Saz et al. BMC Oral Health (2026) 26:1518
https://doi.org/10.1186/s12903-026-08725-5

BMC Oral Health

RESEARCH

Open Access

Stress distribution in titanium and zirconia implants with full-arch prostheses: a finite element analysis

Bahattin Saz[1*†], Ozgun Yusuf Ozyilmaz[2] and Ozge Doganay Ozyilmaz[3†]

Abstract

Objective The stress distribution and mechanical properties of materials used in dental implants are critically important for implant success and long-term stability. The aim of this study was to evaluate the stress distribution on implant, prosthetic system, and peri-implant tissues when titanium and zirconia implants are used with different framework materials using three-dimensional finite element analysis (FEA).

Methods A three-dimensional edentulous maxilla model was reconstructed from computed tomography data, and twelve finite element models were subsequently developed based on this anatomy to represent different implant and framework configurations. Within the scope of the study, titanium and zirconia implants were modeled in combination with cantilevered and noncantilevered prosthesis types and Co-Cr, PEKK, and zirconium framework materials. An oblique static load of 200 N was applied at a 45° angle in the palato-buccal direction to the central fossa of the first molar on the models. The Von Mises and principal stress distributions in the implant, abutment, screw, framework, and peri-implant bone were examined.

Results The highest Von Mises value was recorded in the cantilevered PEKK framework zirconia implant model (378.388 MPa). Compared with the Co-Cr and zirconium framework, the PEKK framework resulted in higher Von Mises stresses and greater prosthesis displacement. The presence of a cantilever increased stress levels in all framework materials, and stress concentrations were observed particularly in posterior abutments and peri-implant bone. Furthermore, stress values in trabecular bone were recorded above the physiological threshold level in the cantilevered PEKK framework models.

Conclusions Although zirconia implants exhibited greater stress than titanium implants, they remained within safe limits. Rigid framework materials and cantilever-free designs provide more balanced biomechanical results.

Keywords Zirconia implant, Full-arch prosthesis, Stress distribution, Cantilever, Zirconium/PEKK/Co-Cr framework, Finite element analysis

†Bahattin Saz and Ozge Doganay Ozyilmaz contributed equally to this work.

*Correspondence:
Bahattin Saz
bahattinsaz@gmail.com

[1]Department of Oral and Maxillofacial Surgery, Institute of Health Sciences, Bezmialem Vakif University Adnan Menderes Bulvarı, Vatan Caddesi, Fatih, Istanbul 34093, Türkiye
[2]Department of Prosthodontics, Faculty of Dentistry, Istanbul Galata University, Istanbul, Türkiye
[3]Department of Oral and Maxillofacial Surgery, Bezmialem Vakif University, Istanbul, Türkiye

Introduction

Tooth loss can negatively impact an individual's quality of life by impairing function, phonation, and aesthetics. Endosseous implants, which are frequently used in clinical dental practice, are widely employed in the treatment of tooth loss [1, 2].

Titanium-aluminum-vanadium alloy (Ti-6Al-4 V) is widely preferred in dental implant production due to its high mechanical strength, low density, and resistance to corrosion in physiological environments [3]. Titanium implants have been used in clinical practice for many years, with high success rates. However, bacterial colonization around the implant can lead to infection in the early stages and, in later stages, inflammation in the peri-implant tissues and resorption of the surrounding bone, resulting in implant loss [4, 5]. In addition, titanium metal allergy, which is rare but can occur in some individuals, raises questions about its biocompatibility [6, 7]. Furthermore, issues related to the material's wear resistance and surface stability have been reported with long-term use; it has been noted that ions released through wear and corrosion processes can enter the systemic circulation and pose various biological risks [8, 9]. These disadvantages have accelerated the search for alternative biocompatible materials for use in dental implants [10].

Zirconia implants are typically made from yttria-stabilized tetragonal zirconia polycrystal (Y-TZP)-based ceramic materials, sometimes with a small amount of alumina added, and have been developed as alternatives to titanium implants. Zirconium oxide stands out in animal and in vitro models for its high biocompatibility, low bacterial colonization potential, aesthetic properties, and corrosion resistance; compared with titanium, it has also been shown to be associated with less biofilm accumulation, bone resorption, and inflammatory response [11, 12]. Because zirconium does not dissolve in environments such as saliva, sweat, and acid owing to the stable oxide layer formed on its surface, ions are not released into circulation. This property, along with its high corrosion resistance, biocompatibility, high hardness, and wear resistance, makes it a strong biological and mechanical alternative in implantology [13, 14].

The framework materials used in implant-supported prostheses play a decisive role in biomechanical performance and long-term stability [15]. The literature reports that cobalt-chromium, zirconium, and PEKK offer different biomechanical and clinical advantages in their use in implant-supported fixed prostheses. The resistance of cobalt-chromium to deformation and its reliable mechanical performance; the high biocompatibility, reduced plaque accumulation, and aesthetic properties of zirconium; and the high pressure resistance, shock absorption capacity, and bone-like elastic modulus of PEKK are among the main features that distinguish these materials [15–18].

Three-dimensional finite element analysis (FEA) is an effective computational method that allows the evaluation of stress distributions caused by different design parameters and prosthetic components in dental implant systems. It is widely used in the analysis of load transfer mechanisms that cannot be directly observed clinically and is an important tool, particularly for predicting the mechanical performance of new materials under intraoral loads [19, 20].

This study aimed to evaluate the effects of titanium and zirconia implants using different framework materials on the stress distribution in the implant, prosthetic system, and peri-implant tissues via three-dimensional finite element analysis (FEA).

Materials and methods

This study was supported by the Bezmialem Vakif University Scientific Research Projects Coordination Unit (Project No: 2023/1210). A three-dimensional (3D) model of an edentulous maxilla was created using computed tomography (CT) data obtained from an adult patient. The CT data were processed using 3DSlicer software and converted to stereolithography (STL) format. Reverse engineering processes were performed using Blender software; preparation for finite element analysis (FEA) and optimization of the mesh structure were achieved using ALTAIR Hypermesh. Model solutions were completed using the ALTAIR OptiStruct (ALTAIR, Troy, MI, USA) solver. Visible Human Project data were used as a basis for bone modeling, and cortical and cancellous bone structures were modeled separately. The internal bone structure was created with a defined cortical thickness of 1 mm, and the internal volume was filled with trabecular bone.

Within the scope of the mechanical analysis, models were created, and analyses were performed using two different implant materials, titanium and zirconia; two prosthesis types, cantilevered and non-cantilevered designs; and three different framework materials, Cr-Co, PEKK, and zirconium (Table 1). The Toronto-type prosthesis framework material and monolithic zirconia were preferred in all models.

Three-dimensional digital models of the Neodent Zi (4.3 × 10 mm) zirconia and Straumann BLT (4.1 × 10 mm) titanium implant systems were designed in a computer-aided design (CAD) environment based on the manufacturers' catalog specifications. Each implant assembly, comprising 30-degree angled and straight multiunit abutments with occlusal screws, was modeled with high geometric fidelity to ensure accurate representation for finite element analysis (Fig. 1).

Table 1 Implant groups, nodes and elements

Group	Implant material	Framework and prosthetic design	Nodes	Elements
1	Zirconium	Zirconium with cantilever	484,510	1,863,466
2	Zirconium	Co-cr with cantilever	484,510	1,863,466
3	Zirconium	PEKK with cantilever	484,510	1,863,466
4	Titanium	Zirconium with cantilever	456,870	1,754,947
5	Titanium	Co-cr with cantilever	456,870	1,754,947
6	Titanium	PEKK with cantilever	456,870	1,754,947
7	Zirconium	Zirconium without cantilever	378,644	1,438,800
8	Zirconium	Co-cr without cantilever	378,644	1,438,800
9	Zirconium	PEKK without cantilever	378,644	1,438,800
10	Titanium	Zirconium without cantilever	357,738	1,355,892
11	Titanium	Co-cr without cantilever	357,738	1,355,892
12	Titanium	PEKK without cantilever	357,738	1,355,892

Co-Cr Cobalt-chromium, *PEKK* polyetherketoneketon

A total of four implants were used in the cantilevered system, with the anterior implants placed vertically and the posterior implants placed at a 30° angle. In the non-cantilevered system, a total of six implants were placed, with the implants in the lateral incisor, first premolar, and first molar regions positioned vertically (Fig. 2). The detailed group configurations are presented in Table 3.

Table 2 Details of all implant and prosthetic component

	Diameter/thickness	Length/width
Titanium Implant (Strauman BLT)	4.1 mm diameter	10 mm in length
Zirconium Implant (Neodent Zi)	4.3 mm diameter	10 mm in length
PEKK framework	5 mm in thickness	5 mm in width
Zirconium framework	5 mm in thickness	5 mm in width
Co-Cr framework	5 mm in thickness	5 mm in width
Fixed Prosthesis	15 mm in thickness	12 teeth
Cantilever distance		11 mm in length
Cement [22]	50 µm in thickness	

Co-Cr Cobalt-chromium, *PEKK* Polyetherketoneketone

The tooth dimensions in the superstructure were determined using Wheeler's Dental Anatomy Atlas as a reference, and the modeling was performed using Blender software. A detailed list of all components used in the study is presented in Table 2 [21].

Under loading conditions, an oblique static force of 200 N was applied at a 45° angle in the palato-buccal direction to the central fossa of the first molar tooth (Fig. 3). The implant–bone interface was modeled assuming full

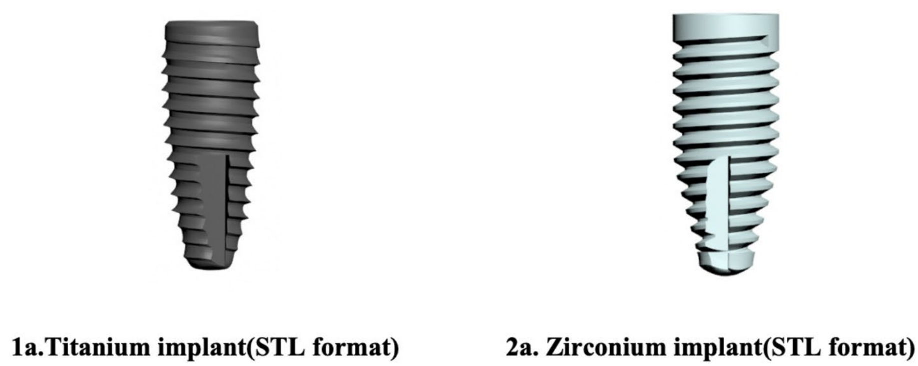


Fig. 1 Three-dimensional computer-generated models of titanium and zirconia implants (converted into STL format) used for finite element simulations

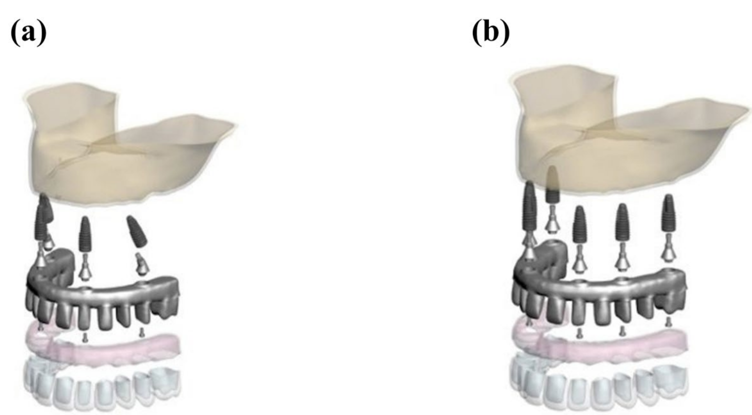


Fig. 2 Schematic representation of implant-supported full-arch designs: **A** Four implants with distal cantilever extensions; **B** Six implants without cantilever extensions

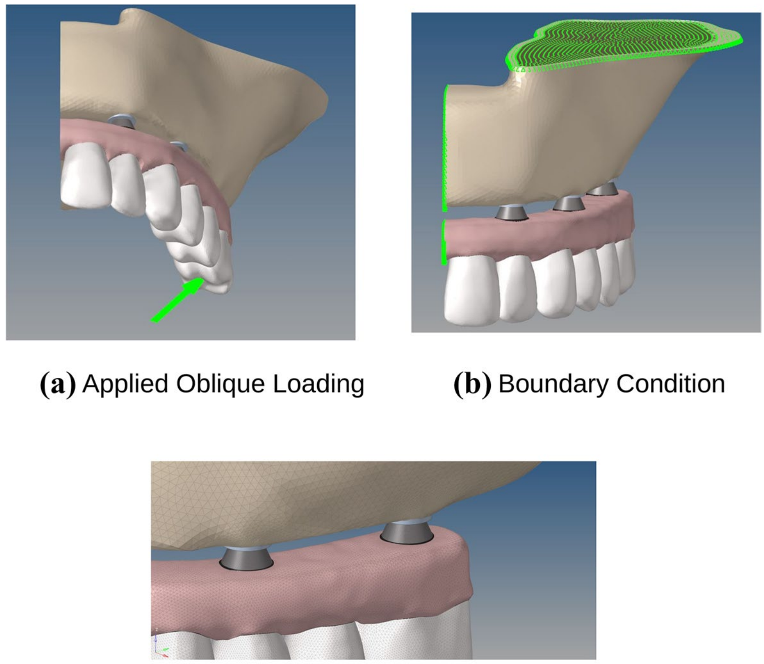


Fig. 3 Applied oblique loading (**A**), boundary conditions (**B**), and representative finite element mesh (**C**) of the finite element model

Table 3 Mechanical properties of all materials

Material	Elastic modulus [MPa]	Poisson's ratio[v]	Reference
Cortical Bone	13,700	0.30	[23]
Trabecular Bone	1370	0.30	[23]
Co-Cr	218,000	0.33	[23]
Zirconium	200,000	0.31	[24]
PEKK	5100	0.40	[25]
Titanium Implant	110,000	0.28	[25]
Neodent Zirconia Implant	246,204	0.31	
Resin Sement	11,860	0.30	[22]
Monolithic Zirconia	210,000	0.35	[26]

Co-Cr Cobalt-chromium, *MPa* Megapascal, *PEKK* Polyetherketoneketone

osseointegration, and the connections between the prosthesis components were considered rigid.

All analyses related to the structural and mechanical characterization of zirconia implants were performed at the Metallurgy and Materials Engineering Laboratory of Marmara University. Microstructure examinations were conducted using scanning electron microscopy (SEM; Thermo Scientific, Quattro S**)**, and the elemental compositions were analyzed using energy-dispersive X-ray spectroscopy (EDX; integrated with the same SEM system). X-ray diffraction (XRD; Rigaku MiniFlex) was used to determine phase compositions, while mechanical properties were evaluated using nanoindentation tests, and Young's modulus and Poisson's ratio were determined. The elastic modulus, Poisson's ratio, and Young's modulus values of all materials used are summarized in Table 3.

The von Mises stress criterion is widely used for predicting possible mechanical failure in ductile materials. Within the scope of FEA, the von Mises stress values for different framework materials with implants, abutments, and connecting screws were calculated. In addition, the maximum and minimum principal stresses formed in cortical and trabecular bone and the displacement amounts in the prosthesis structure were analyzed.

Results

The stress values were found to be higher in all groups except for the occlusal screw in ceramic implants than in titanium implants (Table 4). The highest von Mises value among all models was observed in the PEKK framework model with zirconia implants and a cantilever, which was calculated as 378.388 MPa (Table 4). In the groups in which the PEKK material was used, the von Mises stress values of the framework were lower than those of the Co-Cr and zirconium framework materials.

The lowest von Mises stress value observed in the implants (96,101 MPa) was found in the model using a titanium implant, without a cantilever, and with a Co-Cr framework material. The next lowest von Mises stress value was observed in the same type of model containing a zirconium framework (97.711 MPa) (Table 4).

The stress values were higher in the cantilevered groups than in the noncantilevered groups. The presence

Table 4 Von Mises and principal stress extreme values for each component are presented separately, and all values are expressed in megapascals (MPa)

Group	Von Mises implant	Von Mises occlusal screw	Von Mises abutment	Von Mises framework	Maximum principal trabecular bone	Maximum principal cortical bone	Prosthetic displacement value
1	163.420	74.917	197.109	192.569	6.237	25.147	0.05856 mm
2	160.860	73.875	189.538	189.593	6.154	24.816	0.05674 mm
3	378.388	398.51	553.259	153.424	8.723	36.588	0.2521 mm
4	128.186	93.783	149.458	173.954	5.797	26.364	0.06281 mm
5	126.279	92.559	144.296	168.736	5.718	25.992	0.06081 mm
6	322.676	403.747	472.881	137.388	8.583	33.754	0.2756 mm
7	127.271	45.210	141.229	90.590	2.903	16.803	0.03455 mm
8	124.078	42.432	136.694	89,833	2.868	16.458	0.03350 mm
9	270.460	473.519	329.083	75.539	3.202	25.586	0.1274 mm
10	97.711	41.900	117.051	80.407	2.878	16.150	0.03797 mm
11	96.101	40.135	114.942	79.802	2.853	15.925	0.03674 mm
12	263.308	368.064	298.288	63.870	3.184	21.699	0.1430 mm

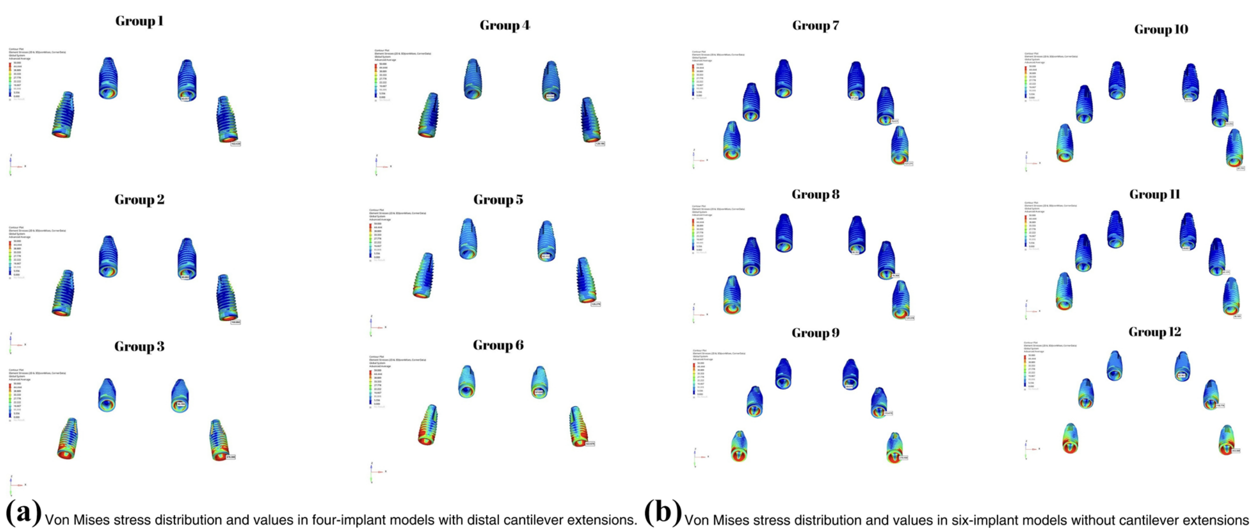


Fig. 4 Von Mises stress distribution (MPa) in the titanium and zirconia implant bodies under oblique loading conditions (**A**) four-implant models with distal cantilever extensions and (**B**) six-implant models without cantilever extensions

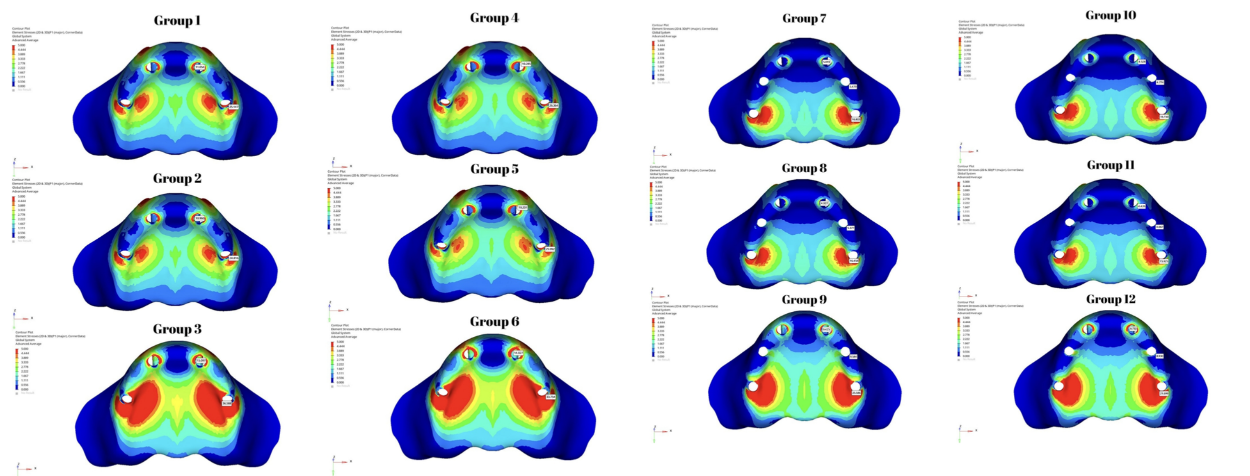
of a cantilever increased the stress on the framework, regardless of the material used. Furthermore, the stress levels increased for all the framework materials (Fig. 4). The highest stress values in the abutments were detected in the cantilevered models located in the posterior region and with a PEEK framework (553.259 MPa and 472.881 MPa). In contrast, these values were significantly lower in the Co-Cr and zirconium framework models (Table 4).

When the ceramic and titanium implants were compared, the maximum principal stress values in the cortical bone were quite close to each other (Fig. 5). The highest compressive stresses in the cortical and trabecular bone tissues were detected in the posterior implant regions (Fig. 6).

The amount of displacement in the cantilevered prostheses was greater than that in the noncantilevered groups (Fig. 7). While the values obtained for titanium and zirconia implants were similar, the amount of prosthetic displacement in the PEKK framework models was found to be greater than that in the models using Co-Cr and zirconium frameworks (Table 4).

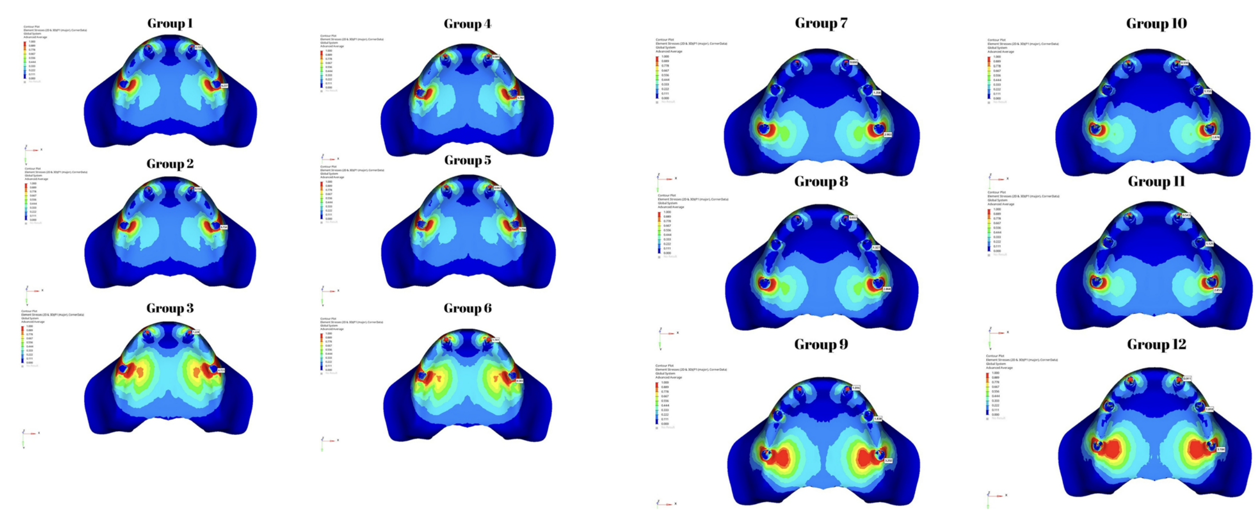
Discussion

Zirconia implants have a higher elastic modulus than titanium implants. According to Hooke's law, as the elastic modulus of a material increases, its resistance to deformation increases, and a higher level of stress occurs under constant deformation conditions. This mechanical property causes zirconia implants to absorb applied loads to a greater extent than titanium implants. Indeed, Pérez-Pevida et al. demonstrated that stiffer implants structurally accommodate more stress under the same loading and design conditions [27]. Similarly, a finite element analysis conducted by Bal et al. reported that zirconia



(a) Maximum principal stress distribution and values in four-implant models with distal cantilever extensions. **(b)** Maximum principal stress distribution and values in six-implant models without cantilever extensions.

Fig. 5 Maximum principal stress values (MPa) and stress distribution in maxillary cortical bone under oblique loading: (**A**) four-implant models with distal cantilever extensions and (**B**) six-implant models without cantilever extensions

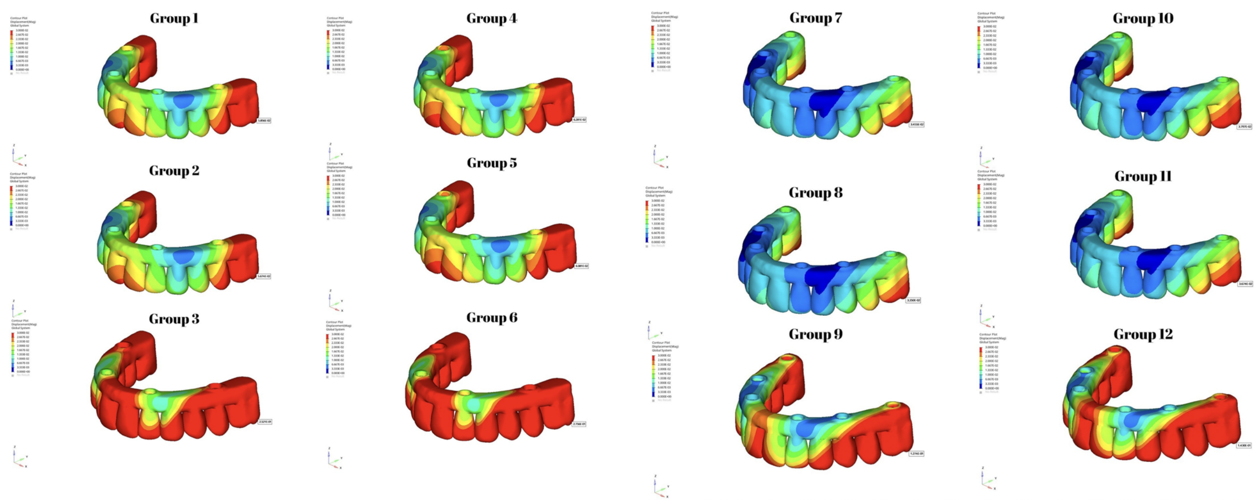


(a) Maximum principal stress distribution and values in four-implant models with distal cantilever extensions. **(b)** Maximum principal stress distribution and values in six-implant models without cantilever extensions (X = distal side; Y = buccal side).

Fig. 6 Maximum principal stress distribution (MPa) in the maxillary trabecular bone under oblique loading conditions: (**A**) four-implant models with distal cantilever extensions and (**B**) six-implant models without cantilever extensions

implants exhibited higher stress values than titanium implants [28]. This study found that zirconia implants created higher stress accumulation than titanium implants in all regions, which is consistent with previous findings in the literature. When groups without cantilevers were compared, the higher von Mises stress levels in the zirconia implants than in the titanium implants can be attributed to the high elastic modulus of the zirconium material, resulting in stress being absorbed within its own structure.

In implant-supported fixed prostheses, the framework material plays a decisive role in the transmission of occlusal forces to the implant and peri-implant bone tissues [29]. PEKK, a type of high-performance polymer, is increasingly preferred in clinical applications due to its biocompatibility, aesthetic advantages, low density, and ease of processing. Compared with PEEK, PEKK offers greater compressive strength and improved mechanical properties, making it an aesthetically strong alternative to traditional cobalt-chromium frameworks in fixed prostheses [17, 18, 30]. On the other hand, its low elastic modulus is considered a limiting factor in terms of long-term biomechanical stability, as it transmits more stress to peri-implant tissues and leads to high prosthetic displacement. Findings in the literature regarding PEKK's load transfer dynamics show conflicting results. While



(a) Displacement distribution and values in four-implant models with distal cantilever extensions. **(b)** Displacement distribution and values in six-implant models without cantilever extensions.

Fig. 7 Displacemen values: (**A**) four-implant models with distal cantilever extensions and (**B**) six-implant models without cantilever extensions

some studies report that its flexible structure reduces stress levels in the implant and surrounding bone, others have shown that it increases stress accumulation, particularly in the implant neck region where tensile stresses are concentrated [18, 31]. Consistent with the literature, this study found that compared with those in the Co-Cr and zirconium framework models, the von Mises stress levels in all the groups in the PEKK framework models were greater. Therefore, the indications for PEKK frameworks should be carefully evaluated, especially in cases involving bruxism or parafunctional habits.

It has been reported that stress accumulation in distal implants and the associated risk of marginal bone loss increase in the presence of cantilevers; therefore, cantilever-free prosthesis designs are recommended to improve stress distribution. Silva et al. reported that maximum von Mises stress values increased by approximately 100% in the presence of cantilevers [32]. Horita et al. [33] demonstrated that peak stress decreased by 45.3–52.5% in cantilever-free applications, emphasizing the biomechanical importance of cantilever elimination. Similarly, Keshavarz Valian et al. reported that reducing the cantilever length significantly decreased stress accumulation [34]. These results are consistent with the stress increase observed in the presence of a cantilever in our current study and indicate that the cantilever length should be carefully planned from a clinical perspective. Similarly, this study also showed that stress values were higher in the cantilevered designs than in noncantilevered designs. Therefore, when low elastic modulus framework materials such as PEKK are used, cantilever-free designs should be preferred to balance the stress distribution and prevent excessive stress on the implant–screw. In cases where the use of a distal cantilever is unavoidable, the selection of high-rigidity framework materials such as Co-Cr or zirconium may contribute to reducing the stress transmitted to the peri-implant tissues and preserving long-term biomechanical stability and functional integrity.

In the literature, it has been reported that zirconia implants create lower stress peaks than titanium implants do, particularly in the cortical bone surrounding the implant platform [35]. In the present study, zirconia implants also transmitted slightly lower stress to the bone than titanium implants. The forces transmitted to cortical and cancellous bone are clinically significant in terms of preventing stress shielding. According to Harold M. Frost's theory, bone tissue responds physiologically to mechanical stresses in the range of 2–40 MPa (100–2000 με); within these limits, bone mass is preserved or increased [36]. On the other hand, a study by Baggi and colleagues indicated that loads exceeding 5 MPa in trabecular bone are associated with overload and may increase the resorptive response [37]. Therefore, in implant-supported restorations, transmitting stress to the bone within physiological limits, preventing the stress shielding effect, and preserving peri-implant bone integrity are important factors to consider.

Stress levels exceeding physiological limits were detected in trabecular bone in the cantilevered PEKK framework model (Group 3: 8.723 MPa; Group 6: 8.583 MPa). Similarly, Sirandoni et al. [15] compared different frame materials in full-arch prostheses and reported that Co-Cr and zirconium, which have high elasticity moduli, remained within physiological limits in bone, whereas flexible materials caused tensile stresses exceeding critical limits in trabecular bone. The results of the study by Şahin et al. using PEEK material are similar to our current findings [38]. It is thought that the force of the PEKK material is largely transmitted to the implant and then to the bone, thereby further increasing the stress levels in trabecular bone. However, angulated distal implant placements, which are recommended to reduce this effect, have also been reported to possibly cause local stress increases in the implant neck and marginal bone [39]. Similar to previous FEA studies, this study also confirms that the highest stresses are mostly concentrated in the neck region of most distal implants [39–41]. This is related to the moment arm effect at the point where the restoration ends in the posterior region and the bending moments are created by occlusal forces. Studies have reported that loading direction also plays a decisive role in this mechanism; specifically, oblique forces create a bending moment in the buccolingual direction, leading to higher von Mises stresses in distal implants than in vertical loading [42]. The results support that cantilever use and oblique loading lead to stress concentration in distal implants; therefore, it is necessary to optimize the implant placement angle, implant number, and prosthesis design, especially in posterior regions, to ensure a balanced distribution of occlusal forces.

Prosthesis displacement is a critical indicator of biomechanical success in full-arch implant-supported restorations. Current findings indicate that low-elasticity modulus PEEK frameworks exhibit greater displacement under occlusal loads than zirconium and Co-Cr frameworks [38, 43]. This situation can lead to reduced chewing efficiency and compromised occlusal stability, especially in the presence of cantilevers. It has been reported that increasing the number of implants resulted in a 16% improvement in displacement levels [44]. It is anticipated that the amount of prosthetic displacement can be optimized by the number and location of implants, the selection of high-rigidity framework materials, and a cantilever-free prosthesis design.

Compared with vertical implants, angular implants tend to generate greater bending moments because they are more exposed to the lateral components of occlusal forces. One study reported that the Von Mises values measured at the neck of angled implants were greater than those measured at the neck of vertical implants, and greater stress accumulation was also observed around the peri-implant bone [23]. In contrast, lower stress values were recorded in both the implant components and the surrounding bone in the vertical implants. Similarly, in our study, inclined implants were found to generate higher stress values both at the implant level and in the peri-implant bone, which is consistent with findings reported in the literature.

The literature indicates that the fracture threshold of zirconia implants under static forces varies depending on the implant design, diameter, loading conditions, manufacturing method, and material composition, with values ranging from 372.4–783 N [45–48]. A study by Ward et al. reported that the typical flexural strength of 3Y-TZP ceramic is in the range of 950–1310 MPa [49]. Another finite element analysis indicated that the average flexural strength of 3Y-TZP is 952 MPa and that zirconia implants could be safely used under chewing loads up to 500 N [50]. In this study, the tensile stress values obtained in all the groups remained within the safe loading limits reported in the literature; the stress values measured in zirconia implants ranged from 59.075 to 378.388 MPa, and therefore, the safety margin was maintained. The risk of fracture in zirconia implants is low under the applied scenarios. These findings show that zirconia implants are a good alternative not only because of their aesthetic superiority but also because of their safe performance under suitable mechanical conditions.

Although finite element analysis is effective for evaluating stress distribution and material behavior, it cannot fully reflect intraoral biomechanical and biological conditions, thus limiting the direct generalization of clinical results. Furthermore, mucosal tissue was not included in the modeling process, assuming its minimal effect on the distribution of peri-implant stress. The analyses were performed with a loading condition applied in a single region from an oblique direction; however, in the clinical environment, the direction and intensity of occlusal forces vary with each cycle, which can directly affect fatigue resistance and long-term performance. Due to differences in the surface properties of zirconia and titanium, changes in bone integration, healing time, and associated force transmission may occur; furthermore, the fact that microcracks possibly occurring during surface treatments can increase the risk of fracture has been neglected [51, 52]. Dynamic analysis was not performed because the primary objective of this study was to compare the stress distribution among different implants, framework materials, and prosthesis designs. Therefore, linear static analysis was preferred. In addition, the titanium and zirconia implant systems used in this study were not fully identical in terms of connection design, implant geometry, and thread characteristics. Accordingly, the observed biomechanical differences should be interpreted as the combined effect of material properties and system-specific design features. However, supporting the findings with long-term clinical follow-up and dynamic load tests is important for demonstrating the biomechanical reliability of zirconia implants in a more robust and comprehensive manner. Taken together, these considerations outline the principal limitations of the present study.

Conclusion

The results of this study demonstrate that zirconia implants, despite exhibiting higher stress concentrations within the implant body compared with titanium implants, remain within physiologically safe limits and can be used with mechanical confidence under appropriate clinical conditions. The presence of cantilevers increased the stress in all the models, whereas the stress and displacement values of the PEKK frameworks were higher than those of other models. In contrast, implants positioned vertically with Co-Cr and zirconium framework provided more balanced biomechanical results. Clinically, it is recommended that the number and location of zirconia implants be planned carefully to reduce the risk of complications, that rigid framework materials be preferred, and that cantilever-free designs be used whenever possible. However, since finite element analysis cannot fully reflect biological and functional conditions, it is crucial to support these findings with long-term clinical follow-up and dynamic load tests.

Abbreviations

FEA	Finite Element Analysis
Zr	Zirconium
Co-Cr	Cobalt chromium
PEKK	Polyetherketonketone
Y-TZP	Yttria-stabilised tetragonal zirconia polycrystals
CT	Computed tomography
STL	Stereolithography
SEM	Scanning electron microscopy
EDX	Energy-dispersive X-ray spectroscopy
XRD	X-ray diffraction

Acknowledgements
Not applicable.

Authors' contributions
B.S. wrote the article and performed the analyses. O.D.O. and O.Y.O. reviewed and revised the article. All authors reviewed the article and contributed to the development of the concept.

Funding
This study was supported by the Scientific Research Projects Coordination Unit of Bezmialem Vakif University (Project No: 2023/1210).

Data availability
Data are presented within the article.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

Received: 5 September 2025 / Accepted: 20 May 2026
Published online: 13 June 2026

References

1. Cordioli G, Castagna S, Consolati E. Single-tooth implant rehabilitation: a retrospective study of 67 implants. Int J Prosthodont. 1994;7(6):523–8.
2. Mardinger O, Oubaid S, Manor Y, Nissan J, Chaushu G. Factors affecting the decision to replace failed implants: a retrospective study. J Periodontol. 2008;79(12):2262–6.
3. Long M, Rack HJ. Titanium alloys in total joint replacement—a materials science perspective. Biomaterials. 1998;19(18):1621–39.
4. Veerachamy S, Yarlagadda T, Manivasagam G, Yarlagadda PKDV. Bacterial adherence and biofilm formation on medical implants: a review. Proc Inst Mech Eng H. 2014;228(10):1083–99.
5. Willis J, Li S, Crean SJ, Barrak FN. Is titanium alloy Ti-6Al-4V cytotoxic to gingival fibroblasts? A systematic review. Clin Exp Dent Res. 2021;7(6):1037–44.
6. Sicilia A, Cuesta S, Coma G, Arregui I, Guisasola C, Ruiz E, et al. Titanium allergy in dental implant patients: a clinical study on 1500 consecutive patients. Clin Oral Implants Res. 2008;19(8):823–35.
7. Siddiqi A, Payne AGT, De Silva RK, Duncan WJ. Titanium allergy: could it affect dental implant integration? Clin Oral Implants Res. 2011;22(7):673–80.
8. Jomova K, Alomar SY, Nepovimova E, Kuca K, Valko M. Heavy metals: toxicity and human health effects. Arch Toxicol. 2025;99(1):153–209.
9. Willhite CC, Karyakina NA, Yokel RA, Yenugadhati N, Wisniewski TM, Arnold IMF, et al. Systematic review of potential health risks posed by exposures to aluminum and its compounds. Crit Rev Toxicol. 2014;44(Suppl 4):1–80.
10. Pirker W, Kocher A. Immediate, non-submerged, root-analogue zirconia implant in single tooth replacement. J Oral Maxillofac Surg. 2008;37(3):293–5.
11. Andreiotelli M, Wenz HJ, Kohal RJ. Are ceramic implants a viable alternative to titanium implants? A systematic literature review. Clin Oral Implants Res. 2009;20(Suppl 4):32–47.
12. Scarano A, Piattelli M, Caputi S, Favero GA, Piattelli A. Bacterial adhesion on commercially pure titanium and zirconium oxide disks: an in vivo human study. J Periodontol. 2004;75(2):292–6.
13. Kniha K, Heussen N, Modabber A, Hölzle F, Möhlhenrich SC. The effect of zirconia and titanium surfaces on biofilm formation and on host-derived immunological parameters. Int J Oral Maxillofac Surg. 2021;50(10):1361–74.
14. Oberoi G, Kornfellner E, Aigner D, Unger E, Schwentenwein M, Bomze D, et al. Design and optimization of a novel patient-specific subperiosteal implant additively manufactured in yttria-stabilized zirconia. Dent Mater. 2024;40(1):102–15.
15. Sirandoni D, Leal E, Weber B, Noritomi P, Fuentes R, Borie E. Effect of different framework materials in implant-supported fixed mandibular prostheses: a finite element analysis. Int J Oral Maxillofac Implants. 2019;34(3):e107–14.
16. Barootchi S, Askar H, Ravidà A, Gargallo-Albiol J, Travan S, Wang HL. Long-term clinical outcomes and cost-effectiveness of full-arch implant-supported zirconia-based and metal-acrylic fixed dental prostheses: a retrospective analysis. Int J Oral Maxillofac Implants. 2020;35(2):395–405.
17. Villefort RF, Diamantino PJS, Von Zeidler SLV, Borges ALS, Silva-Concílio LR, Saavedra GDFA, et al. Mechanical response of PEKK and PEEK as frameworks for implant-supported full-arch fixed dental prosthesis: 3D finite element analysis. Eur J Dent. 2022;16(1):115–21.
18. Lee KS, Shin SW, Lee SP, Kim JE, Kim JH, Lee JY. Comparative evaluation of a four-implant–supported polyetherketoneketone framework prosthesis: a three-dimensional finite element analysis based on CBCT and CAD. Int J Prosthodont. 2017;30(6):581–5.
19. Vaidyanathan A, Banu RF. Finite element analysis—concepts for knowledge and implementation in dental research. J Indian Prosthodont Soc. 2022;22(2):111–8.
20. Trivedi S. Finite element analysis: a boon to dentistry. J Oral Biol Craniofac Res. 2014;4(3):200–3.
21. Wadhwani C, Piñeyro A. Technique for controlling the cement for an implant crown. J Prosthet Dent. 2009;102(1):57–8.
22. Satpathy M, Pham H, Shah S. Material properties and finite element analysis of adhesive cements used for zirconia crowns on dental implants. Comput Methods Biomech Biomed Engin. 2024;27(8):741–9.
23. Doganay O, Kilic E. Comparative finite element analysis of short implants with different treatment approaches in the atrophic mandible. Int J Oral Maxillofac Implants. 2020;35(3):e69-76.
24. Caglar A, Bal BT, Karakoca S, Aydin C, Yilmaz H, Sarisoy S. Three-dimensional finite element analysis of titanium and yttrium-stabilized zirconium dioxide abutments and implants. Int J Oral Maxillofac Implants. 2011;26(5):961–9.
25. Dayan SC, Geckili O. The influence of framework material on stress distribution in maxillary complete-arch fixed prostheses supported by four dental implants: a three-dimensional finite element analysis. Comput Methods Biomech Biomed Engin. 2021;24(15):1606–17.
26. Yesilyurt NG, Tuncdemir AR. An evaluation of the stress effect of different occlusion concepts on hybrid abutment and implant-supported monolithic

zirconia fixed prosthesis: a finite element analysis. J Adv Prosthodont. 2021;13(4):216–25.
27. Pérez-Pevida E, Brizuela-Velasco A, Chávarri-Prado D, Jiménez-Garrudo A, Sánchez-Lasheras F, Solaberrieta-Méndez E, et al. Biomechanical consequences of the elastic properties of dental implant alloys on the supporting bone: finite element analysis. BioMed Res Int. 2016;2016:1850401.
28. Bal BT, Caglar A, Aydin C, Yilmaz H, Bankoglu M, Eser A. Finite element analysis of stress distribution with splinted and nonsplinted maxillary anterior fixed prostheses supported by zirconia or titanium implants. Int J Oral Maxillofac Implants. 2013;28(1):e27-38.
29. Shash YH, El-Wakad MT, Eldosoky MAA, Dohiem MM. Evaluation of stress and strain on the mandible caused by the "All-on-Four" system from PEEK in hybrid prostheses: finite element analysis. Odontology. 2023;111(3):618–29.
30. Karakaya K, Mutluay Ünal S. Evaluation of stress distribution of different marginal designs on PEEK and PEKK substructure materials, cortical and cancellous bone: a finite element analysis. Comput Biol Med. 2024;178:108708.
31. Erkmen E, Meriç G, Kurt A, Tunç Y, Eser A. Biomechanical comparison of implant-retained fixed partial dentures with fiber-reinforced composite versus conventional metal frameworks: a 3D finite element analysis. J Mech Behav Biomed Mater. 2011;4(2):273–83.
32. Silva GC, Mendonça JA, Lopes LR, Landre J Jr. Stress patterns on implants in prostheses supported by four or six implants: a three-dimensional finite element analysis. Int J Oral Maxillofac Implants. 2010;25(4):751–6.
33. Horita S, Sugiura T, Yamamoto K, Murakami K, Kirita T. Biomechanical analysis of immediately loaded implants according to the "All-on-Four" concept. J Prosthodont Res. 2017;61(2):123–32.
34. Keshavarz Valian N, Talebi Ardakani MR, Aziz Ahari A, Baghani MT, Shidfar S. Patterns of stress and strain in complete-arch prostheses supported by four or six implants: a literature review of finite element analyses. J Adv Periodontol Implant Dent. 2019;10(1):77–84.
35. Lopez CAV, Vasco MAA, Ruales E, Bedoya KA, Benfatti CM, Bezzon OL, et al. Three-dimensional finite element analysis of stress distribution in zirconia and titanium dental implants. J Oral Implantol. 2018;44(6):409–15.
36. Frost HM. A 2003 update of bone physiology and Wolff's Law for clinicians. Angle Orthod. 2004;74(1):3–15.
37. Baggi L, Cappelloni I, Di Girolamo M, Maceri F, Vairo G. The influence of implant diameter and length on stress distribution of osseointegrated implants related to crestal bone geometry: a three-dimensional finite element analysis. J Prosthet Dent. 2008;100(6):422–31.
38. Sahin Hazir D, Sozen Yanik I, Guncu MB, Canay RS. Biomechanical behavior of titanium, cobalt-chromium, zirconia, and PEEK frameworks in implant-supported prostheses: a dynamic finite element analysis. BMC Oral Health. 2025;25(1):48.
39. Takahashi T, Shimamura I, Sakurai K. Influence of number and inclination angle of implants on stress distribution in mandibular cortical bone with the all-on-4 concept. J Prosthodont Res. 2010;54(4):179–84.
40. Desai SR, Koulgikar KD, Alqhtani NR, Alqahtani AR, Alqahtani AS, Alenazi A, et al. Three-dimensional FEA analysis of the stress distribution on titanium and graphene frameworks supported by 3- or 6-implant models. Biomimetics (Basel). 2023;8(1):15.
41. Tezerişener HA, Özalp Ö, Altay MA, Sindel A. Comparison of stress distribution around all-on-four implants of different angulations and zygoma implants: a 7-model finite element analysis. BMC Oral Health. 2024;24(1):176.
42. Ulu M, Yasin M, Sahin O, Akcay H. A finite element analysis to study the stress distribution on distal implants in all-on-six treatment concepts as affected by tilted and short implants. J Oral Implantol. 2024;50(4):245–53.
43. Kelkar KC, Bhat V, Hegde C. Finite element analysis of the effect of framework materials at the bone–implant interface in the all-on-four implant system. Dent Res J. 2021;18:42.
44. Bhering CLB, Mesquita MF, Kemmoku DT, Noritomi PY, Consani RLX, Barao VAR. Comparison between all-on-four and all-on-six treatment concepts and framework material on stress distribution in atrophic maxilla: a prototyping-guided 3D-FEA study. Mater Sci Eng C Mater Biol Appl. 2016;69:715–25.
45. Bethke A, Pieralli S, Kohal RJ, Burkhardt F, von Stein-Lausnitz M, Vach K, et al. Fracture resistance of zirconia oral implants in vitro: a systematic review and meta-analysis. Materials. 2020;13(3):562.
46. Rosentritt M, Hagemann A, Hahnel S, Behr M, Preis V. In vitro performance of zirconia and titanium implant/abutment systems for anterior application. J Dent. 2014;42(8):1019–26.
47. Kohal RJ, Kilian JB, Stampf S, Spies BC. All-ceramic single crown restoration of zirconia oral implants and its influence on fracture resistance: an investigation in the artificial mouth. Materials (Basel). 2015;8(4):1577–89.
48. Kohal RJ, Schikofski T, Adolfsson E, Vach K, Patzelt SBM, Nold J, et al. Fracture resistance of a two-piece zirconia implant system after artificial loading and/or hydrothermal aging: an in vitro investigation. J Funct Biomater. 2023;14(12):567.
49. Ward PAC, Ward FAC, Ward TM, Santos C, Freitas RX, Moreira LP. A strength behavior approach for 3Y-TZP ceramics dental implants based on finite element simulations. Mater Res. 2023;26(6):e20230145.
50. da Costa Ward PA, Ward F, Alves MFRP, Moreira da Silva CR, Moreira LP, Santos C. Numerical analysis of the mechanical behavior of ceramic dental implants based on Ce-TZP/Al2O3 composite. J Mech Behav Biomed Mater. 2024;150:106335.
51. Zhang F, Monzavi M, Li M, Čokić S, Manesh A, Nowzari H, et al. Fracture analysis of one/two-piece clinically failed zirconia dental implants. Dent Mater. 2022;38(10):1633–47.
52. Bosshardt DD, Chappuis V, Buser D. Osseointegration of titanium, titanium alloy and zirconia dental implants: current knowledge and open questions. Periodontol 2000. 2017;73(1):22–40.

Publisher's Note