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Open Access Original Article

Comparative Evaluation of the Marginal Fit of Graphene-Based Crowns and Two Other Computer-Aided Design/Computer-Aided Manufacturing (CAD/CAM)-Fabricated Crown Materials: An In Vitro Study

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Review began 11/02/2026
Review ended 11/12/2026
Published 11/19/2026

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DOI: 10.7759/cureus.119936

Abstract

Background and objective: Marginal adaptation is an important parameter in assessing the fit of indirect dental restorations. This in vitro study compared the marginal fit of computer-aided design and computer-aided manufacturing (CAD/CAM)-fabricated polyetheretherketone (PEEK), graphene-containing, and zirconia crowns.

Materials and methods: Forty-five crowns were divided equally into three groups. Group I (PEEK), group II (graphene-containing), and group III (zirconia), with 15 crowns per group. The crowns were cemented onto their corresponding dies, and marginal gaps were evaluated using scanning electron microscopy (SEM) at four locations: mid-buccal, mid-lingual, mid-mesial, and mid-distal. Measurements were recorded in micrometers (µm). One-way ANOVA, followed by Tukey's post hoc test, was used to compare the groups. Statistical significance was set at $p < 0.05$.

Results: Significant differences among the three groups were observed at all four measurement sites ($p < 0.001$). The PEEK crowns demonstrated the lowest mean marginal gaps at the buccal (25.98 ± 3.10 µm), lingual (25.04 ± 2.64 µm), mesial (25.97 ± 3.01 µm), and distal (24.86 ± 3.22 µm) sites. Zirconia crowns exhibited the highest values at the buccal (48.65 ± 6.02 µm), lingual (46.70 ± 8.87 µm), mesial (45.50 ± 6.77 µm), and distal (43.20 ± 7.53 µm) sites, while graphene-containing crowns showed intermediate values. Post hoc analysis identified significant differences between PEEK and both other materials at all sites ($p < 0.001$). Differences between graphene-containing and zirconia crowns were significant at the buccal, lingual, and distal sites, but not at the mesial site ($p = 0.061$).

Conclusion: Under the conditions of this in vitro study, PEEK crowns demonstrated smaller marginal gaps than graphene-containing and zirconia crowns. Further investigations incorporating simulated oral aging, mechanical testing, and clinical follow-up are needed to establish the clinical relevance and long-term performance of these materials.

Categories: Dentistry
Keywords: computer-aided design and computer-aided manufacturing (cad/cam), graphene, marginal fit, polyetheretherketone (peek), scanning electron microscopy (sem), zirconia

Introduction

The long-term success of fixed dental restorations depends on their mechanical properties, esthetic performance, and marginal and internal adaptation. Suboptimal marginal adaptation has been associated with increased plaque retention, leakage at the tooth-restoration interface, secondary caries, periodontal inflammation, and deterioration of the cement layer, which may jeopardize restoration longevity. Therefore, achieving accurate marginal adaptation is an important consideration when selecting restorative materials and fabrication techniques [1,2].

The findings of McLean and von Fraunhofer indicated that marginal discrepancies close to 120 µm are generally considered acceptable in clinical practice [3]. However, marginal adaptation is influenced by several factors, including the restorative material, tooth preparation design, computer-aided design and computer-aided manufacturing (CAD/CAM) system, milling parameters, and cementation procedure. The CAD/CAM technology has improved the standardization and efficiency of indirect restoration fabrication,

enabling the production of crowns from ceramic and polymer-based materials [4,5].

Zirconia is widely used in fixed prosthodontics because of its strength, chemical stability, and biocompatibility. Nevertheless, its optical properties vary according to composition and translucency, while veneered zirconia restorations may be susceptible to chipping [6,7]. Polyetheretherketone (PEEK), a high-performance thermoplastic polymer, has attracted interest in dentistry because of its low density, chemical resistance, and favorable mechanical characteristics. However, its limited translucency and grayish appearance may restrict its use in highly esthetic areas without additional modification or veneering [8]. The CAD/CAM-fabricated polymethyl methacrylate (PMMA) materials also offer advantages through industrialized processing and standardized milling. Their performance, however, depends on the specific formulation and intended clinical indication [9].

Graphene is a carbon-based nanomaterial with a two-dimensional honeycomb structure that has attracted interest because of its distinctive mechanical and surface properties. Incorporating graphene or its derivatives into polymeric dental materials may modify their mechanical behavior, wear resistance, and surface characteristics [10,11]. Recent research has investigated graphene-reinforced PMMA for CAD/CAM-fabricated dental crowns, including its wear resistance and surface roughness compared with conventional PMMA [12]. A 2026 in vitro study also reported differences in marginal fit and internal adaptation between graphene-reinforced CAD/CAM crowns and zirconia crowns for primary molars [13]. These findings provide an emerging evidence base for graphene-containing restorative materials, although the results should be interpreted in relation to the specific material formulation, crown design, and experimental protocol.

Marginal fit can be assessed using direct microscopic measurement, silicone replica analysis, scanning electron microscopy (SEM), and other imaging techniques. Differences in measurement methods, specimen preparation, cementation protocols, and fabrication systems may influence the values obtained, making standardized experimental conditions essential for reliable comparisons. Recent literature has also examined the marginal adaptation of CAD/CAM-fabricated zirconia and PEEK restorations, highlighting the importance of material-specific evaluation [14]. However, further comparative evidence is needed to understand how graphene-reinforced polymer crowns perform relative to both PEEK and zirconia under the same experimental conditions.

In light of these considerations, this laboratory-based study examines and compares the marginal fit of CAD/CAM-manufactured graphene-reinforced PMMA, PEEK, and zirconia crowns following cementation with resin cement. The null hypothesis was that no statistically significant differences would exist in marginal-gap measurements among PEEK, graphene-containing, and zirconia crowns at the four evaluated locations.

Materials And Methods

Study design, setting, and ethical approval

The protocol for this in vitro comparative study was reviewed and approved by the Government Dental College and Hospital, Rajiv Gandhi Institute of Medical Sciences (Kadapa, AP, IND), on May 4, 2022, and was conducted at its premises from December 2023 to February 2024. The experimental procedures involved only artificial dental models and laboratory materials. No human participants, extracted human teeth, human tissues, blood, saliva, cell lines, or patient-derived biological specimens were used. Therefore, informed consent was not applicable to this study.

Sample size, tooth preparation, and die fabrication

The sample size was calculated with a two-sided alpha error of 5%, equal group allocation, and a target statistical power of 80%. A total of 45 crowns were included, with 15 specimens assigned to each material group. A standardized artificial mandibular first molar typodont replacement tooth was used as the reference model for tooth preparation. The iDENTical (Vasa Denticity Ltd., New Delhi, IND) typodont replacement tooth, compatible with a Nissin-type jaw set, was used. The product was imported from China. The tooth was prepared for a full-coverage crown using a crown and bridge preparation bur kit. The preparation involved approximately 1 mm of axial reduction and 2 mm of occlusal reduction. A shoulder finish line was established, with the margins positioned supragingivally. The total occlusal convergence was reported as 6°.

An impression of the prepared tooth was made using addition silicone putty impression material (Flexceed, GC Corp., Tokyo, JPN) (Figure *1a*). A wax pattern was fabricated from the impression and invested using phosphate-bonded investment material. The wax pattern was subsequently cast in cobalt-chromium alloy to obtain a metal replica of the prepared tooth. This metal replica was duplicated using addition silicone to produce 45 die models for the experimental crowns (Figure *1b*). The 45 crowns were divided into three groups according to the restorative material, with 15 specimens in each group. Group I included PEEK crowns (n = 15) (bredent GmbH & Co. KG, Senden, DEU) (Figure *1c*). Group II comprised graphene-containing polymer crowns (n = 15) (Graphenano Dental, Paterna, Valencia, ESP) (Figure *1d*). Group III featured zirconia crowns (n = 15) (Henry Schein Inc., Melville, NY, USA) (Figure *1e*). All crowns were

cemented onto their corresponding dies using RelyX U200 self-adhesive resin cement (3M, St. Paul, MN, USA). Each crown was seated using firm manual finger pressure and maintained in position during the cementation procedure.

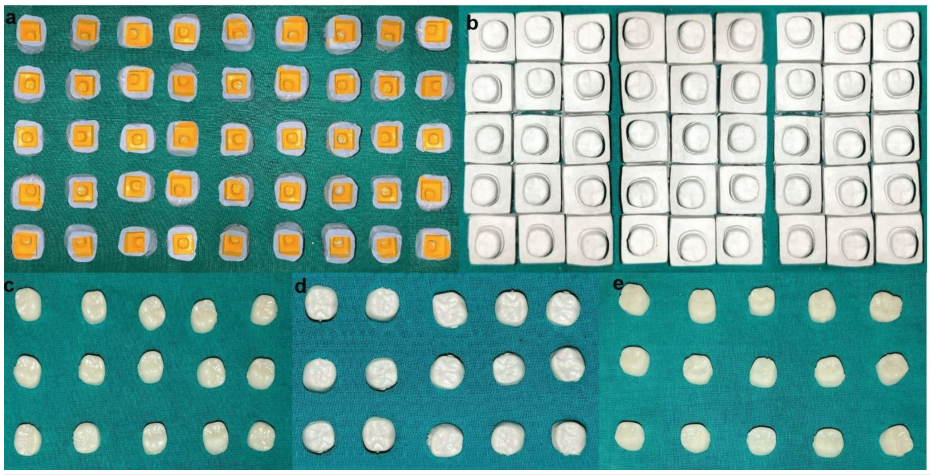

FIGURE 1: The 45 experimental crowns

a: Putty light body impressions of metal die; b: Die stone models; c: 15 PEEK crowns; d: 15 graphene crowns; e: 15 zirconia crowns

PEEK: Polyetheretherketone

Assessment of marginal fit

All SEM measurements were performed by a single examiner using a consistent measurement procedure. The marginal gap was assessed at four predetermined locations (mid-buccal, mid-lingual, mid-mesial, and mid-distal) for each crown under 1,000× magnification. The same measurement approach was applied to all three material groups: PEEK crowns (group I) (Figure *2*), graphene-containing crowns (group II) (Figure *3*), and zirconia crowns (group III) (Figure *4*).

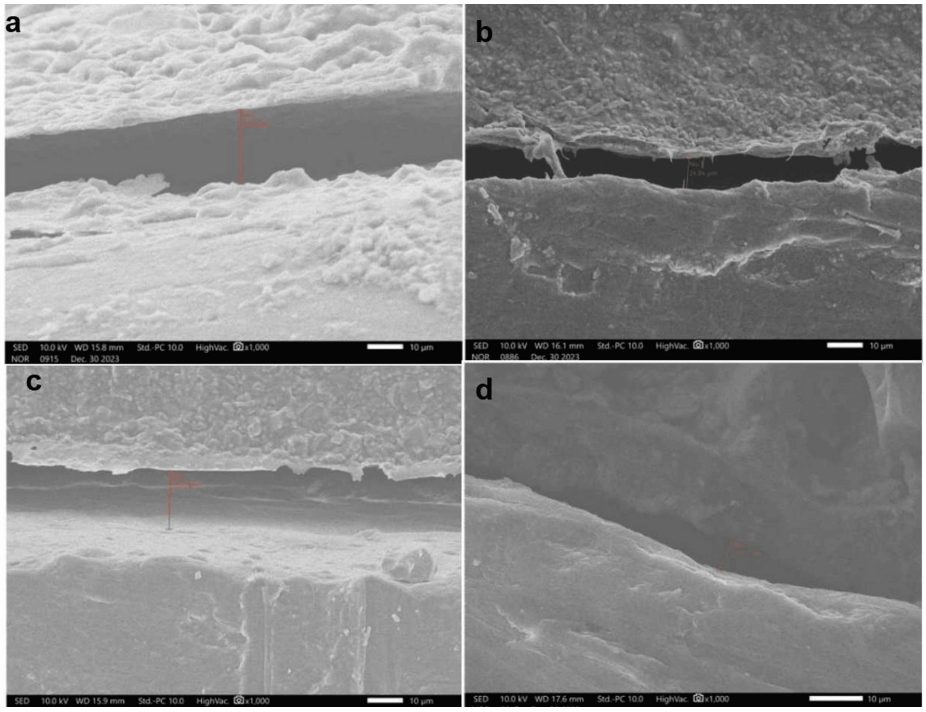

FIGURE 2: SEM images showing marginal-gap measurements at the crown-die interface in group I (PEEK) crowns (1000× magnification).

a: Mid-buccal region; b: Mid-lingual region; c: Mid-mesial region; d: Mid-distal region. Red measurement markers indicate the marginal gap at each respective location. Scale bars: 10 µm.

SEM: Scanning electron microscopy

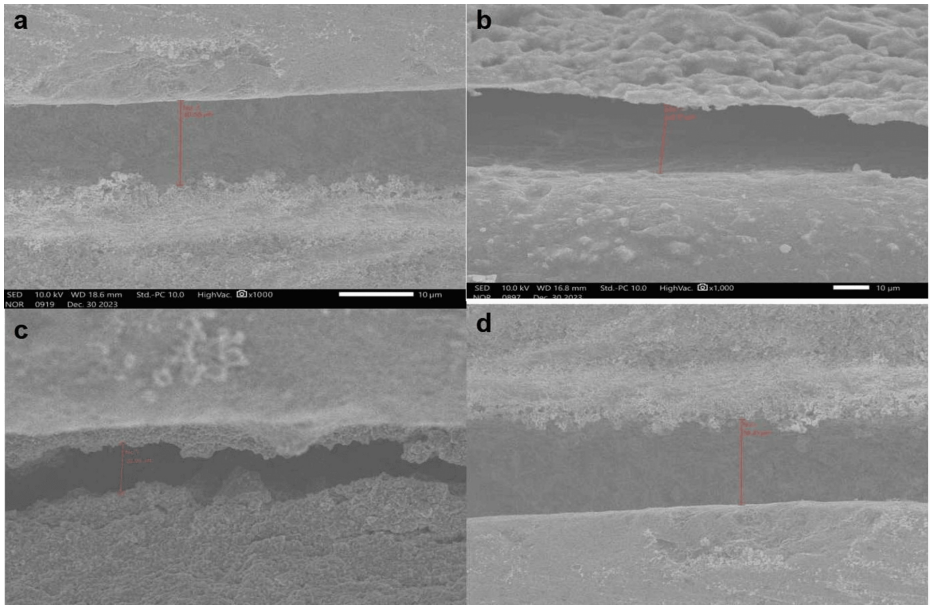

FIGURE 3: SEM images showing marginal-gap measurements at the crown-die interface in group II (graphene-containing) crowns (1000× magnification)

a: Mid-buccal region; b: Mid-lingual region; c: Mid-mesial region; d: Mid-distal region. Red measurement markers indicate the marginal gap at each respective location. Scale bars: 10 µm.

SEM: Scanning electron microscopy

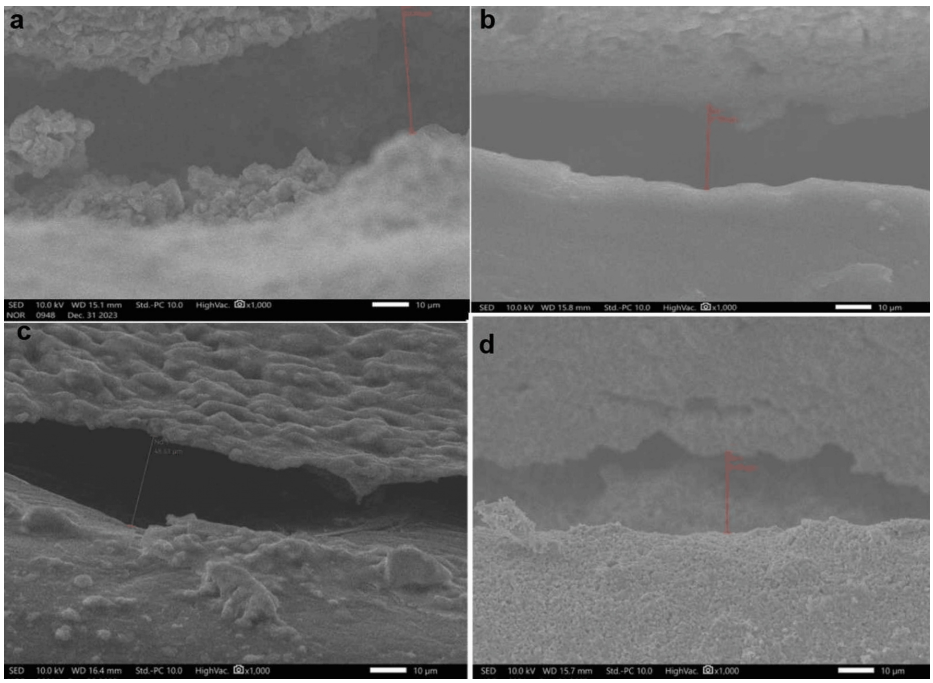

FIGURE 4: SEM images showing marginal-gap measurements at the crown-die interface in group III (zirconia) crowns (1000× magnification)

a: Mid-buccal region; b: Mid-lingual region; c: Mid-mesial region; d: Mid-distal region. Red measurement markers indicate the marginal gap at each respective location. Scale bars: 10 µm.

SEM: Scanning electron microscopy

Statistical analysis

The data were analyzed using SPSS Statistics version 20.0 (IBM Corp., Armonk, NY, USA). One-way ANOVA was used to compare marginal-fit measurements among the three groups, followed by Tukey's post hoc test for pairwise comparisons. Statistical significance was set at $p < 0.05$, with a 95% confidence level.

Results

Comparison of marginal fit among the three groups

The mean marginal-gap measurements were consistently lowest for PEEK crowns, followed by graphene crowns and zirconia crowns at all four measurement locations (Table *1*). The one-way ANOVA demonstrated statistically significant differences among the three groups at each location ($p < 0.001$). The highest mean marginal gap was observed in the zirconia group at the mid-buccal location (48.65 ± 6.02 µm), whereas the lowest was recorded in the PEEK group at the mid-distal location (24.86 ± 3.22 µm).

Measurement location	PEEK, mean ± SD (µm)	Graphene, mean ± SD (µm)	Zirconia, mean ± SD (µm)	F-value	p-value
Mid-buccal	25.98 ± 3.10	39.32 ± 5.31	48.65 ± 6.02	78.94	<0.001
Mid-lingual	25.04 ± 2.64	37.36 ± 4.70	46.70 ± 8.87	49.33	<0.001
Mid-mesial	25.97 ± 3.01	40.58 ± 6.67	45.50 ± 6.77	46.74	<0.001
Mid-distal	24.86 ± 3.22	35.08 ± 4.59	43.20 ± 7.53	43.14	<0.001

TABLE 1: Comparison of marginal-gap measurements among the three crown materials

Post hoc comparisons

Tukey's post hoc analysis showed statistically significant differences between PEEK and graphene crowns and between PEEK and zirconia crowns at all four measurement locations ($p < 0.001$). Comparisons between graphene and zirconia crowns were statistically significant at the mid-buccal, mid-lingual, and mid-distal locations. However, the difference between these two groups at the mid-mesial location was not statistically significant ($p = 0.061$) (Table *2*).

Measurement site	PEEK vs. graphene: Mean difference (µm)	p-value	PEEK vs. zirconia: Mean difference (µm)	p-value	Graphene vs. zirconia: Mean difference (µm)	p-value
Mid-buccal	−13.34	<0.001	−22.67	<0.001	−9.33	<0.001
Mid-lingual	−12.33	<0.001	−21.66	<0.001	−9.33	<0.001
Mid-mesial	−14.61	<0.001	−19.53	<0.001	−4.92	0.061
Mid-distal	−10.22	<0.001	−18.34	<0.001	−8.13	0.001

TABLE 2: Tukey's post hoc comparison of marginal-gap measurements among the three crown material groups

Post hoc Tukey p <0.05* considered statistically significant. Mean differences represent differences in marginal-gap measurements, expressed in micrometres (µm).

Discussion

Marginal adaptation is an important consideration in evaluating the performance and longevity of fixed dental restorations. Excessive marginal discrepancies may compromise the marginal seal, increase the exposure of the luting cement to oral fluids, and contribute to plaque accumulation and subsequent biological complications [3]. The present study compared the marginal adaptation of PEEK, graphene-containing, and zirconia crowns fabricated using CAD/CAM technology. The PEEK crowns demonstrated the lowest mean marginal-gap values across all four measurement sites, followed by graphene-containing and zirconia crowns. Differences among the three groups were statistically significant at every site ($p < 0.001$). Post hoc analysis revealed significant differences between PEEK and each of the other materials at all four sites. However, the difference between graphene-containing and zirconia crowns was not statistically

significant at the mesial site (p = 0.061). These findings indicate that marginal adaptation varied with the material used, although the differences were not uniform across all locations.

The superior marginal adaptation observed for PEEK in the present study is consistent with findings reported by Amalorpavam et al. [15], who observed lower mean marginal-gap values for PEEK copings than for zirconia copings. Similarly, Chouksey et al. [16] reported better marginal adaptation with PEEK at all four evaluated sites. Bae et al. [17] also found better marginal and internal fit for polyetherketoneketone (PEKK) copings than for zirconia. Although PEKK and PEEK belong to the same broader polymer family, they are distinct materials, and findings from PEKK cannot be directly extrapolated to PEEK. Nevertheless, these studies indicate that polymer-based restorative materials can demonstrate favorable marginal adaptation under particular fabrication conditions.

Conversely, the literature does not consistently favor PEEK over zirconia. Makky et al. [18] reported better marginal and internal fit for zirconia copings than for CAD/CAM-milled and pressed PEEK copings. More recently, Jangade et al. [19] found significantly lower marginal discrepancies with zirconia than with PEEK copings fabricated using a four-axis milling system. In contrast, Jayesh and Praveen [20] reported no statistically significant difference in marginal fit among PEEK, zirconia, and metal-ceramic crowns. These conflicting findings suggest that marginal adaptation cannot be attributed to material composition alone. Differences in scanning systems, milling equipment, bur dimensions, finish-line geometry, cement space, sintering procedures, and measurement protocols may contribute to the variation observed across studies. The present findings should therefore be interpreted in the context of the specific materials and experimental conditions evaluated.

Graphene-containing crowns exhibited intermediate marginal-gap values in the present study, with lower mean discrepancies than zirconia crowns at all four sites. The difference between these two materials was statistically significant at the buccal, lingual, and distal sites, but not at the mesial site. Consistent with the present findings, an in vitro investigation conducted by Rajesh et al. demonstrated significantly smaller marginal discrepancies in graphene-reinforced CAD/CAM crowns compared with prefabricated zirconia crowns used for primary molars [13]. This finding is directionally consistent with the present results, although differences in dentition, crown fabrication, and measurement methods limit direct comparison of the absolute values. The mechanical performance of a graphene-reinforced PMMA dental material was examined by De Angelis et al.; however, mechanical-property findings do not independently establish marginal accuracy [21]. Further research should evaluate the relationship between material composition, fabrication accuracy, and the clinical performance of graphene-containing restorations.

The measurement method also warrants consideration when comparing the findings with previous research. The validity and reproducibility of different methods for measuring marginal adaptation were reviewed by Nawafleh et al. [22], while Park et al. [23] conducted a comparative analysis of the silicone replica technique and three-dimensional superimposition methods. In the present study, SEM was used to assess marginal gaps at four predetermined locations. This approach enabled a standardized, site-specific comparison among the three groups. However, measurements obtained at discrete points cannot fully characterize the circumferential adaptation of a crown, and differences between measurement techniques may limit direct comparisons among studies.

The seating force applied during cementation may influence the final position of a restoration and consequently affect the measured marginal discrepancy. In the present study, manual finger pressure was used to seat the crowns; however, the applied force was not quantified. Variations in operator-applied pressure may therefore have contributed to differences in crown seating. Future investigations should employ a standardized loading device to control cementation pressure and improve measurement reproducibility.

The present investigation focused on marginal-gap measurements and did not include three-dimensional internal adaptation analysis or artificial aging procedures. Consequently, the findings represent the initial marginal adaptation of the crowns under laboratory conditions and do not establish their behavior following prolonged exposure to oral environmental challenges. Thermocycling may also influence the durability of the restorative interface. Alakeel et al. reported that thermocycling affected the bond strength between translucent zirconia and resin cement, highlighting the importance of evaluating restorative materials under simulated oral aging conditions [24].

A strength of the present study is the direct comparison of three restorative materials under a common experimental protocol, with equal group sizes and marginal-gap assessment at four anatomical locations. This design enabled both overall group comparisons at individual sites and the identification of site-specific differences that might be obscured by reporting a single mean value for each material. The inclusion of graphene-containing crowns alongside PEEK and zirconia also provides comparative evidence relevant to the evaluation of newer restorative materials.

Future studies should examine these materials using larger samples, standardized and instrument-controlled seating forces, and comprehensive three-dimensional assessment of marginal adaptation.

Thermomechanical aging, thermal cycling, and functional loading should be incorporated to investigate whether the observed differences persist under simulated oral conditions. Evaluations using extracted human teeth and different preparation designs would improve clinical relevance, while prospective clinical studies are needed to establish long-term performance and determine whether differences in marginal adaptation translate into meaningful clinical outcomes.

Limitations

Several limitations should be acknowledged. First, the in vitro design and use of a standardized typodont-derived model do not reproduce the anatomical variability and complex oral environment encountered clinically. Second, crown seating was performed using finger pressure, which may have introduced variation in the applied force and final seating position. Third, measurements were restricted to four predetermined sites and therefore did not represent the complete circumferential marginal fit. The study also did not evaluate internal adaptation, material aging, fracture resistance, or long-term clinical outcomes. All SEM measurements were performed by a single examiner using a standardized protocol. However, intra-examiner and inter-examiner reliability assessments were not performed. Therefore, potential examiner-related measurement variability cannot be completely excluded. Finally, the sample size of 15 crowns per group limits the generalizability of the findings. Accordingly, the results should be interpreted as a comparison of marginal adaptation under the conditions tested rather than definitive evidence of the overall clinical superiority of any one material.

Conclusions

Within the limitations of this in vitro investigation, PEEK crowns demonstrated lower marginal-gap measurements than graphene-containing and zirconia crowns at all four evaluated locations. Although statistically significant differences were observed among the restorative materials, these findings reflect marginal adaptation under the specific experimental conditions and should not be interpreted as evidence of superior long-term clinical performance. Further investigations incorporating artificial aging, mechanical testing, and clinical evaluation are necessary to establish the long-term behavior of these materials.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

Concept and design: Kuppala Venkata Sreekanth, Anjuru Sowmya, Bhavana K.V, Santosh Pusuluri, Anuja Singaraju

Acquisition, analysis, or interpretation of data: Kuppala Venkata Sreekanth, Anjuru Sowmya, Bhavana K.V, Santosh Pusuluri, Venkata Ratna Kumar Rudravaram, Deepthi Maya

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Disclosures

Human subjects: All authors have confirmed that this study did not involve human participants or tissue. **Animal subjects:** All authors have confirmed that this study did not involve animal subjects or tissue. **AI use statement:** The authors used ChatGPT and Microsoft Copilot as follows: language polishing, structure or formatting, drafting summaries in Introduction and discussion . The authors reviewed, edited, and validated all AI-assisted content. Facts, statistics, and references were cross-checked with the original scientific literature to ensure accuracy and reliability. Any necessary corrections were made prior to manuscript submission, and the authors accept full responsibility for the final content. The authors confirm that they have reviewed and verified all AI-assisted content and take full responsibility for the work. **Conflicts of interest:** In compliance with the ICMJE uniform disclosure form, all authors declare the following: **Payment/services info:** All authors have declared that no financial support was received from any organization for the submitted work. **Financial relationships:** All authors have declared that they have no financial relationships at present or within the previous three years with any organizations that might have an interest in the submitted work. **Other relationships:** All authors have declared that there are no other relationships or activities that could appear to have influenced the submitted work.

Acknowledgements

OpenAI's ChatGPT and Microsoft Copilot were used to support the drafting and editing of portions of this manuscript. The authors critically reviewed and revised all AI-assisted content, verified the accuracy of the scientific statements and references, and accept full responsibility for the final version of the manuscript.

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