JFCR

Journal of Fundamental and Clinical Research
https://jfcr.journals.ekb.eg/
ISSN 2735-023X
Vol. 3, No. 2, 154-169, December 2023

Fracture Resistance and Finite Element Analysis of PEEK Versus Titanium Single-piece Implant Restorative Systems (An In-vitro Study)

Tharwat Abaza[1], Moustafa Hussein[2], Tamer Hamza[3]

ABSTRACT

Background: PEEK is an alternative to titanium in implant dentistry due to its favorable mechanical properties. ***Aim:*** To compare the fracture resistance and stress distribution of titanium and PEEK one-piece implant restorative systems. ***Materials and Methods:*** 16 implants were divided into two groups (n=8): titanium implants (Group Ti) and PEEK implants (Group P). All samples received PEEK crowns simulating lower premolars. One-piece titanium implant was scanned and replicated as PEEK implants. Samples were embedded in epoxy resin bases, and PEEK crowns were designed using a biogeneric copy on ExoCAD software. The crowns were cemented to their abutments. Fracture resistance was performed using a universal testing machine. Finite Element Analysis (FEA) was conducted to evaluate stress distribution under different loading scenarios. ***Results:*** Group Ti exhibited significantly higher fracture resistance than Group P ($P < 0.001$). Moreover, there was a notable difference in failure modes ($P < 0.001$), with Group P experiencing more catastrophic failures in fixtures. FEA revealed higher stresses in PEEK than in titanium under various loading conditions. ***Conclusion:*** Titanium showed superior fracture resistance when compared to PEEK and distributed stresses in a more favorable manner than PEEK. Therefore, clinically, PEEK, in its current form, cannot substitute titanium as an implant material.

Keywords: Fracture resistance, one-piece implants, PEEK, stress distribution.

INTRODUCTION

Dental implants are a conservative treatment modality for restoring missing teeth; they have gained preference by practitioners as the optimum treatment of choice owing to their high success rates, long-term stability, and ability to restore function and esthetics. The long-term success of dental implants in the oral cavity depends on successful osseointegration with the bone and favorable load distribution along the implant and the surrounding anatomical structures.[1,2]

1-Postgraduate Researcher, Fixed Prosthodontics Department, Faculty of Oral and Dental Medicine, Misr International University, Cairo, Egypt.

2-Lecturer of Fixed Prosthodontics, Fixed Prosthodontics Department, Faculty of Oral and Dental Medicine, Misr International University, Cairo, Egypt.

3-Professor of Fixed Prosthodontics, Fixed Prosthodontics Department, Dean of Faculty of Dentistry, Badr University, Cairo, Egypt.

Continuous introduction of new implant materials over the years has occurred with the purpose of overcoming the limitations of already existing materials, which include the biomechanical behavior of implants, such as load distribution along the implant, its superstructure, and the supporting bone. Polyetheretherketone (PEEK) has been introduced to dentistry given its promising and unique mechanical properties, which can contribute to favorable stress distribution owing to its strength, elasticity, and wear resistance.[3–5] PEEK was introduced as an ideal candidate for implantology as both an implant material and a fixed implant superstructure. Moreover, as an implant, PEEK's lower modulus of elasticity compared to titanium has been shown to reduce stress shielding, which may result in better preservation of the surrounding crestal bone.[4,6,7]

One-piece dental implants offer several advantages compared to two-piece implants, such as functional rehabilitation with no damage to surrounding tissues, less pain and inflammation to the patient, and fewer prosthetic procedures and visits. They offer better osseointegration, lesser micromovements, and good soft tissue healing. Moreover, they are a predictable alternative to fixed partial dentures and adhesive bridges. These implants have been shown to have high long-term survival rates and the capacity to maintain stable hard and soft tissues around implants after initial bone remodeling. In some cases, using one-piece implants eliminated the need for multiple bone regeneration procedures.[8,9]

Regarding load distribution, a FEA conducted by **Wu et al.**[10] concluded that the stress values were greater in the crestal bone encompassing the two-piece dental implants than one-piece implants. Results were proposed as a potential reason for increased marginal bone loss in the two-piece implants.

Regarding the biomechanical behavior of PEEK as an implant, it was clear that further in vitro and in vivo research was needed to understand better the full potential of PEEK and its use in implant dentistry, as well as pure PEEK implants and one-piece PEEK implants and how such different scenarios influenced the stress distribution transmitted throughout the restorative system and the surrounding bone and the fracture resistance of the material.

Therefore, the purpose of this study was to evaluate and compare the fracture resistance between two implant materials, titanium and PEEK in one-piece implant forms, and stress distribution and the resulting strain in each of the materials and how it translates to the surrounding peri-implant bone.

The null hypothesis was that there would be no significant difference in fracture resistance and stress distribution between PEEK and titanium.

MATERIALS AND METHODS

Materials used in this study are listed in **Table (1)**.

A prefabricated titanium implant (Dentium, SlimLine, Korea) of 3 mm in diameter and 10 mm in length **(Figure 1)** was coated with an antireflection spray (Bilkim, Turkey) and scanned using an optical desktop scanner (DS Mizar, Italy) to generate a Standard Tessellation Language (STL) file. This STL file was exported (Chitu Box Software, China) and 3D printed (Any Cubic Photon Mono SE, China) into castable burn-out resin. The resin model was then sprued and invested before being placed in a preheating furnace. The temperature was gradually increased to 900°C and held for 30

Table (1): Materials used in the study.

Material	Brand Name	Material Description	Manufacturer
BioHPP® Granulat	Bredent	PEEK granules used for pressing fixed retorations	Bredent® GmbH & Co. KG, Senden, Germany
Dentium® SlimLine	Dentium	One-piece Titanium implant system, fix type implant.	Dentium Co., Seoul, Korea

Sample Size Calculation:

This power analysis used fracture resistance as the primary outcome. Based upon the results of **Atsü SS et al.**[11] and the minimum estimated sample size was eight specimens per group. Sample size calculation was performed using G*Power Version 3.1.9.2.

Testing and Sample Grouping:

A total of 16 Samples were divided into two groups (n=8) according to the material of implants. Group (Ti): Eight one-piece titanium implants with PEEK restoration (Control group). Group (P): Eight one-piece PEEK implants with PEEK restoration.

Fabrication of PEEK implants:

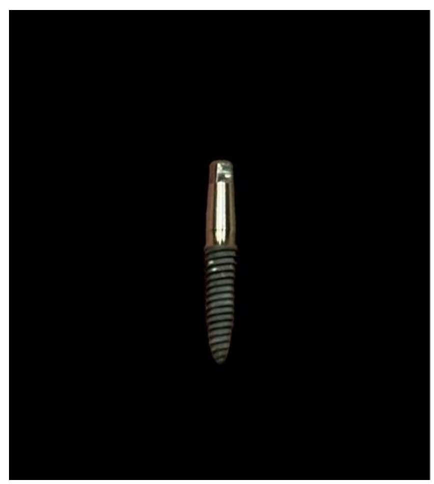


Figure (1): Prefabricated Titanium Implant (Dentium, SlimLine).

minutes, followed by cooling to 400°C. PEEK (Bredent, BioHPP Granulat, Germany) granules were inserted with a plunger into the mold at the same temperature for 20 minutes. Subsequently, the mold was transferred to a vacuum press device (Bredent, for 2 Press, Germany). The pressing was carried out automatically, and after the vacuum was completed, the mold was cooled down to room temperature with maintained pressing pressure. The PEEK implants were then divested, rinsed in a water bath, and cleared of remnants using a fine blasting device. The PEEK implants were finished and polished **(Figure 2)**.

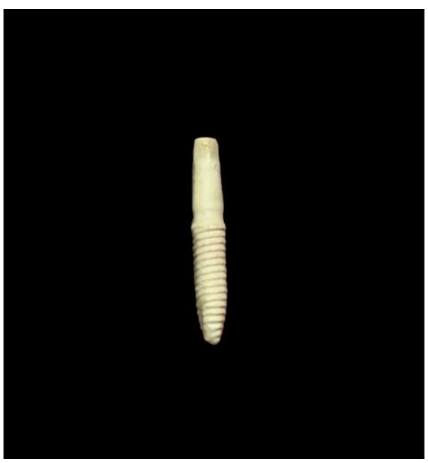


Figure (2): Finished PEEK Implant.

All implants were embedded in epoxy resin cylinders using a silicone mold. The epoxy resin was mixed with a ratio of 2 parts resin to 1 part hardener. The implants were secured to a surveyor apparatus for accurate positioning during the curing process for consistent placement and stabilization. Epoxy resin was fully cured after 72 hours.

Fabrication of PEEK superstructure:

For the fabrication of the superstructure, the implant abutments were scanned, and the crowns were designed using the CAD software (ExoCAD) to replace a lower first premolar with dimensions adjusted to the implant abutments and a cement space of 100 µm. A single crown design was generated using a biogeneric copy and adjusted to fit each implant abutment. CAD/CAM wax discs were used to mill the crowns using a 5-axis milling machine (SHERA Eco-mill 5x). The same pressing procedure used for the PEEK implants was followed. Finally, the PEEK crowns were finished and polished. To standardize the cementation process, sandblasting was performed on all PEEK crowns and all implant abutments using aluminum oxide particles (COJET Sand, 3M, ESPE) 110 µm at a pressure of 3 bar for 15 seconds, and the nozzle was fixed at 50 mm from samples.[12,13] A composite primer (Bredent Visio.Link, Germany) was applied to the intaglios of the crowns, as well as the PEEK abutments, and light cured for 20 seconds according to the manufacturer's recommendations. For the titanium implant, a specialized metal primer (Bredent MKZ primer, Germany) was used. Auto-mix adhesive resin cement (Bredent DTK Kebler, Germany) was utilized to fill the intaglios of the crowns in order to eliminate air bubbles and unify the cementation process. A custom cementing device was employed to apply consistent force (3 kg) directly on the central fossa of the crowns, in line with previous studies.[14] Upon removal of excess cement, all samples were cured using a light-curing box (Bredent Bre.Lux Power Unit 2, Germany) for 90 seconds each.

Fracture Resistance:

Each sample was mounted on a computer-controlled testing machine equipped with a 5 kN load cell and data recording software (Bluehill Lite Software, Instron®). Samples were secured to the lower fixed compartment of the machine. The fracture test was performed in a compressive mode, applying an occlusal load with a metallic rod with a rounded tip (3.4 mm diameter). The crosshead speed was set at 1 mm/min, with a tin foil sheet placed in-between to ensure homogeneous stress distribution and minimize local force peak transmission. The load was applied to the central fossa of superstructures. Failure was detected by an audible crack and confirmed by a sudden drop in the load-deflection curve recorded using computer software. The fracture load was recorded in N.[11,15]

Finite Element Analysis:

The previously acquired STL files were used to create the FEA model using software (ANSYS Workbench version 16.0, USA). An intermediate software (3-Matic version 7.01, Materialise NV, Belgium) refined the data points and generated an outer surface exported in IGES format. Solidworks (Dassault Systèmes Inc., France) was used to address errors and export the solid component as a STEP file. The bone geometry was simplified as two coaxial cylinders representing cancellous (12 mm diameter x 20 mm high) and cortical bone (16 mm diameter x 24 mm high). Boolean operations were performed to create a cement layer of 100µm[16] around the implant. The complete model was assembled in ANSYS. Materials' elastic moduli and Poisson's ratios were defined as listed in **Table (2)**. The model was meshed using ANSYS Workbench.[17] A meshing convergence test was conducted by applying test loads to various mesh densities, ensuring result accuracy for the discrete model. The resulting node and element counts are detailed in **Table (3)**. Vertical and oblique (45°), 100 N and 50 N, respectively, were tested.[18]

RESULTS

1. **Fracture Resistance Test:**

Numerical data were explored for normality

Table (2): Material Properties.

Material	Young's modules [MPa]	Posison's ratio
Crown PEEK	4,200	0.37
Resin Cement	8,000	0.30
Implant: Ti	110,000	0.33
Implant: PEEK	4,200	0.37
Mucosa	10	0.40
Cortical bone	14,600	0.30
Cancellous bone	1,400	0.30

Table (3): Model components and respective mesh density.

Component	Number of Nodes	Number of Elements
Crown	17,464	11,877
Resin Cement	2,317	1,139
Implant	41,470	28,043
Mucosa	20,817	13,225
Cortical bone	114,879	73,646
Cancellous bone	140,446	96,109

by checking the distribution of data and using Kolmogorov-Smirnov and Shapiro-Wilk tests. Fracture resistance data showed normal (parametric) distribution. Data were presented as mean and standard deviation (SD) values. Student's t-test was used to compare between the two groups. Ti group showed statistically significantly higher mean fracture resistance than the P group (*P*-value <0.001, Effect size = 2.519), as shown in **Table (4) and Figure (3).** Failure mode data were presented as frequencies and percentages. Fisher's exact test was used to compare between failure modes of the two groups. The significance level was set at P ≤ 0.05. Statistical analysis was performed with IBM SPSS Statistics for Windows (Version 23.0. Armonk, NY: IBM Corp). There was a statistically significant difference between failure modes in the two groups (*P*-value <0.001, Effect size = 1). Ti group showed a higher prevalence of deformation in superstructure without and with fracture than P group, which showed a higher prevalence

Table (4): Descriptive statistics and results of Student's t-test for comparison between fracture resistance (N) of the two materials.

Ti (n = 8)		P (n = 8)		*P*-value	Effect size *(Eta squared)*
Mean	SD	Mean	SD		
749.4	168.3	373.1	127.8	<0.001*	2.519

**: Significant at P ≤ 0.05.*

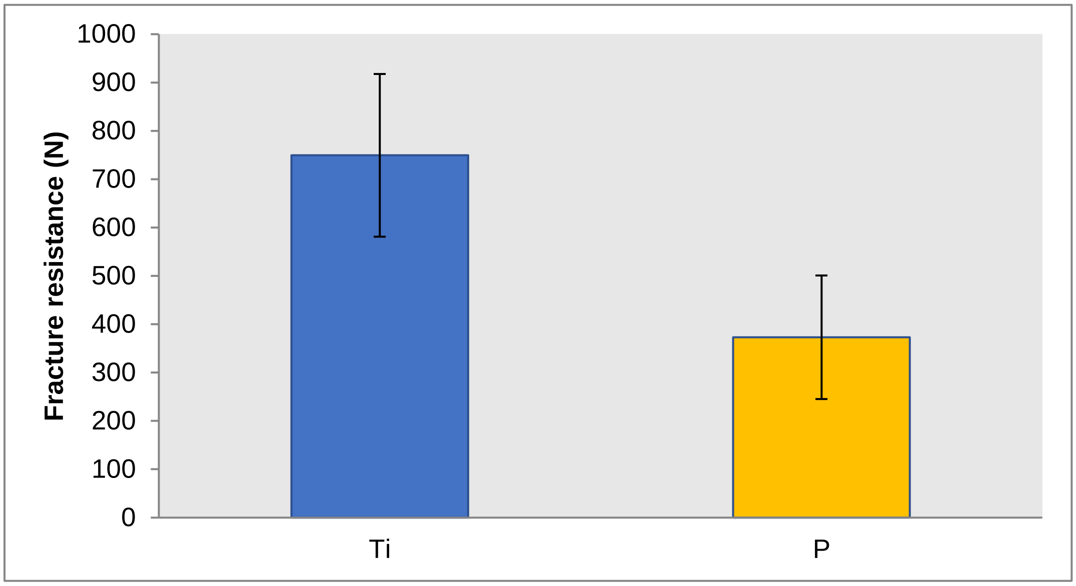


Figure (3): Bar chart representing mean and standard deviation values for fracture resistance in the two groups.

of catastrophic fracture and deformation with fracture in fixture and superstructure as shown in **Table (5) and Figure (4).**

1. Finite Element Analysis:

When the titanium model was loaded **(Figure 5 a)**, the PEEK crown experienced

Table (5): Frequencies (n), percentages (%) and results of Fisher's Exact test for comparison between failure modes of the two groups.

Failure mode	Ti (n = 8)		P (n = 8)		*P*-value	Effect size *(v)*
	n	%	n	%		
Deformation without fracture in superstructure	3	37.5	0	0	<0.001*	1
Deformation with fracture in superstructure	3	37.5	0	0		
Fracture in superstructure	1	12.5	0	0		
Fracture in fixture	1	12.5	0	0		
Catastrophic fracture	0	0	7	87.5		
Deformation without fracture in fixture	0	0	1	12.5		

**: Significant at P ≤ 0.05.*

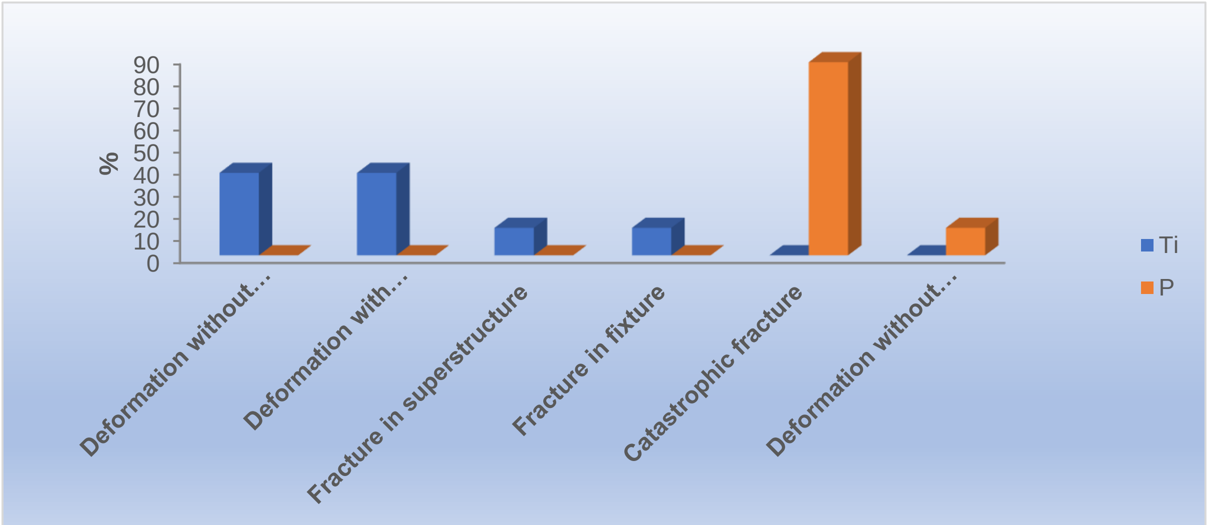


Figure (4): Bar chart representing failure modes of the two groups.

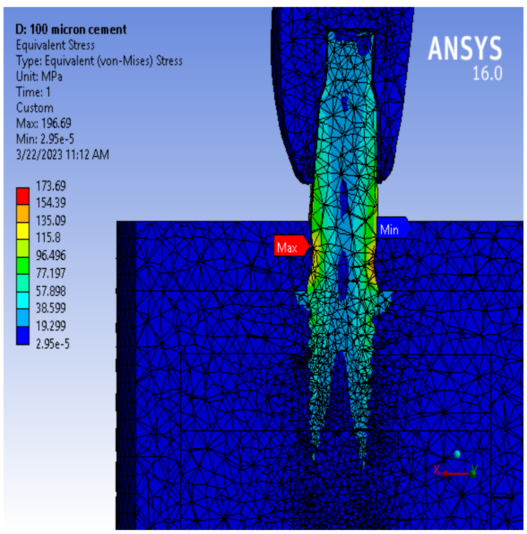


Figure (5 a): Total Von Mises stresses on Titanium model.

high stresses but a limited deformation, suggesting potential crown survival. The cement layer showed acceptable stresses. Vertical loading showed comparable stress values for titanium and PEEK implants, but under oblique loading, titanium had significantly lower stresses on surrounding structures compared to PEEK. Titanium kept stress values within the physiological limits of the cortical bone, indicating long-term durability.

The PEEK model **(Figure 5 b)** showed

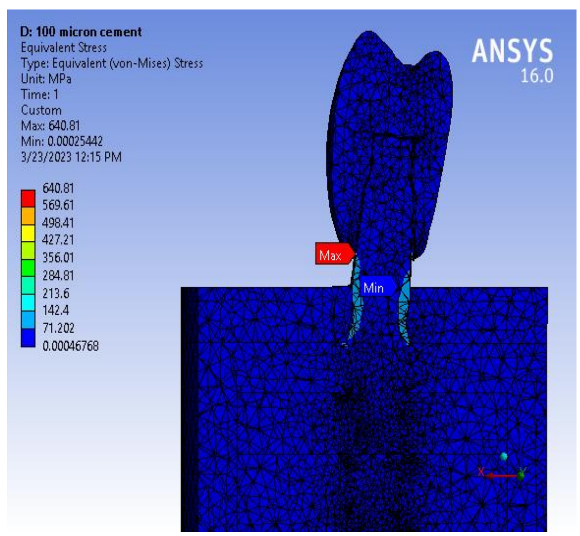
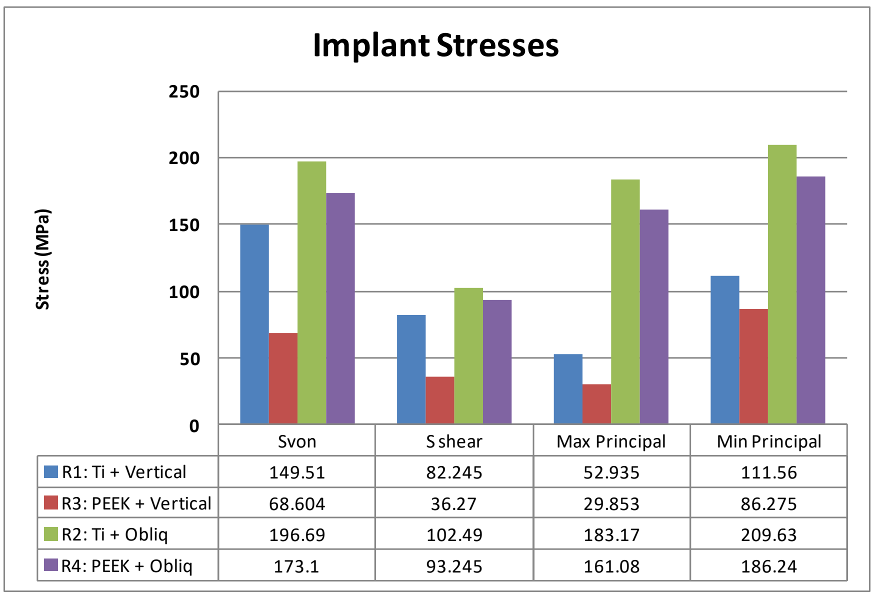


Figure (5 b): Total Von Mises stresses on PEEK model.

inferior results in all aspects. The PEEK crown supported by a PEEK implant showed a deformation of up to 1mm. Deformation values of the cement layer above the PEEK implant were very high, indicating possible cement layer failure. The PEEK implant experienced significantly greater deformation than titanium (approximately five times more). While stresses in both implants were similar under vertical loading, the PEEK implant failed under oblique loading. For the cortical bone, the PEEK implant could potentially survive vertical loading but might cause cortical bone failure under oblique loading. (**Figures 6 a & b).**

Furthermore, they could be used in restoring minimal edentulous spaces, and they allow for minimally invasive surgical procedures that foster improved soft tissue adhesion.[22]

Numerous studies have explored the load distribution in one-piece and two-piece implants. The results indicated that stress distribution might be more favorable in one-piece implants versus the two-piece; stress concentration was found to be usually higher at the junction between abutments and



	Svon	S shear	Max Principal	Min Principal
R1: Ti + Vertical	149.51	82.245	52.935	111.56
R3: PEEK + Vertical	68.604	36.27	29.853	86.275
R2: Ti + Obliq	196.69	102.49	183.17	209.63
R4: PEEK + Obliq	173.1	93.245	161.08	186.24

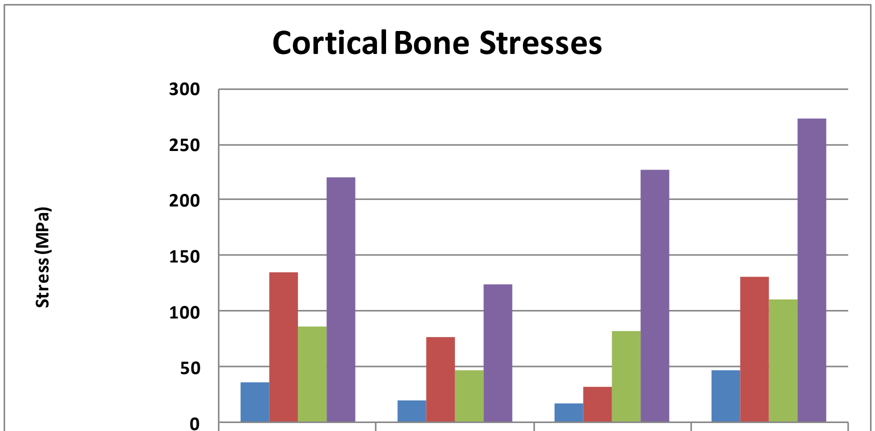
Figure (6 a): Bar chart showing Von Mises stresses on implants.

DISCUSSION

One-piece implants offer numerous biomechanical advantages in comparison to two-piece implants. Among the advantages is the absence of microgaps between the implant platform and abutment, reducing vertical bone loss, which may occur at a slower rate with one-piece implants.[19–21]

fixtures. These findings suggest that one-piece implants might offer better mechanical performance in terms of stress distribution.[22]

The rationale behind the selected dimensions of the one-piece implant in this study was to simulate cases with minimal width of edentulous space; hence lower first premolar scenario was chosen and implant



	Svon	S shear	Max Principal	Min Principal
R1: Ti + Vertical	35.904	19.441	17.651	47.422
R3: PEEK + Vertical	134.45	76.786	31.816	131.06
R2: Ti + Obliq	86.332	46.888	82.647	110.03
R4: PEEK + Obliq	220.69	124.46	226.54	273.03

Figure (6 b): Bar chart showing Von Mises stresses on cortical bone.

diameter of 3mm.[23,24] Many studies accepted that 10 mm length in implants maintained good bone to implant contact levels.[24–26]

For standardization of PEEK implants fabrication, a one-piece prefabricated titanium implant was scanned to produce an STL file which was then used to produce 3D printed burn-out resin models, which were processed into PEEK implants using the pressing technique. As for the superstructure, a single crown simulating a lower premolar was designed using a biogeneric copy over the previously scanned titanium implant's abutment. The design was adapted to each implant abutment. The cement space was set to 100 µm, which contributes to favorable stress distribution and success of the implant restoration according to numerous studies.[27–30]

The pressing method was preferred for the fabrication of PEEK implants and crowns due to its ability to accurately reproduce the intricate features of the titanium implant that were vital to the research objectives which agrees with a study conducted by **Das et al.**[31]

The testing was divided into two parts: For fracture resistance, samples were subjected to static vertical loading of 5kN at a crosshead speed of 1mm/min. The load was applied on the central fossa of the superstructure, with a tin foil sheet placed in-between to ensure homogeneous stress distribution.[32]

According to the outcomes of this study, the null hypothesis was rejected as there was significant difference in fracture resistance and stress distribution between PEEK and titanium.

The results showed a statistically significant difference between failure modes in the two groups. Titanium showed higher fracture resistance values than PEEK. Furthermore, titanium showed a higher prevalence of deformation in the superstructure with fracture of the superstructure in some cases. However, only one of the titanium fixtures showed fracture. On the other hand, PEEK showed fracture in superstructure as well as in fixtures. The results agreed with other studies conducted by **Neumann et al.**[33] and **Ortega-Martinez et al.**[34]

Our findings were not in agreement with **Atsü et al.,**[11] who concluded that PEEK had greater fracture resistance. However, this disagreement could be attributed to their use of PEEK as an abutment only.

Several potential factors could explain the outcomes observed in this study; the PEEK susceptibility to undergo significant plastic deformation followed by fracture under compressive loading may be attributed to their high flexural performance and low elastic modulus.[35]

As for FEA, the aim was to simulate the diverse oral loads, therefore, two loading scenarios were chosen; the first was vertical loading at 100 N on the distal fossa and the buccal cusp tip. While the second was oblique loading at 45° and 50 N applied on the buccal cusp slope of the buccal surface.[18]

Results showed extreme stress values which exceeded the yielding stress of the PEEK material (100-110 MPa). However, it's noteworthy that these values were concentrated in the loading sites only, indicating a long lifespan for the crown body. This agrees with a study conducted by **Schmeiser et al.,**[36] where PEEK might respond to load with minimal deformation over time.

In this study, high directional and deformation values with elevated stresses in the cement above the PEEK implant suggested potential failure of cement layer. These findings partially agreed with the findings of **Tamrakar et al.,**[37] who concluded that stresses at the cement layer were increased when PEEK crowns were used with PEEK implants as opposed to titanium implants.

Under vertical loading, both materials showed favorable results. However, PEEK implant exhibited very high stresses under oblique loading, indicating failure. These results agreed with **Harinee et al.,**[38] who found that PEEK showed the highest stresses under oblique loading.

It was also found that PEEK implant could lead to cortical bone failure under oblique loading as the stresses it generated exceeds the yield strength of the bone. Conversely, when PEEK implant was subjected to vertical or compressive loading, the results showed safer values.

Titanium implants demonstrated stress values indicating successful implantation and a long lifetime under the tested loads. These findings agreed with the FEA conducted by **Schwitalla et al.,**[3] who concluded that the highest stress values in the cortical bone were found in PEEK.

The findings in this study showed some variations from other studies as we utilized PEEK as both a one-piece implant and superstructure. Moreover, other studies used different PEEK generations or used PEEK only as a specific component in the assembly.[4,39,40]

Certain limitations were present in this study:

1. Inability to simulate oral environment's diverse loading conditions.
2. A single PEEK generation was utilized in the study. Many other modifications of the material should also be studied.
3. FEA involves simplifying the complex anatomical structures of the oral cavity. These simplifications can affect the accuracy and reliability of the results.

CONCLUSION

Within the limitations of the study, the following was concluded:

1. Fracture resistance testing showed that titanium had a higher fracture resistance than PEEK.
2. The PEEK implant exhibited significant deformation, particularly under oblique loads, which had adverse effects on both the crown and cortical bone.
3. The cortical bone exhibited stresses within acceptable physiological limits when paired with a titanium implant.

FUNDING: This research received no external funding.

CONFLICTS OF INTEREST: The authors declare no conflict of interest.

REFERENCES

1. Buser D, Janner SFM, Wittneben JG, Brägger U, Ramseier CA, Salvi GE. 10-Year Survival and Success Rates of 511 Titanium Implants with a Sandblasted and Acid-Etched Surface: A Retrospective Study in 303 Partially Edentulous Patients. Clin Implant Dent Relat Res. 2012 Dec;14(6):839–51.
2. Buser D, Sennerby L, De Bruyn H. Modern implant dentistry based on osseointegration: 50 years of progress, current trends and open questions. Periodontol 2000. Blackwell Munksgaar-

d; 2017 Feb;73(1):7–21.

3. Schwitalla AD, Abou-Emara M, Spintig T, Lackmann J, Müller WD. Finite element analysis of the biomechanical effects of PEEK dental implants on the peri-implant bone. J Biomech. 2015 Jan 2;48(1):1–7.
4. Tekin S, Cangül S, Adıgüzel Ö, Değer Y. Areas for use of PEEK material in dentistry. IDR. 2018 Aug 27;8(2):84–92.
5. Wang B, Huang M, Dang P, Xie J, Zhang X, Yan X. PEEK in Fixed Dental Prostheses: Application and Adhesion Improvement. Polym. 2022;14(12):1–19.
6. Skirbutis G, Dzingutė A, Masiliūnaitė V, Šulcaitė G, Žilinskas J. A review of PEEK polymer's properties and its use in prosthodontics. Stomatologia, Baltic Dent and Maxillofac Journal. 2018;20(2):54–8.
7. Adem N, Bal B, Kazazoğlu E. Comparative Study of Chemical and Mechanical Surface Treatment Effects on Shear Bond Strength of PEEK to Veneering Ceramic. Int J Prosthodont. 2022 Mar;35(2):201–7.
8. Barrachina-Diez JM, Tashkandi E, Stampf S, Att W. Long-Term Outcome of One-Piece Implants. Part I: Implant Characteristics and Loading Protocols. A Systematic Literature Review with Meta-Analysis. Int J Oral Maxillofac Implants. 2013 Mar;28(2):503–18.
9. Durrani F, Pandey RN, Singh P, Pandey A. One-piece implants: Careful approach for complex rehabilitation. National Journal of Maxillofac Surgery. 2021 May 1;12(2):266–70.
10. Wu AYJ, Hsu JT, Chee W, Lin Y, Fuh LJ, Huang HL. Biomechanical evaluation of one-piece and two-piece small-diameter dental implants: In-vitro experimental and three-dimensional finite element analyses. J Formos Med Assoc. 2016 Sep 1;115(9):794–800.
11. Atsü S, Aksan M, Bulut A. Fracture Resistance of Titanium, Zirconia, and Ceramic-Reinforced Polyetheretherketone Implant Abutments Supporting CAD/CAM Monolithic Lithium Disilicate Ceramic Crowns After Aging. Int J Oral Maxillofac Implants. 2019 May;34(3):622–30.
12. Elfiky, Y., Nabil, O., & Alansary, H. The effect of different air blasting pressure of polyetheretherketone (PEEK) on surface roughness and bond strength to adhesive resin cement: An in-vitro study. Int J Appl Dent Sci, 2023 Jan;*9*(2), 259–66.
13. Elawadly, T., Radi, I. A. W., el Khadem, A., & Osman, R. B. Can PEEK Be an Implant Material? Evaluation of Surface

Topography and Wettability of Filled Versus Unfilled PEEK With Different Surface Roughness. Journal of Oral Implantology, 2017; 43(6), 456–61.

14. Hegazy, M., Shakal, M., el Sharkawy, S., & Sultan, S. Effect of Cement Space Settings on the Vertical Marginal gap of Cement Retained - Implant Supported Crowns: An in vitro study. Adv Dent J, 2022;*4*(2), 110–22.
15. Attia MA, Amr H. Effect of different Restorative Crowns on Fracture Resistance and Stress Distribution In Single Implants; An In Vitro Study. Vol. 64, Egypt Dent J. 2018 October;(64):3813–22
16. Al Qahtani WMS, Yousief SA, El-Anwar MI. Recent Advances in Material and Geometrical Modelling in Dental Applications.Maced J Med Sci. 2018;6(6):1138–44.
17. Al Qahtani WMS, El-Anwar MI. Advanced Computational Methods in Bio-Mechanics. Maced J Med Sci. 2018 Apr 8;6(4):742–6.
18. Cinel S, Celik E, Sagirkaya E, Sahin O. Experimental evaluation of stress distribution with narrow diameter implants: A finite element analysis. J Prosthet Dent. 2018 March;119(3);417-25.
19. Engquist B, Astrand P, Anzén B, et al. Simplified methods of implant treatment in the edentulous lower jaw. A controlled prospective study. Part I: one-stage versus two-stage surgery. Clin Implant Dent Relat Res. 2002;4(2):93–103.
20. Száva DT, Ormenișan A, Markovics E, Bögözi B, Mártha K. Alveolar Bone Resorption Evaluation Around Single-piece Designed Bicortical Implants, Using Immediate Loading Protocol, Based on Orthopantomographs. JIM. 2017 Dec 1;2(4):328–31.
21. Badr A, Zaki M. Radiographic evaluation of crestal bone loss around one- piece versus two-piece implant with bar retaining mandibular overdenture (A Randomized clinical trial). Egypt Dent J. 2022 Oct 1;68(4):3717–24.
22. Rajput N. Minimally Invasive Transmucosal Insertion and Immediate Provisonalization of One- Piece Implant in Partially Edentulous Posterior Mandible. JCDR. 2013; 7(9):2070–3.
23. Saad M, Assaf A, Gerges E. The Use of Narrow Diameter Implants in the Molar Area. Int J Dent. 2016 May;(2016)1–8.
24. Himmlová L, Dostálová T, Kácovský A, Konvičková S. Influence of implant length and diameter on stress distribution:

A finite element analysis. J Prosthet Dent. 2004 Jan;91(1):20–5.

25. Aragoneses J, Aragoneses J, Brugal V, Gomez M, Suarez A. Relationship between Implant Length and Implant Stability of Single-Implant Restorations: A 12-Month Follow-Up Clinical Study. Medicina (B Aires). 2020 May 27;56(6):263–74.
26. Svezia L, Casotto F. Short Dental Implants (6 mm) Versus Standard Dental Implants (10 mm) Supporting Single Crowns in the Posterior Maxilla and/or Mandible: 2-Year Results from a Prospective Cohort Comparative Trial. J Oral Maxillofac Res. 2018 Sep 30;9(3);(e4)1–4.
27. Sokolowski G, Krasowski M, Szczesio-Wlodarczyk A, Konieczny B, Sokolowski J, Bociong K. The Influence of Cement Layer Thickness on the Stress State of Metal Inlay Restorations—Photoelastic Analysis. Mater. 2021 Jan 28;14(3):599–610.
28. He J, Zheng Z, Wu M, Zheng C, Zeng Y, Yan W. Influence of restorative material and cement on the stress distribution of endocrowns: 3D finite element analysis. BMC Oral Health. 2021 Oct 5;21(1):495–504.
29. Hegazy M, Shakal M, El Sharkawy S, Sultan S. Effect of Cement Space Settings on the Vertical Marginal gap of Cement Retained - Implant Supported Crowns: An in vitro study. Adv Dent J. 2022 Apr 1;4(2):110–22.
30. El-Anwar MI, Tamam RA, Fawzy UM, Yousief SA. The effect of luting cement type and thickness on stress distribution in upper premolar implant restored with metal ceramic crowns. Tanta Dent J. 2015 Mar;12(1):48–55.
31. Das G, Rana MH, Khan SA, Chaudhary MAG, Sibghatullah M, Kumar B. Assessment of Fracture Resistance of PEEK and Fibre Posts of the Endodontically Treated Teeth. Mat Plast. 2022;59(1):207–13.
32. Donmez MB, Diken Turksayar AA, Olcay EO, Sahmali SM. Fracture Resistance of Single-Unit Implant-Supported Crowns: Effects of Prosthetic Design and Restorative Material. J Prosthodont. 2022 Apr 30;31(4):348–55.
33. Neumann F, Villar C, Franca F. Fracture resistance of abutment screws made of titanium, polyetheretherketone, and carbon fiber-reinforced polyetherethe-rketone. Braz Oral Res. 2014 Aug 4;28(1):1–5.

34. Ortega-Martínez J, Delgado LM, Ortiz-Hernández M, Punset M, Cano-Batalla J, Cayon MR, et al. In vitro assessment of PEEK and titanium implant abutments: Screw loosening and microleakage evaluations under dynamic mechanical testing. J Prosthet Dent. 2022 Mar;127(3):470–76.
35. Stawarczyk B, Eichberger M, Uhrenbacher J, Wimmer T, Edelhoff D, Schmidlin PR. Three-unit reinforced polyetheretherketone composite FDPs: Influence of fabrication method on load-bearing capacity and failure types. Dent Mater. 2015;34(1):7–12.
36. Schmeiser F, Arbogast F, Ruppel H, Mayinger F, Reymus M, Stawarczyk B. Methodology investigation: Impact of crown geometry, crown, abutment and antagonist material and thermal loading on the two-body wear of dental materials. Dent Mater. 2022 Feb;38(2):266–80.
37. Tamrakar S, Mishra S, Chowdhary R, Rao S. Comparative analysis of stress distribution around CFR-PEEK implants and titanium implants with different prosthetic crowns: A finite element analysis. Dent Med Probl. 2021 Sep 30;58(3):359–67.
38. Harinee A. Comparison of Mechanical Properties of Implant materials, Zirconia, Titanium, and PEEK. Finite Element Analysis. Int J Adv Res (Indore). 2023 Feb 28;11(02):656–63.
39. Tekin S, Adıgüzel Ö, Cangül S, Ataş O. Evaluation of the use of PEEK material in post-core and crown restorations using finite element analysis. Am J Dent. 2020 Oct;33(5):251–57.
40. Hossam M, Elshahawy W, Masoud GE. Evaluation of Marginal Adaptation and Fracture Resistance of BioHPP and Zirconia. Egypt Dent J. 2019 Mar;64:1489–501.