RESEARCH PAPER

# Fracture Resistance of Titanium and Modified PEEK Implant Abutments Restored with DMLS and Monolithic CAD/CAM PEEK Crowns: An *In Vitro* Comparative Study

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## ABSTRACT

***Background:*** The material used for an implant abutment and crown can influence the strength and clinical performance of the restoration. This study compared the fracture resistance of three implant abutment–crown combinations. ***Methods:*** Forty-five specimens were divided into three groups (n=15): titanium abutments with direct metal laser-sintered porcelain-fused-to-metal (DMLS PFM) crowns, titanium abutments with CAD/CAM-milled high-impact polymer composite (HIPC) crowns, and modified PEEK abutments with HIPC crowns. Each specimen was subjected to compressive loading in a universal testing machine until failure. Fracture loads and locations were recorded. Data were analysed using one-way ANOVA, Bonferroni post-hoc comparisons and the chi-square test. ***Results:*** Mean fracture resistance was highest for titanium abutments with DMLS PFM crowns (2151.29 ± 1105.05 N), followed by titanium abutments with HIPC crowns (1384.93 ± 541.51 N) and modified PEEK abutments with HIPC crowns (683.31 ± 309.77 N). The overall difference was statistically significant ($p<0.001$), and all pairwise comparisons were significant ($p<0.05$). Buccal fractures were most common in PFM crowns, whereas HIPC crowns mainly showed occlusal fractures ($p<0.001$). ***Conclusion:*** Titanium-supported restorations showed greater fracture resistance than the modified PEEK abutment–HIPC combination. Modified PEEK abutments may have potential in lower-load aesthetic regions, but further fatigue and clinical studies are needed.
**Keywords:** CAD/CAM; dental implant abutment; fracture resistance; HIPC; PEEK; titanium.

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## INTRODUCTION

Dental implants are a reliable treatment option for replacing missing teeth and have shown favourable long-term clinical outcomes. However, the success of an implant-supported restoration depends on several factors, including the selection of the definitive abutment and crown material. These materials should provide adequate strength, biocompatibility, stability and acceptable aesthetics, particularly when used in areas exposed to high occlusal forces.[1]

Titanium is commonly used for definitive implant abutments because of its excellent mechanical properties, biocompatibility and clinical reliability. Nevertheless, its metallic colour may compromise aesthetics, especially in patients with thin gingival tissue or a high smile line.[2] Polyetheretherketone (PEEK) has therefore emerged as a metal-free alternative. Its natural whitish colour, ease of processing and favourable biological properties make it suitable for implant-supported restorations.[3]

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PEEK is a semi-crystalline polymer belonging to the polyaryletherketone family. It has low density, limited plaque affinity, good chemical stability and a tensile strength of approximately 90–100 MPa.[4] Its elastic modulus is closer to that of bone than that of titanium, allowing it to absorb and distribute functional stresses. Modified PEEK materials can be pressed or milled using computer-aided design and computer-aided manufacturing (CAD/CAM). They have been used for crowns, fixed dental prostheses, implant abutments and implant-supported frameworks.[5]

Despite these advantages, evidence regarding the load-bearing ability of modified PEEK abutments combined with different crown materials remains limited. This is particularly important in posterior regions, where restorations experience greater occlusal forces. Therefore, this in vitro study aimed to evaluate and compare the fracture resistance of titanium and modified PEEK implant abutments restored with direct metal laser-sintered and monolithic CAD/CAM PEEK crowns.

**Materials and Methods Study design and sample size**

This in vitro study compared the fracture resistance of three implant abutment–crown combinations. The sample size was estimated using G*Power version 3.0.1 (Universität Kiel, Germany). Based on an effect size of 0.55, a significance level of 5%, and 80% statistical power, 45 specimens were included, with 15 specimens in each group.

**Preparation of the reference model**

An aluminium reference model was prepared according to ISO 14801. An internal-hex endosseous implant measuring 4.5 mm in diameter and 12 mm in length (Implantium, Dentium, Seoul, South Korea) was embedded in clear autopolymerizing polymethyl methacrylate resin within an aluminium receptacle. To simulate peri-implant bone loss, 3 mm of the implant surface was left exposed apical to the implant collar. The implant was positioned at an angle of 30° to the direction of loading.

**Specimen preparation and grouping**

The specimens were divided into three groups (n=15 each):

- **Group 1:** Titanium abutments restored with direct metal laser-sintered porcelain-fused-to-metal crowns
- **Group 2:** Titanium abutments restored with CAD/CAM-milled high-impact polymer composite crowns
- **Group 3:** Modified PEEK abutments restored with CAD/CAM-milled high-impact polymer composite crowns

For Group 1, a prefabricated straight titanium abutment measuring 4.5 mm in diameter and 4.5 mm in height (Implantium, Dentium) was connected to the implant and tightened to 35 Ncm. Fifteen porcelain-fused-to-metal crowns were fabricated using direct metal laser sintering.

For Group 2, 15 high-impact polymer composite (HIPC; Bredent, Germany) crowns were milled using CAD/CAM technology and placed on prefabricated titanium abutments.

For Group 3, a modified PEEK abutment (BioHPP; Bredent) supported by a titanium base was designed from a digital impression and fabricated using CAD/CAM technology. Fifteen corresponding HIPC crowns were then milled. All abutments were tightened to 35 Ncm, and the crowns were cemented using self-adhesive resin cement (RelyX Unicem, 3M) (Figure 1).

**Fracture-resistance testing**

Each assembly was mounted in a universal testing machine (MultiTest-i). A compressive load was applied using an 8-mm-diameter stainless-steel loading head at a crosshead speed of 0.5 mm/min. A 2-mm-thick Teflon sheet measuring 7 × 7 mm was placed between the crown and loading head to distribute the load evenly and reduce contact damage. Loading continued until catastrophic failure occurred, and the maximum fracture load was recorded in newtons. Fractured specimens were examined under a stereomicroscope at ×50 magnification, and the fracture location was documented (Figure 2).

**Statistical analysis**

Data were entered into Microsoft Excel and analysed using SPSS version 25.0 (IBM Corp., Armonk, NY, USA). Normality of the fracture-resistance data was assessed using the Shapiro–Wilk test. Mean fracture resistance among the three groups was compared using one-way analysis of variance, followed by Bonferroni-adjusted post-hoc comparisons. The distribution of fracture locations among the groups was compared using the chi-square test. A two-sided p-value <0.05 was considered statistically significant.

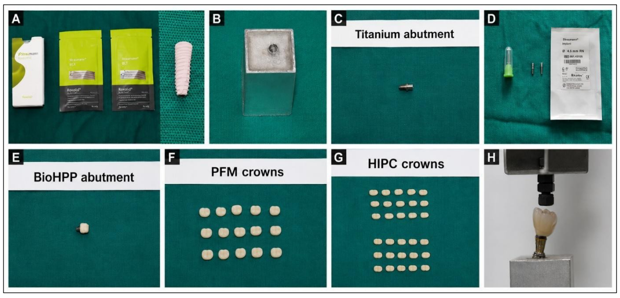


**Figure 1. Materials and experimental procedure used for fracture-resistance testing.**

(A) Internal-hex implant fixture and prefabricated titanium abutment; (B) aluminium reference model with the implant embedded at 30° to the direction of loading; (C) prefabricated titanium abutment; (D &E) CAD/CAM-fabricated modified PEEK (BioHPP) abutment supported by a titanium base; (F&G) DMLS porcelain-fused-to-metal and CAD/CAM-milled HIPC crowns; and (H) implant–abutment–crown assembly mounted in the universal testing machine.

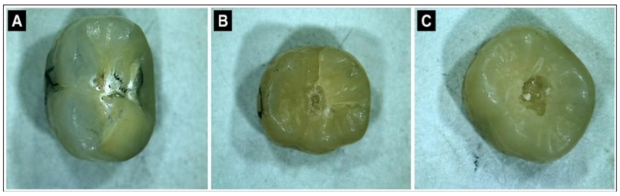


**Figure 2. Representative fracture patterns observed after mechanical testing.**
(A) Buccal-surface fracture of a DMLS porcelain-fused-to-metal crown supported by a titanium abutment; (B) occlusal-surface fracture of a HIPC crown supported by a titanium abutment; and (C) occlusal-surface fracture of a HIPC crown supported by a modified PEEK (BioHPP) abutment.

## RESULTS

A total of 45 specimens were evaluated, with 15 specimens in each group. Group 1, comprising titanium abutments restored with DMLS PFM crowns, showed the highest mean fracture resistance (2151.29 ± 1105.05 N), followed by Group 2, comprising titanium abutments restored with HIPC crowns (1384.93± 541.51 N). Group 3, comprising modified PEEK abutments restored with HIPC crowns, showed the lowest mean fracture resistance (683.31 ± 309.77 N). One-way ANOVA demonstrated a statistically significant difference in fracture resistance among the three groups ($F=15.06$, $p<0.001$) (Table 1).

Bonferroni-adjusted pairwise analysis showed that the fracture resistance of Group 1 was significantly higher than that of Group 2, with a mean difference of 766.36 N ($p=0.019$). Group 1 also demonstrated significantly greater fracture resistance than Group 3, with a mean difference of 1467.97 N ($p<0.001$). Similarly, Group 2 had significantly higher fracture resistance than Group 3, with a mean difference of 701.61 N ($p=0.036$) (Table 2).

The location of fracture differed significantly among the three groups ($\chi^2=32.56$, $df=2$; $p<0.001$). In Group 1, fractures occurred mainly on the buccal surface (86.7%), while 13.3% occurred on the occlusal surface. In contrast, occlusal fractures predominated in Group 2 (93.3%) and occurred in all specimens in Group 3 (100.0%). Only one specimen in Group 2 showed a buccal fracture. No lingual or proximal fractures were observed in any group (Table 3).

**Table 1. Comparison of fracture resistance among the three abutment–crown combinations**

| Group | Abutment–crown combination | n | Mean ± SD (N) | Median (N) | Range (N) | F-value | p-value |
|---|---|---|---|---|---|---|---|
| Group 1 | Titanium abutment with DMLS PFM crown | 15 | 2151.29 ± 1105.05 | 2183.40 | 642.20 – 4465.10 | 15.06 | <0.001* |
| Group 2 | Titanium abutment with HIPC crown | 15 | 1384.93 ± 541.51 | 1271.60 | 355.30 – 2184.90 | | |
| Group 3 | Modified PEEK abutment with HIPC crown | 15 | 683.31 ± 309.77 | 694.30 | 150.50 – 1528.60 | | |

*Comparison was performed using one-way analysis of variance (ANOVA). *Statistically significant at p<0.05.*

**Table 2. Bonferroni-adjusted pairwise comparison of fracture resistance**

| Comparison | Mean difference (N) | p-value |
|---|---|---|
| Group 1 versus Group 2 | 766.36 | 0.019* |
| Group 1 versus Group 3 | 1467.97 | <0.001* |
| Group 2 versus Group 3 | 701.61 | 0.036* |

**Table 3. Comparison of fracture locations among the three abutment–crown combinations**

| Group | Abutment–crown combination | Buccal Fracture n (%) | Occlusal Fracture n (%) | Lingual Fracture n (%) | Proximal Fracture n (%) | p-value |
|---|---|---|---|---|---|---|
| Group 1 | Titanium abutment with DMLS PFM crown | 13 (86.7) | 2 (13.3) | 0 (0.0) | 0 (0.0) | <0.001* |
| Group 2 | Titanium abutment with HIPC crown | 1 (6.7) | 14 (93.3) | 0 (0.0) | 0 (0.0) | |
| Group 3 | Modified PEEK abutment with HIPC crown | 0 (0.0) | 15 (100.0) | 0 (0.0) | 0 (0.0) | |

*The distribution of buccal and occlusal fractures was compared using the chi-square test ($\chi^2=32.56$, $df=2$). Lingual and proximal fracture categories were excluded from statistical comparison because no events occurred in these categories. *Statistically significant at p<0.05.*

## DISCUSSION

This study compared the fracture resistance of three implant-supported restorative combinations. Titanium abutments restored with DMLS PFM crowns showed the highest fracture resistance (2151.29 ± 1105.05 N), followed by titanium abutments with HIPC crowns (1384.93 ± 541.51 N). Modified PEEK abutments restored with HIPC crowns recorded the lowest value (683.31 ± 309.77 N). The differences between all three groups were statistically significant. These findings show that both the abutment and crown materials influence the load-bearing capacity of an implant-supported restoration.

Fracture resistance is an important mechanical property because it indicates the ability of a restoration to withstand functional loading. However, measured fracture loads may vary with the abutment material, crown design, manufacturing technique, cementation procedure and testing conditions. Therefore, fracture strength should be considered together with the location and pattern of failure.[6,7]

PEEK has a high modulus of resilience and can absorb more elastic energy before permanent deformation than several rigid restorative materials.[8] Stawarczyk et al. reported deformation of three-unit PEEK prostheses at approximately 1200 N and connector fracture at 1383 N, suggesting that PEEK may tolerate considerable functional loading.[9] Similarly, Nazari et al. reported a mean failure load of 1430 ± 262 N for PEEK restorations, compared with 2086 ± 362 N for zirconia and 5591 ± 1200 N for nickel–chromium restorations.[6] These findings are comparable to the fracture resistance of HIPC crowns supported by titanium abutments in the present study.

The lower fracture resistance of the modified PEEK abutment–HIPC crown combination may be related to the relatively low elastic modulus of both components. Greater deformation of the abutment during loading may increase stress within the overlying crown. This explanation agrees with the findings of Tekin et al., who observed that PEEK crowns reduced the stresses transferred to themselves, whereas PEEK abutments increased stress within the crowns.[10] Variation in the mechanical behaviour of different high-performance polymers and their titanium-base connections has also been reported.[11]

The mean fracture resistance of the modified PEEK abutment–HIPC crown group was below the reported maximum posterior bite force of approximately 880 N.[6] Nevertheless, it remained above the average forces commonly reported in the anterior region.[10] This combination may therefore have potential in aesthetically demanding areas with lower functional loads. However, this observation should not be interpreted as a clinical recommendation because the present study used static loading under controlled laboratory conditions.

Failure location also differed significantly among the groups. Buccal fractures predominated in DMLS PFM crowns, whereas HIPC crowns mainly fractured on the occlusal surface. Similar buccal involvement in metal–ceramic restorations has been reported previously.[6] No visible abutment fracture occurred, indicating that failure was largely confined to the crowns, consistent with observations by Santing et al.[3]

The study was limited by its in vitro design, static loading, small sample size and absence of thermal cycling, fatigue loading and oral environmental conditions. Further studies incorporating artificial ageing and cyclic loading are needed before the long-term clinical use of modified PEEK abutments with HIPC crowns can be established.

## CONCLUSION

Within the limitations of this in vitro study, titanium abutments restored with DMLS PFM crowns showed the highest fracture resistance, followed by titanium abutments with HIPC crowns. Modified PEEK abutments with HIPC crowns demonstrated the lowest resistance. Titanium-supported restorations may withstand posterior masticatory forces, whereas the modified PEEK–HIPC combination may be more appropriate for lower-load anterior regions. PFM crowns fractured mainly on the buccal surface, while HIPC crowns predominantly showed occlusal fractures. Further clinical studies are required to confirm these findings.

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