Comparison of Biomechanical Behavior of Dental All-Ceramics in Tooth or Implant Supported 3-Unit Fixed Partial Prosthesis with Finite Element Analysis

Dental Tam Seramiklerin Diş ve İmplant Destekli 3 Üyeli Sabit Bölümlü Protezlerde Biyomekanik Davranışlarının Sonlu Elemanlar Analizi ile Karşılaştırılması

Merve BOTSALI[1] https://orcid.org/0000-0002-0184-3080
Hüseyin BOTSALI[2] https://orcid.org/0000-0002-6011-3993

[1]Sakarya University Faculty of Dentistry, Department of Prosthodontics, Sakarya
[2]Sakarya University of Applied Sciences, Machinery and Metal Technologies, Sakarya

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ABSTRACT

AIM: The aim of the study is to calculate the stresses under vertical and oblique loadings in 3-unit fixed partial dentures using finite element analysis (FEA) and to evaluate the biomechanical behavior.

MATERIALS AND METHODS: 3-unit fixed partial dentures were designed as implant-supported and tooth-supported. Zirconia, lithium disilicate, and zirconia-reinforced lithium silicate were defined in geometric models. Occlusal forces of 400 N were applied vertically and 45° obliquely on the models, and the von Misses stresses occurring in the models were calculated with FEA. The safety factors of the materials were calculated and compared.

RESULTS: A higher amount of stress occurred in the models under 45° oblique loading compared to vertical loading. Under both loading conditions, it was observed that the stresses in implant-supported restorations were greater than the stresses in tooth-supported restorations. When the materials were compared, the high elastic modulus increased the value of stress and the highest safety factor belonged to zirconia.

CONCLUSION: The stresses occurring in fixed prosthetic restorations are affected by factors such as the direction of the force and the support of the restoration by the implant or prepared tooth. High elastic modulus increased the stress in the restoration, but the higher the bending strength value, the higher the safety factor.

Keywords: *Dental ceramic, Lithium disilicate, Finite element analysis, Zirconia-reinforced lithium silicate, Zirconia*

ÖZET

AMAÇ: Çalışmanın amacı; zirkonya ile güçlendirilmiş lityum silikat seramikten üretilen 3 üyeli sabit bölümlü protezlerde vertikal ve oblik okluzal kuvvetler altında oluşan streslerin sonlu elemanlar analizi (FEA) ile hesaplanması ve materyalin biyomekanik davranışının değerlendirilmesidir.

YÖNTEM ve GEREÇLER: Çalışmada 3 üyeli sabit bölümlü protezler implant destekli ve diş destekli olarak tasarlanarak geometrik modeller elde edilmiştir. Geometrik modellere zirkonya, lityum disilikat ve zirkonya ile güçlendirilmiş lityum silikat materyalleri tanımlanmıştır. Modeller üzerine 400 N'luk okluzal kuvvetler vertikal ve 45° oblik olarak uygulanmış ve modellerde oluşan von Misses stresleri FEA ile hesaplanmıştır. Materyalde oluşan en yüksek von Mises stres değerinin materyalin bükülme dayanımına oranlanarak hesaplanan güvenlik katsayısı (safety factor) elde edilerek malzemelerin güvenlikleri karşılaştırılmıştır.

BULGULAR: Vertikal yükleme koşullarına kıyasla 45° oblik okluzal yükleme altında modellerde daha yüksek miktarda stres oluşmuştur. Her iki yükleme koşulu altında, implant destekli restorasyonlarda oluşan streslerin diş destekli restorasyonlarda oluşan streslerden fazla olduğu görülmüştür. Materyaller karşılaştırıldığında yüksek elastik modulü, oluşan stresin rakamsal değerini artırmıştır ve en yüksek güvenlik katsayısı zirkonyaya ait olmuştur.

SONUÇ: Sabit protetik restorasyonlarda oluşan stresler, kuvvetin yönü ve restorasyonun implant yada prepare edilmiş diş tarafından desteklenmesi faktörinlerden etkilenmiştir. Yüksek elastik modülü restorasyonda oluşan stresi artırmıştır ancak bükülme dayanım değeri ne kadar yüksekse güvenlik katsayısı da o kadar yüksek bulunmuştur.

Anahtar Kelimeler: *Dental seramik, Lityum disilikat, Sonlu elemanlar analizi, Zirkonya ile güçlendirilmiş lityum silikat, Zirkonya*

Corresponding author: mervebotsali@sakarya.edu.tr
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INTRODUCTION

Fixed partial dentures are an important treatment option used in the rehabilitation of partial tooth deficiencies; they provide the restoration of missing teeth, function, phonetics, and aesthetics. In cases where there are natural teeth adjacent to the edentulous space and these adjacent teeth provide sufficient tissue support, tooth-supported fixed partial dentures can be preferred as a traditional treatment method.[1] Today, implant-supported fixed partial dentures are an important alternative to traditional treatment methods. Prosthetic treatments performed with the support of dental implants provide 91% satisfaction among patients by enhancing their speech and chewing functions, as well as their comfort, self-confidence, and aesthetics. Both approaches continue to be employed in clinical settings.

Before the creation of all-ceramic systems, metal-ceramic restorations were believed to combine the mechanical properties of metal frameworks with the aesthetic qualities of ceramics.[2] However, the need for metal-free materials with good optical qualities and translucency similar to natural teeth has increased due to growing aesthetic standards and technological advancements. Thus, all-ceramic restorations with high aesthetic properties and biocompatibility have been developed. Over time, the improvement of all-ceramic materials' mechanical qualities and clinical indications has become more significant in addition to satisfying aesthetic standards. In recent years, a large number of new dental ceramic materials have been developed to enhance the mechanical stability of all-ceramic restorations and meet aesthetic expectations. Among these materials, lithium disilicate (LD) glass ceramics and oxide ceramics such as zirconia have been found to be promising for different indications.[3]

Compared to polycrystalline ceramics like zirconia, which have excellent strength, lithium disilicate glass ceramics have superior translucency, which gives them high aesthetic qualities. However, their usage in posterior regions is limited by their inferior mechanical characteristics when compared to zirconia. Zirconia-reinforced lithium silicate (ZLS) ceramics are a new generation material that combines the positive mechanical properties of zirconia with the aesthetic qualities of LD glass ceramics.[4] The addition of zirconia to the structure is thought to increase the material's mechanical strength by stopping cracks from spreading. Because of this advantageous characteristic, ZLS ceramic material has lately emerged as one of the most popular and favored prosthetic materials and has been proven to be dependable for clinical application.

The quantity and distribution of stress in dental systems (prosthetic parts, implants, surrounding bone tissue, etc.) are examined using finite element analysis (FEA), a computer-aided digital testing technique used in dentistry. FEA is a probabilistic analysis used to examine the force-stress interaction and predict the reliability of all-ceramic restorations under occlusal loading.[5]

In recent years, many studies have proven that ZLS restorations possess fracture strength values that exceed physiological occlusal chewing forces.[6] The indications for ZLS ceramics have been expanded to include their use in posterior single crowns and multi-unit fixed partial dentures (up to 3 units) where the last abutment is the second premolar.[7] With the expanding range of indications, studies conducted on this material, which stands out in current clinical use, are gaining importance.

Glass ceramics are only indicated for a maximum of 3-unit restorations in multi-unit fixed partial dentures, where the second premolar serves as the final abutment.[7] This study start with the observation that, despite extensive experimental and clinical research[8] on the success rate and mechanical properties of zirconia-reinforced lithium silicate (ZLS) as a glass ceramic in anterior and posterior single crowns, there are very few studies examining the biomechanical properties in multi-unit restorations.

Therefore, our study examined ZLS ceramics, zirconia, and lithium disilicate ceramics regarding the stresses generated by tooth-supported and implant-supported 3-unit fixed partial dentures using FEA. Nevertheless, the stress generated in the restoration alone is inadequate to demonstrate the material's performance; so, the safety factor was determined by comparing the maximum von Mises stress in the restoration with the material's flexural strength, allowing for a comparison of material safety. The first null hypothesis proposes that the stress induced in zirconia restorations will be lower; the second hypothesis states that zirconia would have a greater safety factor, so enhancing its safety.

MATERIALS AND METHODS

In our study, 3-unit fixed partial dentures were designed in two different ways: tooth-supported and implant-supported. In the tooth-supported restoration model (D), a 3-unit fixed partial denture was designed using the canine and second premolar teeth as abutments, providing a treatment option for the absence of the mandibular right first premolar tooth (Figure 1a). In the implant-supported restoration model (I), a 3-unit fixed partial denture was designed using implants positioned in the locations of the mandibular canine and second premolar teeth as abutments (Figure 1b). All models were defined using zirconia (Zr; inCoris TZI; Sirona Dental Systems, Bensheim, Germany), lithium disilicate (LD; IPS e-max CAD; Ivoclar Vivadent AG, Schaan, Liechtenstein), and zirconia-reinforced lithium silicate (ZLS; VITA Suprinity PC; Vita Zahnfabrik, Bad Säckingen, Germany) (Table 1).

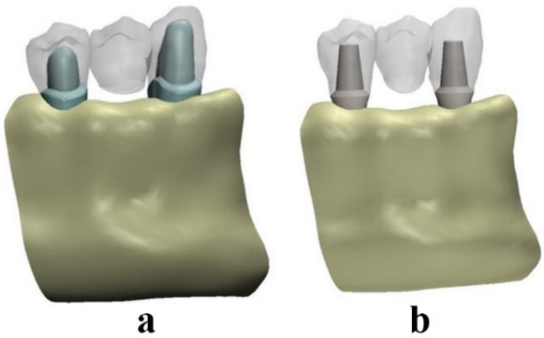

Figure 1. Finite element models used in the study; a: Tooth-supported 3-unit fixed partial denture model (D), b: Implant-supported 3-unit fixed partial denture model (I).

Table 1. Evaluated models, symbols, and specified materials

Models	Model Symbol	Product and Manufacturer
Tooth-supported zirconia	D-Zr	inCoris TZI; Sirona Dental Systems, Bensheim, Germany
Tooth-supported lithium disilicate	D-LD	IPS e-max CAD; Ivoclar Vivadent AG, Schaan, Liechtenstein
Tooth-supported zirconia-reinforced lithium silicate	D-ZLS	VITA Suprinity PC; Vita Zahnfabrik, Bad Säckingen, Germany
Implant supported zirconia	I-Zr	inCoris TZI; Sirona Dental Systems, Bensheim, Germany
Implant-supported lithium disilicate	I-LD	IPS e-max CAD; Ivoclar Vivadent AG, Schaan, Liechtenstein
Implant-supported zirconia-reinforced lithium silicate	I-ZLS	VITA Suprinity PC; Vita Zahnfabrik, Bad Säckingen, Germany

Obtaining Solid Models

The study's models included the mandibular canine, first and second premolar teeth, enamel, dentin, periodontal ligament, bone tissue (cortical bone and spongious bone), resin cement, titanium implant, and titanium abutment. To accurately represent the anatomical structure, the teeth were obtained from a tomographic image utilizing the Mimics® (Materialise, Belgium) tissue modeling software, and the standard tessellation language (STL) file extensions generated by this software were imported into the SOLIDWORKS® (Dassault Systemes, USA) application. In implant-supported models, depending on the standard abutment size, restoration thicknesses on the axial surfaces of anterior and premolar crowns can reach up to 2.5 mm, while in tooth-supported models, the restoration thickness for crowns is 2 mm. A connection cross-section of 16 mm² (4 mm × 4 mm), a pontic width of 8 mm, a shoulder step finish line of 1 mm, and a resin cement thickness of 50 µm were specified for all models.

Finite Element Analysis

The solid models have been imported into the SOLIDWORKS Simulation (SOLIDWORKS® Dassault Systemes, USA) software for FEA. Solid models were transformed into mathematical models via pre-processing processes, which included defining material properties before analysis, determining contact relationships, setting boundary conditions, and creating the finite element mesh. The elasticity modulus (Young's modulus) and Poisson's ratio values, which reflect the mechanical properties of each tissue and material, which reflect the mechanical properties of each tissue and material, have been determined based on the literature and the manufacturer's guidelines (Table 2). The cortical bone was fixed at the surfaces in contact with the jaw, and the other components were considered to be in bonded contact with each other, and analyses were performed accordingly.

Table 2. The modulus of elasticity, Poisson's ratio, and flexural strength values of tissues and materials

Tissues and Materials	Modulus of Elasticity (GPa)	Poisson's Ratio	Flexural Strength (MPa)	References
Enamel	84,1	0,33		9
Dentin	18,6	0,32		9
Periodontal Ligament	0,05	0,45		10
Spongious Bone	1,37	0,30		11
Cortical Bone	13,7	0,30		11
Titanium	110	0,30		11
inCoris TZI	210	0,26	900*	12
IPS e-max CAD	102,7	0,22	530*	13
VITA Suprinity PC	70	0,21	420*	7
Resin Cement	8,3	0,35		12

* Values provided by manufacturers.

The amplitude and direction of occlusal loads are critical for estimating the longevity of materials utilized in fixed partial dentures; therefore, 400 N loads were applied to the models in both a vertical and a 45° oblique direction (from lingual to buccal) to simulate maximum occlusal loading during mastication.

Vertical Loading: A occlusal load of 400 N was applied vertically throughout the entire occlusal surface of the restoration, paralleled with the long axis of the teeth (Figure 2a).

Oblique Loading: A occlusal load of 400 N was applied obliquely at the 45° angle to the long axis of the teeth throughout the entire occlusal surface of the restoration (Figure 2b).

Occlusal loads were applied on the surfaces of the teeth that interact with food. It has been assumed that the foods contact the palatal surface of the anterior crown[10] and the occlusal surface of the posterior crown[14] (Figure 2). Following confirming the loading conditions, the finite element mesh was created with second-order tetrahedral elements, as shown in Figure 3. After concluding the pre-processing phases, the 3-unit fixed-partial prosthesis models became appropriate for analysis, and finally, the analysis was solved to obtain the highest von Mises stress values.

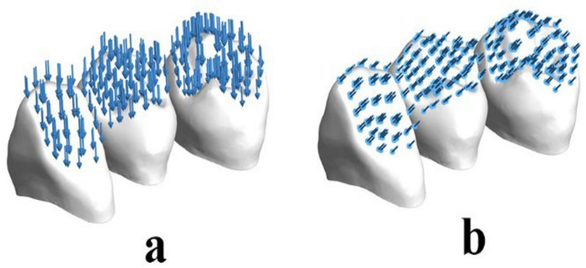

Figure 2. Occlusal loads applied to the models; a: Vertical loading, b: Oblique loading.

Calculation of The Safety Factor

The highest von Mises stress values were recorded after applying occlusal loading to the models. The safety factors for each model were obtained separately by using the flexural strength values obtained from the manufacturers and the highest von Mises stress values, with follow equation.

$$Safety\ Factor = \frac{Flexural\ Strength}{Maximum\ von\ Mises\ Stress}$$

RESULTS

Assessment of The von Mises Stress Results Under Vertical Loading

Stress Level and Concentration Zones in Tooth-Supported Models (D)

The D-ZLS, D-LD, and D-Zr models exhibited peak von Mises stress in the connector regions, recorded at 65.64 MPa, 66.21 MPa, and 68.67 MPa, respectively. The second greatest value was recorded at the interface between the prepared tooth and restoration, as well as at the margins next to the connector area (Figure 3a).

Stress Level and Concentration Zones in Implant-Supported Models (I)

The I-ZLS, I-LD, and I-Zr models exhibited peak von Mises stress in the connector regions, recorded at 95,92 MPa, 97,83 MPa and 106,80 MPa, respectively. The second greatest value was recorded at the interface between the abutment and restoration, as well as at the margins next to the connector area (Figure 3b).

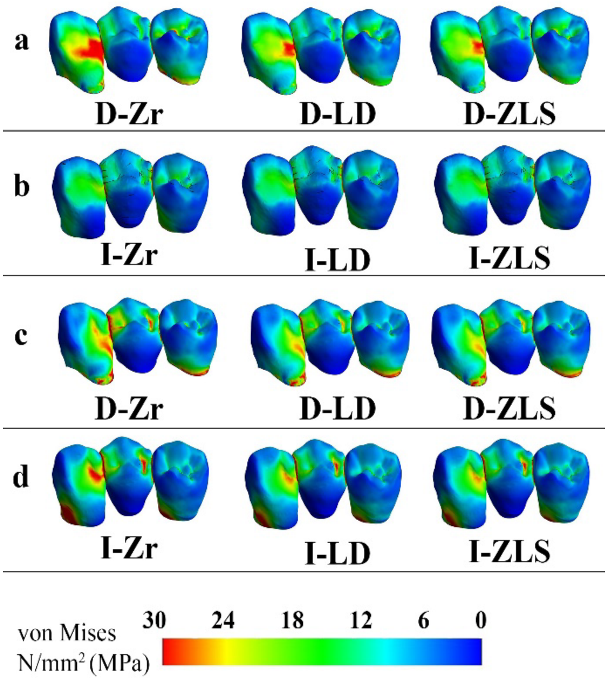

Figure 3. Stress distributions in the models resulting from loadings (a: Stress distributions in tooth-supported models resulting under vertical loading, b: Stress distributions in implant-supported models resulting under vertical loading, c: Stress distributions in tooth-supported models resulting under oblique loading, d: Stress distributions in implant-supported models resulting under oblique loading)

Assessment of The von Mises Stress Results Under Oblique Loading

Stress Level and Concentration Zones in Tooth-Supported Models (D)

The D-ZLS, D-LD, and D-Zr models exhibited peak von Mises stress in the connector regions, recorded at 123,56 MPa, 130,37 MPa and 153,02 MPa, respectively. The second greatest value was recorded at the interface between the prepared tooth and restoration, as well as at the margins next to the connector area (Figure 3c).

Stress Level and Concentration Zones in Implant-Supported Models (I)

The I-ZLS, I-LD, and I-Zr models exhibited peak von Mises stress in the connector regions, recorded at 188,83 MPa, 196,61 MPa and 227,64 MPa, respectively. The second greatest value was recorded at the interface between the abutment and restoration, as well as at the margins next to the connector area (Figure 3d).

Graphical Visualization of Results in Models

Evaluation of the graph showing von Mises stress values across all models reveals that the implant-supported 3-unit fixed partial denture models exhibit elevated stress levels, with oblique loading conditions inducing greater stress than vertical loading conditions in all restorations. Furthermore, the differences between oblique loading and vertical loading is greater in implant-supported models (Figure 4).

Evaluation of Safety Factors in Models

The safety factor, obtained by relating the maximum von Mises stress in the models to the material's flexural strength, was computed for each model and presented in Table 3. Upon examination of the table, it is evident that in both tooth-supported and implant-supported models, zirconia exhibits the maximum safety factor under both loading conditions, therefore indicating that zirconia is the safest alternative.

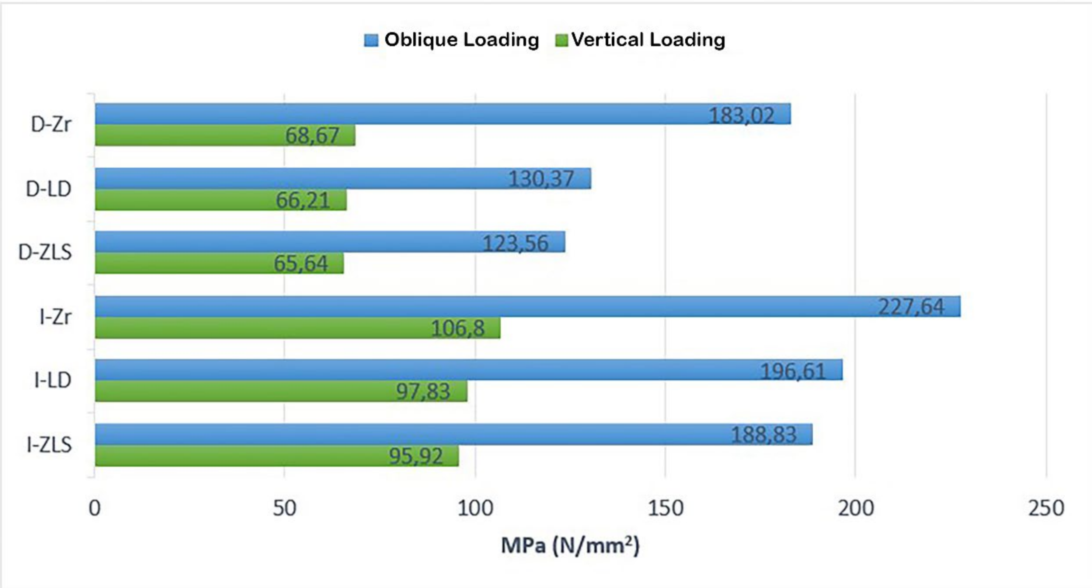

Figure 4. The highest von Mises stress values generated in the models

Table 3. Safety factors of the models.

	Under Vertical Loading		Under Oblique Loading	
	Tooth-supported	**Implant-supported**	**Tooth-supported**	**Implant-supported**
Zr	13,10	8,42	4,91	3,95
LD	8,00	5,41	4,06	2,69
ZLS	6,39	4,48	3,39	2,27

DISCUSSION

A survey research (n=721) revealed that most dentists favored all-ceramics for fixed restorations. Twenty percent of these dentists favored ZLS for single-unit fixed prostheses in the anterior region, but they selected lithium disilicate for multi-unit fixed prostheses up to the second premolar in the posterior region. Neither ZLS nor lithium disilicate ceramics were favored for multi-unit fixed prostheses in the molar region, as the indications for these ceramics do not include posterior fixed prostheses.[15] This study aims to examine the biomechanical behavior of ZLS in three-unit fixed partial dentures, an area that has been inadequately explored compared to the extensive experimental and clinical research[8] validating its efficacy in single-unit restorations, and to compare it with lithium disilicate and zirconia, thereby enhancing its appeal to dental practitioners. A breakthrough designed to enhance restorations, namely monolithic restorations, has been created to prevent some complication, such as porcelain veneer chipping observed in zirconia-based restorations. Consequently, in our research, ceramics were formulated and assessed as monolithic.

Occlusal loads significantly influence the functional efficacy of the prosthesis. Occlusal loading during function depends on biting force, which is affected by variables including gender, age, dental condition, and the efficacy of the masticatory system. Varga et al. documented the bite force in the right posterior region as 777.7 ± 78.7 N for men and 481.6 ± 190.4 N for women.[16] In our study, average bite force values for men and women resulted in the application of 400 N forces to the models both obliquely and vertically. Oblique occlusal forces impose greater stress on prosthetic restorations than vertical and horizontal forces, necessitating increased clinical attention. The research revealed that the von Mises stresses under oblique loading exceeded those under vertical loading across all models. Numerous research investigating the impact of occlusal loading direction on mechanical response have demonstrated that oblique loading influences the mechanical response and results in increased stress values relative to vertical loading.[17]

The findings indicate that the method is considered honest due to the similarity of results from FEA with the comparative test results, and that the outcomes derived exclusively from FEA are adequate.[29] Consequently, the study employed the FEA method. During the assessment of the analytical outcomes, von Mises stresses were computed. The von Mises stresses, which express the equivalent stress in the material under load, convey information regarding the stresses and densities within the material, while also assessing the material's stress resistance.[5] The safety factor values, calculated from The maximum von Mises stresses and the materials' bending strength, have been acquired, yielding the most precise data regarding material safety.

Dental caries, traumas, and periodontal diseases resulting in tooth loss are prevalent concerns in dentistry requiring treatment. Regardless of the etiology of partial tooth loss, appropriate function can be restored with tooth or implant-supported prostheses. In conventional tooth-supported treatment approaches, depending on the remaining hard and soft tissues of patients, the success rate is documented at 50% over 15 years, attributed to biological risk factors that may adversely impact the prognosis of adjacent teeth. Implant-supported fixed dentures, a significant alternative to conventional treatment procedures, demonstrate a success rate of up to 97% over a 10-year follow-up period.[1] Therefore, in our study, 3-unit restorations were fabricated with both tooth and implant supported and evaluated regarding the stresses they generated. FEA results indicate that the stresses in implant-supported restorations exceed those in tooth-supported restorations. Implant-supported restorations lack periodontal tissues and are incapable of absorbing intraoral stresses. Consequently, they have heightened sensitivity to occlusal forces, resulting in increased stress accumulation on the restorations.[19] Pjetursson et al. have indicated that the occurrence of technical complications for implant-supported fixed prostheses is considerably increased, with a 10-year survival rate of 86.7% for implant-supported fixed partial prostheses and 89.2% for tooth-supported fixed partial prostheses. In contrast to our findings, Rand et al. reported in their study that analyzed 4-unit fixed partial dentures designed from monolithic zirconia in three configurations (tooth-supported, implant-tooth combination, and implant-supported) using FEA, the highest stress was observed in the tooth-supported model, whereas the lowest stress was noted in the implant-supported model.[20] Their results indicated that increased rigidity of the support correlates with reduced stresses in the restoration. Consequently, additional research is required to assess the stresses generate in restorations of implant and tooth-supported models. In multi-unit fixed partial dentures, the unsupported area, termed as the body, which replaces the lost teeth, triggers deformations in the restorative structure, hence increasing stress in the connector regions. Research on multi-unit fixed restorations has demonstrated that variations in connector thickness influence stress, and that an increase in connector area substantially enhances mechanical strength.[21] This condition emphasizes the need of employing connectors of optimal thickness concerning the biomechanical aspects of 3-unit fixed partial dentures. Borba et al. highlighted in their experimental study that restorations with a connector area of 16 mm² produced superior mechanical outcomes and demonstrated their suitability for clinical application.[22] Nevertheless, while it has been documented that the stress produced reduces inversely with the thickness of the connector, research indicates that regardless of the restoration material and connector thickness, the stress in the restoration is predominantly concentrated in the connector regions.[23] In this context, the observation that the maximum von Mises stress value across all models in our study was recorded in the connector regions aligns with the biomechanical characteristics of 3-unit fixed-partial dentures, and the stress results obtained are not above the flexural strength thresholds of the materials. This issue is attributed to the thickness of the connector chosen (16 mm²). In clinical use, to enhance the longevity of 3-unit fixed partial dentures, a connector thickness of no less than 16 mm² (4 × 4 mm) is recommended.

In our research, the monolithic Zr exhibited the greatest von Mises stress value, leading to the rejection of our initial null hypothesis. Dal Piva et al. assessed the stress induced by different monolithic ceramic restorations in a posterior molar crown model utilizing FEA.[14] This study, including zirconia, lithium disilicate, and zirconia-reinforced lithium silicate specimens, indicated that an increase in the material's elastic modulus correlates with elevated stress in the restorations.

The safety factor for each model has been calculated and shown in Table 3. The results support our second null hypothesis and indicate that the Zr models have the highest safety factor. Notwithstanding the increased stress experienced by the models, Zr's superior safety factor can be attributed to its high flexural strength. Researches indicates that materials with increased crystalline content have superior mechanical performance.[24] Liu et al. evaluated the characteristic strength and estimated survive of Zr, LD, and ZLS dental ceramics, observing that Zr exhibits the highest characteristic strength among the three materials.[25] However, considering the limitations of our study, long-term clinical studies are required to corroborate our findings.

CONCLUSION

Our research revealed that the majority of stress occurred in the connector of the implant-supported zirconia restoration under oblique loading, although zirconia also exhibited the highest safety factor. The stress experienced in fixed prosthetic restorations made from zirconia, lithium disilicate, and zirconia-reinforced lithium silicate ceramics is determined by the load direction and the type of support, either an implant or a prepared tooth. The higher elastic modulus of the material increases the stress in the restoration, while the substantial safety factor relies on the high flexural strength value. Moreover, in 3-unit restorations, regardless of the material type, load direction, and support type, stress concentrations were noted in the connector regions, highlighting the significance of optimal connector thickness in clinical applications.

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