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STRESS DISTRIBUTION IN TITANIUM AND PEEK DENTAL IMPLANTS WITH INTERCHANGEABLE ABUTMENTS AND CROWNS: A FINITE ELEMENT ANALYSIS STUDY

Prosthodontics

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ABSTRACT

Background: The physical and mechanical properties of implants, abutments and crowns differ from material to material owing to their variable composition. Therefore, changes in abutment and crown materials can alter the stress distribution in implants. **Aim:** The purpose of this study was to evaluate and compare the stress distribution in implants using titanium and polyether ether ketone (PEEK) as implant materials with interchangeable abutments and crowns by Finite Element Analysis (FEA). **Material And Method:** A three-dimensional (3D) model of a bone block was created to represent the left mandibular 1[st] molar region with a bone-level implant of 4.0 * 10 mm system of Titanium and PEEK material, straight abutment and cement retained crown with 100% osseointegration, using Geomagic software. The study involved eight models that were divided into four groups, which were created according to the variation in the implant material (PEEK or Titanium), abutment material (PEEK or Titanium), and crown material (PEEK or PFM). Group 1: titanium implant, titanium abutment with PFM and PEEK crowns; Group 2: titanium implant, PEEK abutment with PFM and PEEK crowns; Group 3: - PEEK implant, titanium abutment with PFM and PEEK crowns; and Group 4: - PEEK implant, PEEK abutment with PFM and PEEK crowns. In each model, the implants were subjected to a vertical load of 200 N (on the central fossa), oblique load of 70 N (at 45° to the buccal cusp), and horizontal load of 50 N (on the occlusal 1/3[rd] of the buccal surface of the mesiobuccal cusp) to mimic clinical forces, and stress distribution was evaluated through von Mises stress analysis. **Results:** The study revealed that titanium implants (Group 1) exhibited higher stress levels than PEEK implants (Group 4), particularly under oblique and horizontal loads. PEEK implants with titanium abutments (Group 3) showed the lowest stress levels and damage across all loading conditions. **Conclusion:** PEEK implants with titanium abutments can be used, as they are likely to provide enhanced durability and longevity under high stress conditions to mitigate the risk of implant failure.

KEYWORDS

Finite Element Analysis, Stress distribution, PEEK implant, Titanium implant.

INTRODUCTION

Throughout history, societies have valued having a full set of teeth, for both functional and aesthetic reasons. Removable complete dentures are the standard treatment for complete edentulism. Lack of appropriate occlusion, taste loss, speech impairment, and inadequate denture stability are the primary reasons why patients are dissatisfied with complete dentures.[1,2]

To restore a patient's function, comfort, and appearance, an implant supporting a single crown has emerged as the best option for single-tooth replacement. In addition to osseointegration, an implant should be able to maintain prosthetic and esthetic function without causing pain or exhibiting any indications of local disease. According to literature, incorrect biomechanics of dental implants often cause implant failure. Furthermore, a significant contributing factor to implant failure, particularly in the posterior region, is the distribution of occlusal force.[3]

Since dental implants do not have the periodontal ligament, they are securely affixed to bones. Therefore, there was a slight loss of bone due to the absence of the masticatory muscle proprioceptive feedback process. According to reports, a crestal vertical bone loss of 1 mm during the first year and 0.01 mm in following years. If the material used for implants had an elastic modulus comparable to that of bone, the supporting tissues might experience a more uniform distribution of stress.[4,5]

Since its introduction by Branemark in 1978, Titanium (Ti) has been the preferred material for dental implants. However, the literature has documented some disadvantages of using Ti, including its propensity to trigger allergic responses and hypersensitivity.[6] In recent years, polyetheretherketone (PEEK) has drawn attention which was created in 1978, it is an organic, synthetic, polymeric substance with good mechanical qualities, biocompatibility, and chemical resistance. It is utilized in implant-supported hybrid prostheses, the abutment, the implant fixture, and the implant superstructure.[4,6]

Finite element analysis (FEA) is a novel and important method for biomechanical assessment in biological research in which solid objects are divided into multiple elements that are joined at a common nodal point to create a finite-element model. This is the most effective method for modeling complex structures and studying their mechanical properties. The physical and mechanical property of implant, abutment and crown differs from material to material because of variable composition.[7-9]

Static loading is typically used for stress analysis, and the mechanical characteristics of materials are assumed to be isotropic and linearly elastic, even though this is not the case in practice. Without mandibular motions, static stresses are applied from the mandible to the maxilla, and their intensity doesn't change over time.[8,10]

In order to identify an appropriate selection criterion, various abutment and crown materials were taken into account, and all anticipated loading circumstances were integrated. Hence, this study aimed to evaluate and compare the stress occurring in PEEK and Titanium implants with interchangeable abutments and crowns by loading through FEA.

MATERIAL AND METHODS

Data Collection

CT Scan

A CBCT scan of a healthy adolescent skull, showing no signs of skeletal abnormalities, trauma, or lesions, was retrieved from the archives of a well-known CBCT scanning facility. The scan involved a full set of teeth including the second molars. The resulting DICOM files were generated at scanning interval of 0.5 mm.

Fabrication of Geometric Model

All DICOM files were imported into MIMICS software to build a 3D model. A standard tessellation language (STL) file was then exported to depict the 3D reconstruction of all DICOM slices. The STL file was converted into a CAD model, which was then imported into Geomagic software, where the STL file was modified into a surface-based CAD model. Finally, the CAD model was saved and imported into the FEM software, and further analysis was performed using Altair HyperMesh software.

3D Model of Implant & Abutment

OSSTEM Dental Implant details were obtained from OSSTEM Documentation received from the Implant manufacturer. Numerous CAD techniques, such as Extrude, Revolve, and Sweep were used to build the implant substructure (Figure 1).

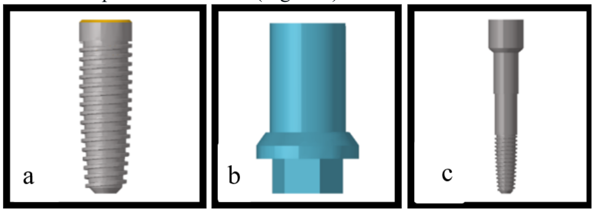


Figure 1: (a) Implant;(b) Abutment;(c) Abutment screw

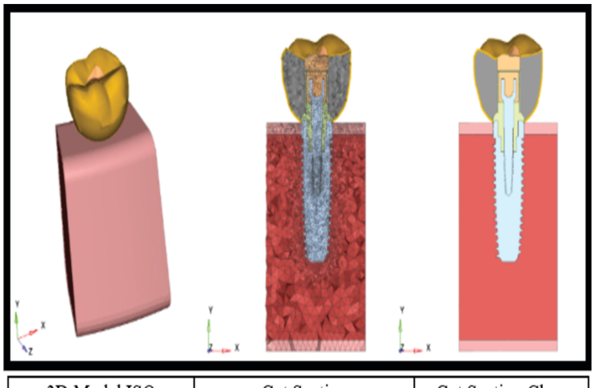
Pre-Processing

Establishment Of The Model

Eight three-dimensional models of OSSTEM implants were positioned in the D2 type of bone with a first mandibular molar crown and a straight hex abutment. Four groups with three distinct material combinations for the implant, abutment, and crown were included in the study (Table 1). All eight models were created using a base model (Figure 2).

Table – 1 Groups According To Implant, Abutment And Crown Materials

GROUP	IMPLANT MATERIAL	ABUTMENT	CROWN
Group 1	Titanium	Titanium	PFM
	Titanium	Titanium	PEEK
Group 2	Titanium	PEEK	PFM
	Titanium	PEEK	PEEK
Group 3	PEEK	Titanium	PFM
	PEEK	Titanium	PEEK
Group 4	PEEK	PEEK	PFM
	PEEK	PEEK	PEEK



3D Model ISO View	Cut Section Mesh View	Cut Section Clear View

Figure 2: 3D model view

Mesh Creation / Geometric Model Conversion To Finite Element Modeling

The mesh refinement level was limited by converting the mesh with a controlled and connected element corresponding to each structure (Table 2): -

Table – 2 Meshing Details Of Components

Sr. No.	Component	Nodes	Elements
1	Crown	74267	355566
2	Cortical Bone	51112	218788
3	Medullary Bone	85322	438993
4	Abutment	21478	91806
5	Implant	29273	131564
6	Screw	10535	45762
7	Composite	3500	14642
8	Teflon	8402	35609
9	Abutment	23216	96096

Applying Material Properties

The Young's modulus and Poisson's ratio of each material were obtained from the manufacturer and published studies, respectively. Each model's constituent parts were thought to be linearly elastic, homogenous, and isotropic (Table 3).

Table – 3 Applying Material Properties

Material	Young's Modulus	Poisson's Ratio
Cortical bone	13700MPa	0.30
Trabecular bone	1100MPa	0.30
Commercial pure titanium	110 X 10^3 Pa	0.30
Titanium alloy	117 X 10^3 Pa	0.33
PEEK	4100 MPa	0.40
Composite	10.7 GPa	0.30

Applying Boundary Conditions

In each models the implants were subjected to vertical load of 200 N (on central fossa), oblique load of 70 N (at 45° to the buccal cusp), and horizontal load of 50 N (on occlusal 1/3rd of buccal surface of mesiobuccal cusp) to mimic clinical forces and stress distribution was evaluated through the Von mises stress analysis (Figure 3).

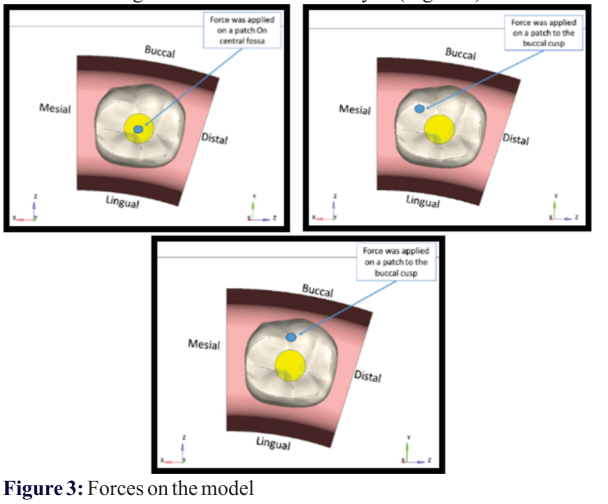


Figure 3: Forces on the model

Solving & Post-Processing

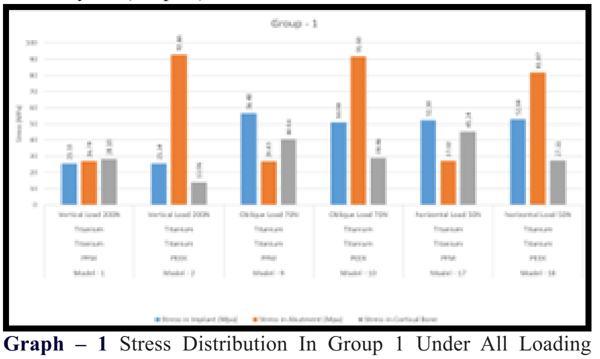
Each model's solver deck file was sent to Altair Optistruct 2021, which computes and produces results using Finite Element analysis. Altair HyperView software was used to extract, visualize and analyse the FEA results. Because the numerical values obtained from the stress analysis are mathematical calculations without variance, statistical analyses were not required, as in a routine procedure for a conclusion. The patterns of stress distribution in the implant and abutment through the bone were the main focus of this investigation. Therefore, the von Mises stress was used to interpret the results.

RESULTS

The forces were applied in 3 directions in each model. The stress distribution for implants and abutments with fatigue life were evaluated for each model; they are presented in Table 4.

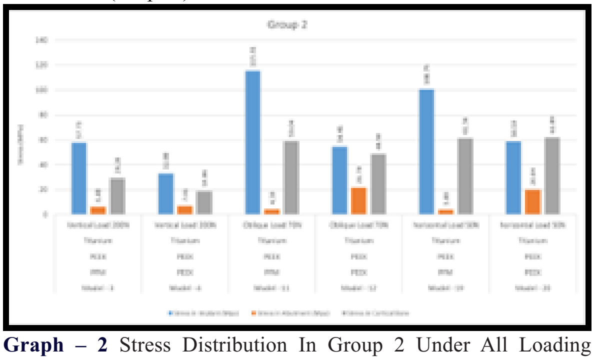
The stress levels for models in Group 1 (Models 1 and 2) under vertical loading were consistent, around 25.33 to 25.34 MPa, indicating a robust design that can handle vertical forces well. However, the fatigue life varies significantly, with Model 1 (Titanium-PFM) showing the highest fatigue life of approximately 134 million cycles, compared to Model 2's 110 million cycles (Titanium-PEEK). Under oblique loading, the stress levels are notably higher with values ranging from

50.90 MPa to 56.48 MPa. The fatigue life decreased significantly, with the highest value being just over one million cycles for Model 10 (Titanium-PEEK). The damage values also indicated a higher potential for failure particularly for Model 9 (Titanium-PFM), which exhibited a damage value of 2.9056. Horizontal loading resulted in stress levels between 52.38 and 52.84 MPa and fatigue life ranging from 9 to 20 million cycles (Graph 1).



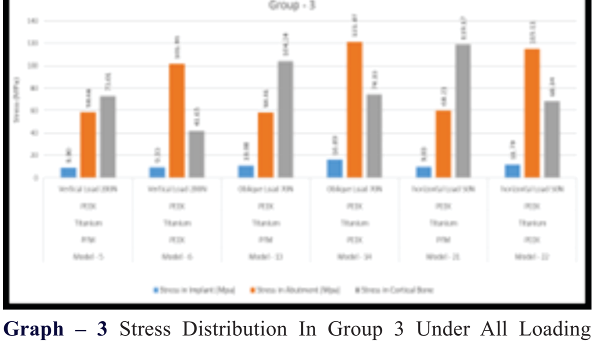
Graph – 1 Stress Distribution In Group 1 Under All Loading Conditions

Under Vertical Loading, Models 3 and 4 in Group 2 showed significantly higher stress levels under vertical loading, with Model 3 (Titanium-PEEK-PFM) reaching 57.73 MPa. The fatigue life was correspondingly low, with Model 3 showing only approximately 7.6 million cycles. Stress levels under oblique loading were extremely high for Group 2, particularly for Model 11 (Titanium-PEEK-PFM), which reaches 115.31 MPa. The fatigue life was the shortest among all groups, with Model 11 showing a life of 293,187 cycles. The high damage value of 3.4108 further indicates that this combination is prone to failure under oblique loading. Horizontal loading also produced high stress levels, particularly in Model 19 (Titanium-PEEK-PFM) at 100.75 MPa (Graph 2).



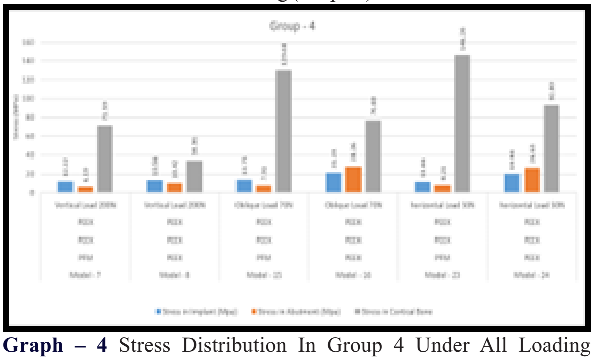
Graph – 2 Stress Distribution In Group 2 Under All Loading Conditions

The stress levels in Group 3 were the lowest among all the groups under vertical loading, with values ranging from 9.00 to 9.33 MPa. The fatigue life was extraordinarily high, with Model 5 (PEEK-Titanium-PFM) showing over 1.27E+13 cycles. Stress levels remained low under oblique loading, with Model 13 (PEEK-Titanium-PFM) showing just 10.88 MPa. The fatigue life was again extremely high, with Model 13 exhibiting over 2.23E+18 cycles. Horizontal loading remained well below the levels observed in titanium implants (Graph 3).



Graph – 3 Stress Distribution In Group 3 Under All Loading Conditions

Group 4 exhibited slightly higher stress levels compared to Group 3 under vertical loading condition, with values around 13.56 MPa. The fatigue life, while lower than Group 3, remained high enough to suggest good durability under vertical loading. The damage values were also low, indicating a low risk of failure. Stress levels under oblique loading were slightly higher than in Group 3, with Model 16 (PEEK-PEEK-PEEK) showing 21.23 MPa. Similar trends were observed under horizontal loading (Graph 4).



Graph – 4 Stress Distribution In Group 4 Under All Loading Conditions

The ANOVA analysis for vertical, horizontal and oblique loading showed a significant difference in stress levels between the groups ($p < 0.05$). The stress levels are significantly higher in Group 2 compared to Groups 3 and 4, indicating that the PEEK abutment combined with a titanium implant may lead to higher stress concentrations under oblique loading. Group 2 again exhibited the highest stress levels, particularly when titanium implants were paired with PEEK abutments.

DISCUSSION

Dental implants, particularly those subjected to various mechanical loads, are at the forefront of prosthodontic research owing to their critical role in inpatient rehabilitation. The design and material composition of these implants significantly affect their biomechanical behavior, including stress distribution, fatigue life, and potential for damage under different loading conditions.

Titanium is a highly durable metal known for its high strength, rigidity, and biocompatibility. However, the high modulus of elasticity of titanium, which is significantly greater than that of bone, can lead to stress shielding. This phenomenon occurs when a stiffer implant material absorbs a disproportionate amount of load, reducing the load transferred to the surrounding bone. This can lead to bone resorption and implant failure.

Conversely, the elasticity modulus of the high-performance polymer Polyether Ether Ketone (PEEK) is closer to that of bone. This similarity in mechanical properties allows PEEK implants to better mimic the natural load distribution of bone, thereby reducing the risk of stress shielding.

These data support the above-mentioned literature, as titanium implants generally exhibit higher stress levels, especially under oblique and horizontal loads. Implants made from PEEK consistently exhibited lower stress levels across all loading conditions compared to titanium implants. For example, under vertical loading (200 N), a PEEK implant (Model 5) combined with a titanium abutment and PFM crown experiences a stress level of just 9.00 MPa, significantly lower than the 25.33 MPa observed in a titanium implant (Model 1) under similar conditions.

Mourya A and Nahar R et al.[4] evaluated the distribution of stress under parafunctional loading in the straight and angled abutments surrounding titanium and carbon fiber-reinforced polyetheretherketone (CFR-PEEK) implants with two distinct prosthetic crowns. According to the study's findings, patients with bruxism may benefit from receiving a straight abutment and PEEK crown to lessen the concentration of stress in their bones and avoid implant failure.

Similarly in a 2024 study by Hong and Choi H[11] sought to use three-dimensional finite element analysis (FEA) was used to compare the impact of titanium and polyetheretherketone (PEEK) abutments on implant prosthetic systems and the supporting bone. PEEK abutments show a similar distribution of stress in the surrounding bone when compared to titanium.

Different loading conditions had a profound impact on the stress levels. Vertical loading generally results in lower stress, whereas oblique and horizontal loading lead to significantly higher stress levels. This aligns with the findings of prosthodontic research, where oblique and horizontal forces are more likely to cause implant failure because of their greater potential to induce bending moments and shear forces.

For example, titanium implants (Model 9) show stress levels as high as 56.48 MPa under oblique loading (70 N at 45°), while PEEK implants (Model 13) show a significantly lower stress level of 10.88 MPa. This significant reduction in stress suggests that PEEK implants are better suited to handle complex loading without transferring excessive stress to the bone-implant interface, lowering the possibility of little motions that can cause the implant to loosen and eventually fail. Similarly, under horizontal loading (50 N), the stress level in PEEK implants (Model 21) is just 9.83 MPa, compared to 52.38 MPa in titanium implants (Model 17). This five-fold difference in stress further highlights the potential benefits of using PEEK as an implant material, particularly in patients who may be more prone to implant-related complications owing to high-stress environments.

Tamrakar SK and Mishra SK et al.[6] did a study to assess the distribution of stress around Ti and CFR-PEEK implants using five distinct prosthetic crowns. They concluded that under oblique loading, CFR-PEEK implants with various restorative crowns produced less stress in the bone than Ti implants. This may reduce crestal bone loss and lateral stress on the implants.

Under vertical loading, **Group 3** exhibited the highest fatigue life, indicating that this combination was the most resistant to vertical compressive forces. This is followed by **Group 1**, which also performed well, but not as well as the PEEK-titanium combination. The results for oblique loading show that **Group 3** outperforms all the other groups by a large margin, indicating exceptional resistance to oblique forces. **Group 4** also performed well, but was inferior to the PEEK-titanium combination. This suggests that while PEEK is highly effective as an implant material, its combination with titanium abutments offers the best results under oblique loading. The analysis for horizontal loading confirmed **Group 3** showing the highest number of cycles followed by **Group 4**.

Titanium implants in Groups 1 and 2 exhibited higher stress levels across all load conditions, potentially increasing the risk of fatigue-related failure. On the other hand, PEEK's lower modulus of elasticity not only reduces stress levels but also improves its fatigue resistance. The significantly lower stress levels observed in PEEK implants suggest that they are less likely to experience fatigue failure, making them a reliable option for long-term dental restorations. This is particularly evident in the data for vertical loading, where PEEK implants (Model 5) exhibited an astonishingly high number of cycles (1.27E+13), indicating superior durability compared with titanium implants, which have a much lower fatigue life.

The superior performance of PEEK-Titanium combinations under all loading scenarios supports their use in load-bearing areas of the mouth, where the implants are subject to significant mechanical stress. **Group 3** consistently showed the lowest damage across all loading conditions. This suggests that PEEK implants combined with Titanium abutments provide superior resistance to damage, making them highly suitable for patients with high occlusal forces or other demanding conditions. **Group 2** showed the highest damage in most loading conditions. This indicates that while PEEK abutments might offer other benefits, such as flexibility or reduced stress shielding, they may not be as durable when paired with Titanium implants under high mechanical loads. **Group 4** also performed well, with low damage levels, particularly under oblique and horizontal loads. This combination may be advantageous in scenarios where minimizing material degradation is critical. **Group 1** displayed moderate damage across all conditions, making them a reliable choice for many clinical applications, but potentially less optimal than PEEK-Titanium combinations for high-stress scenarios.

While the damage data provides valuable insights, clinical significance can only be fully validated through long-term, real-world studies. Future research should focus on correlating these findings with patient outcomes over extended periods, especially in diverse patient populations with varying oral habits and health conditions.

Despite the fact that in vitro studies allow for test uniformity by eliminating oral conditions, the current study has several drawbacks. Furthermore, it is simplistic to assess stress distribution using static loads, which do not accurately reflect the dynamic forces the implant might experience in vivo. Compared to a lab setting, the clinical reality of implant stress distribution is far more complicated. To assess the stress distribution in implants, abutments and prosthesis, long-term randomized clinical trials that examine masticatory efficiency and performances are advised.

TABLE – 4 STRESS DISTRIBUTION IN IMPLANT AND ABUTMENT UNDER DIFFERENT LOADING CONDITIONS

GROUPS	MODELS	IMPLANT	ABUTMENTS	CROWNS	LOADS APPLIED	Stress in Implant (MPa)	Stress in Abutment (MPa)	No. of Cycles (Life)	Damage
Group 1	Model - 1	Titanium	Titanium	PFM	VERTICAL: 200 N (On central fossa)	25.33	26.79	1,34,26,470	0.0745
	Model - 2	Titanium	Titanium	PEEK		25.34	92.66	1,10,62,081	0.0904
Group 2	Model - 3	Titanium	PEEK	PFM		57.73	6.48	7,59,937	1.3159
	Model - 4	Titanium	PEEK	PEEK		32.88	7.01	9,67,706	1.0334
Group 3	Model - 5	PEEK	Titanium	PFM		9.00	58.66	1,27,46,26,63,167	7.85E-06
	Model - 6	PEEK	Titanium	PEEK		9.33	101.93	28,42,83,98,337	3.52E-05
Group 4	Model - 7	PEEK	PEEK	PFM		12.22	6.19	1,04,53,821	0.0957
	Model - 8	PEEK	PEEK	PEEK		13.56	10.42	7,99,38,07,496	0.0001
Group 1	Model - 9	Titanium	Titanium	PFM	OBLIQUE: 70 N at 45° (to the buccal cusp)	56.48	26.63	3,44,168	2.9056
	Model - 10	Titanium	Titanium	PEEK		50.90	91.60	10,28,216	0.9726
Group 2	Model - 11	Titanium	PEEK	PFM		115.31	4.39	2,93,187	3.4108
	Model - 12	Titanium	PEEK	PEEK		54.45	21.70	8,57,396	1.1663
Group 3	Model - 13	PEEK	Titanium	PFM		10.88	58.31	23,6,92,46,63,754	4.48E-08
	Model - 14	PEEK	Titanium	PEEK		16.09	121.47	18,54,137	0.5393
Group 4	Model - 15	PEEK	PEEK	PFM		13.75	7.91	1,29,42,88,971	0.0008
	Model - 16	PEEK	PEEK	PEEK		21.23	28.26	3,44,75,286	0.0290
Group 1	Model - 17	Titanium	Titanium	PFM	HORIZONTAL: 50 N (On occlusal 1/3rd of buccal surface of mesio-buccal cusp)	52.38	27.02	9,10,841	1.0979
	Model - 18	Titanium	Titanium	PEEK		52.84	81.87	20,16,047	0.4960
Group 2	Model - 19	Titanium	PEEK	PFM		100.75	3.88	9,91,460	1.0086
	Model - 20	Titanium	PEEK	PEEK		58.59	20.04	2,62,841	3.8046
Group 3	Model - 21	PEEK	Titanium	PFM		9.83	60.21	65,09,61,55,11,337	1.54E-07
	Model - 22	PEEK	Titanium	PEEK		11.79	115.11	28,18,440	0.3548
Group 4	Model - 23	PEEK	PEEK	PFM		11.66	8.21	37,76,99,916	0.0026
	Model - 24	PEEK	PEEK	PEEK		19.94	26.63	99,72,07,93,87,960	0.0000

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CONCLUSIONS

The current study's findings indicated a noteworthy distinction among the four groups. It was interpreted that:

1) Preliminary analysis suggests significant differences between the groups, particularly between titanium-based (Groups 1 and 2) and PEEK-based (Groups 3 and 4) implants.
2) PEEK implants consistently show lower stress levels, indicating a statistically significant advantage in reducing stress on the implant.
3) Damage values, while generally low in PEEK-based implants, show significant variability in titanium implants. Statistical tests indicate that PEEK implants have a statistically significant lower damage rate across all loading conditions, further supporting the hypothesis that PEEK is a superior material for implant longevity.

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