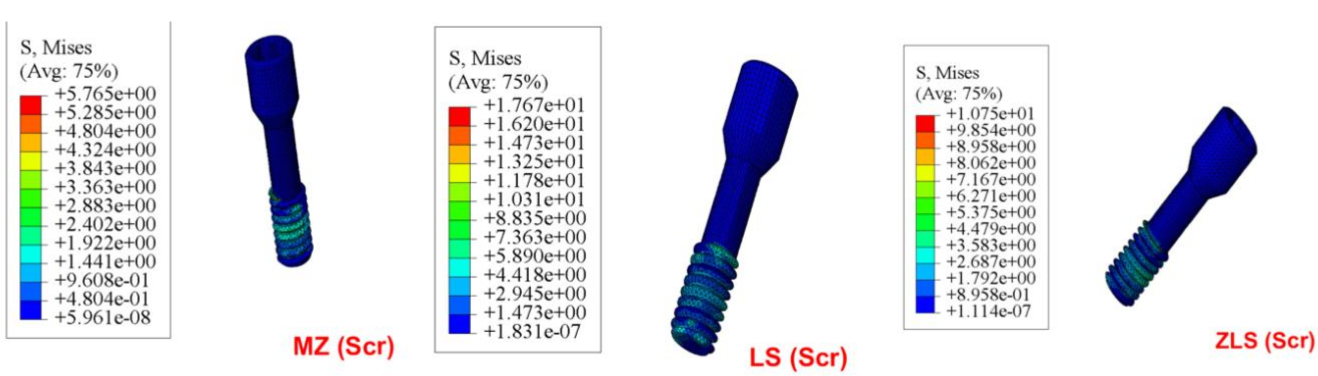

Figure 6. Von Mises stress values on abutment screw

Discussion

After examining the results of this study, the null hypothesis was rejected. The restoration material exhibited the highest von Mises stress values with MZ. Previous studies have reported that the MZ is more resistant to occlusal load. In the studies conducted, MZ, LS, and ZLS were evaluated, and as a result, it was determined that MZ demonstrated statistically superior fracture resistance compared to LS and ZLS (33).

Similar results were reported for cement. Considering the diffusion of the cement material applied during the cementation of resin-cemented all-ceramic restorations into the crystalline structure of the restorations, causing them to behave as a whole with the restoration, resin cement may have led to a prosthetic restoration-like outcome for this study (34).

Similar findings have been supported by other studies. Considering this, although the VMS observed in the MZ is higher than that in the LS and ZLS, it can be assumed to exhibit better resistance against applied loads.

In this study, unlike the restoration material and cement, the highest values were observed in LS for the abutment, abutment screw, cortical, and trabecular bone (35). VMS values were consistently highest for the LS material and lowest for the MZ material in the implant, abutment, abutment screw, cortical bone, and trabecular bone. However, the VMS values observed in the restoration materials were higher for MZ and lower for LS.

The selection of a restorative material is a significant decision, as it can affect cases involving excessive biting forces or parafunctional habits. Additionally, considering that bone behavior depends on the magnitude of the load, the right material choice can help protect bone tissue from damage. However, some studies in the literature suggest that restorative material may not have an impact on the long-term survival of the implant (36). This indicates that, depending on the material used, it may have limited influence on the implant's long-term success.

In another finite element analysis investigating the impact of various types of cement on stress distribution in monolithic zirconia restorations, it was determined that cements with a lower elastic modulus, such as resin-based cements, more effectively distribute stress compared to those with a higher elastic modulus, like zinc phosphate-based cements (37). For this reason, resinous cement was chosen for crown cementation in the present study.

Rungsiyakull et al. conducted a finite element analysis comparing load distribution patterns in structures with varying cusp inclinations and different points of force application. Their findings indicated that both cusp inclination and the location of force application significantly affected the way loads were transferred to the supporting structures (38). Consequently, in this study, loads were applied at the center of the crown to minimize potential variations caused by anatomical differences in the cusps among the samples within each group.

Previous studies have reported conflicting results regarding how different restorative materials used in crown fabrication influence the transfer of loads to the supporting tissues.

Based on the fact that the higher the elasticity modulus of the prosthetic restoration material, the more stress it absorbs and transmits less to other components, it was also observed that the least stress distribution within the restoration material was found in LS, which had the lowest elasticity modulus. Conversely, except for resin cement, the highest elasticity modulus among all components was observed in MZ.

In this study, MZ showed the best results when examining the stress distribution in implant components and cortical bone. The measurement of stresses in the implant, abutment, abutment screw, and marginal bone relatively in the MZ group may pose less risk in terms of potential complications and marginal bone loss compared to other restorative materials.

Conclusion

Although the MZ material exhibited the highest VMS on the restorative material, it has been considered that MZ is more resistant to clinical loads compared to LS and ZLS. Consequently, it was concluded that clinical complications were less likely to occur with MZ.

Disclosures

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